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## Conceptual study of central receiver systems with liquid metals as efficient heat transfer fluids

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### Abstract

Concentrated Solar Power plants (CSP) provide several advantages to other energy conversion concepts. However, they are still not competitive in price, compared to conventional power plants. But there is still potential to reduce the cost. The higher heat conductivity of liquid metals leads to very high heat transfer coefficients – ten times higher as with molten salts. This big advantage could increase the efficiency and lower the cost of CSP plants. In order to optimize such a power plant regarding efficiency and cost, detailed information of each component of the system is necessary. This paper shows several system concepts in which liquid metals can be used as heat transfer fluid. In addition, several liquid metal pump types are investigated as well as thermal energy storage concepts. With the assumptions and boundary conditions taken in this model, direct thermal energy storage with liquid metal is prohibitive. But some innovative indirect storage systems with liquid metals show costs in the same range as with a 2-Tank molten salt storage.

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*Keywords:* Central Receiver System; Heat transfer fluid; Liquid metal; thermal storage.

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## 1. Introduction

One promising option of renewable power generation are Central Receiver Systems. Such power conversion systems often use molten salts both as heat transfer and thermal energy storage material. Examples for current solar towers with molten salt are SolarTwo (1995), Gemasolar (2011) and Crescent Dunes (2014). Molten salts are cost-efficient and not toxic. Furthermore, their high heat capacity and low costs make them suitable as thermal storage material. But they have also some disadvantages inherited. The melting point is above 200 °C. This means high parasitic losses for trace heating. In addition, the upper cycle temperature is limited to about 565 °C due to the chemical decomposition. In reality, the mean receiver outlet temperature is even lower in order to avoid local temperatures above the decomposition temperature in hot spots on the receiver. By using liquid metals these disadvantages could be avoided. The main advantage of liquid metals are their heat transfer coefficients, which are an order of magnitudes higher than that for molten salt [1]. This could increase the receiver efficiency. Moreover, the higher temperatures allow advanced power conversion cycles with increased efficiency. Therefore, the possibility of cost reduction exists, despite the higher costs of liquid metals. The ECOSTAR-study from 2005 estimates the levelized cost of electricity (LCOE) for a 50 MW<sub>el</sub> solar tower plant with molten salt technology to 0.15 €/kWh<sub>el</sub> [2]. Recent calculations of a power plant with the same power output combined with a liquid metal receiver with an ultra-supercritical steam cycles have indicated a reduction potential regarding LCOE of about 15 %, compared to the ECOSTAR molten salt concept [3].

In order to determine the LCOE, annual yields calculation of the particular concept is necessary. This requires efficiency values and cost data for all components of the power plant, especially for part load situations.

### Nomenclature

D	[mm]	diameter of tube
u	[m/s]	velocity of flow
ε	[mm]	roughness of inner tube surface

## 2. Physical properties and advantages of liquid metals as heat transfer fluid

Figure 1 shows on the left the usable temperature range (liquid phase) of several liquid metals compared to solar salt. The alkali metals and the Lead-Bismuth-Eutectic have lower melting points. This means additional hours of operation during times of low radiation and therefore a higher capacity factor of the receiver, but also lower parasitic losses for trace heating. Above 565 °C, solar salt becomes decomposed. Liquid metals, however, stay chemically stable even at higher temperatures. This makes highly efficient thermodynamic power conversion cycles possible.

The main advantage of liquid metals is the heat transfer coefficient. Figure 1 shows on the right the temperature dependent heat transfer coefficient for a single tube with  $D = 12$  mm,  $u = 1$  m/s und  $\epsilon = 0.1$  mm. For a temperature of 400 °C, molten salt has about 4600 W/m<sup>2</sup>/K, whereas over 50000 W/m<sup>2</sup>/K can be achieved with liquid sodium. In principle, there are two different options with a higher heat transfer coefficient: First, staying at the same heat flux density or increasing the latter.

At the same flux density, the higher heat transfer coefficient will decrease the thermal gradient of convection on the inner tube wall surface. This will also reduce tube wall temperature and the risk of temperature hot spots and thus pipe stresses as well. The lower tube wall temperature also increases life span at lower material costs [4]. The lower the receiver temperature the lower are thermal losses by radiation and convection, so higher receiver efficiency is obvious.

Higher flux densities lead to smaller receivers for the same power output. The reduction of absorber surface decreases material and manufacturing costs. According to preliminary receiver performance studies, liquid sodium leads to an absorber area reduction of up to 57 %, compared to solar salt [1]. In addition, due to the absorber area reduction, radiation and convection losses might also decrease. Hence, both options imply higher receiver efficiencies and performance.

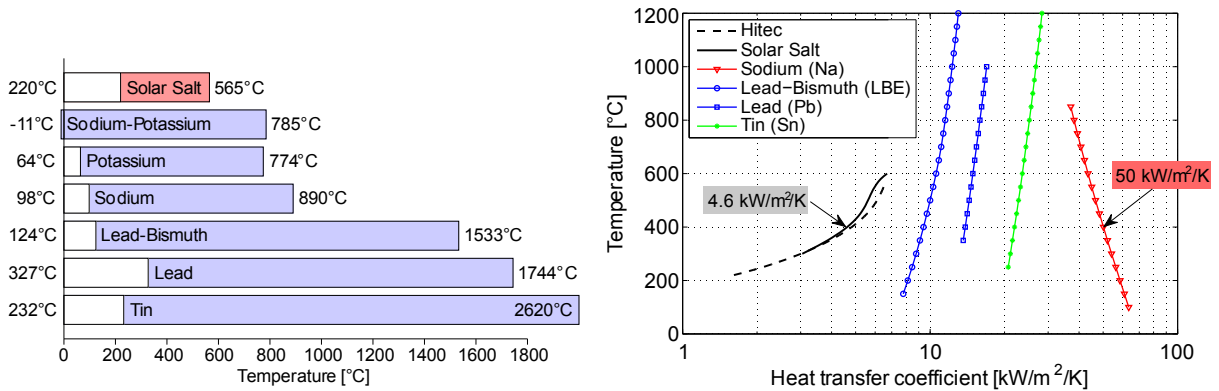


Fig. 1: (left) useable temperature range; (right) Heat transfer coefficient for tubes with  $D = 12$  mm,  $u = 1$  m/s und  $\epsilon = 0.1$  mm.

### 3. Technological concepts for large scale power plants with liquid metal receivers

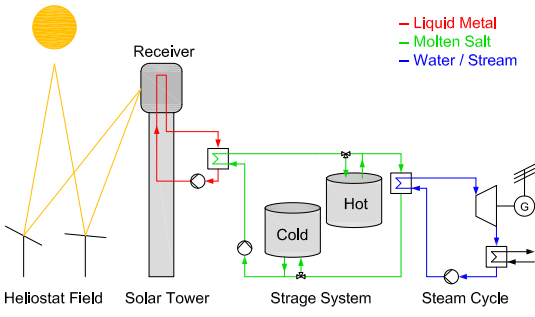
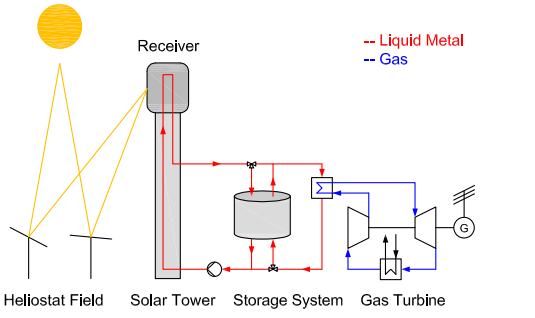
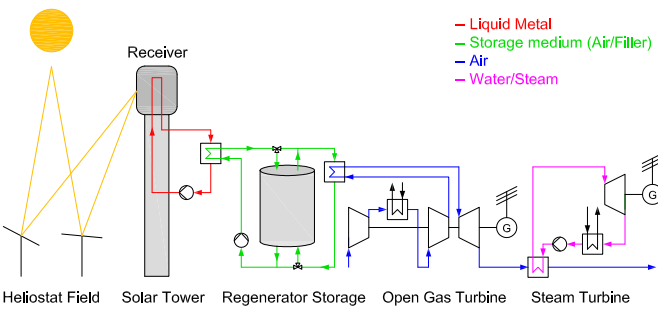
Chapter 2 describes thermodynamic and economic advantages of liquid metals due to their physical properties. In order to make full use of these advantages, correspondent technological concepts must be created. In thermodynamic terms the power conversion efficiency raises with higher temperatures. Considering that higher investment costs might be involved, this potential advantage could be eradicated. The success of liquid metal technology in solar power systems is heavily dependent on the system layout. This chapter classifies the liquid metal concepts in two categories: conventional systems with today available power blocks and innovative systems with up to now only in laboratory scale tested power conversion.

#### 3.1. Conventional power blocks

The most obvious concept is the adaptation of a molten salt system by merely changing the receiver to a liquid metal receiver. Directly after the receiver, the liquid metal transfers the heat to the molten salt storage in an additional heat exchanger. According to the energy demand, the molten salt transfers the thermal energy across the steam generator to the steam turbine (see table 1, sketch 1). Potential candidates of liquid metals for this application are sodium, potassium, lead-bismuth-eutectic (LBE) and tin. For higher temperatures the solar salt storage system needs to be replaced by a high temperature storage system. For example a direct energy storage with liquid metal as heat transfer fluid. In this case, there is no need for an additional heat exchanger which simplifies sketch 1. Another option is a regenerator storage with gas/air or the CellFlux storage concept [5]. But for the CellFlux storage concept, again, a high temperature heat exchanger is necessary.

The connection to a gas turbine (table 1, sketch 2) makes higher temperatures inevitable. This makes a thermal storage with Solar Salt prohibitive. As before a direct storage with liquid metal is possible, but in most of the cases they tend to be too expensive (see chapter 5). However, a thermal storage in a regenerator system with gas/air or with the CellFlux storage concept is also possible. For a closed gas turbine cycle a direct contact heat exchanger (DCHX) can be installed, according to the combination of liquid metal and gas. This option might increase the efficiency, too. The alkali metals, reactive as they are, will not react with any noble gas like helium (He), neon (Ne), argon (Ar), krypton (Kr) and xenon (Xe), but also not with nitrogen ( $N_2$ ) [6]. These gases are therefore suitable for DCHX. For lead or lead-bismuth a DCHX is even possible with water/steam [7]. The combination of gas- and steam turbines in a combined-cycle plant achieves very high system efficiencies. This concept is also applicable to a liquid metal receiver (see table 1, sketch 3).

Table 1: System concepts with liquid metal receiver and conventional power blocks

Concept sketch	Name and properties
 <p style="text-align: center;"> <span style="color: red;">—</span> Liquid Metal  <span style="color: green;">—</span> Molten Salt  <span style="color: blue;">—</span> Water / Stream         </p> <p style="text-align: center;">           Heliostat Field    Solar Tower    Storage System    Steam Cycle         </p>	<p><b>Steam turbine (Rankine cycle)</b></p> <p>Subcritical or supercritical steam</p> <p>Lower temperature: 290 °C</p> <p>Upper temperature: 565 °C (Molten salt storage) 640 °C (Liquid metal storage)</p> <p>Liquid metal candidates: Na, NaK, K Pb, Pb-Bi, Sn</p>
 <p style="text-align: center;"> <span style="color: red;">—</span> Liquid Metal  <span style="color: blue;">—</span> Gas         </p> <p style="text-align: center;">           Heliostat Field    Solar Tower    Storage System    Gas Turbine         </p>	<p><b>Gas turbine (Brayton cycle)</b></p> <p>Open or closed cycle</p> <p>DCHX possible for closed cycle</p> <p>Liquid metal candidates: Up to 850 °C: Na, Pb, Pb-Bi, Sn Above 900 °C: Pb, Pb-Bi, Sn</p>
 <p style="text-align: center;"> <span style="color: red;">—</span> Liquid Metal  <span style="color: green;">—</span> Storage medium (Air/Filler)  <span style="color: blue;">—</span> Air  <span style="color: magenta;">—</span> Water/Steam         </p> <p style="text-align: center;">           Heliostat Field    Solar Tower    Regenerator Storage    Open Gas Turbine    Steam Turbine         </p>	<p><b>Combined cycle with Gas turbine (Brayton cycle)</b></p> <p>Thermal storage with liquid metals + filler material or air in a regenerator storage system</p> <p>Liquid metal candidates Up to 850 °C: Na, Pb, Pb-Bi, Sn Above 900 °C: Pb, Pb-Bi, Sn</p>

### 3.2. Innovative power conversion systems

There are several innovative systems for energy conversion with liquid metals. The two most promising concepts are AMTEC-cells (Alkali metal thermal to electric converter) and LMMHD power conversion systems (Liquid metal magnetohydrodynamic), see table 2, sketch 1 and 2.

The principle of AMTEC is predicated on a sodium beta"-alumina solid electrolyte ceramic called BASE. This ceramic is a conductor of positive ions but an insulator to electrons. In the receiver, the sodium vaporizes and its pressure increases. Due to the pressure difference across the BASE and its differential conductivity between electrons and ions, the sodium ions are diffused through the BASE to the cathode while the electrodes provide a conduction path for the free electrons to pass instead through the external load doing work on their way to the cathode where they are recombined with the ions to reform neutralized sodium vapour. At the cold side, the sodium condenses and the cycle restarts again. The AMTEC device is characterized by high potential efficiencies and no moving parts except the liquid metal itself. It accepts a heat input in a range from about 600 – 1000 °C and produces direct current with predicted device efficiencies of 10 – 30 % [8]. It can be used as a topping cycle with a bottoming Rankine cycle (see table 2, sketch 1).

The LMMHD is another promising option for power conversion. This generator produces electric power by an accelerated conducting fluid through a magnetic field. Thus, the conversion of energy is thermal to kinetic to electric. In order to accelerate the liquid metal flow, there are several possibilities. In a one-component flow, the liquid metal becomes partially gaseous in the receiver. The occurring density difference accelerates the liquid metal flow. In a two component operation, the thermodynamic working fluid (gas/steam) and electrodynamic fluid (liquid metal) are mixed. As mentioned before, possible combinations are alkali metals with helium or argon, but also lead or lead alloys with water. This mixer is similar to a direct contact heat exchanger and acts in fact like a pump. In well-designed cycles even natural circulation is possible [9]. The expansion of the gas drives the liquid metal across the magnetic field in the MHD channel, generating electric power. Then, the two phases are separated and the cycle can restart. The LMMHD generator can be used as a topping cycle with a bottoming Brayton or Rankine cycle, depending on the choice of working fluid. Like with the AMTEC device, the LMMHD generator has no moving parts. For the two component operation, relatively low temperatures are possible. The theoretical efficiencies of the device can exceed 60 % [11,12,13]. In laboratory scale, a LMMHD generator achieved already a measured efficiency of 48 % with a power output of 10.8 kW [10].

Table 2: Innovative power conversion systems

Concept sketch	Name and properties
	<p><b>AMTEC cell in the receiver</b></p> <p>Only for alkali metals (Na, K, NaK)</p> <p>Heat input: 600 – 1000 °C</p> <p>Molten salt storage and bottoming Rankine cycle</p> <p>Predicted efficiency: 10 – 30 % [8]</p>
	<p><b>LM MHD Generator</b></p> <p>2-phase liquid metal flow:</p> <ul style="list-style-type: none"> <li>Temperature &gt; <math>T_{\text{boil}}</math></li> <li>Liquid metal candidates: Na, NaK, K</li> </ul> <p>2-component flow: Liquid metal + Gas/Steam</p> <ul style="list-style-type: none"> <li>Temperatures: 350 – 800 °C</li> <li>Liquid metal candidates: All proposed</li> </ul> <p>Predicted efficiency: Up to 60 % [10,11,12]</p> <p>Measured efficiency: 48 % at 10.8 kW [10]</p>

#### 4. Pumping technology for liquid metals

For our purpose three groups of pumps are considered - Electromagnetic pumps (EMP), Mechanical pumps (MP) and Air lift pumps. EMP are using electrical conductivity of liquid metals to generate force. Nowadays, there are two main groups of EMP - conduction and induction pumps. In conduction pumps external magnetic field directed perpendicularly to conduction current, which is applied by electrodes attached to the wall of the flow duct. For DC

current conduction pumps special power supply is necessary which can provide several thousands of amps current with fraction of volt voltage. Design of such power supply requires special attention. The benefit of using AC current conduction pumps is easier generation of high-current, low-voltage feeding, e.g. by use of transformers. Conduction pumps can develop higher pressure than induction pumps, because it is possible to supply higher currents. However, they are usually limited in flow rate [13]. In induction pumps currents within the liquid metal are induced by means of alternating magnetic field. The driving forces are created by interaction of induced currents and magnetic field. The windings, which generate magnetic field, are usually connected in poly-phase, thus creating traveling magnetic field. There are two most usual types of induction pumps with static windings - Flat Linear Induction Pump (FLIP) and Annular Linear Induction Pump (ALIP). In FLIP the windings are placed on either side of the channel, or in one sided FLIP windings are placed on one side of channel and ferromagnetic yoke on the other one. Such geometry leads to more uniform field distribution in channel and to easier replacement possibilities, as windings can be removed without disassembling the channel. In ALIP windings surround the annular pipe with ferromagnetic core in centre of annulus. ALIP have usually higher efficiency than FLIP. At high flow rates the efficiency of induction pumps exceed the efficiency of conduction pumps. However, they are limited in developed pressure [13]. The efficiency of EM pumps is below 40% for alkali metals and below 10% for heavy metals, like Lead or Lead-Bismuth. MP have main benefit in comparison to EM pumps - the efficiency is reasonably higher, it may vary between 60% and 90% depending on the operating conditions and pump type. The most important advantage, however, is significant base of knowledge and experience, even in liquid metal pumping. On the other hand, weakest point of those pumps are mechanical seals and bearings. As seal is the part of the pump that fails most frequently, use of MP is limited for alkali metals. Furthermore, these pumps require lubrication and regular maintenance. Additional disadvantage is the erosion and corrosion within the pump housing. MP that are suited for liquid metals are commercially available on the market, with many companies offering solutions for lead, zinc, aluminium, tin, etc. However, no mechanical pumps are found on the market for alkali metals. In air lift (or gas lift) pumps air bubbles act like a pistons, pushing liquid up along the piping. In other words - gas-liquid mixture is less dense than liquid and therefore is pushed upwards. They are normally used only where small heads are required. Centrifugal blowers typically operate at pressures below 1bar and are effective and inexpensive way to pump air. Therefore this type of pumping is cheap and reliable. Pump has no moving parts and is therefore long-living and stable in operation. On the other hand, these pumps have several disadvantages. First of all - cost of compressed air, which is high in comparison with amount of pumped liquid, therefore efficiency is relatively low, typical efficiency is 30-55%. Furthermore - efficiency decreases rapidly with increase of flow rate [14]. Their flow rate and developed head are strongly limited, furthermore precise flow control is hard to achieve due to non-linear air flow/liquid flow dependence. After passing the active pumping region, not all gas is still removed from liquid. Different efficiencies of the pumps might be misleading, because main losses of EM pumps is dissipated in heat, which is recoverable in power plant applications. In [15] it is estimated that impact on overall plant efficiency due to efficiency differences of EMP and MP is 0.4%. Therefore efficiency of EMP should not be a main criterion for the choice of a pump. On the other hand losses in air lift pumps are not connected with heat generation and therefore cannot be recovered, except the LM MHD, where it is used as thermodynamic working fluid (see chapter 3.2). Table 3 shows constructed liquid metal pumps with detailed information

Table 3: Constructed liquid metal pumps with their main data.

Pump type	Liquid	$T_{work}$ [°C]	$\Delta p$ [bar]	$Q_p$ [m <sup>3</sup> /h]	$P_{ei}$ [kW]	Efficiency	Application and Reference
DC	Na	410	5.17	1885	540	50 %	Intended for EBR-II reactor (1955) [16]
ALIP	Na	410	5.17	1885	600	45 %	Intended for EBR-II reactor (1955) [16]
ALIP	Na	335	2.8	9600	1680	45 %	Built in 1998. Largest flow rate EM pump [17]
FLIP	Na	370	2.76	273	70	36 %	Built in 1953 [18]
Centrifugal	Na	500	2.2	1500	118	82 %	Sodium pump in Hallam Nuclear Facility [19]
PMP	Pb-Bi	400	3.5	3.6	-	-	Installed at the liquid metal plant at ENEA research center in Brasimone (Italy) [20]
ALIP	Pb-Bi	320	1	15	5.3	8.1 %	Lead-bismuth target complex TC-1 [21]

## 5. Thermal storage concepts for liquid metal systems

In comparison to other renewable energies solar thermal power plants offer an important advantage due to the simple energy storage system which compensates fluctuations in the solar radiation. In theory, full dispatchability with operation 24h/day is possible. For this reason, the electricity production is not linked to the instantaneous irradiation. The Gemasolar power plant for example contains a molten salt storage system and can produce electricity for up to 15h without solar irradiation [22]. As mentioned before the temperature of molten salt is limited to about 565 °C, due to the chemical decomposition. If higher temperatures are involved, alternative storage media have to be used. The success of a storage technology basically depends on the storage costs. The 2-Tank molten salt storage of the SolarTwo power plant for example, indicates storage costs of about 23 €/kWh [23]. In order to detect storage costs for liquid metal systems, a model with different storage options was developed.

### 5.1. Storage modelling

The storage model in this paper analyses four different storage concepts: 2-Tank, Thermocline with floating baffle, Thermocline with a filler material/matrix and a segmented Thermocline storage with a filler material/matrix. The idea of the latter is to reduce the amount of expensive liquid metal drastically and replace it with a low cost solid filler material or a matrix. For this reason, the storage container in the segmented storage type is divided in several compartments, which are insulated (see figure 2 on the right). During storage charging the hot liquid metal flows across one compartment and transfers the heat to the filler material. This procedure can be repeated until all compartments are hot. In discharging mode cold liquid metal flows through the compartments where the filler material transfers its heat to the liquid metal. Figure 2 shows sketches of the investigated storage concepts. The boundary conditions are based on the publications of thermal storage systems from NREL [24,25]. In all cases the design and the calculations were made for a 10 h storage system of a 125 MW<sub>el</sub> power block with 40 % efficiency.

The 2-Tank system is composed of a hot storage tank and a cold storage tank. In this model, both are constructed in the same way, except the inliner material which is made of steel with higher temperature resistance for the hot tank. The Thermocline storage without matrix or filler material contains an insulated floating baffle (see middle of figure 2), which separates the hot part of the storage from the cold part. In this model five different heat transfer fluids are investigated (Solar Salt, Sodium, Lead, Lead-Bismuth-Eutectic and Tin) as well as three different matrix/filler materials, namely Graphite, Quartzite and Aluminium oxide. For both the Thermocline and the segmented storage type, the volume fraction of the filler material/matrix is fixed to 0.75.

The cost of the segmented storage depends on the number of compartments. For one single compartment, there is no difference to the Thermocline with filler material, so only variations with more than one compartment are considered for the segmented type. For each combination of heat transfer fluid and filler material there is one number of compartments at optimal cost. This work only compares the segmented storage types with optimal number of compartments to the other storage concepts.

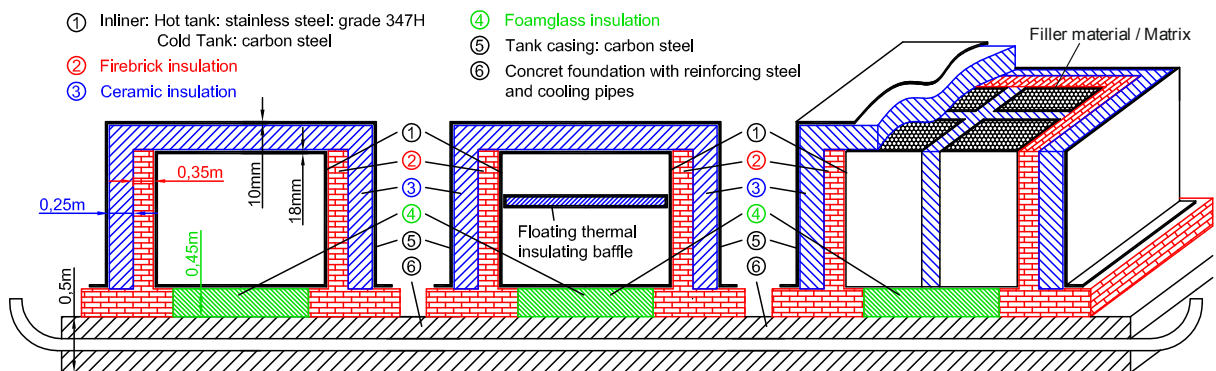


Fig. 2: (left) 2-Tank storage; (middle) Thermocline storage with floating baffle; (right) Segmented storage type with filler material / matrix.

Measurement instrumentation for control of operation as well as pipework and valves are neglected in this storage model. All storage types have the same wall thickness (see figure 2) despite different storage tank sizes and different hydrostatic pressure depending on the storage concept and the chosen liquid metal. The lower temperature is related to 250 °C, except for heat transfer fluids with higher melting points. In these cases, the lower temperature is set to the melting temperature with an additional safety distance (table 4). The cost of the storage system depends mainly on the used material data. The physical properties of the heat transfer fluid and the insulation and construction material are measured values and accessible in publications. But the cost data of heat transfer fluids always changes with time, thus it's very difficult to get significant values. However, the cost assumptions given in table 4 are the result of an intensive literature research, averaging and personal talks with related experts.

Table 4: Heat transfer fluid and filler material data with storage model assumptions [24 - 31]

Heat transfer fluid	Solar Salt (NaNO <sub>3</sub> /KNO <sub>3</sub> )	Sodium (Na)	Lead (Pb)	Lead-Bismuth (LBE)	Tin (Sn)	Graphite (C)	Quartzite (98% SiO <sub>2</sub> )	Aluminium oxide (85% Al <sub>2</sub> O <sub>3</sub> )	
Upper temperature [°C]	565	640	640	640	640				
Lower temperature [°C]	250	250	350	250	250				
Density [kg/m <sup>3</sup> ]	1831	802	9967	9660	6330	2500	2651	3560	
Heat capacity [kJ/kg/K]	1.51	1.25	0.15	0.15	0.24	0.71	1.2	1.2	
Cost [€/kg]	1	2.6	1.6	12	18	1.5	0.5	1	
Hot Tank material: Grade 347H stainless steel		3.7	€/kg	Ceramic insulation				1.1	€/kg
Cold Tank: Grade 70 carbon steel		0.8	€/kg	Foamglass insulation				260	€/m <sup>3</sup>
Casing (carbon steel)		0.6	€/kg	Welding				1000	€/m <sup>2</sup>
Fire brick insulation wall		1.5	€/kg	Assembly of Isolation				100	€/m <sup>2</sup>
Fire brick insulation bottom		1.5	€/kg	Assembly of Firebricks				100	€/m <sup>3</sup>
Concrete foundation: reinforcing steel / cooling pipes		150	€/m <sup>3</sup>	Installation concrete slab: reinforcing steel / cooling pipes				100	€/m <sup>3</sup>

## 5.2. Results of the storage model

Figure 3 shows the result for a 10 h storage system for a 125 MW<sub>el</sub> power conversion system, thus thermal storage energy in the range of 3500-4000 MWh<sub>th</sub>, depending on the efficiency and parasitic losses of the storage system. The first result is that direct thermal storage with liquid metals in a 2-Tank or Thermocline doesn't make sense in an economical point of view. The storage costs of a 2-Tank configuration with the boundary conditions from table 4 rises up to 700 €/kWh<sub>th</sub> (see figure 3 on the left). The cheapest liquid metal is sodium, but direct storage costs are still nearly twice the number of a solar salt direct storage system.

The right chart in figure 3 shows only cases with storage costs below 30 €/kWh. It is important to note that sodium stays below this border for all storage types. Moreover, only for direct storage in 2-Tank or Thermocline storage molten salts are cheaper. In every other combination (indirect storage), liquid sodium shows slightly cheaper values than solar salt. However, the figure shows that thermal storage with heavy metals is not easy. There are only a few indirect storage types with Quartzite or Aluminium oxide which show both costs below 30 €/kWh, but they are still more expensive than molten salt direct storage types. In all cases, the cheapest storage systems are those with Quartzite as filler material.

The lower cycle temperature for the storage systems is set to 250 °C (see table 4). This lower temperature depends on the power conversion cycle but also on the melting point of the heat transfer fluid. The latter limits the lower temperature of solar salt, but some liquid metals offer potential if the lower cycle temperature can be decreased (see figure 1 on the left). Despite this cost reduction potential of liquid metal based storage, additional research and experiences are necessary for a detailed assessment. Transient behaviour, oxidation and contamination as well as corrosion effects have probably a wide influence on the storage system.



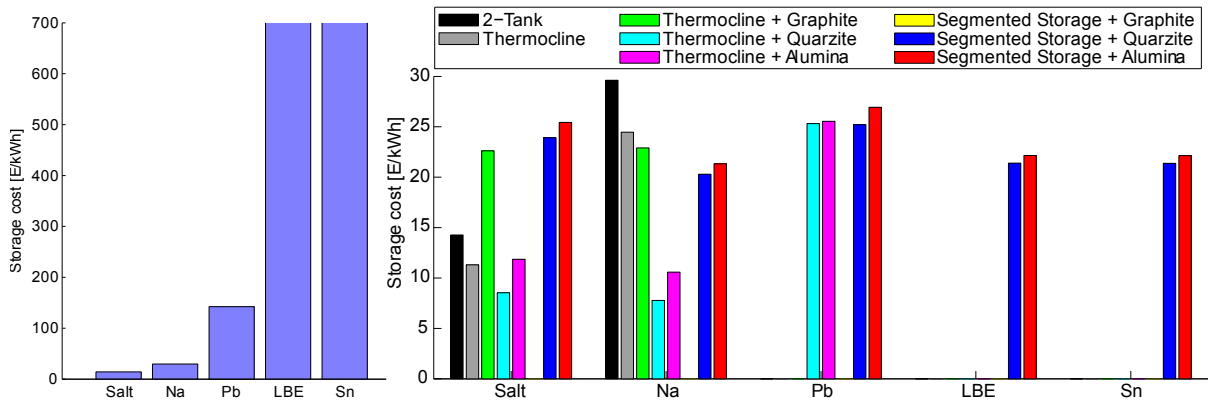


Fig. 3: Storage costs of 10h storage for 125 MW<sub>el</sub> power block. (left) 2-Tank direct storage. (right) All storage types with costs below 30 €/kWh<sub>th</sub>.

## 6. Experimental validation system

Parallel to this preliminary design study for commercial scale CSP plants, validation tests are currently in preparation. CFD simulations with liquid metals in a single tube under radiation to one side are carried out with experimental validation to get values for Nusselt correlations and pressure drop. Additionally, a small demonstration system in the 10 kW<sub>th</sub> range with Lead-Bismuth as heat transfer fluid is currently under erection at Karlsruhe Institute of Technology (KIT). The preliminary basic design of the test loop involves a liquid metal receiver, liquid metal piping, liquid metal based storage, flow control, liquid metal pumping, auxiliary heating systems and monitoring systems. These components will be tested using concentrating radiation sources (solar spectrum) in the range of 1000 kW/m<sup>2</sup> to demonstrate feasibility of a Lead-Bismuth loop under solar radiation. Several operating conditions (full load, part load) are conducted to get information about the heat transfer for different radiation ratios.

## 7. Conclusions

Based on previous investigations with liquid metals as heat transfer fluid in CSP plants [32], this paper goes into detail with liquid metal pumping technology and liquid metal based storage concepts. For all considered liquid metals, a suitable thermal storage system could be detected with costs in the same range as with a 2-Tank molten salt storage system. However, this thermal storage model is based on assumptions. Additional research and experiences are necessary for a detailed assessment in order to determine the real cost of liquid metal based storage. Transient behaviour in charging and discharging mode, high temperature valve reliability, oxidation and contamination of the liquid metal as well as corrosion effects are questions of further research activities.

In order to optimize CSP systems regarding LCOE, annual yields calculations are necessary. This requires efficiency values and cost data for all the components of a CSP plant (heliostat field, receiver, pumping, heat exchanger, thermal storage and the power block).

This paper shows promising liquid metal concepts for energy conversion. Further steps are a detailed receiver model for liquid metals and a power block calculation and optimization tool with adapted operational strategies. After this, detailed concept analysis can be conducted in order to assess liquid metal technology in CSP systems.

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## References

- [1] Boerema N., Morrison G., Taylor R., Rosengarten G.; Liquid sodium versus Hitec as a heat transfer fluid in solar thermal central receiver systems. *Solar Energy* 2012; Vol.86/2293-2305
- [2] Pitz-Paal R., Deutsches Zentrum für Luft- und Raumfahrt; ECOSTAR: European Concentrated Solar Thermal Road-Mapping, Roadmap Document, 2005
- [3] Singer Cs., Buck R., Pitz-Paal R., Müller-Steinhagen H.; Assessment of Solar Power Tower Driven Ultrasupercritical Steam Cycles Applying Tubular Central Receivers With Varied Heat Transfer Media. *Journal of Solar Energy Engineering* 2010; Vol.132/041010
- [4] Boerema N., Morrison G., Taylor R., Rosengarten G.; High temperature solar thermal central-receiver billboard design. *Solar Energy* (2013); Vol.97/356-368
- [5] Steinmann W., Laing D., Odenthal C.; Development of the CellFlux storage concept for sensible heat. *Journal of Solar Energy Engineering* 2014; Vol. 136/011011, pages 1-8
- [6] Anderson F.; A primer for the safe use of liquid alkali metals, OAK Ridge national laboratory, reactor division; January 1967
- [7] Abdulla S H., Liu X, Anderson M.H., Bonazza R., Corradini M.L., Cho D., Page R.; Liquid-Metal/Water Direct Contact Heat Exchange: Flow Visualization, Flow Stability, and Heat Transfer Using Real-Time X-Ray Imaging; *Nuclear Science and Engineering / Volume 150 / Number 2 / Pages 182-220*; June 2005
- [8] Wu S., Xiao L., Cao Y.; A review on advances in alkali metal thermal to electric converters (AMTECs). *International Journal of Energy Research* 2009; Vol33/868-892
- [9] Saito M., Nakamura, Nezu A., Kamiyama K. and Fujii Y. Basic study on liquid-metal MHD power generation system using two-phase natural circulation. *MHD –International Conference, Volume1, Chapter 19, 165-175*; 1996
- [10] Elliott D.; Direct Current Liquid-Metal Magnetohydrodynamic Power Generation. *AIAA Journal* 1966; Vol.4, No.4
- [11] Branover H., El-Boher A., Greenspan E., Barak A. Promising applications of the liquid metal MHD energy conversion technology. *Energy Conversion Engineering Conference, IECEC-89., Proceedings of the 24th Intersociety*; Pages 1051 - 1058 vol.2; 1989
- [12] Petrick M. Liquid-metal magnetohydrodynamics, *IEEE Spectrum* Volume2, Issue 3; Pages 137-151; 1965
- [13] Baker R. and Tessier M., *Handbook of electromagnetic pump technology*. New York: Elsevier Science Publishing Co.Inc, 1987.
- [14] Reinemann D., Parlange J., and Timmons M., "Theory of small-diameter airlift pumps," *Int.J. Multiphase Flow*, vol. 16, pp. 113-122, 1990.
- [15] Cage J.F. Jr., *Electromagnetic pumps for large pool-concept LMFBR.*; General Electric Co., Technical Report.
- [16] Blake L.R. Conduction and induction pumps for liquid metals. *Proceedings of the IEE - Part A: Power Engineering*, 104:49–67; 1957.
- [17] Ota H., Katsuki K., Funato M., Taguchi J., Fanning A., Doi Y., Nibe N., Ueta M. and Inagaki J. Development of 160m<sup>3</sup>/min large capacity sodium-immersed selfcooled electromagnetic pump. *Nuclear Science and Technology*, 41:511–523; 2004.
- [18] Polzin K.A. Liquid metal pump technologies for nuclear surface power. In *Proceedings of Space Nuclear Conference*, June 2007;
- [19] Smith P.G. Experience with high-temperature centrifugal pumps in nuclear reactors and their application to molten salt thermal breeder reactors. *Technical Report ORNL-TM-1993, NASA*; 1967.
- [20] Bucenicks I.E. High pressure and high flowrate induction pumps with permanent magnets. *Magnetohydrodynamics*, 39:411–417; 2003.
- [21] Gromov B.F. Development of molten lead-bismuth target complex tc-1 for the lancee-accelerator. *Technical Report ORNL-TM-1993, State Scientific Center of Russian Federation, Institute for Physics and Power Engineering*; 2001.
- [22] Burgaleta J.I., Arias S. and Salbidegoitia I. B.: Operative Advantages of a Central Tower Solar Plant with Thermal Storage System. *Proc. 15th Int. SolarPACES Symposium*, 15.-18. Sept., Berlin; 2009.
- [23] Reilly H. E. and Kolb G. J. An Evaluation of Molten-Salt Power Towers Including Results of the Solar Two Project. *Sandia National Laboratories, Albuquerque, NM Report No. SAND2001-3674*, November 2001.
- [24] Kelly, B. Kearney D. Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System. *Subcontract Report NREL/SR-550-40166*; July 2006
- [25] Jonemann M. Advanced Thermal Storage System with Novel Molten Salt. *Subcontract Report NREL/SR-5200-58595*; May 2013
- [26] Pacheco J.E., Ralph M.E., Chavez J.M., Dunkin S.R., Rush E.E., Ghanbari C.M. and Matthews M.W.; Results of Molten Salt Panel and Component Experiments for Solar Central Receivers, Department of Energy, Sandia National Laboratories; January 1995
- [27] Geyer M.A.; *Thermal Storage for Solar Power Plants*, Ch. 6 of C.-J. Winter, R.L.Sizmann, L.L. Vant-Hull (Eds.), *Solar Power Plants*, Springer-Verlag, New York; 1991.
- [28] Pacio J., Singer Cs., Wetzel Th., Uhlig R.; Thermodynamic evaluation of liquid metals as heat transfer fluids in concentrated solar power plants; *Applied Thermal Engineering* 2013, Vol.60; 295-302
- [29] Forsberg C.W., Peterson P.F., Zhao H.; High-Temperature Liquid-Fluoride-Salt Closed-Brayton-Cycle Solar Power Towers; *Journal of Solar Engineering* 2007, Vol. 129; 141-146
- [30] Li P.W., Lew J.V., Karaki W., Chan C.L., Stephens J. and O'Brien J.E.; Transient Heat Transfer and Energy Transport in Packed Bed Thermal Storage Systems; *Developments in Heat Transfer*, Chapter 20, 373 – 416.
- [31] Pacheco J.E., Showalter S.K., Kolb W.J.; Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants; *Journal of Solar Energy Engineering* 2002, Vol. 124, 153 – 159.
- [32] Pacio J., Fritsch A., Singer Cs., Uhlig R.; Liquid metals as efficient coolants for high-intensity point-focus receivers: implications to the design and performance of next-generation CSP systems. *Energy Procedia* 2014, Vol. 49; 647.–655.