Integration of Pumped-Heat-Electricity-Storage into Water / Steam Cycles of Thermal Power Plants

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Abstract

Due to the variable and intermittent nature of wind and solar, thermal plants are typically used as a backup for grid stabilization in periods of low or no wind or solar radiation. Therefore, thermal plant capacity is not directly displaced by renewables, thus resulting in an installed overcapacity of power generation systems. There are at least two main consequences of this renewable-driven overcapacity: First, existing thermal plants are underutilized and their operational utilization factors tend to decline with increased wind and solar integration. Second, installation of energy storage systems results in an additional overcapacity compared to the already existing one. Apart from that, there is a clear need for cost-effective energy storage systems to effectively adopt electricity provided by renewables to the demand side. Integrated-Pumped-Heat-Energy-Storage (I-PHES) technology aims at resolving these issues by making use of the existing, underutilized thermal plant assets, as a part of an energy storage system.

I-PHES consists of a heat pump cycle, converting the excess electricity into heat. The heat is stored and transferred to a thermal plant for reconversion into electricity when required. In addition to fuel savings and the increase of the capacity factor of the thermal plant, the benefits are mostly flexibility oriented such as power boost, lower load operation, faster start-up time etc. Integration of such storage systems into water / steam cycles allow to achieve round-trip-efficiencies of around 60%. Different I-PHES concepts related to water / steam cycles for creation of large-scale storage capacities are thermodynamically assessed and technical aspects discussed in order to evaluate the potentials of this technology.

Nomenclature

Variables		**Acronyms**	
E	Exergy	HP	Heat pump
COEP	Coeff. of exergetic performance	WSC	Water / steam cycle
COP	Coefficient of performance	H2P	Heat to power cycle
η_i	Energetic efficiency of process i	P2H	Power to heat cycle
η_s	Isentropic efficiency	PHES	Pumped-Heat-Electricity-Storage
η_{RT}	Round trip efficiency	I-PHES	Integrated Pumped-Heat-Electricity-Storage
P	Power output	RTE	Round trip efficiency
p	Pressure	TEES	Thermo-Electric Energy Storage
$\dot{Q}$	Heat flow	CSP	Concentrated Solar power
q	Specific heat	Full-PT	Complete preheating train
T	Temperature	HP-PT	High-pressure preheating train
ζ_i	Exergetic efficiency of process i	LP-PT	Low-pressure preheating train

Introduction

An economic and feasible technical solution on large-scale site-independent electricity storage is not yet available. The aim of the present work is the identification of the potentials of Pumped-Heat-Electricity-Storage systems integrated into water / steam cycles of thermal power plants by means of cycle studies.

Motivation

The storage of electricity in large-scale will be required in future in order to stabilize the electricity grid. In particular, it is reasoned by the increasing degree of integration of renewables –especially wind and solar power [1]. That means a more variable supply side has to be adapted to the demand side [2], [3], [4]. For this purpose, different types of storage technology are considered, which are topic of current research and development activities, refer to e.g. [5] and [6].

A potential alternative to storage systems is a more flexible demand side management. For example, certain electricity intensive industrial processes can be conducted only in times of high electricity generation. A more flexible demand side is a very cost-effective way to adapt to the future situation. It does only require an improved management, but it does not require the installation of new power generation plants or storage facilities. For this reason, electricity storage systems have to be cost-effective to be competitive. Consequently, different important design aspects are implied. First, a high storage efficiency –the so called round-trip-efficiency– is required. Second, the system complexity should be low in order to avoid installation of a high number of facility components. Third, the implemented components should not require the application of elaborated and therefore expensive materials. Fourth, a high degree of flexibility is necessary to respond on short-time fluctuations at the electricity supply side as well as at the demand side.

Electricity storage by intermediate conversion into heat –Thermo-Electric Energy Storage (TEES) – is one approach to create storage capacities for grid stabilization, see e.g. [7], [8]. The conversion of electricity into heat (P2H) can be realized in two ways. First, electric heaters can be used to generate heat via ohmic resistors. Second, electricity is converted into heat by utilization of a heat pump –so called Pumped-Heat-Electricity-Storage (PHES). In case of electricity demand, a heat to power cycle (H2P) reconverts stored heat. Pumped-Heat-Electricity-Storage is generally more promising for realization of high storage efficiencies compared to power to heat conversion utilizing electric heaters. Some approaches on PHES systems exist, which are dedicated to be small-scale stand-alone applications, see e.g. [9], [10], [11] & [12].

The increasing amount of generated wind and solar power also affects the operational requirements of thermal power plants [12]. Thermal plant capacity is not replaced one by one by renewables because it is required as a backup for grid reliability reasons. This results in an installed overcapacity of power generation systems. Existing thermal plants are underutilized and their capacity factors tend to decline with increased amounts of renewables. Therefore, different approaches to increase the utilization of existing facilities are considered. The integration of storage capacities into existing power plants is one of them. An example of a current idea of integrating storage capacities into concentrated solar power plants (CSP) is the application of an electric heater connected to the molten salt tanks [13].

The integration of Pumped-Heat-Electricity-Storage into power plants is an interesting option to increase the utilization factor of the power plant and to reduce costs of the storage system by usage of already existing devices.

Present research

The present research is about the potentials of integrating electricity storage capacities into existing power plants by utilization of heat pumps –Integrated-Pumped-Heat-Energy-Storage (I-PHES). In particular, I-PHES on large-scale water/steam cycles (WSC) is the focus of this work. Reason is that especially these types of WSCs have a low operational utilization factor or probably will have in future. A further reason is that the typical temperature ranges at which these cycles receive heat are within the feasible operational ranges of state-of-the-art air compressors, which are substantial part of the related heat pump cycles. CO2 compressors could theoretically be designed to achieve 600°C as well, according to [14] but the realization of such compressors is technically challenging; the current temperature limit is in range of 450-500°C [16]. Consequently, this technology has the potential to be applied without the requirement of extensive research on appropriate facility devices. Additionally, these cycles have a high nominal power output and are therefore promising for creation of large-scale storage capacities.

Many options for integration of limited amounts of heat from storage into WSCs are conceivable [15]. However, only few options for the integration of large amounts of heat are available. Two of these options –a high-temperature and a low-temperature concept– are assessed in detail, which are shown in Figure 1. Characterizing parameters of the WSC –considered as a reference for this study– are summarized in Table 1.

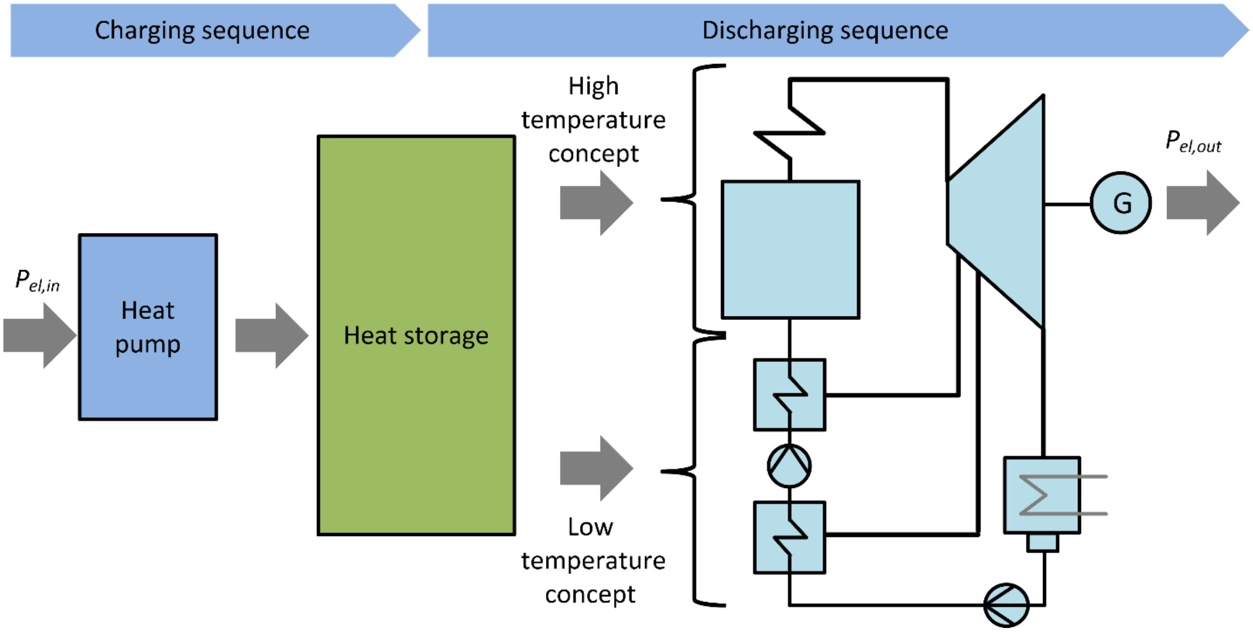

Figure 1: Basic configuration of the high- and the low-temperature I-PHES concept on water / steam cycles

First, a full heat supply of the plant from storage is considered. This option requires integration of a second steam generator into the WSC. In this case, fossil firing is not necessary during a discharging sequence. Molten salt heat storage is intended for applications on this high-temperature concept. Facility technology for molten salt, including the tank system, heat exchangers and steam generators, is state-of-the-art due to its standard application in concentrated solar power plants. The feasible operational range of molten salt mixtures fits well to the temperature ranges of the required heat for steam generation in WSCs with extended preheating trains.

Parameter	Variable	Value	Note
Nominal power output	P_{el}	≈ 900 MW	
Live steam temperature	T_{max}	≈ 600/620°C	Reheated cycle
Live steam pressure	p_{max}	≈ 285 bar	
High-pressure preheating train – outlet temperature	T_{HP}	≈ 300°C	3 HP preheaters
Low-pressure preheating train – outlet temperature	T_{LP}	≈ 160°C	5 LP preheaters

Table 1: Characterizing values of the reference water / steam cycle

Second, heat supply from storage to the preheating train of the WSC is considered in the low-temperature concept. In this case corresponding steam extractions are closed, increasing the power output of the turbine; the steam generator operates fossil-fired. Various options for specific combinations of supplied preheaters are available. Depending on the specific integration concept, it is possible to utilize pressurized water tanks for low-temperature heat storage. Equal to molten salt storage systems, this technology is available and cost-effective.

Two types of heat pump processes are considered for the above-mentioned purposes –a trans-critical process using CO_2 and super-critical processes using air or Argon. These fluids are proposed in literature for PHES applications, refer to e.g. [10], [11], [8]. Within this study, it is assessed which type of HP process (working fluid) is most suitable for the individual I-PHES application on WSCs. Design aspects and engineering challenges on CO_2 heat pumps are outlined.

Assessment Approach

In the following, the applied approach for the calculation of the round-trip-efficiency (RTE) of the storage systems is presented. Although, other measures like the costs are important as well, the RTE is an essential characteristic of an electricity storage system because it indicates the physical and technological potential of a specific concept and allows for direct comparison with other storage system approaches. Additionally, the heat pump model including the assumed parameters and boundary conditions is introduced.

Round-Trip-Efficiency

The round-trip-efficiency η_{RT} of any storage system is defined as the ratio of the useful quantity output E_{out} and input E_{in} within one charging and discharging cycle. Useful quantities of an electric storage system can be calculated by two parameters –the overall electric power output rate $P_{el,out}$ during the discharging sequence and the overall electric power input rate $P_{el,in}$ of a charging sequence

$$\eta_{RT} = \frac{E_{out}}{E_{in}} = \frac{\int_{t_{out}} P_{el,out} dt}{\int_{t_{in}} P_{el,in} dt}$$

Within this study, the system is assumed to operate at constant conditions. These conditions can either represent operation at nominal conditions or appropriate average values of dynamic operation. With the goal to estimate RTEs of the different concept designs for the purpose of comparison and estimation of the order of scale, this approach is considered sufficient. The overall storage process can be split into different sub-processes each of them associated with losses. Figure 2 shows the sub-processes involved in the I-PHES storage concept. Referring to this classification of the involved sub-processes, the RTE can be evaluated based on energetic or exergetic quantities according to

$$\eta_{RT} = \frac{E_{out}}{E_{in}} = \prod_i \eta_i = \eta_M \cdot COP \cdot \eta_{HP\rightarrow S} \cdot \eta_S \cdot \eta_{S\rightarrow WSC} \cdot \eta_{WSC} \cdot \eta_{Gen}$$

$$\eta_{RT} = \frac{E_{out}}{E_{in}} = \prod_i \zeta_i = \zeta_M \cdot COEP \cdot \zeta_{HP\rightarrow S} \cdot \zeta_S \cdot \zeta_{S\rightarrow WSC} \cdot \zeta_{WSC} \cdot \zeta_{Gen}$$

For the purpose of clarity, the exergetic efficiency of the heat pump is referred to as COEP in analogy to the coefficient of performance COP. The approach using exergetic quantities has some advantages and is applied in this study. In this approach, each efficiency measure of the sub-processes maximizes the

RTE if itself is maximized and states a clear measure for optimization purposes. In contrast, the COP does not state an efficiency measure with this property. Because of its thermodynamic definition, the COP decreases with increasing temperature spread of the heat pump. It is only a clear efficiency measure referring to storage systems if the quality of heat is specified preliminary by a defined temperature interval. With regards to the exergetic approach it is important to consider that the exergy –a measure for the potential of heat to power conversion in a specified environment- has to be related to the effective lower thermal potential created by the heat pump in case that a concept involves cold storage as well.

Figure 2 provides general value ranges of the exergetic efficiency measures of the different sub-processes, which are part of the storage concepts assessed in this study.

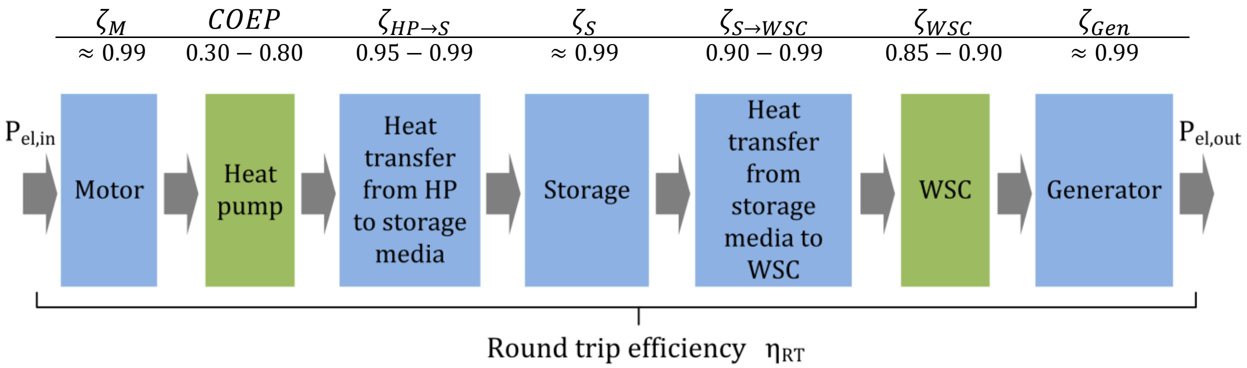

Figure 2: Defined sub-processes for the round-trip-efficiency evaluation & value ranges of the related exergetic efficiency measures for the investigated concepts

For storage concepts in which discharging sequences involve both –fossil firing and usage of stored heat– it is required to assign the corresponding parts of the steam turbine power output to the related energy inputs in order to identify the individual conversion efficiencies. This is essential to provide reliable estimates for the RTE achieved with the storage concept. It is assumed that the heat inputs and the related exergy inputs are converted into electricity with equal efficiency. Consequently, the individual exergetic conversion efficiencies of the heats are equal to the overall exergetic efficiency of the WSC. This is a reasonable assumption as long as the exergetic evaluation approach is applied. The reason is that the exergetic efficiency of the WSC does not include the Carnot-factor. Especially, if WSCs are considered, which release heat to the environment at temperatures very close to the ambient temperature (condenser), the exergetic efficiency of the WSC is almost a pure measure of internal irreversibilities. Two consequences can be derived from that. First, the overall exergetic efficiency is only modified (decreased) by increased internal losses caused by cycle modifications and / or related off-design operation. For I-PHES concepts including multiple heat inputs (low-temperature concepts), the decreased efficiency is evaluated using detailed WSC simulation models, which regard these modifications; the decrease of the exergetic efficiency in these cases is in range of less than 5% points. Second, the individual conversion efficiencies of the integrated heats of different qualities (temperatures) only distinguish in so far as they are subject to different irreversible (lossy) conversions inside the cycle. With regards to this, a clear thermodynamic distinction is not possible by simple means. A more reasonable solution might be derived using sophisticated theoretic approaches. For example, the average temperatures of the heat inputs can be considered as an appropriate quality measure and related to individual process internal losses.

Heat Pump Design and Modelling

Different options of heat integration into the WSC are assessed. Dependent on the specific integration option, the heat pump has to provide heat in an appropriate temperature range. A general heat pump configuration suitable for the purposes of the investigated I-PHES concepts is shown in Figure 3. The heat pump cycle includes a recuperator to allow for an optimized design concerning the temperature range of the required heat.

The parameters assumed for the heat pump model that are used within this study are summarized in Table 2. These assumptions and boundary conditions are applied for all concept assessments independent of the working fluid. Terminal temperature differences of all heat exchangers involved in the storage concept, apart from internal heat exchangers of the WSC, are presumed to be equal to 5 Kelvin.

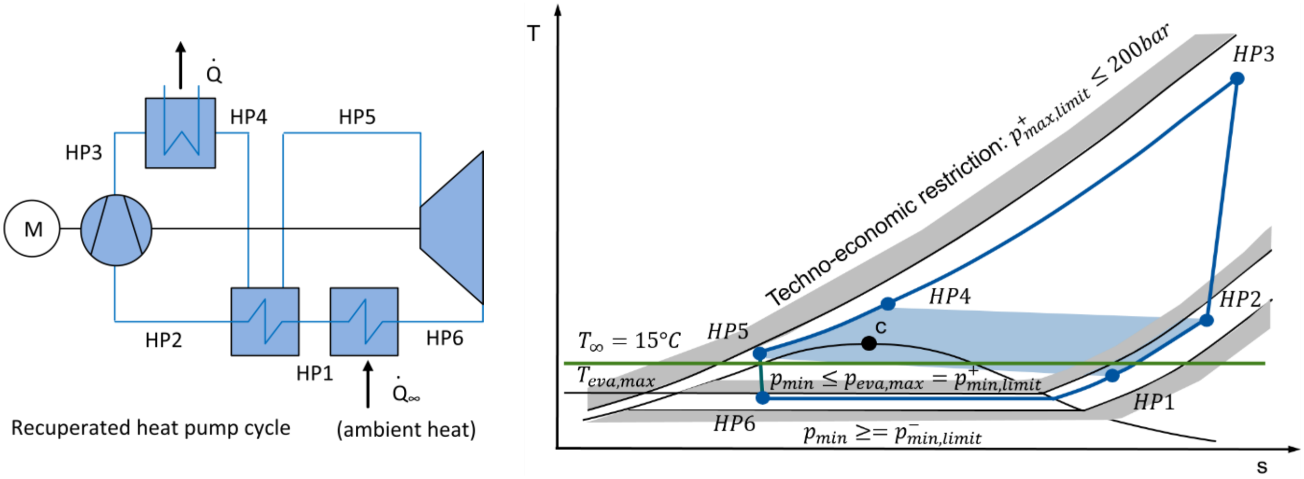

Figure 3: Heat pump configuration and related process design

Pressure losses inside the HP cycle are assumed negligible within this phase of comparative concept evaluation. The optimized design with regards to the chosen pressure level of the HP cycle is dependent on the working fluid and type of process (trans-critical / super-critical). Maximum HP efficiencies (COEP) are established at high-pressure levels if the working fluid is CO_2 for the cases regarded in this study. For techno-economic reasons the maximum allowed design pressure is limited to 200bar according to [14]. At even higher pressure levels the COEP can be increased by a few percent points, but the corresponding pressure levels are significantly above 200bar. Considering the requirement for a cost-effective HP design, it is reasonable to limit the maximum pressure. For air and Argon, the HP efficiency is almost independent of the design pressure level. The maximum HP efficiency tends to be highest at low pressure levels in the simulations. The lower pressure limit for all designs, relevant for the HP states between turbine outlet and compressor inlet, is set to 1bar. Thereby, it is taken into account that the sealing effort at pressures lower than ambient pressure is enhanced to avoid intrusion of ambient air into the cycle. Besides, high volume flow rates are limited and related large-sized facilities avoided.

A comparative evaluation of the round-trip-efficiency of different storage concepts involving different heat pump designs is only reasonable if the heat pump designs are specifically optimized on the defined application. As indicated above, different working fluids require different nominal process designs. Therefore, all HP cycle designs are individually optimized referring to the exergetic HP efficiency (COEP) according to their degrees of freedom within the specified boundary conditions (pressure ranges).

Parameter	Variable	Value	Note
Ambient temperature	T_∞	15°C	T_{ISO}
Temperature range of the provided heat	$T_{HP3} \leftrightarrow T_{HP4}$	predefined	boundary condition dependent on I-PHES concept and reference WSC parameters
Terminal temperature difference of heat exchangers	ΔT_{HEx}	5K	
Evaporator temperature difference	ΔT_{Eva}	≥ 15K	CO_2 heat pump only
Upper HP pressure level	$p_{max} = p_{HP3}$ $= p_{HP4}$ $= p_{HP5}$	variable / subject to optimization	$\leq p^{+}_{max,limit} = 200bar$
Lower HP pressure level	$p_{min} = p_{HP1}$ $= p_{HP2}$ $= p_{HP6}$	variable / subject to optimization	$\leq p^{+}_{min,limit} = p_{s,CO2}(T_\infty - \Delta T_{Eva}) =$ $34.85bar$ (CO_2 heat pump only) $\geq p^{-}_{min,limit} = 1bar$
Isentropic compressor efficiency	$\eta_{s,C}$	0.8	conservative estimate (mainly responsible for irreversibilities within the HP cycle)
Isentropic turbine efficiency	$\eta_{s,T}$	0.9	

Table 2: Heat pump design parameters and boundary conditions

High-temperature I-PHES concept

In Figure 4, the storage system configuration of the high-temperature I-PHES concept is presented. The T-s-Diagram shows the corresponding trans-critical heat pump cycle (HP), using the working fluid CO2, which is optimized (COEP) on the specific application. It can be observed that the HP cycle is characterized by a high degree of recuperation; the steam fraction at the turbine outlet is relatively low (≈70%). The process design is limited by the maximum pressure constraint of 200bar. A moderate pressure ratio of a value of roughly 7 is established. Figure 5 shows the estimated round-trip-efficiencies (RTE) of the concept. Using the working fluid CO_2, a RTE of about 63% can be achieved[1]. Using the working fluids air or Argon, which indicate a super-critical HP design, results in equal RTE values.

From the thermodynamic point of view, the working fluids and corresponding HP cycle designs are equivalent for this application, which requires explication: The fluid properties of CO_2 (location of the wet steam region) provide the desirable feature for the HP design that heat can be obtained at almost constant temperature. This allows to receive heat at an average temperature, which is very close to the temperature of the heat source (ambient heat). Therefore, usually high COEPs can be achieved compared to super-critical cycle designs. In this application, caused by the high maximum temperature

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[1] The application of the high-temperature I-PHES concept on combined cycle water /steam cycles was also assessed. These types of WSCs receive heat from the heat-recovery-steam-generator in range of approximetely 80°C to 600°C. The I-PHES concept is dedicated to use molten salt heat storage. The lower temperature limit of molten salt mixtures is usually in range of 250°C to 300°C. The mismatch of the temperature ranges results in significantly decreased exergetic heat transfer efficiencies between the storage medium and the WSC. Therefore, the achievable round-trip-efficiencies are in range of 52%. This is about 11% less compared to the application on the reference WSC, which includes an extended preheating train. Consequently, the application of the high-temperature I-PHES concept on combined cycle WSCs is significantly less promising from thermodynamic viewpoint.

of the provided heat of the HP, this effect is not significant compared to related super-critical HP cycle designs. Consequently, a trans-critical HP design is not necessarily indicated for this storage concept.

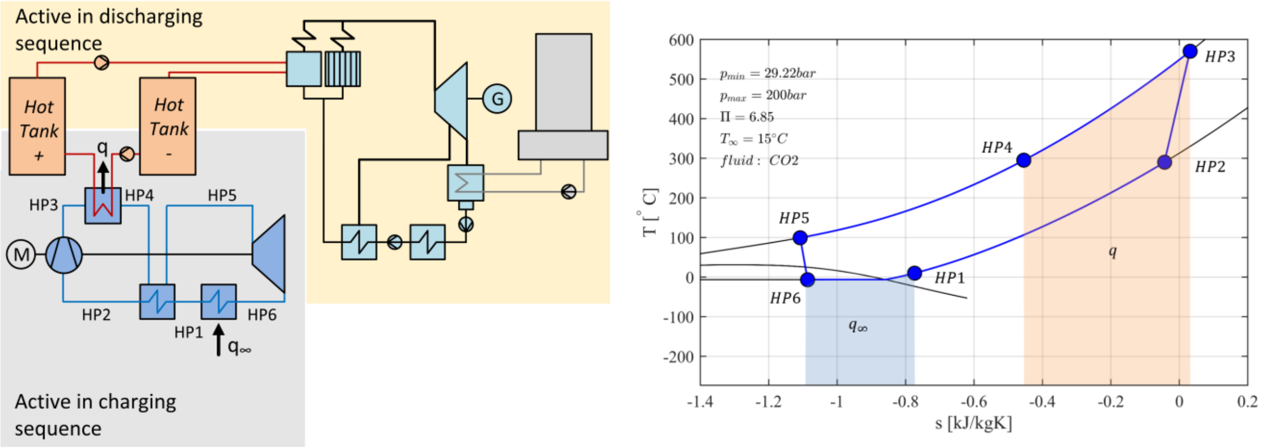

Figure 4: High-temperature I-PHES concept – System configuration and related heat pump process

Water / steam cycles are designed regarding the technical limitation caused by too low steam fractions at the turbine outlet to avoid erosion. The limit of the steam fraction is in range of 85-90% [17]. This limit is exceeded considering the trans-critical CO_2 HP cycle. For the low-temperature concepts, discussed in the next section, the steam fractions are even lower than 70%; in these cases, the expansion has to be established between the liquid state region and the wet steam region at very low steam fractions. Referring to literature, it could not be verified if it is technically possible to realize CO_2 turbines suitable for these applications. For this reason, the high-temperature concept is also assessed assuming that a throttle valve realizes the expansion. In this case, technical work cannot be recovered and the HP efficiency decreases.

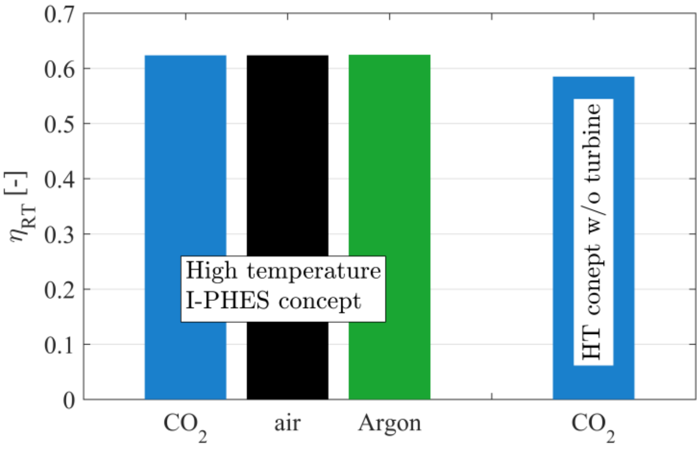

Figure 5: High-temperature I-PHES concept - Estimation of round-trip-efficiencies

A systematic study beyond the present storage system application shows that the COEP decreases by about 6-12% points dependent on the heat pump design if a throttle valve replaces the turbine. In the present case, the RTE of the complete storage concept decreases by approximately 4% points to a value of 59%. This means that the integration of an appropriate CO_2 turbine is important to establish high RTEs.

Figure 6 shows the configuration of two further –more complex– high-temperature concepts.

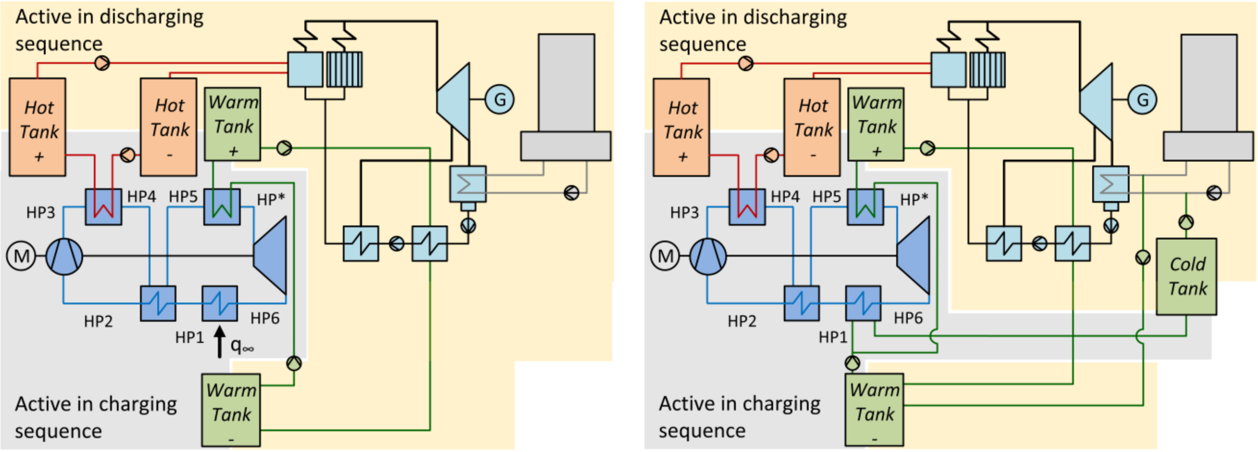

Figure 6: High-temperature I-PHES concept – Design modifications

The idea applied in both concepts is to extract additional low-temperature heat from the heat pump cycle downstream of the heat pump recuperator. This heat is stored in pressurized water tanks for the supply of the first preheaters of the WSC during a discharging sequence. By this means the discharge power rate can be increased. A thermodynamic assessment shows that this feature has no impact on the round-trip-efficiency. On the one hand, a higher amount of useful heat (exergy) is extracted from the HP cycle. On the other hand, the potential for expansion inside the turbine is decreased and less work is recovered. The two effects are compensating each other, resulting in the same HP efficiency as in the initial concept. The efficiency of the WSC is almost equal compared to the initial concept so that the same round-trip-efficiency is established. The significant increase of the system complexity and thereby enhanced costs without generating an efficiency benefit do not make this concept considerable.
This concept, including low-temperature heat extraction, as well as the following one, can only be realized using the working fluid CO_2. A temperature of approximately 100°C is present on the hot side outlet of the recuperator, which allows for low-temperature heat extraction. Reason is the strong dependency of the specific heat capacity of CO_2 on temperature. For the super-critical HP cycles, using air or Argon, the corresponding temperature is very close to the ambient temperature so that low-temperature heat cannot be extracted effectively.
The concept configuration on the right side of Figure 6 is dedicated to additionally exploit the lower thermal potential created by the HP process [18]. It includes cold storage of pressurized water for application as condenser cooling water at the WSC during a discharge sequence. The idea is thermodynamically reasonable in order to increase the thermal potential for heat to power conversion inside the WSC by decreasing the condenser temperature. The assessment of the concept shows that the potential of cold pressurized water cannot effectively be transferred to the WSC. The temperature available at the condenser cooling water inlet is almost equal to the temperature, which can be established by the re-cooling unit (cooling tower). The reason is the terminal temperature differences of the involved heat exchangers that increase the temperature of the cold water stepwise during the transfer process. Consequently, a RTE identical to the initial concept can be established and realization of this very complex concept is not reasonable.

Low-Temperature I-PHES concept

A series of low-temperature I-PHES concepts –characterized by heat integration into the preheating train of the reference WSC during a discharging sequence– is assessed. The assessed cases differ in the number and positions of the supplied preheaters in the preheating train and consequently require different HP designs. Figure 7 shows the system configuration and the corresponding T-s-diagram of the optimized CO_2 heat pump cycle for the case of complete supply of the low-pressure preheating train (LP-PT).

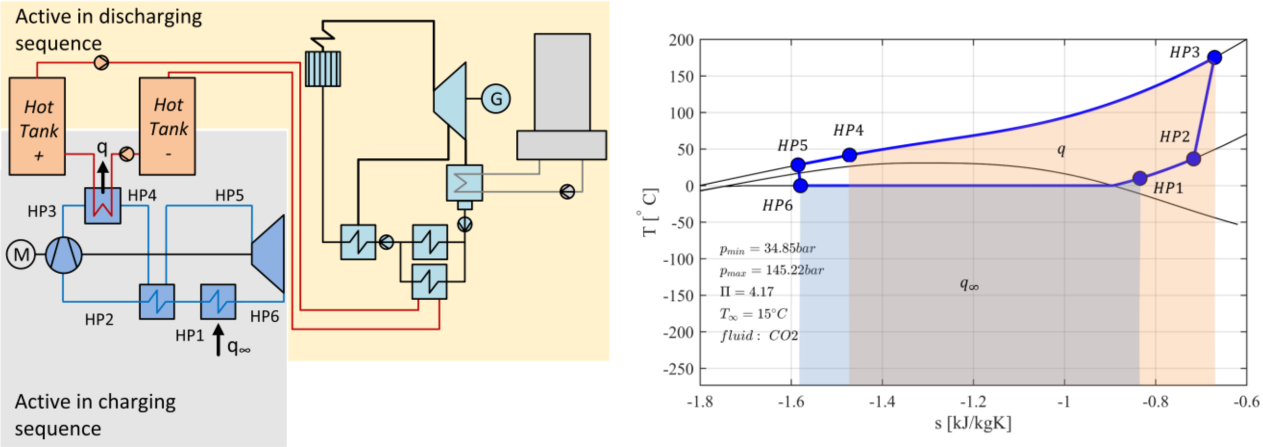

Figure 7: Low-temperature I-PHES concept – System configuration and related heat pump process (HP case: full supply of the low-pressure preheating train (LP-PT))

The heat pump processes distinguish strongly concerning the specific integration option into the preheating train; the maximum temperature as well as the degree of internal recuperation are different. Figure 8 shows the estimated RTEs of different integration options. Maximum RTEs of about 58% can be achieved using CO_2 heat pumps; the variation of the RTEs is high. The lowest RTEs of only 20-30% are present if only the first preheaters of the low-pressure preheating train are supplied; the highest RTEs can be established if heat is integrated into preheaters of the high-pressure preheating train (HP-PT), only.

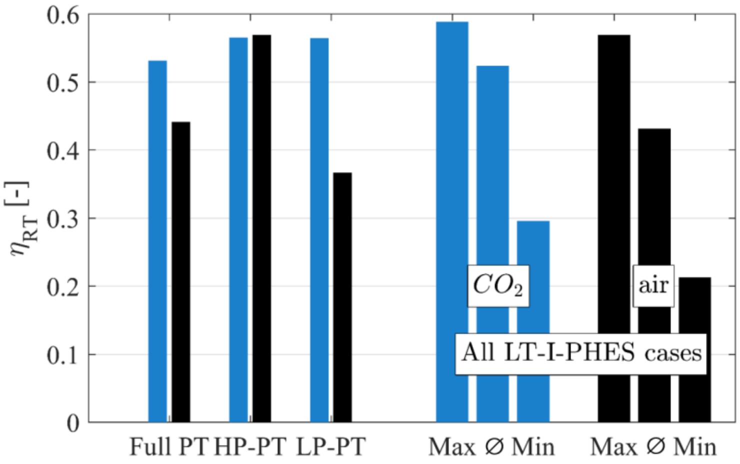

Figure 8: Low-temperature I-PHES concept - Estimation of round-trip-efficiencies

For this I-PHES concept, CO_2 heat pumps are superior to air or Argon heat pumps. The difference of the average RTE values of all 15 integration options analyzed in this study differ by 10% (CO_2 compared to air). This aspect strongly indicates CO_2 HP applications for this type of I-PHES concept.

Three specific integration options are depicted explicitly in Figure 8 – the full supply of the preheating train (Full-PT), the complete supply of the high-pressure preheating train (HP-PT) and the complete supply of the low-pressure preheating train (LP-PT). The most promising option is the complete supply of the low-pressure preheating train. Here, a RTE of about 56% can be achieved and expected costs are comparatively low because of the moderate maximum temperatures of the HP, which is below 200°C. A further reason is that the technical risk is lower compared to integration options including supply of any high-pressure preheaters. If high-pressure preheaters are supplied, the closing of the corresponding steam extractions leads to increased steam mass flows through the reheat section of the fossil-fired steam generator. Consequently, the internal thermal conditions of the steam generator are changed significantly.

Discussion

The round-trip-efficiency of the high-temperature I-PHES concept was evaluated to 62%; the maximum RTEs of the low-temperature concept are about 58%. The thermodynamic assessment approach includes simplifications like disregarding pressure losses etc. Therefore, it is reasonable to consider lower RTE values for practically realizations of the concepts. A realistic range for the achievable RTEs is probably 50-60%; a more precise determination of the practically achievable RTE requires a more detailed cycle analysis.

The presented assessment of the two I-PHES concepts bases on the application on a reference WSC of high efficiency. Dependent on the type and specific design of the power plant, WSCs distinguish significantly with regards to their characterizing parameters like the live steam pressure and temperature. For example, these parameters are lower for WSCs of concentrated solar power plants and waste-to-power plants. The assessment of the application of the I-PHES concept at WSCs with reduced thermodynamic parameters shows that the achievable round-trip-efficiencies tend to be lower. Considering the high-temperature concept, the achievable heat pump efficiencies are lower because the maximum temperature of the heat required by the WSC is decreased. At maximum temperatures in range of 400°C instead of 600°C, the COEP of the heat pump is approximately 5% (CO_2) to 7% (air, Argon) points lower. However, the main reason for the decreased RTE is the lower exergetic efficiency of the WSCs, which are usually less sophisticated from technical point of view, if the plants are designed for lower live steam parameters. Along with the high-temperature concept, RTEs of above 50% are realizable. Similar conclusions can be made for the low-temperature concept.

The HP cycle design for the high-temperature concept does not require realization of trans-critical processes using CO_2 to establish high round-trip-efficiencies. Super-critical cycles using air or Argon are equally suitable and are potentially more cost-effective because they do not involve evaporators and multiphase heat exchangers.

A further potential advantage of super-critical HP designs is the probably higher flexibility with regards to start-up times. Electricity storage technology will not necessarily be operated over long periods at nominal load in certain markets. Consequently, the involved heat pumps might require flexible load changing abilities. Operation is then characterized by short periods of charging and discharging. Short-start up times are required to respond effectively to the current situation on the electricity market. Besides, it is desirable to keep start-ups short, because the heat pump does not operate in the design point –at best efficiency- within this time. Additionally, heat is not provided at nominal conditions, which further decreases the overall efficiency. If typical start-up times of gas turbines of about 10 to 20 minutes are assumed for super-critical HP cycles, trans-critical HP cycles will probably be less fast. Reason is the slow response time of the included evaporator. In general, it is questionable if start-up times of at least 10-20 minutes are sufficient for storage systems required to respond quickly. This topic is not yet addressed in literature related to Pumped-Heat-Electricity-Storage. Nevertheless, a study on this topic is indicated for the mentioned reasons.

High system response times at discharging sequences are also required. In the high-temperature I-PHES concept a molten salt steam generator has to be started. Pre-warming for a fast start-up is required. But presuming appropriate pre-warming it still has to be verified, which start-up times can be realized.

For the low-temperature concept, the situation is more promising concerning discharging response times. Considering the WSC to operate fossil-fired already in times of high electricity demand, a cold start-up of the pressurized water preheaters connected in parallel to the original preheating train can be realized. Fast closing of related steam extractions should also be possible without significant constraints.

CO_2 as a HP working fluid and a related trans-critical cycle design is clearly indicated in order to achieve a high round-trip-efficiency along with the low-temperature concept. This is in contrast to the findings on the high-temperature concept and clearly points to the favorable application range for CO_2 HPs involved in electricity storage concepts. A rough estimation of the maximum temperature limit ranges between 200-300°C considering thermodynamic and economic aspects.

The efficient design of low-temperature HPs requires turbine designs, which allow expansion from the liquid state region into the wet steam region at low steam fractions. The design of suitable turbines, which are able to operate at these conditions, might be technically challenging.

In [11] it is referred to a study which reveals that turbo devices using CO_2 can potentially be designed at higher efficiencies compared to air devices at the same boundary conditions. The assessments of this study do not take this aspect into account –the assumed compressor and turbine efficiencies are independent of the fluid type. This indicates even clearer the application of CO_2 HPs within the low-temperature concept. Regarding the high-temperature concept it might lead to slightly increased RTEs compared to the utilization of air but does not make the application of CO_2 preferable if the other discussed aspects are still considered.

As the heat source of the heat pump is the environment, changes of the environmental temperature have a direct impact on the heat pump performance. The estimated RTEs presented in this paper refer to heat pump designs optimized for an environmental temperature of 15°C; this is a low value for many locations. Two effective measures are appropriate to keep the heat input at design conditions if the environmental temperature changes; both measures can be applied separately or in combination. First, ground heat can be used; by this means the heat pump performance is less affected by the local average temperature level and variations of the temperature as well. Second, the mass flow on the warm side of the heat exchanger can be controlled appropriately. In case of increased environmental temperatures, the heat flow has to be decreased to establish design conditions at the heat exchanger outlet on the heat pump fluid side. This can be realized if the mass flow on the warm side is reduced; accordingly, the driving temperature difference is modified. The application range of this approach is dependent on the design terminal temperature difference of the heat exchanger.

Considering the discussed technical aspects, a further necessary step is an economic assessment of the I-PHES concepts in order to investigate if a business case can be created for this technology. This analysis should not only be related to the storage system itself but also regard benefits on the operational utilization factor and the field of use of under-utilized water / steam cycles in general.

Additionally, a more detailed thermodynamic and technical assessment of the system is indicated which goes beyond a basic cycle analysis like presented here. Part load characteristics and dynamics of the involved cycles should be analyzed concerning realistic operational scenarios.

Summary

A concept for the integration of electric storage capacities into water / steam cycles based on Pumped-Heat-Electricity-Storage (PHES) was presented. The utilization factor and the flexibility of water / steam cycles of thermal power plants can be increased hereby. The concept was assessed with regards to the achievable round-trip-efficiencies and technical aspects. These aspects were comparatively analyzed with regards to the heat pump working fluids CO2 (trans-critical cycle design), air and Argon (super-critical cycle designs). The concepts include a high-temperature and a low-temperature configuration.

Molten salt heat storage is intended to be utilized in the high-temperature configuration. The heat is used for steam generation in the water / steam cycle during a discharging sequence. It could be shown that equal round-trip-efficiencies can be realized for all heat pump working fluids and the corresponding processes (trans-critical/ super-critical). CO_2 is therefore not preliminary preferable for the application in the high-temperature concept. Other technical aspects (e.g. start-up times) point to the conclusion that super-critical heat pump cycles might be more reasonable for application. The estimated round-trip-efficiency of this storage concept is 62%.

Several low-temperature configurations were assessed. The low-temperature concept is dedicated to integrate stored heat into the preheating train of the water / steam cycle during a discharging sequence. For this application, CO_2 heat pumps are clearly preferable to air heat pumps. The assessment showed that round-trip-efficiencies up to 58% are possible using CO_2 heat pumps. Supply of the complete low-pressure preheating train was identified to be the most promising configuration. Reason are the high round-trip-efficiency of approximately 56% and the low technical risks for practical realization.

It was found that the promising temperature application range for CO_2 heat pumps in connection with Integrated-Pumped-Heat-Electricity-Storage (I-PHES) is below 300°C.

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