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Direct Molten Salt Linear receiver CSP-concepts with MS-TES compared with Direct Steam Generation Linear receiver CSP-concepts with solid bed TES

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Abstract

The use of molten salt in line focusing systems is under investigation by several CSP market players along the supply chain of a typical CSP-plant. In this paper, an economical analysis is performed, in order to compare the DMS system with a DSG-system with solid bed thermal storage and a classical parabolic trough system using thermal oil and a molten-salt storage system.
The resulting LCOE values are further analyzed with a sensitivity analysis and further technical and operational optimization. As results, the economical values for the DMS show a good potential. The DSG-system with solid bed as thermal storage offers also a high and promising potential to achieve even clear lower LCOE-values, with very stable LCOE-level with regard to the sensitivity analysis. As one outcome of this study, the LCOE values for the DMS and the DSG-system are in any case lower compared to current state of the art solutions.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG.

Keywords: Linear Receivers, Direct molten salt, Direct steam generation, solid bed, storage system, TES

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1. Introduction

Parabolic trough systems using thermal oil as heat transfer fluid (HTF) in the solar field in combination with molten salt (MS) as material for thermal energy storage (TES) are the most recent technology used for large thermal solar systems.

Nomenclature

CSP	Concentrated solar power
DNI	Direct normal irradiation
DSG	Direct steam generation
HTF	Heat transfer fluid
HX	Heat exchanger
LCOE	Levelized costs of Energy
LFR	Linear Fresne
LPG	Liquefied Petroleum Gas
MS	Molten salt
PPA	Power purchase agreement
ROIC	Return on investment
TES	Thermal energy storage
TMY	Typical meteorological year

Due to the temperature limit of the thermal oil at approximate 400 °C the increase in efficiency is limited. Therefore new concepts for trough systems are under development like systems using directly molten salt as HTF because MS systems can be operated up to temperatures of 500 - 550 °C. Meanwhile Linear Fresnel direct steam generation (DSG) systems have reached state of the art status with the advantage to be operated also at temperatures around 500 to 550 °C. The challenge of DSG systems is to implement high temperature thermal storage systems.

1.1. Dispatchability as key factor for CSP-plants

The dispatchability of CSP power plants is a huge advantage compared to other renewable energy sources such as wind or PV and is getting more and more mandatory for grid operators. Beside the fact that there are no battery storage systems in connection with PV- or wind-power plants in the range of several 100 MWh_{el} are installed, it can be stated that for sites with reasonable high DNI-figures the LCOE from a large scale CSP power plant with a thermal storage system will be clear cheaper than from concepts applying known battery technologies.

For CSP tower systems, three different solutions are available, one using molten salt as HTF and storage medium, another one using air as heat transfer medium with a short term TES and another one with direct steam generation without a TES. All this receivers are operating at temperatures in the range of 500 °C or above. In this study the focus has been on line focusing systems and no comparison has been made with CSP tower systems.

1.2. Reducing energy generation costs

In order to increase the overall efficiency of Parabolic Trough systems as well as Linear Fresnel systems the current development of line focused receivers are aiming to use direct molten salt as heat transfer fluid combined with a MS-TES. Among obvious advantages of the thermodynamics molten salt thermal storage systems are proven systems and therefore it is expected to get much easier the financing in place for CSP projects applying such technologies.

As a matter of fact it can be stated that up to today there is no commercial large scale CSP power project realized using molten salt as heat transfer fluid and storage material, neither Parabolic Trough nor Linear Fresnel.

On the other hand there is no large scale CSP project realized with direct steam used as heat transfer fluid in combination with a solid bed TES.

The aim of this study has been to evaluate the technical main issues of the different concepts and the expected financials and impact on the Levelized Cost of Energy (LCOE). Furthermore a comparison of the different concepts shall allow the determination which technical concept might be economically ahead of the others under the defined frame parameters.

2. Methodology and Parameters

The modeling of all considered plant configuration is done in two major steps. At first the overall plant setup including the main components like the solar field, thermal storage, heat exchangers and all necessary auxiliary components like pumps is modeled using EBSILON Professional.

Based on these models different load cases are calculated. The results of these calculations are used to develop simplified characteristic diagrams describing the behavior of the plant under different load and ambient conditions. With these diagrams, the plant behavior over a whole year on hourly basis is simulated as second step.

In order to model the components, public available information and detailed discussion with several manufacturing companies (e.g. for receivers, solar field, thermal storage) have been taken into account, to ensure that all components have been modeled to current concepts. [1]

As reference a site in Kenya near Lamu with public available solar data was chosen. The average daily sum of the direct normal irradiation as well as a geographical overview of the site is given in Fig. 1. This potential site (CSP-plant in feasibility-study state) was chosen based on its location near to the equator, a comparable DNI situation to most emerging markets in the world.

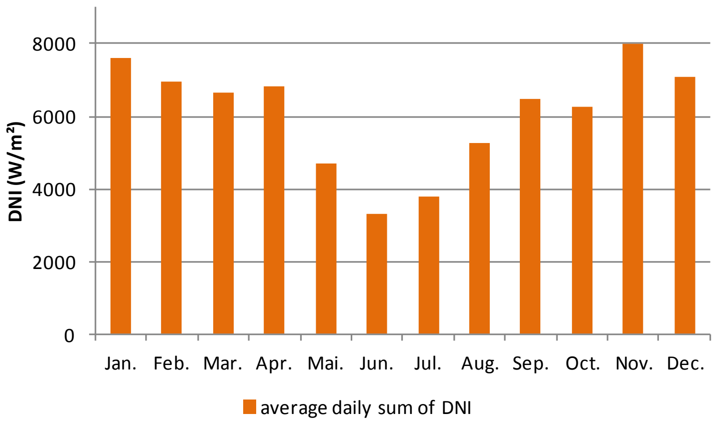

Fig.1. Used reference conditions for the considered site

The annual sum of the DNI value is slightly above 2220 kWh/m², and the site is located very close to the equator (2° S), offering very stable conditions concerning the optical efficiency especially for Linear-Fresnel systems.

One parameter was the requirement of all evaluated concepts to deliver a comparable amount of electrical energy to the grid. The idea is that CSP will be used as dispatchable medium load/base load power plant with clear more than 6000 operational hours per year. This makes the comparison of the LCOE easier. However, it is clear that the LCOE might be different for the concepts in case this amount of GWh would be left open.

As a further parameter was set that natural gas is allowed to be used in the different concepts, since nobody would build a CSP power plant where molten salt is used without the possibility of heating with gas (or LPG or diesel).

3. Description of the different CSP-concepts

Within this study two different plant configurations will be introduced:

1. A Linear Fresnel plant using molten salt (solar salt) as HTF and storage material, including gas fired auxiliary heating system covering heat losses during night for optimization of the LCOE (LFR-DMS-system + molten salt TES; described in Fig. 2 (left));
2. A Linear Fresnel plant using direct steam generation in combination with a solid bed storage system (LFR-DSG-system + solid bed TES; described in Fig. 2. (right)).

For comparison

3. a Parabolic trough plant using thermal oil as HTF and molten salt (solar salt) as storage material, including natural gas firing for freeze protection of thermal oil and molten salt (PT-system + molten salt TES)

will be used as a standard CSP-plant.

All plant configurations have a gross production of 100 MW_{el} in common. The key elements varying in each configuration are as follows:

- In 1) solar salt (60 % $NaNO_3$ / 40 % KNO_3) is used as HTF and storage material (two-tank direct molten salt storage) as well. The upper temperature of the solar salt is set to 500 °C, the lower temperature to 290 °C. Live steam parameters of 488 °C at 100 bar are reached, with an intermediate superheating of the steam at 15.5 bar from 243.8 °C to 490 °C using solar salt. Heat losses during night have been considered on the basis of receiver heat losses data and a first optimization with regard to required mass flow and temperature during night has been implemented.
- In 2) the feed water is heated up, evaporated and superheated directly in the absorber tube of the Linear Fresnel collectors. The collector field is divided into a collector field charging the TES and a collector field for day operation of the steam turbine. The concept is explained in detail in [2]. Via heat exchangers the heat of the charging collector field is transferred to air and stored in a solid bed TES at 475 °C using small stones as heat storage material. During discharging, the stored heat is transferred to ambient air, resulting in an air temperature of 460 °C at the outlet of the storage. Via heat exchangers, steam is then generated at two pressure stages of 90 bar and more than 16.5 bar, with superheated live steam at 440 °C. The solid bed system with silica oxide (SiO_2) as heat storage material which has been used for this study is the HTTESS under development at Storasol [3]. The basis for the temperature differences and pressure losses are results of measurements at the Storasol-TESS 002 C pilot plant.
- In 3) a parabolic trough collector using Therminol-VP1 as HTF is evaluated. Therminol-VP1 is heated up to 393 °C, transferring its heat either to solar salt (40 % $NaNO_3$ / 60 % KNO_3) for storage purposes (two-tank indirect molten salt storage) or the water/steam cycle for electricity production. Live steam parameters of 371 °C at 100 bar are set.

All concepts have been implemented and designed using the software EBSILON Professional. The yearly simulation was done using a quasi steady-state simulation with time intervals of 1 hour. Own consumption of electricity and heat have been considered, as well minimum load restrictions when operating the steam turbine.

Since it is not expectable, that a large scale CSP power plant, which is using molten salt, will be build as ’solar only’ CSP-plant, a first economic optimization has been performed with the use of natural gas. The consumption of natural gas was designed reasonably close to a ‘solar only’ operated CSP-plant, with natural gas neither used for direct nor indirect electricity production.

For reference, the TMY-DNI data of Lamu, Kenya (2223 kWh/m²) has been used to evaluate the electricity yield of each plant configuration, which has been equally set to 575 GWh_{el} (± 4 GWh_{el}) for a base load operation of about 6500 h per year.

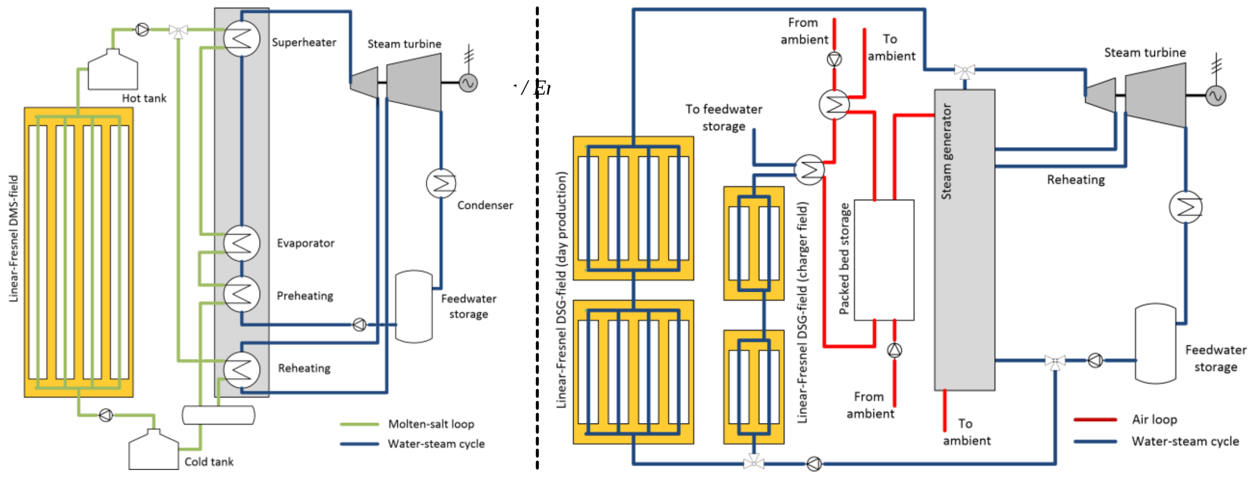

Fig. 2.Schematic plant configuration for 1) LFR-DMS system (left) and 2) LFR-DSG system (right)

4. Results of the Evaluation

To evaluate the LCOE of each plant configuration the financial parameters shown in Table 1 have been used. The investment costs have been derived from actual CSP-projects and from market information about equipment costs (e.g. heat exchanger, solar field, salt costs). The O&M-costs have been derived from information out of other projects and finally have been set as equal for all concepts (without gas). This might be slightly to the disadvantage of the DMS- and DSG-system compared to the ‘classical’ PT-system with thermal oil and molten salt TES, but has been considered good enough for this study.

Table 1. Financial parameters for the evaluation of the LCOE.

	1) LFR-DMS system + molten salt TES	2) LFR-DSG system + solid bed TES	3) PT-system + molten salt TES
Investment costs	666 Mio €	604 Mio €	792 Mio €
Construction period	3 years	3 years	3 years
Natural gas consumption (per year)	13 GWh_{th}	0 GWh_{th}	20 GWh_{th}
Natural gas costs	Equal for all scenarios: 50 €/$MWh_{th,LHV}$ (annual increase: 2 %)		
Increase of electricity price	Equal for all scenarios: None		
Increase of personnel costs	Equal for all scenarios: 3 % per year		
Increase of material costs	Equal for all scenarios: 1 % per year		
PPA-duration	20 years	20 years	20 years
ROIC	8 %	8 %	8 %

A breakdown of the investment costs of each plant configuration with an electricity yield of 575 GWh_{el} is shown in Fig. 3. It can be seen that the investment costs of CSP-plants are mostly dependant on the cost of the solar field. In 1) a significant reduction of costs in terms of storage and heat exchanger (HX) can be identified in comparison with 3) due to the combined use of molten salt as HTF and storage material. An even more significant reduction in investment costs is achieved by using a solid bed TES as it is implemented in 2). The reason for this much lower cost is the very cheap storage material (sand/small stones, with the main portion out of SiO_2). The disadvantage of the solid bed TES-system are the high costs for the large heat exchangers (steam/air and air/steam), but still the total TES-costs remain much lower than in molten salt systems.

To get a clearer picture in the comparison of the different concepts and the impact of the different cost packages a sensitivity analysis has been made.

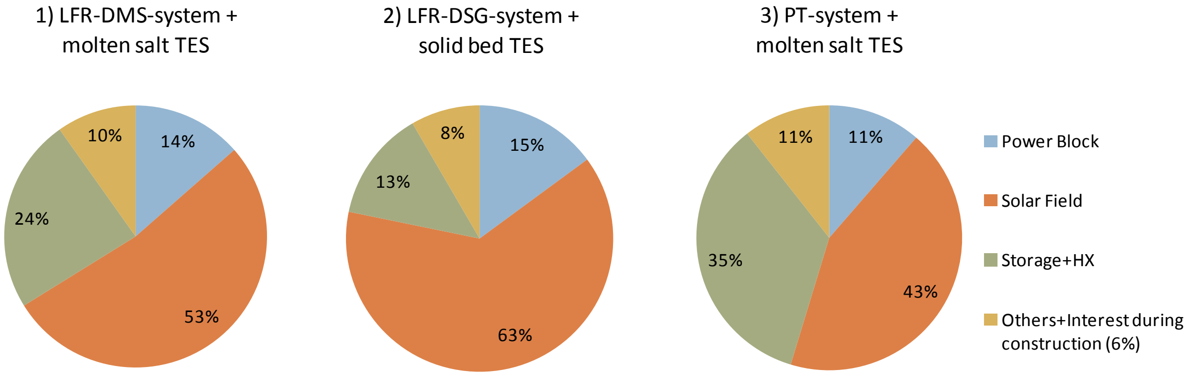

Fig. 3. Breakdown of investment costs for each plant configuration

The overall results of LCOE are shown in Fig. 4. The graphs describe a huge potential of the LFR-DSG-system with a solid bed TES for a further reduction of LCOE of a base load operated CSP-plant.

As already mentioned, the impact of solar field costs is significant on the LCOE. With a moderate decrease of 20 % in solar field costs, LCOEs of roughly 1.5 €ct/kWh less than the evaluated LCOEs through all plant configurations can be achieved, which corresponds respectively to a decrease of 8 – 12 %.

The sensitivity of LCOE with reference to storage costs is quite different within the three plant configurations, depending on the share of investment cost regarding storage and heat exchanger. A 20 % increase in storage and heat exchanger costs has minor impact on the LCOE of the LFR-DSG-system with the low priced solid bed TES (+ 2.9 %), as it has compared to the LFR-DMS-system (+ 4.4 %) and the PT-system (+ 4.5 %).

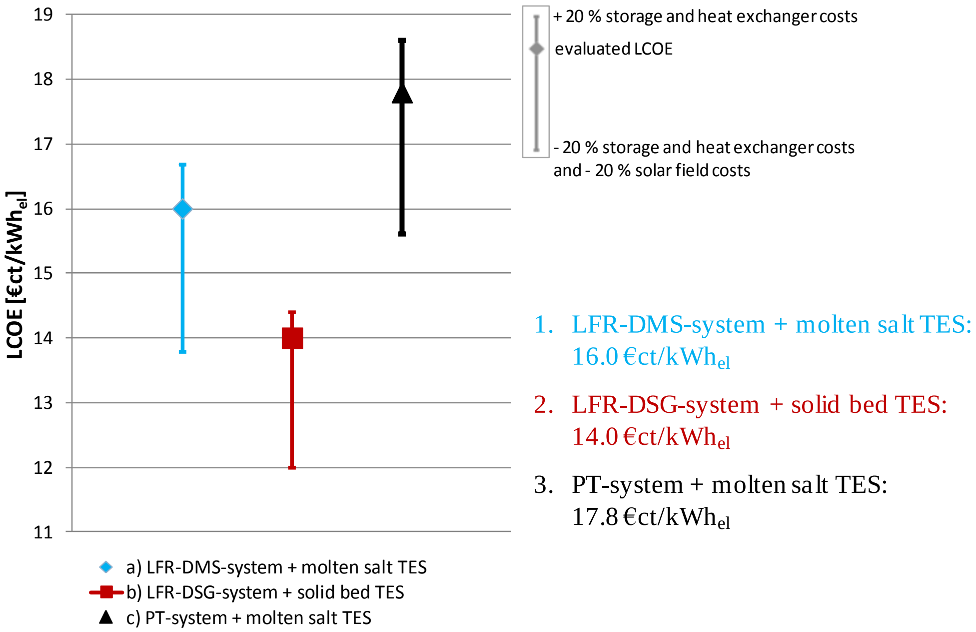

Fig. 4.LCOE of each plant configuration, including sensitivity analysis regarding solar field (-20 %) and storage costs (± 20 %)

The aim of this study was to get a first result about the potential of new CSP-concepts with linear receivers. Of course the results are only valid for the considered boundary conditions, especially to used location and the considered solar irradiation. An equal energy output was taken as basis for the calculation in order to make the different technologies comparable. As the optimal yearly energy output of every CSP-plant is different, this adds an additional uncertainty to the calculation. The influence of the optimal CSP-layout on the LCOE is analyzed in the following chapter. But nevertheless, especially taking into account the sensitivity analysis, the outcome of this study provides some first key points regarding these two promising technologies.

5. Improvement of LCOE

In addition to the already performed sensitivity analysis, further technical and operational optimization possibility are taken into account for every regarded system. Some of the most promising possibilities are presented within the next chapters.

5.1. Improvement of LFR-DMS system

For further improvement potential of the LCOE of LFR-DMS-systems, Hitec salt instead of the commonly used solar salt (60 % $NaNO_3$ / 40 % KNO_3) could be used. Hitec salt allows for lower operation temperatures (down to 210 °C compared to 290 °C with the common solar salt) and thus a higher heat transfer to the water/steam cycle [4]. This results in lower heat losses in solar field, piping and tanks and enables also a lower salt mass flow and smaller scale molten salt tanks. These positive aspects are faced with the negative impact of a 10 – 15 % higher price of Hitec salt compared to the common solar salt. To conclude, the savings in investment costs regarding the reduced amount of salt are approx. neutralized by the higher price of Hitec salt. The use of Hitec salt reduces the investment costs slightly due to smaller scale molten salt tanks and additionally reduces O&M-costs due to lower heat losses and thus lower auxiliary gas consumption.

5.2. Improvement of DSG-solid bed TES system

Further improvements concerning the design of the boiler for the DSG-solid bed TES concept could be based on the design of the steam generator for the discharging of the solid bed TES. As this steam generator is only used for discharge operation and not for daily solar field operation, the design of this steam generator must be focused on the thermal storage. This single operation mode allows the operation on one single operation point during discharging, resulting in a more efficient operation than compared to a duel operation mode.

In order to increase the useable temperature range with regard to the pinch-point of the water-steam cycle, a water-steam boiler with two or even three pressure stages could be used. With such a boiler, often used in conventional combined cycle gas turbine plants, the efficiency of the storage operation mode of the DSG-solid bed TES concept could be further increased, while the LCOEs could be reduced.

The influence of the raised efficiency is clearly visible in the sensitivity analysis of the annual plant outcome, shown in Fig. 5. Within this figure, possible plant configurations are shown, that achieve the annual performance value of 575 GWh_{el} with a sensitivity of ±5 %. The increased efficiency of the water steam boiler with two pressure stages is resulting in a smaller solar field, while the useable storage size could be slightly extended. In comparison to the DMS solution, the influence of the connection between TES size and solar field is sharper for the DSG solution.

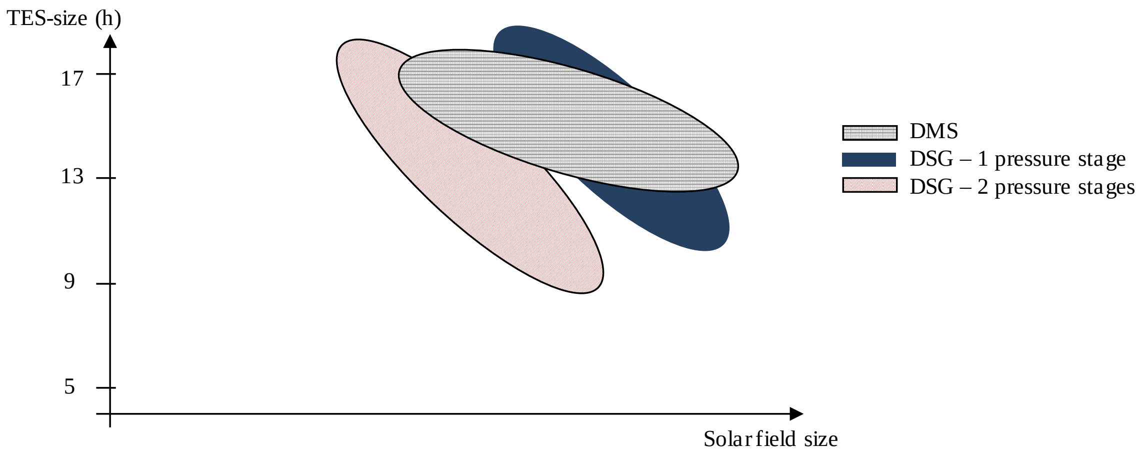

Fig. 5. Influence of storage and solar field size on the yearly energy output

In case of an optimization of the DSG-solid bed TES concept LCOE-levels of approx. 10 €ct/kWh can be reached for 20 year PPA-terms with 'standard'-project finance schemes.

5.3. Improvement of PT-system

Concerning the 'classical' parabolic trough system, also further improvement potential concerning the different components (especially the mirror system) are expected. Compared to the other technologies, these further developments will not dramatically influence the overall setup of the concept, but will result in particular improvements. As one example the development of the Ultimate Trough [5] will result in a larger mirror surface and will therefore reduce the required amount of solar collector elements. Such cost reductions are considered in the evaluation with the presented sensitivity analysis.

6. Conclusion

As a result of this study it can be stated that LFR-DMS-Systems are allowing lower LCOE than conventional PT-systems. DSG-solid bed-systems are even in conservative scenarios promising much lower LCOE-figures than the other two concepts. The study is confirming that technical step-changes are allowing for significant lower LCOE than actual state of the art-CSP-technologies and it is therefore highly recommendable to develop such technologies further.

In the course of this study it has been recognized that such new CSP-concepts are requiring answers on many questions. As an example for the DMS-system it is a fact that the chemistry of the salt is changing when applying higher temperatures of clear more than 400 °C, possible negative effects need to be addressed. Another challenge is the operational concept and the detailed arrangement of additional components required for the safe and proper operation of a DMS linear receiver solar field.

As next steps such new concepts should be in more detail further evaluated, analyzed and optimized. Demonstration plants can provide evidence about the technical feasibility and form the bridge to get finally a competitive financing scheme in place for large scale commercial projects.

With regard to the DSG-solar field there is already experience available which forms a solid basis for higher temperatures and pressures and the challenges are meanwhile well known. But the application of a solid bed-TESS in such arrangement is new, and even if the storage itself is solid and the main questions can meanwhile be answered, attention is required on the design and optimization of the heat exchangers for charging such solid bed-TES-systems.

Another key factor to implement new technologies and new concepts in order to reduce the LCOE costs of CSP plants is that all the relevant players in the market as for example project developer, equity and loan providers like banks or funds are open to accept at the beginning a slightly higher technology risk which will be compensated by the expected lower LCOE. Therefore an additional key role in the project development is dedicated to major players like EIB, WB, KfW or other strategic investment banks.

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