# Concepts for Cost Reduction in CSP Power Plants

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*Abstract*

In solar thermal power plants concentrating collectors are used to provide the high-temperature heat for the power plant. There are a number of different concepts available in which the heat transfer fluid is either directly used in the power plant cycle (e.g. water vapor), or alternatively a secondary cycle with a different fluid (e.g. thermal oil) is used to collect the solar energy. To date, especially parabolic trough systems that use synthetic thermal oil as heat transfer medium are the dominant technology in the market. However alternative approaches that use other concentrator geometries (like central receiver tower power plants) and /or alternative heat transfer fluids are increasingly showing up. The lecture introduces two different concepts that use molten salt as heat transfer as well as storage medium. Technological strengths and weaknesses as well as expectations with respect to efficiency and cost are discussed.

## 1. Introduction to CSP Technology

Concentrating Solar Thermal Power (CSP) systems use high temperature heat from concentrating solar collectors to generate power in a conventional power cycle instead of - or in addition to - burning fossil fuel. Only direct radiation can be concentrated in optical systems. In order to achieve significant concentration factors sun-tracking is required during the day, involving a certain amount of maintenance. Therefore, the concept is most suitable for centralized power production, where maintenance can be performed efficiently, and in areas with high direct solar radiation levels. The benefit of this technology option compared to the utilization of photovoltaic cells that convert solar radiation to electricity directly is that the high temperature heat can be easily stored by putting the heat transfer fluid in large containers so that the electricity generation can be effectively shifted and performed during high demand times. In particular if high shares of intermittent renewable electricity (by wind and PV) are integrated into the electricity grid part of the input may be curtailed as it does not match the demand so that a shift of the production is desired. In contrast to electric storage, where the inclusion of storage capacity always leads to higher investments and higher electricity prices, CSP systems with storage are potentially cheaper than CSP systems without storage. This becomes clear when comparing a solar power plant without storage of e.g. 100 $MW_{el}$ capacity that is operated approx. 2000 equivalent full-load hours per year at a typical site to a system with half the capacity (50 $MW_{el}$) but the same size solar field and a suitable thermal energy storage. In this case the smaller power block is used for 4’000 equivalent full load hours so that both systems can produce the same amount of electricity per year. Assuming low storage costs, the investment in the second system could potentially be lower than the no-storage design. In addition the power could be sold more flexibly at times of

high revenue rates. The relative size of storage, collector field and turbine is used to match the power output of the system for different load situations as illustrated in figure 1.
In the next section of this paper, state of the art of solar thermal power systems that is based on parabolic trough technology using thermal oil as heat transfer fluid is summarized. It covers today more than 85% of all commercial installations. In this concept, the integration of thermal storage is done through heat exchange with a separate fluid cycle using molten salt as storage media. Future efficiency increase and cost reduction is anticipated if the salt would also be used directly as heat transfer fluid. This concept has been used in first commercial installations in solar tower designs as discussed in subsequent section. Also the replacement of the thermal oil in parabolic trough with molten salt is under consideration in current research and demonstration projects. Challenges und benefits are discussed accordingly.

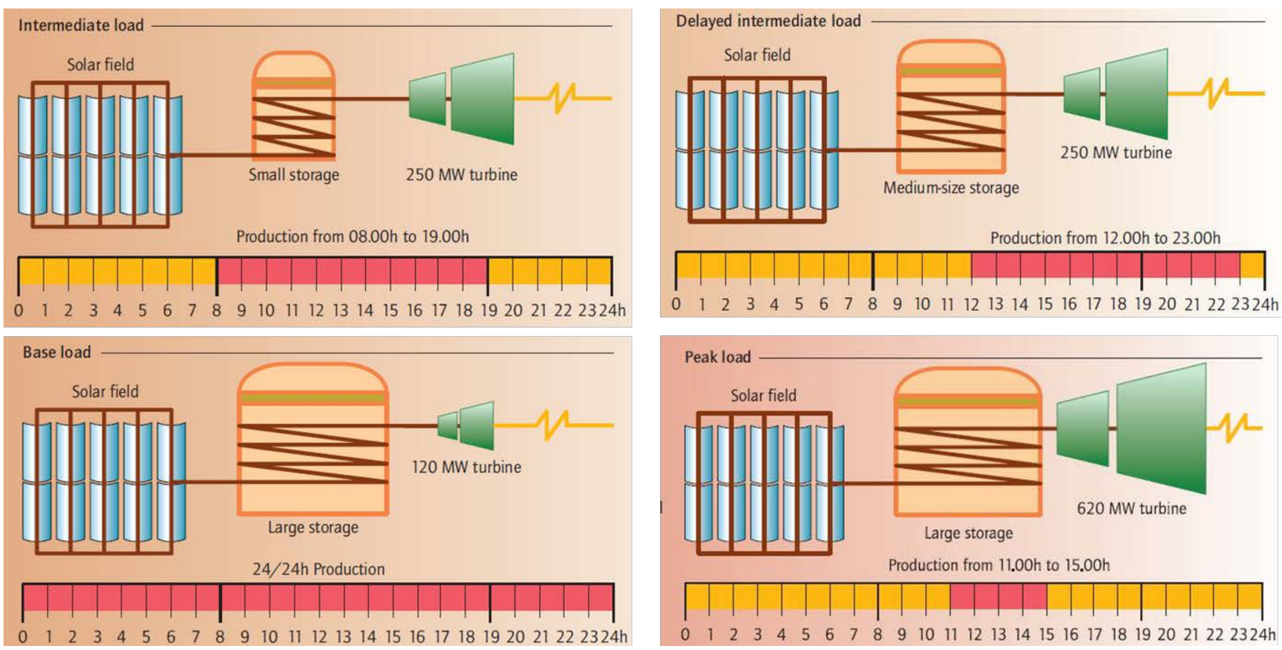


*Figure 1: Design options for CSP Technology with thermal storage [IEA]*

## 2. State of the Art Technology

Most of today's commercial CSP power plants (> 3 $GW_e$) are based on the design of the ANDASOL parabolic trough power plant (see figure 2) that was put in operation in Spain in November 2008. The plant design integrates three different fluid cycles: a eutectic mixture of 73.5 % diphenyl oxide und 26.5 % biphenyl is used as heat transfer fluid in the collector field. It is operated between 290° and 390°C (that is also its upper temperature limit of that thermal oil) and provides the collected heat through heat exchangers either to the thermal storage cycle or to the power cycle. The latter uses water steam like in conventional power plants whereas a eutectic mixture of $KNO_3$ and $NaNO_3$ is used as storage medium that is operated almost in the same temperature range as the collector fluid. It is selected as it is about 4 times cheaper than the thermal oil. The salt is contained in two tanks, one on a lower temperature of about 290 °C and after being heated up in the heat exchanger in a hot tank at almost 390°C. The salt mixture material is available extensively in nature (mining) and used also as fertilizer with a capacity of many 100 of thousands of tons per year. As it freezes at 238°C it needs to be kept above significantly that temperature during the lifetime of the power plant. The storage density of such a system is approximately 78 $kWh_{th}/m^3$ or 42 $kWh_{th}/t$. To provide a 100 $MW_e$ trough power plant with a 6 hour of storage capacity about 38'000 t of salt are required. The largest commercial installation that uses such a storage system was put in operation in October 2013. It is the 280 $MW_e$ Solana plant in Arizona (US) equipped with a 6 hours storage equivalent to 4'400 $MWh_{th}$ of storage capacity distributed in 6 pairs of tanks of hot and cold salt each about 38 m in diameter and 14 m high. The heat losses of such tanks are significantly below 3% of the energy throughput and even two weeks of interruption does not require active heating for freezing protection of the storage tanks. Heat exchangers, pumps valves and piping need to be equipped with electrical trace heating to avoid freezing problems during start-up.

Such a power plant concept can achieve annual gross solar-to-electric efficiency figures of up to 16%.

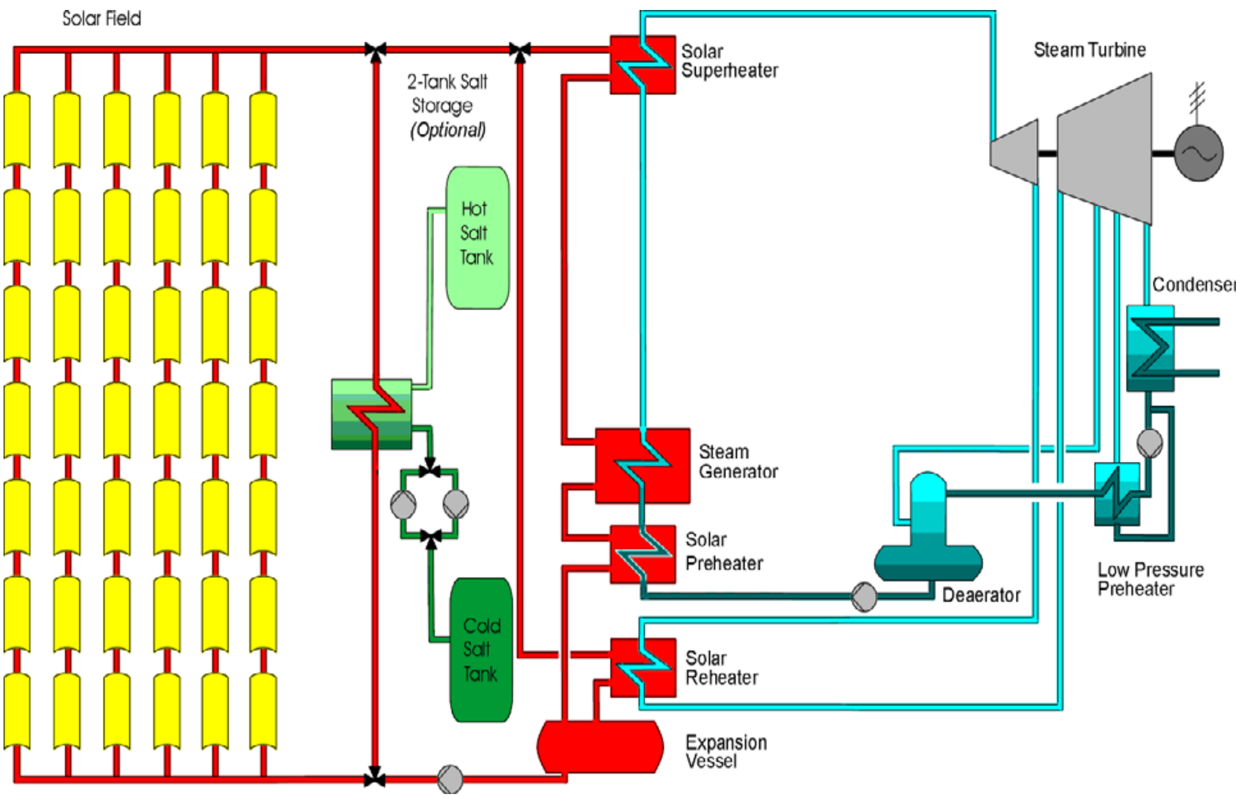


*Figure 2: Schematic of a parabolic trough power plant integrated into a steam power cycle using thermal oil as secondary heat transfer fluid and a two tank molten salt storage*

## 3. Concepts for Cost Reduction

The current concept has a number of limitations in terms of power plant efficiency and storage density that lead to the development of alternative designs. First, the synthetic oil heat transfer is rather expensive and limited in temperature to approximately 400°C. This limits on the one hand the potential life steam conditions in the power block and thus the efficiency of the power cycle to values below those of fossil fuel driven steam power plants. Second it limits the amount of heat that can be stored in the salt as it depends on the temperature difference between hot and cold tank. Steam has been investigated as alternative heat transfer fluid that is also used in the power cycle; however the integration into a storage system is difficult as the phase change characteristics of the steam during evaporation leads to a temperature profile that does not correspond to the sensible heating of the salt mixture. Using salt also as heat transfer fluid may overcome many of the limitations as the operation temperature of the salt can be extended to 550°C that is a more typical operation temperature of conventional steam cycle power plants. Such a replacement would also avoid the expensive thermal oil cycle. The challenge however is to avoid freezing of the salt in the extended collector field in any circumstance. This is addressed in two different concepts that are discussed in the following.

### 3.1. Molten Salt Power Tower

In solar tower systems a field of individually tracked mirrors (heliostats) concentrates the solar radiation on a heat exchanger located on top of a central tower. In such a point-focus arrangement higher concentration factors (≈1000) can be archived compared to parabolic trough technology (≈100) that generates a line-focus. The collection of the energy is not performed by an extended piping circuit of more than 100 km length (including the parabolic trough receiver tubes) like in a parabolic trough field rather by transferring the “radiation energy” to a central location limiting the piping length to a couple of 100 m necessary to transport the heat transfer fluid from the top of the tower to the storage and steam generator system located on the ground (see figure 2). The arrangement has the benefit that gravity supports the draining of the complete salt fluid back to the storage tanks during times where operation is not foreseen (e.g. overnight) which reduces the auxiliary electric power requirements to trace heat the piping in order to avoid freezing, in the case that molten salt is used as heat transfer and storage fluid. However, such arrangement also shows some significant drawbacks: A liquid salt column of 100 m equals 19 bar pressure. As the tower in a commercial solar system is typically more than 150 m tall and the pressure in the storage tanks at the ground level should be kept close to atmospheric pressure to limit its construction cost, the salt circulation system cannot be designed as a closed circuit in which only friction losses need to be overcome by the pump. In an open cycle the energy required to lift the salt to the tower top needs also to be invested.

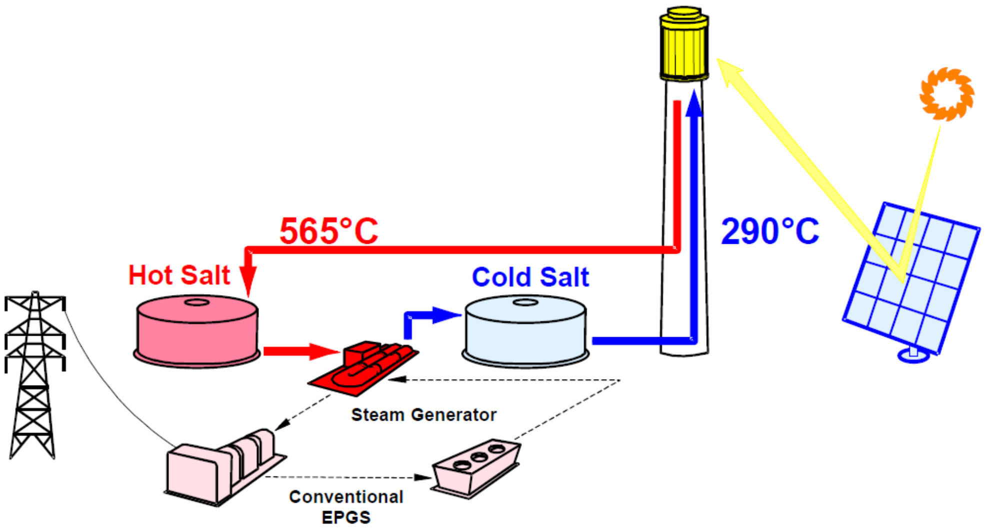


*Figure 2: Schematic of a Solar Tower Systems using salt as heat transfer and storage fluid integrated into a steam cycle power plant [4]*

For the temperatures given in figure 2 each kg of salt carries 416 kJ of thermal energy out of which approximately 166 kJ of electricity will be produced. To lift up the salt a 200 m tall tower with an annual average pump efficiency of 50% -60% [18] almost 2% of this electricity is required just to overcome the gravity.In particular challenging is the start-up of a drained receiver heat exchanger. Such a receiver consists of several irradiatepanels that are connected in series. The fluid is first brought to the tower top to electrically preheated vessels (see figure 3 left). The header of each panel is also insulated and equipped with radiant heaters for preheating. The panel itself if heated up by concentrated radiation of the heliostat field starting with small number of heliostats and a low flow rate. Special experience is needed to avoid on the one hand side a freezing by too cold piping and to limit material stresses by adjustment o the temperature gradients.

In figure 4 the overall effectiveness of such a system has been analyzed theoretically on an annual base. Approximately 57% of the solar energy on the heliostat field is collected as useful heat in the salt. Heat losses of the tanks as well as trace heating requirements are very small whereas pumping requirements of the salt, power block and condenser are the major auxiliary demand. Overall net efficiency of almost 17% is expected to be achievable by such a concept.

The levelized cost of electricity for such a system of 100 $MW_e$ power is estimated to be around 12€cents/kWh. Further cost reduction is particularly envisaged by mass production of the heliostat field as well as of scaling of the power plant to 200 MW. Also the operation at slightly increased temperatures of 580°C together with a further advanced heliostat design may give a further 10% reduction reaching a level of about 9 €cent/kWh if corrosion challenges aspects can be handled without major cost increase (figure 5). The technology has been developed already during the end of last century in in number of research and pilot project as listed in table 1. The implementation of the commercial projects as listed in Table 2 started just recently and will prove in the next couple of years whether such expectations can be met.

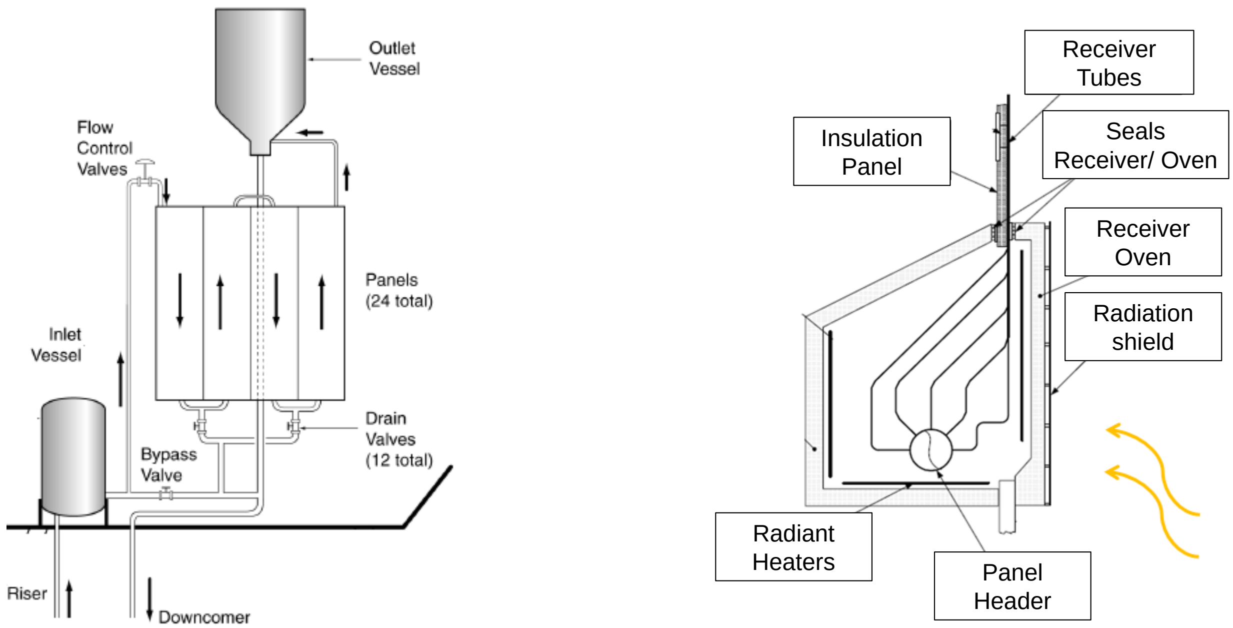


*Figure3: Design of a Molten Salt Receiver System (left Receiver overview[16]; right details on trace heating[17])*

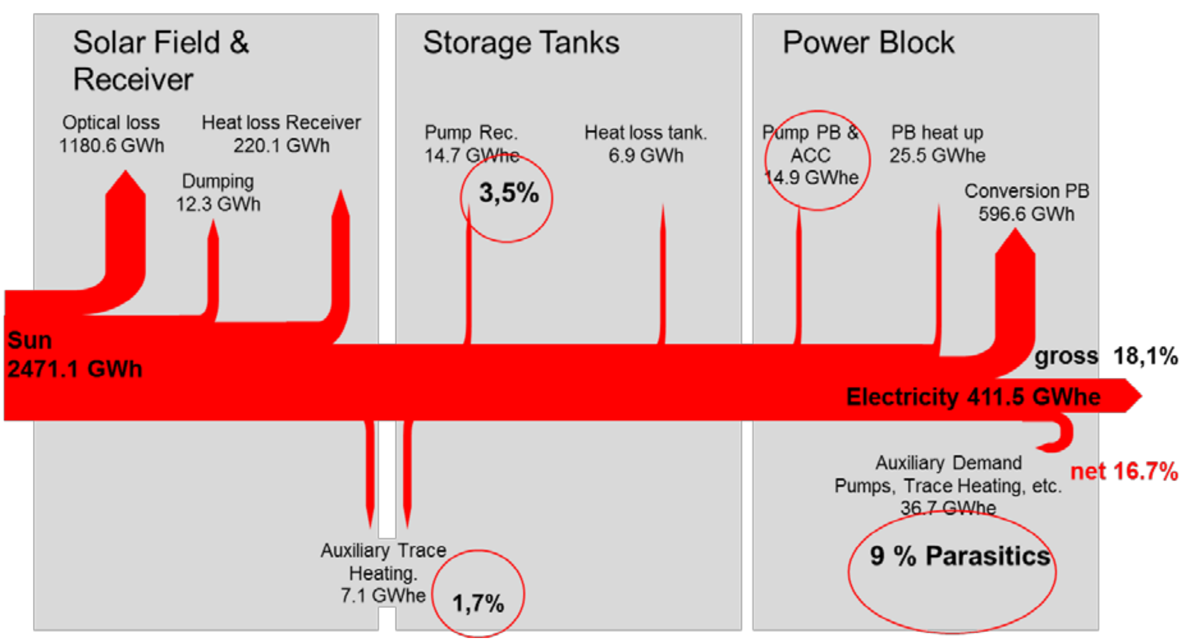


*Figure 4: Exemplary Sankey Diagram for power tower system using molten salt heat transfer and storage fluid*

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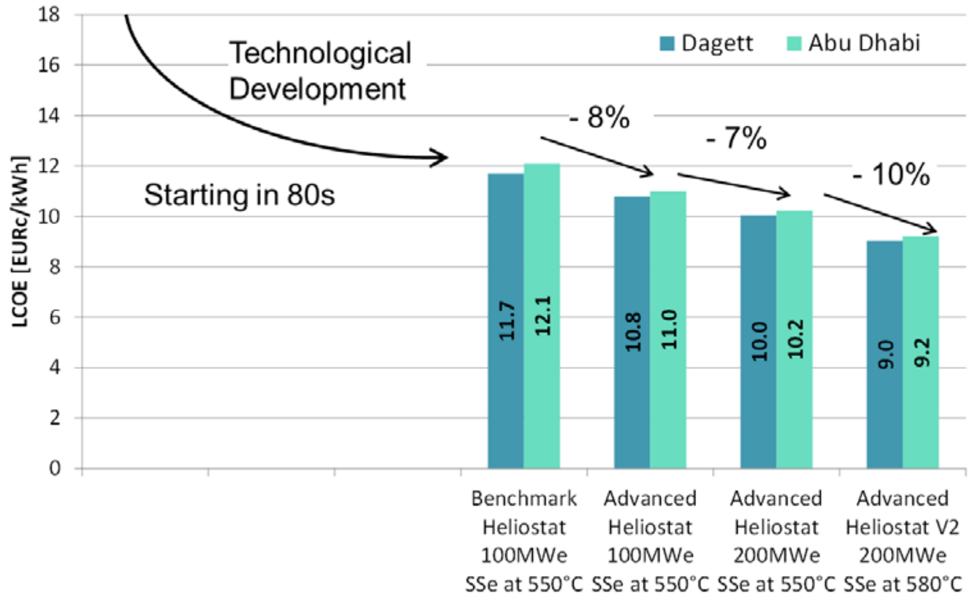
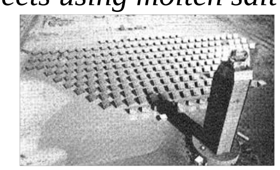


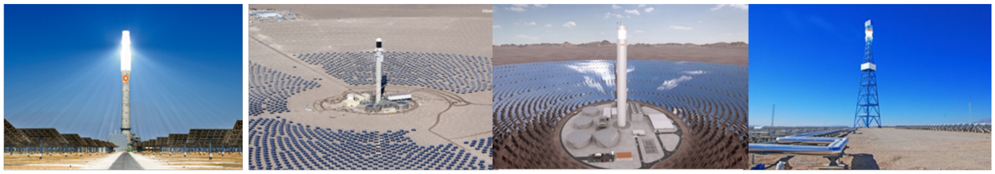

*Figure 5: Cost reduction potential for future power tower systems using molten salt (Data from [1] and own calculations)*

*Table 1: Research and demonstration projects using molten salt tower technology [2-4]*


| | MSEE (1985) | Thémis (1983-1986) | Solar Two (1996-1999) |
|---|---|---|---|
| Site | Albuquerque (New Mexico) | Targasonne (Frankreich) | Daggett (California) |
| Design | Martin Marietta | CNIM | Rocketdyne |
| HTF | Solar Salt | Hitec | Solar Salt |
| Receiver type | Cavity | Cavity | External |
| Thermal power | 5 $MW_{th}$ | 9 $MW_{th}$ | 42.2 $MW_{th}$ |
| Electrical power | 0.75 $MW_{el}$ | 2 $MW_{el}$ | 10 $MW_{el}$ |

*Table 2: Commercial projects using molten salt tower technology [14, 15]]*



| | Gemasolar | Crescent Dunes | Cerro Dominador | Supcon Solar |
|---|---|---|---|---|
| Status | In Operation | In Construction | In Construction | In Construction |
| Site | Sevilla, Spain | Tonopah, Nevada | Calama, Chile | Delingha, China |
| Design | SENER/CIEMAT | SolarReserve | Abengoa | Supcon Solar |
| HTF | Solar Salt | Solar Salt | Molten Salt | Molten Salt |
| Receiver type | External | External | External | External |
| Thermal power | 120 $MW_{th}$ | 560 $MW_{th}$ | not public | not public |
| Storage capacity | 15 h | 15 h | 18 h | 2.5 h |
| Electrical power | 20 $MW_{el}$ | 110 $MW_{el}$ | 110 $MW_{el}$ | 50 $MW_{el}$ |

### 3.2. Parabolic Trough with molten salt heat transfer fluids

The concept has been transferred also to the parabolic trough system. In this case the molten salt needs to be circulated through the whole collector field (>100 km of piping) and a complete draining of the systems (e.g. overnight) does not seem to be an attractive option. In order to prevent the salt form freezing in the absorber tubes recirculation is foreseen using salt from the cold tank and redirecting it back to the cold tank. Any drop in temperature of the cold tank will be compensated by small amounts of solar-heated molten salt from the hot tank. Once the hot tank is empty the heat will be provided by the auxiliary heater. Typically the auxiliary heater is not used after a sunny day. As molten salt always circulates through the solar field, it requires energy for pumping. The additionally installed electric heating devices are only installed for emergency cases and will not be used in a regular operation of the plant.

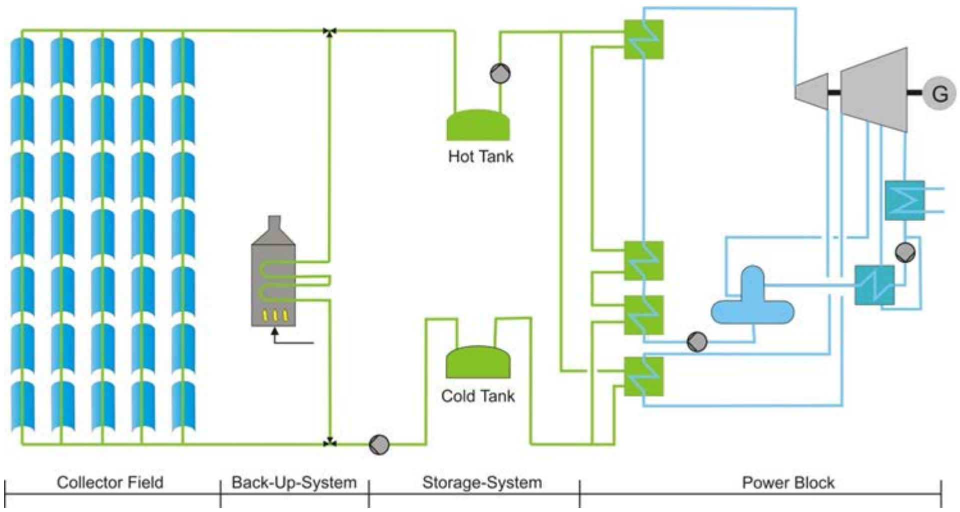



*Figure 6: Schematic of a parabolic trough power plant integrated into a steam power cycle using molten salt directly a heat transfer fluid and storage fluid (recirculation piping for night operation not shown in this figure)*

The freezing temperature of the salt significantly influences the amount energy required, so that different salt mixtures with lower freezing temperatures are also under consideration to be used in parabolic trough systems. Two potential ternary salt mixtures are listed in table 3. Their freezing temperature are around 150°C, however the upper temperature that can be exploited is also lower than the upper temperature of the reference binary salt NaK-$NO_3$. The cost of the Li-based ternary salt mixture is significantly higher, so that one option could be to use it only as heat transfer fluid and keep to the reference salt in the storage, however adding costs for additional heat exchangers. Another important factor influencing the amount of energy for the recirculation is the amount of solar radiation available, as in times where the sun shines no additional effort for recirculation is required. In figure 6, the amount of hours (anti-freeze) that need support from the storage or fossil fuel heating are shown for two different sites (e.g. different solar radiation) and different heat transfer fluids. Under favorable conditions, new salt mixture limit the amount of fossil fuel energy required for anti-freezing drastically [10].

*Table 3: Properties of different molten salt mixtures [5,7,9]*

| ***Salt Mixtures*** | ***Decomposition Temperature*** | ***Freezing Temperature*** |
|---|---|---|
| ***NaK-$NO_3$*** | *>550°C* | *238°C @ 60/40 Mixture* |
| ***NaKCa-$NO_3$*** | *<500°C* | *~150°C* |
| ***NaKLi-$NO_3$*** | *~530°C* | *~140°C* |

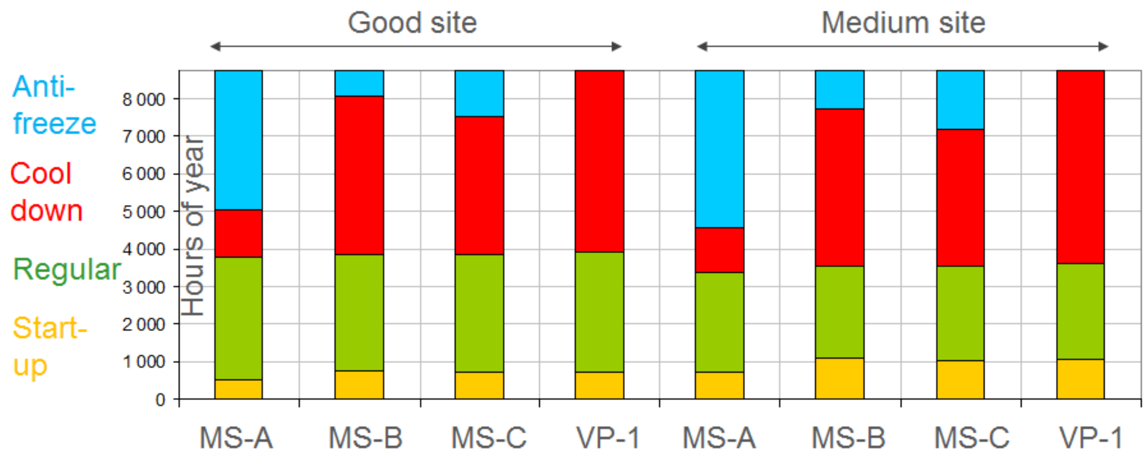



*Figure 6: Number of Hours in different operation regimes in a parabolic trough power plant using molten salt or thermal oil as heat transfer fluid (A=NaK-$NO_3$; B=NaKCa-$NO_3$;C=NaKLi-$NO_3$;VP1 = Thermal Oil)*

In figure 7 the overall effectiveness of such a system has been analyzed theoretically. Approximately 60% of the solar energy on the solar field is collected as useful heat in the salt. Heat losses of the tanks and pumping requirements of the salt, power block are relatively small, whereas auxiliary heating requires additional fossil fuel supplying additional 2.5% of thermal energy to the solar heated salted content to avoid freezing. An overall net efficiency of about 18% is expected to be achievable by such a concept.

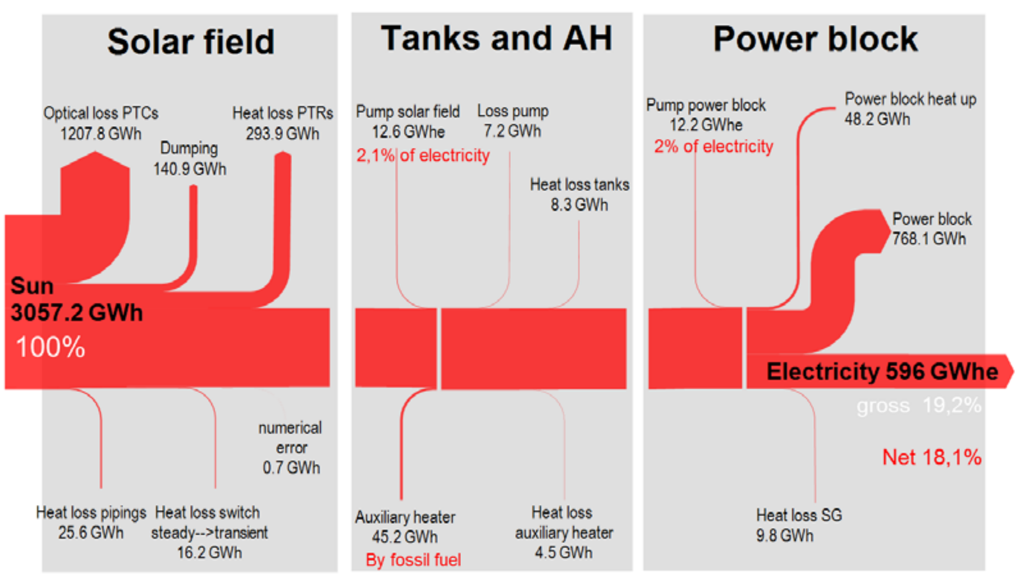



*Figure 7: Exemplary Sankey Diagram for parabolic trough power plant system using molten salt heat transfer and storage fluid*

In figure 8 the potential for cost reduction is shown: the change to new and larger collector design (named UltimateTrough) together with a scale up from 50 to100 MW power block size brings a reduction of almost 20 % in the levelized cost of electricity. If the thermal oil is replaced by the standard solar salt in this configuration an additional steep of 20% is expected. Further scaling to

200MW block sizes anticipates a cost reduction of another 10% whereas the change to an advances salt mixture has a potential to reduce the costs by another 3%. Thus the overall expectation is to achieve cost below 10€cents/kWh for flexible solar power by this concept [1].

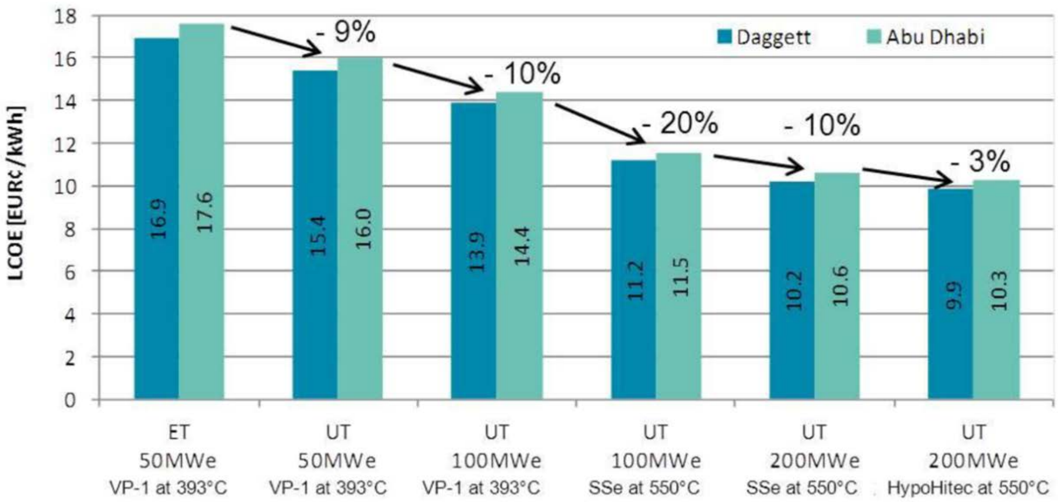



*Figure 8: Cost reduction potential for future power tower systems using molten salt, ET refers to the EuroTrough technology with 5.6 m of aperture width and 105 m collector length, whereas UT refers to the UltimateTrough technology with 7.5 m of aperture and 200 m of collector length. SSe stands for the standard solar salt whereas HypoHitec foresees an advanced salt mixture with a lower freezing point at 150°C [1]*

Today a first prototype system of 20 $MW_{th}$ power is installed in Sicily, Italy, providing the solar heat to the steam turbine system of a combined cycle power plants. Unfortunately, very little information on the performance of this system is available. In addition a couple of small demonstration loops exist or are under construction in different countries [6,13]. The experience with these facilities will help to find the best technical solutions to exploit this concept.

## 4. Conclusions

The use of molten salt as heat transfer fluids offers a couple of potential benefits over the existing standard design of solar thermal power plant that is based on parabolic trough technology with thermal oil heat transfer fluid and an indirect molten salt storage concept. As the typical salt becomes solid at temperatures below 240°C, a significantly modified operation and maintenance concept is needed in that case. Commercial solar towers are already being built but and more mature than parabolic trough systems based on molten salt. The parabolic through technology still must convince stakeholders having reliable safety measures against freezing of the salt. This can be achieved by reliable and safe draining of the solar field or heating systems, However, a detailed analysis showed that the concept appears also feasible in parabolic trough and has a similar cost reduction potential to reach levelized electricity cost below 10 €cents/kWh. Both options also show room for further improvements if advanced salt mixtures are applied. There are therefore explored by research and industry.

## 5. Literature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