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INITIAL INVESTIGATION OF LIQUID GLASS AS A THERMAL MEDIUM IN CSP PLANTS

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ABSTRACT

Utilizing high-temperature supercritical steam cycles instead of state-of-the-art subcritical ones promises higher CSP plant efficiencies and lower levelized cost of the generated electricity. A new glass composition, Haloglass RX, that can reach the required temperatures, is investigated for the use in central receiver CSP plants. It is compared to Solar Salt and liquid sodium in terms of its thermophysical properties.

The fluid's high viscosity and disadvantageous heat transfer capabilities make it appear unfeasible as the heat transfer fluid in an active direct storage cycle. However, due to a high volumetric heat capacity and low cost it is suitable as a storage medium with a differing heat transfer fluid.

A cycle in which a liquid glass storage cycle separates the sodium receiver cycle and the ultra-supercritical steam generator is proposed. A thermal and economic model is developed and validated to compare the proposed plant layout to a state-of-the-art Solar Salt plant.

1 INTRODUCTION

Lowering the levelized cost of electricity (LCOE) remains the major challenge of concentrating solar power (CSP) technologies. One way to address it is to increase a plant's overall efficiency, which can be achieved by increasing the operating temperature of the power cycle. State of the art central receiver plants utilize either molten salt or water/steam as the heat transfer fluid (HTF). Both have limitations: The former has an upper temperature limit of 593 °C and the latter is problematic in terms of storage implementation. Therefore, new combinations of heat transfer fluids and thermal energy storage (TES) media have the potential to significantly improve the viability of CSP plants.

Liquid glasses have interesting characteristics for the use as the HTF or TES medium in CSP plants as they are stable at high temperatures, inert, non-toxic, cheap and have a high volumetric storage capacity. However, they are either solid or highly viscous even at temperatures of more than 1000 °C [1].

Recently, a new commercial glass composition, Haloglass RX, which is pumpable at lower Solar Salt temperatures, has been proposed for the use in CSP plants [2]. In this study, the use of the fluid as the TES medium with different HTFs is investigated. Liquid sodium, Solar Salt and the liquid glass are compared based on their thermophysical properties in the respective proposed operating temperature ranges. Finally, a thermodynamic and economic model is built to enable the comparison of the most promising plant layout utilizing Haloglass RX with a future Solar Salt plant in terms of efficiency and viability.

2 THERMOPHYSICAL PROPERTIES OF CANDIDATE FLUIDS

The uses as an HTF or TES medium impose different requirements on a fluid. Although the aspired properties are similar for both applications, their priorities are different. Requirements of high importance for the use as the HTF in a CSP plant are:

- a high upper temperature limit at a low pressure to allow for the use of highly efficient power cycles and reduce the risk of local degradation and corrosion,
- a low lower temperature limit (freeze point) to avoid the risk of clogging and eliminate the need for freeze protection,
- a high thermal conductivity to increase heat transfer in receiver and heat exchangers,

- a low viscosity to reduce pumping power and operating pressures,
- inertness, compatibility with piping material and non-toxicity.

Properties of major importance for storage media are

- a temperature range suitable to the HTF and power block,
- a high volumetric heat capacity to reduce the storage volume,
- low cost of the raw material,
- thermal cycling stability,
- inertness, compatibility with piping material and non-toxicity.

The whole power plant can be simplified significantly if one medium can be used for both applications. In such a direct active TES system, no heat exchangers besides the steam generator are needed, which reduces costs and improves the first and second law efficiency. In this case, other disadvantages can be compensated for. An example is the use of Solar Salt despite its limited temperature range.

In the following, the investigated fluids' thermophysical properties – namely density, specific heat capacity, thermal conductivity and viscosity – are compared in their respective temperature ranges. Furthermore, their heat transfer coefficients are derived for set boundary conditions.

As the available data for the thermophysical properties of Haloglass RX are incomplete, assumptions had to be made about their change with temperature. For density and thermal conductivity, only one respective data point is available for the whole temperature range [3]. These two properties were estimated to be constant as molten glasses typically show little change in them [4]. For its specific heat capacity and dynamic viscosity, the available data [2] allowed for the determination of curve fits.

To indicate that the plotted data is merely a qualitative estimate based on general behavior of similar fluids, it is referred to as 'LiG' (Liquid Glass) instead of 'Haloglass RX'. The correlations for Solar Salt and liquid sodium (Na) were derived from literature [5,6].

2.1 OPERATING TEMPERATURE RANGE

For the present study, only Rankine steam cycles are considered for the power block. The authors are aware that combined cycles with topping Brayton cycles can achieve higher conversion efficiencies but they are discarded for the problematic heat transfer to a pressurized air stream. State-of-the-art ultra-supercritical (USC) steam cycles feature live steam temperatures of up to 630 °C. Taking into account temperature gradients in heat exchangers, fluid properties are investigated up to a maximum temperature of 700 °C.

Na and LiG are both compatible with these high temperatures, while the maximum operating temperature of Solar Salt is usually associated with sub-critical steam cycles [7]. All fluids' lower operating temperature is well above ambient (see Table 1), necessitating some sort of freeze protection. However, the larger the temperature difference to ambient, the higher the thermal losses and the energy demand for freeze protection. The lower operating temperature limit of Haloglass RX is 160 °C higher than the one of Solar Salt, which is already considered problematic.

Table 1 Operating temperature limits of investigated fluids

Operating temperature	Na	Solar Salt	Haloglass RX
Lower limit [°C]	98	290	450
Upper limit [°C]	883	593	1200

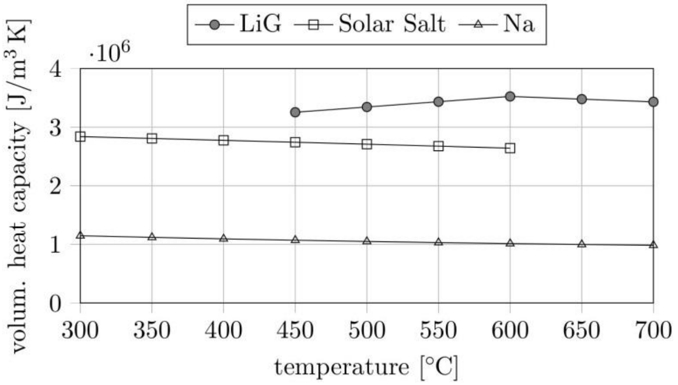

Figure 1 Volumetric heat capacity over operating temperature ranges

2.2 DENSITY, SPECIFIC AND VOLUMETRIC HEAT CAPACITY

Density, specific heat capacity and temperature spread between hot and cold flow determine the required flow speed of an HTF in a receiver of defined rating and geometry. They, therefore, have a strong influence on the required pumping power and operating pressure of a receiver. More importantly, these parameters determine the required volume of the TES tank and mass of the TES medium. These are the determinants of the total TES system cost.

Sodium's low volumetric heat capacity (see Figure 1) – defined as the product of specific heat capacity and density – combined with high specific costs make it unviable as a storage medium. LiG, on the other hand, has a higher volumetric heat capacity than the state-of-the-art Solar Salt.

2.3 THERMAL CONDUCTIVITY

A fluid's thermal conductivity is an important parameter in determining the effectiveness of heat transfer (see Section 2.5). Throughout the operating temperature range, sodium's thermal conductivity is two orders of magnitude higher than that of

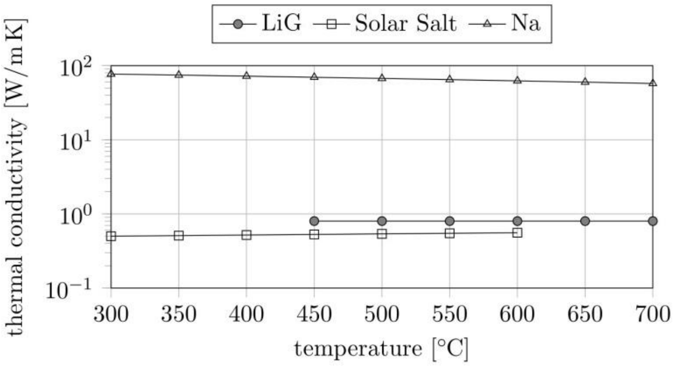

Figure 2 Thermal conductivity over operating temperature ranges

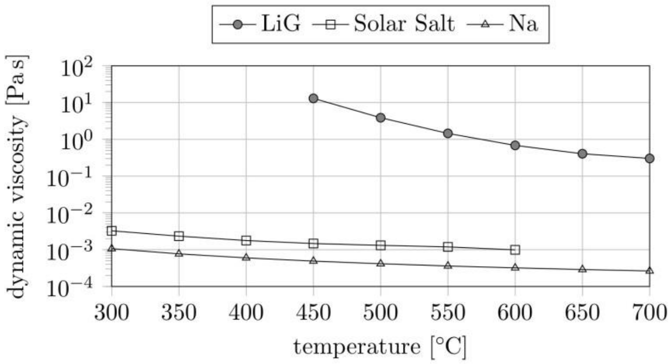

Figure 3 Dynamic viscosity over operating temperature ranges

Solar Salt (see Figure 2). LiG's thermal conductivity is approximately twice as high as that of Solar Salt. The resulting heat transfer coefficients are presented in Section 2.5.

2.4 DYNAMIC VISCOSITY

Sodium's dynamic viscosity is several times lower than that of Solar Salt. LiG, on the other hand, is two to four orders of magnitude more viscous than Solar Salt throughout its temperature range (limited to a maximum of 700 °C), although it reaches higher temperatures than Solar Salt. Haloglass RX's producer defines its viscosity at 450 °C (10 Pa s) as the upper limit for acceptable pumping power requirements [2]. The dynamic viscosity is the only property for which detailed temperature-dependent data of Haloglass RX is available.

2.5 HEAT TRANSFER COEFFICIENT

High values of heat transfer coefficients indicate effective thermal energy removal from surfaces. An HTF with favorable heat transfer properties can cool down the receiver effectively, lower the absorber temperature and increase the allowable flux as well as its efficiency.

As the heat transfer coefficient is not a material property but depends on flow conditions, the determined values for the three fluids are only valid for the specific setup and serve as an example. In this section the boundary conditions are a flow speed (3 m/s) through an infinitely long smooth tube (roughness ε = 3µm) with an inner diameter of D = 10 mm.

The heat transfer coefficients of Solar Salt were calculated by the second Petukhov equation [8]

$$Nu = \frac{(f/8)\ Re\, Pr}{1.07 + 12.7\sqrt{f/8}\left(Pr^{2/3} - 1\right)}$$

with the Prandtl number, Pr, Reynolds number, Re, and the friction factor, f. The latter is determined by use of the Colebrook equation

$$\frac{1}{\sqrt{f}} = -2.0\,\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right).$$

Due to liquid sodium's low Prandtl number, the Nusselt number correlation of Sleicher and Rouse [9] is used for it

$$Nu = 6.3 + 0.0167\,Re^{0.85}\,Pr^{0.93}.$$

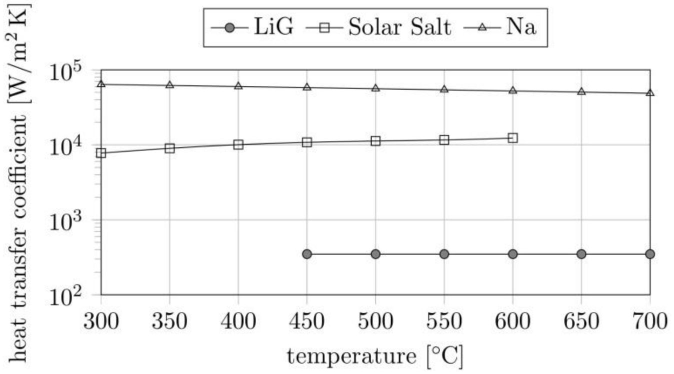

Figure 4 Heat transfer coefficient over operating temperature range

LiG has been found to flow laminar at the set flow velocity and temperatures, so the Nusselt number is constant at a value of Nu = 4.36 (for a constant heat flux boundary condition in a long tube).

For the given boundary conditions and in the defined temperature range, sodium's heat transfer coefficient is four to eight times larger than that of Solar Salt (see Figure 4). The heat transfer coefficient of LiG remains constant at a value approximately 20 times lower than that of Solar Salt.

2.6 LIQUID GLASS' SUITABILITY FOR CSP APPLICATIONS

The lower operating temperature limit of 450 °C is a challenge for any CSP application utilizing Haloglass RX. If used as an HTF or TES medium, effective freeze protection will have to be implemented. Due to shorter piping, a smaller surface area and fewer valves in a TES system, the use as a TES medium appears more viable than as an HTF.

Secondly, also because of shorter piping, the high viscosity of Haloglass RX seems more manageable in a TES system. Pumping of a highly viscous fluid at temperatures exceeding 450 °C will be difficult in a small TES cycle. Pumping it up large-scale central receiver towers seems unfeasible.

Thirdly, the considerably worse heat transfer capability of Haloglass RX compared to Solar Salt – or even more so sodium – would penalize a receiver system in terms of thermal efficiency and pumping power beyond viability.

To conclude, the use of Haloglass RX as the HTF of a CSP plant poses challenges that the authors deem not solvable – at least not in an economically viable manner. As a high-temperature TES medium, on the other hand, it could be desirable due to its advantageous properties. These are namely: a high upper operating temperature limit, a high volumetric heat capacity as well as an expected low material cost and high chemical stability. This option is investigated next.

3 PROPOSED CSP CYCLE WITH HALOGLASS RX TES SYSTEM

As previously concluded, using Haloglass RX as the HTF of a CSP plant is technically challenging and questionable from a heat transfer point of view. In this section, a CSP plant cycle is presented in which Haloglass RX is used solely as the TES medium in an active indirect system. The HTF can be any suitable high-temperature resistant fluid that does not qualify as a direct storage medium, for example, an advanced molten salt

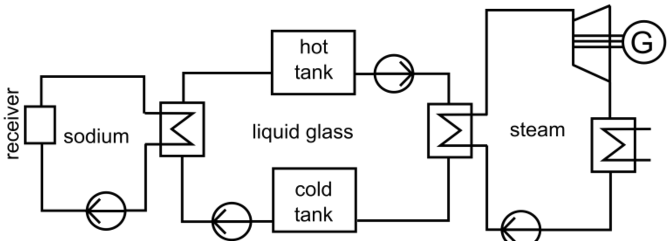

Figure 5 Schematic of the investigated Na-LiG cycle

or sodium. The latter is chosen in this work because it has successfully been tested on a pilot scale [10].

3.1 CYCLE DESCRIPTION

Liquid sodium has been investigated as the HTF of a CSP receiver as early as in the 1980s [10]. The main advantages of sodium as an HTF are the suitable operating temperature range for high-efficiency steam cycles and the good heat transfer properties. The technology has mostly been disregarded because of sodium's highly exothermic reactivity with water, which has led to sodium fires in the past [11]. Its direct use as a TES medium is not viable, as shown in Section 2.2.

The usage of liquid glass as the storage medium minimizes the amount of needed expensive HTF. In the proposed cycle, depicted in Figure 5, the HTF loop is physically separated from the working cycle of the power block by the liquid salt storage loop. This layout further eliminates the potentially hazardous sodium-water heat exchanger. Some components' properties are described in the following.

3.2 CYCLE COMPONENTS

Developing the technology to build a CSP plant utilizing liquid glass is a long-term task. Due to this long project horizon, it is assumed that some components that are not commercially available yet will be developed until project realization. These and other implemented non-standard components are described in the following.

Receiver

Sodium receivers have been shown to withstand heat fluxes up to 2.5 MW/m^2 due to the effective heat removal by the HTF [10]. Compared to a Solar Salt receiver, which can currently accommodate fluxes of only up to 1 MW/m^2 [12], a sodium receiver is able to generate the same thermal output with a smaller surface area. Thus, thermal losses can be reduced or the fluid outlet temperature can be increased at the same thermal efficiency.

Sodium receivers have not been widely investigated recently because of their safety-related issues (see above). However, as sodium is being used as an HTF in such critical systems as nuclear power plants [13], it is assumed that these can be overcome.

Sodium-liquid glass heat exchanger

Compared to an active direct TES system, the heat exchanger between the HTF and TES loop generates additional thermal losses and a larger temperature difference between receiver outlet and steam generator inlet. This necessitates a higher outlet temperature of the receiver than in a one-fluid system, which lowers its thermal efficiency. The low glass temperature at the inlet of the heat exchanger means high viscosities and pressure drops, as well as unfavorable heat transfer properties.

To the authors' knowledge, such high-temperature/high-viscosity heat exchangers have not yet been developed. They are expected to be technically feasible, however, thermodynamically and operationally challenging.

Liquid glass steam generator

Similarly to the Na-LiG heat exchanger, the LiG steam generator necessitates rather a technological evolution than a novel technology. The low viscosity and unfavorable heat transfer properties have to be addressed by adequate design.

Pumps

In a first cycle layout, as depicted in Figure 5, the liquid glass pumps are located upstream of the heat exchangers. This means that one of them has to pump highly viscous glass at a temperature of approximately 450 °C and the other one is exposed to temperatures of approximately 700 °C. At a later stage, this principle might be changed depending on pumps' allowable operating conditions.

Power block

Current state-of-the-art Solar Salt CSP plants run subcritical steam power blocks below 550 °C live steam temperature. Significant improvements in efficiency of the Rankine cycle and the whole plant can be achieved if this temperature can be raised to above 550 °C for supercritical cycles, above 600 °C for ultra-supercritical (USC) cycles or even above 700 °C for future advanced-USC cycles [6,7].

Sodium and Haloglass RX are both capable of withstanding such high temperatures at ambient pressures. The power block is, therefore, seen as one of the limiting components in terms of reachable temperature and overall efficiency.

4 MODEL

An hourly steady-state model of the described cycle and of a reference Solar Salt cycle (see Figure 6) has been developed in MATLAB R2011b to compare them on energetic and economic bases. The fundamental approach of the modeling and selected boundary conditions of the conducted annual simulations are presented in this section.

4.1 COMPONENT MODELING

The Solar Salt plant is modeled with a two-tank active direct TES system as demonstrated in the Solar Two and Gemasolar projects. The LiG plant has the same types of components except for an additional heat exchanger between

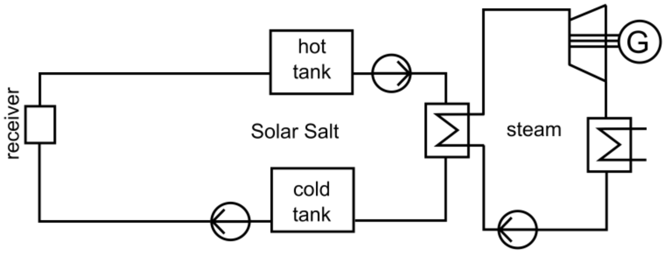

Figure 6 Schematic of the Solar Salt cycle

HTF loop and TES system (see Figure 5). More information on major components' modeling is given in the following.

Solar field

The hourly optical efficiency of the heliostat field was determined in System Advisor Model [16]. The modeled field is based on 144 m^2 heliostats in a surround field with a reflective area of approximately 1.9×10^6 m^2 around a 275 m high tower. The calculated hourly efficiency matrix was not adjusted for different field sizes in the parametric study to minimize computational expenses.

Receiver

The receivers of both models are tubular external receivers with the thermal and optical properties shown in Table 2. The operating temperatures and allowable maximum flux are the only input variables that differ between the two models. However, the flow path length and number of parallel paths in the HTF loop are varied in the parametric study.

The absorber outside facing surface temperature, T_{absorber}, is modeled as constant over the area of the receiver. This simplification was found to not make a significant difference compared to a discretized temperature profile along the flow path.

The incoming concentrated solar radiation from the solar field was modeled to create a constant flux onto the absorber. The flux limit, therefore, defines the *average* flux on the absorber at full load. This is the reason for the chosen values being lower than the maximum flux limit stated in literature.

The thermal efficiency of the receivers is determined by an energy balance with radiative and convective losses calculated by basic correlations.

Power block

The power block of the Solar Salt plant contains a standard subcritical steam cycle with a live steam temperature of 540 °C and a nominal net rating of 125 MW_e. The higher HTF and TES medium temperature of the LiG plant, on the other hand, allows for the use of a more efficient USC cycle with a live steam temperature of 630 °C at the same nominal rating. Both cycles employ dry cooling due to the expected water scarcity in regions with high solar irradiation.

Rankine cycle efficiencies are determined via polynomial fits to look-up tables in dependence of ambient temperature and load conditions [7].

TES system

Both thermal energy storage systems are two-tank active systems. The specific heat loss relative to the temperature difference of the hot fluid, $T_{\text{TES,in}}$, to ambient, T_{amb}, and to the nominal storage capacity, $Q_{\text{TES,max}}$, is identical for both fluids at $ua_{\text{TES}} = 0.288$ $W_t/(W_t\ h\ K)$. The data originates from the Solar Two project [7]. The hourly heat loss of the system is then

$$\dot{Q}_{\text{TES,loss}} = ua_{\text{TES}} \cdot Q_{\text{TES,max}} \left(T_{\text{TES,in}} - T_{\text{amb}}\right).$$

Table 2 Properties of the receivers (partially derived from literature [7,15])

Property	Solar Salt	Na
Max. average flux [kW_t/m^2]	600	2000
$T_{\text{absorber}} - T_{\text{HTF,mean}}$ [K]	50	20
Reflectivity [%]	4	4
Emissivity [%]	88	88
Minimum load [%]	16	16

The fluid temperatures are dictated by the requirements of the power block and the temperature difference in the steam generator. A storage capacity sufficient to supply the steam generator for 15 hours at full load has been chosen for all set-ups.

Heat exchangers

The pressure drop of the Solar Salt steam generator was estimated to be 9 bar – the same as in the Solar Two project [17]. The thermal losses of the heat exchangers are calculated in a similar manner to the TES tanks'. The specific loss relative to HX nominal rating and maximum temperature difference between fluid and ambient is derived from the Solar Two steam generator and has a value of 5.50×10^{-6} $W_t/(W_t\ K)$ [7].

Determining the parameters of the HXs involving LiG – that is the Na-LiG HX and the steam generator – is a non-trivial task due to its high viscosity and low heat transfer coefficient. The design of such HXs is, therefore, not considered part of a first investigation. To still be able to approximate the influence of these HXs on thermal efficiency, parasitic energy demand and cost they are modeled by the following principles.

The specific thermal losses of both HXs are assumed to be the same as for the Solar Salt plant. The temperature differences between hot and cold fluid are set to 30 K and 10 K for the Na-LiG HX and the steam generator, respectively.

The pressure drop on the TES side of both LiG HXs is estimated as a multiple of the pressure drop of the modeled Solar Salt plant steam generator.

Pumps

The cold pump of the Solar Salt plant has to generate the pressure difference caused by the height of the tower and the pressure drop of the receiver (see Figure 6). The kinetic energy of the salt flowing down from the receiver is not used in a closed pressure cycle to decrease the risk of receiver overheating in case of pump failure. The pressure drop in the receiver was calculated via the friction factor of the salt or glass flow. The hot pump has to provide the pressure difference caused by the steam generator only.

Similarly, the HTF pump of the Na-LiG system has to overcome the height difference of the tower and the pressure drop of the receiver. It is assumed that the height of the tower supplies enough pressure to overcome the pressure drop of the Na-LiG HX. The cold and hot LiG pumps have to supply the required pressure drop for the TES side of the Na-LiG HX and the steam generator, respectively.

4.2 ECONOMIC MODEL

All components' cost information – except for the Na-LiG HX – are based on data used by Kolb for *future* CSP plants, which is based on the SUNSHOT program's goals [7].

Herrmann, Kelly and Price [18] estimate the specific cost of an oil-to-salt heat exchanger in dependence of its heat transfer area. This specific cost information was used for the Na-LiG

HX as well, which is an optimistic assumption due to the higher temperatures and more challenging fluids. The heat transfer area can be approximated through the *log mean temperature difference* method. As stated in Section 4.1, the design of LiG HXs was not investigated, which means that their cost is difficult to estimate.

Specific cost of the TES system is not changed from the Solar Salt-derived values although LiG has a higher volumetric heat capacity and a larger operating temperature spread. However, the latter cannot be utilized due to the limitations of steam cycles and the former is expected to be compensated for by higher tank and pump investment costs due to the higher operating temperature and viscosity.

The levelized cost of generated electricity, LCOE, is finally calculated from the fixed charge rate, all capital expenditure, operating expenditure and annual generated electricity. For more information on this method, the reader is referred to Kolb's report [7].

4.3 VALIDATION

To validate the model, a plant was modeled according to specifications used by Kolb for a future subcritical Solar Salt plant [7]. A selection of the key parameters is presented in Table 3. However, some data differed slightly from the reference model due to unavailability (weather data set) or differences in programing (receiver rating, TES capacity).

To compare the two models, the annual energy flows in the subsystems were compared. Throughout the conversion processes, the accumulated energy flows were within 2 % of Kolb's data. The final annual energy yield was calculated to be 746 GWh_e which is 0.9 % higher than the reference. As the summarized solar input of the used data set is approximately 0.5 % larger than the reference, the aberration becomes smaller.

The calculated economic performance indicators come close to the reference values as the cost model is almost identical. The total investment cost and LCOE of the modeled plant are 894 Mio. USD and 0.102 USD/kWh_e, respectively.

5 CONCLUSION

A liquid glass based on Haloglass RX was investigated as the HTF and TES medium for central receiver CSP plants. At temperatures below approximately 450 °C, LiG is too viscous to be pumped. Even at much higher temperatures it is still several times more viscous than other proposed thermal media in CSP plants. At comparable flow conditions LiG has a heat transfer coefficient more than an order of magnitude lower than sodium and Solar Salt. For these reasons, using LiG as the HTF in the receiver system is deemed non-viable.

High-temperature stability, high volumetric heat capacity and low cost are strong benefits of LiG compared to alternative TES media. However, its lower temperature limitation causes a decrease in usable temperature spread and its high viscosity and unfavorable heat transfer characteristics pose challenges on heat exchangers.

Table 3 Plant parameters for validation

Parameter	Value
Heliostat surface area	1.9×10^6 m^2
Receiver aperture area	1833 m^2
TES capacity	15 full-load hours
Hot/cold salt temperature	566 °C / 290 °C
Power block type	subcritical with dry cooling
Weather data set	Barstow, CA [19]

A basic thermodynamic and economic model was developed to enable comparing a Na-LiG plant to a state-of-the-art Solar Salt plant in terms of thermal efficiency and economic viability. A validation of the model by comparison of the Solar Salt plant with a reference study showed good agreement.

Some of the components that should be reviewed to enhance the model's accuracy are the thermophysical properties and cost of Haloglass RX, the heat exchangers, the pumps, the TES system and the sodium receiver.

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