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High Temperature Latent Heat Storage with Direct Electrical Charging – Second Generation Design

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Abstract

The increasing share of renewables in today's generation mix and the accompanying fluctuation in generation requires large scale as well as decentralized storage capacities to secure grid stability. In the described power-to-heat concept, electricity, produced from PV-plants or small scale wind farms, is used to heat up high temperature latent heat storages. The heat can be used in industrial processes. The storage is equipped with electrical heating elements, directly immerged into the phase change material to achieve best conversion efficiency. Discharging takes place by an oil cooled plate heat exchanger. For heat transfer enhancement during discharging, a concept, using moving blades to scrape off the solidifying material, was developed. With this method, the solidified layer of phase change material on the heat exchanger surface is kept at constant thickness, allowing for constant heat flux during the major period of the discharging process. Feasibility of the concept with moving scrapers was demonstrated, proving the advantages over the passive concept. Various aspects have been identified for improvement of the concept. In the second generation design it is intended to combine the electrical heating with the cooling plate to minimize the amount of components and material inside the storage and to maximize the available heat exchanger surface. With this solution, the same heat exchanger surface can be used for charging or discharging. Flat heat exchanger surfaces will allow a very narrow gap between scraper and heat exchanger plate. The mounting of the scraper mechanism is changed from a central slide to a portal frame, supported by four ball bearings. Two bearings each are guided in a track on each sides of the storage. For exact positioning in relation to the cooling plates, two bearings each are mounted in the middle of the traversal trusses, and guided along the middle track. The scraper is re-designed to also be able to scrape off solidifying salt at the bottom of the storage. In addition investigation are under way, to reduce the adhesion between PCM and heat exchanger surface by nanotechnology or any other means.

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Keywords: Thermal energy storage; Latent heat; Power-to-heat; High temperature; Electrical heating.

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1. Introduction

The current conversion of Germany's electricity market, with more than 25 % electricity production from renewables today and the goal of 80 % renewables in the electricity mix by 2050, is a tremendous technological, economic and sociological challenge. An energy system, based on mostly fluctuating renewable energy technologies, requires new infrastructure and new system architecture. Technologically, integration of storage technologies and the synergetic coupling of electricity and heat sector are mandatory. Systemically, efficient and, most important, secure energy supply is required. Smart grids, based on cellular system designs for areal supply as well as supra-regional, are necessary for security of energy supply. This requires decentralized as well as large scale storage capacities as one option to balance demand and supply.

With the increasing share of fluctuating electricity production, the amount of residual load rises and power-to-heat (direct conversion of electricity into heat) becomes a cost effective technology that can be operated with surplus energy produced from renewable energy sources that otherwise will be curtailed. It can also provide more flexibility to the grid by providing negative balancing power and through operation in times of negative electricity prices [1]. Today, power-to-heat is already implemented by the integration of electrode heaters into large water storage tanks, connected to large district heating networks of several public utilities [2]. Heat supply will be of high significance towards a more sustainable energy system in the future. Heat and cold represent 58 % of today's consumption of end-use energy in Germany [3], 21 % are required for process heat, meaning there is a huge potential in the industrial process heat sector, which has got little attention so far and for which high temperature heat storage solutions are required.

All state-of-the-art power-to-heat options are producing low temperature heat around 100 °C. The value of power-to-heat will be significantly raised by producing high temperature heat well above 150°C. The latent heat storage concept of Esslingen University of Applied Sciences can store heat at high temperature (e.g. at 306 °C, using Sodium nitrate as phase change material). Compared to state-of-the-art water storage, this opens up a wide field of applications in combination with industrial process heat. For power-to-heat application, the storage is equipped with electrical heating elements, directly immerged into the phase change material to achieve best conversion efficiency. Discharging takes place by oil cooled plate heat exchangers. A major challenge of latent heat storages is the unfavorable characteristic within the discharging process, due to the insufficient heat transfer between the storage medium and the heat transfer fluid, caused by low thermal conductivity of the storage media [4]. For heat transfer enhancement during discharging, an innovative concept, using moving blades to scrape off the solidifying material, was developed.

In the new concept, the solidified layer of phase change material (PCM) on the heat exchanger surface is kept at constant thickness, allowing for constant heat flux during the major period of the discharging process. Feasibility of the concept with moving scrapers was demonstrated, proving the advantages over the passive concept. Various aspects have been identified for improvement of the concept. In the second generation design it is intended to combine the electrical heating with the cooling plate to minimize the amount of components and material inside the storage and to maximize the available heat exchanger surface. With this solution, the same heat exchanger surface can be used for charging and discharging. The new scraper design consists of a two-part scraper, which can move upwards, when the PCM begins to solidify at the bottom of the storage and will avoid that the scraper stops due to this resistance. In addition investigation are done, if the adhesion between PCM and heat exchanger surface can be reduced by nanotechnology or any other means.

2. Innovative concept for high temperature latent heat storage

A first generation test unit of the innovative high temperature latent heat storage was built and tested in a test loop (**Fehler! Verweisquelle konnte nicht gefunden werden.**) [5]. It has a total volume of 0.36 m³ and is currently filled up with ca. 375 kg of Sodium Nitrate (approx. 65% of complete filling). The storage is equipped with three specially designed electrically heated aluminum plates with an electrical heating power of 4 kW, each. For discharging, two oil cooled pillow plates are emerged into the salt. The moving scrapers are located on each side of both pillow plates, with a gap of approximately 8 mm between scraping surface and pillow plate surface. They are mounted with a metal slide on a rod, supported on the top of the storage tank, and are moved linearly back and forth from one end to the other by a servomotor.

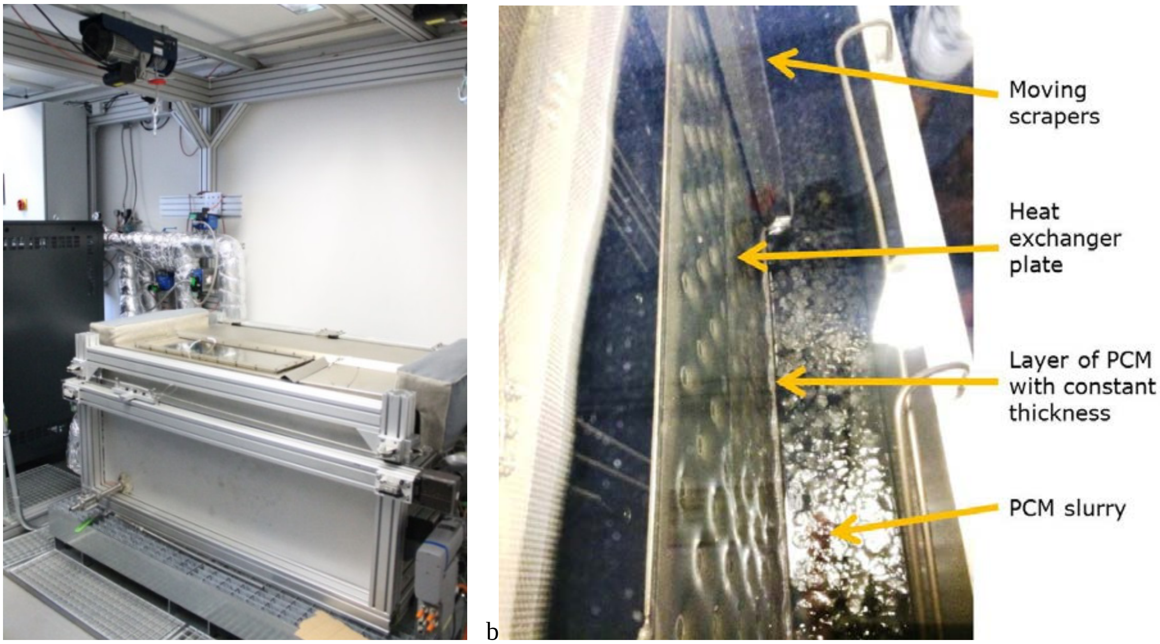

Fig. 1. (a) Test facility with storage unit; (b) storage during commissioning, showing moving scraper that keeps frozen PCM layer at constant thickness.

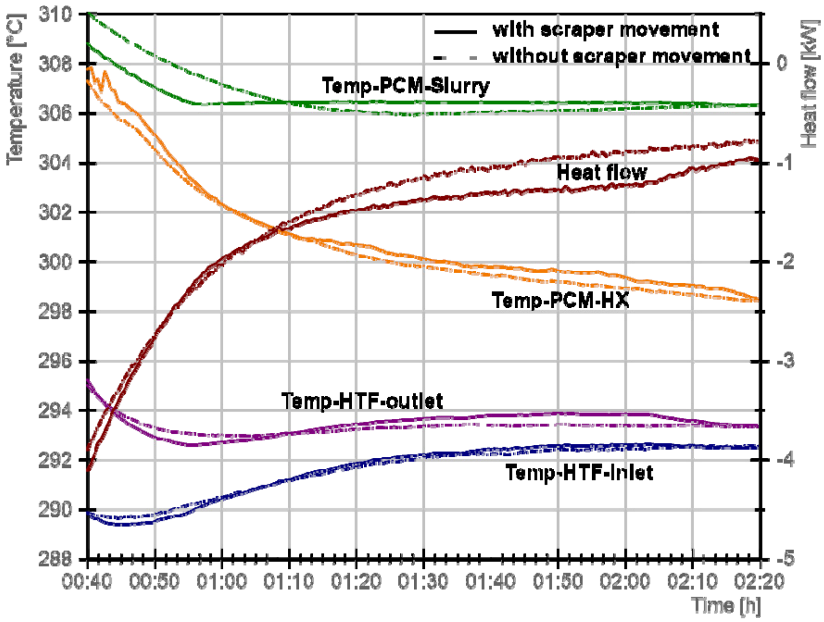

Fig. 2. Comparison of temperatures and heat flow for storage operation with (full line) and without (dashed line) scraper movement.

Fig. 2 shows a comparison of storage discharge with and without movement of the linear scrapers. In both cases the complete storage mass was at 330 °C before discharge was started with a set temperature of 295 °C for the heat transfer fluid (HTF) at storage inlet. The dashed lines represent behavior without and full lines with scraper movement. Apart from HTF inlet and outlet temperatures (Temp-HTF-inlet, Temp-HTF-outlet), the average temperatures of the PCM next to the cooling plates (Temp-PCM-HX) and in the middle between heating and cooling plates (Temp-PCM-Slurry) are shown. The distance between scrapers and heat exchanger plates of the four different scrapers is not the same, due to thermal distortions of the plates and the containment.

2.1. Electric Heating

In the current design, the storage is equipped with three specially designed electrically heated aluminum plates with an electrical heating power of 4 kW, each. Each electric heating plate is built of two aluminum plates, screwed to each other, with a conventional tube heating element fitted in a notch inside one of the plates (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). This design uses a large amount of aluminum and a combination with a cooling mechanism is difficult.

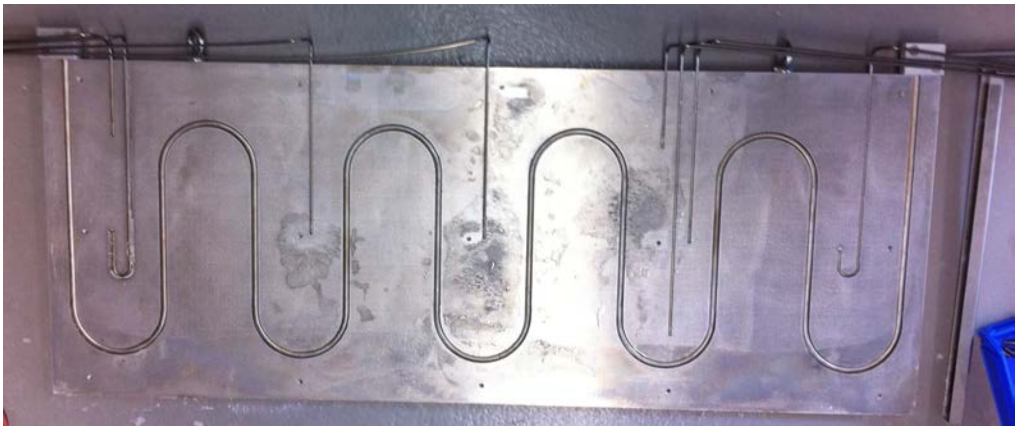

Fig. 3. Current design of electric heating plate with tube heating element and sensors for temperature measurement.

In the second generation design it is intended to combine the electrical heating with the cooling plate to minimize the amount of components and material inside the storage and to maximize the available heat exchanger surface. With this solution, the same heat exchanger surface can be used for charging and discharging.

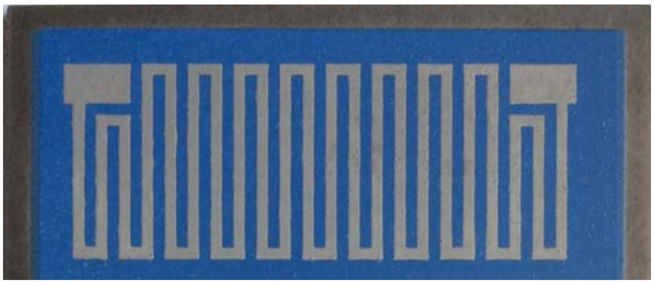

Fig. 4. Printed thick film heater structure without upper isolation layer

A promising solution offers thick film technology. With this PTC (positive temperature coefficient) technology any geometry of heater surface can be printed on a metal substrate (see Fig.). The heating layers are electrically isolated, and thermal resistance is very low, as the layer thickness is less than 50 micro meters. The layer is very robust and not sensitive to breakage or thermal shock. The size of heating plates is in principle only limited by the production facility. Several heating loops can be printed and connected in series. Electric connection needs to be realized carefully outside of PCM. This resistance type of heating is also usable as sensor. Temperature sensors for control can be printed as well. Possibly, temperature self-regulation can be introduced through special PTC materials. With this technology, good heat distribution with low material inventory can be achieved.

For low temperature applications, using paraffin as phase change materials, first prototypes have been built, using resistance heating foils glued onto the heat exchanger surface. For the high temperature storage using Nitrate salts, in a first step these thick film elements will be tested, as in the first generation design, on a separate substrate, and not in combination with the cooling plate. Once these tests are successful, a combined version will be built.

2.2. Linear scraper mechanism

The major drawback of the current linear scraper design was that it got stuck already after approx. 2 hours operation when only about 20 % of the PCM was solid. Due to heat losses of the storage containment, freezing of the salt also occurred at the sides and bottom of the storage. This had two side effects, first, the scraper reversal points at the front sides of the storage moved towards the inner of the storage, as the solid layer at the sides grew, reducing the path length of the scraper movement (see Fig). Second, as soon as the solid layer at the bottom of the storage reached the lower tip of the scraper, the momentum got too high and finally the scraper stopped moving. From the tests, it is clear that the cooling plate's unscraped parts and especially the salt freezing from the bottom mostly influence the mechanism to stop.

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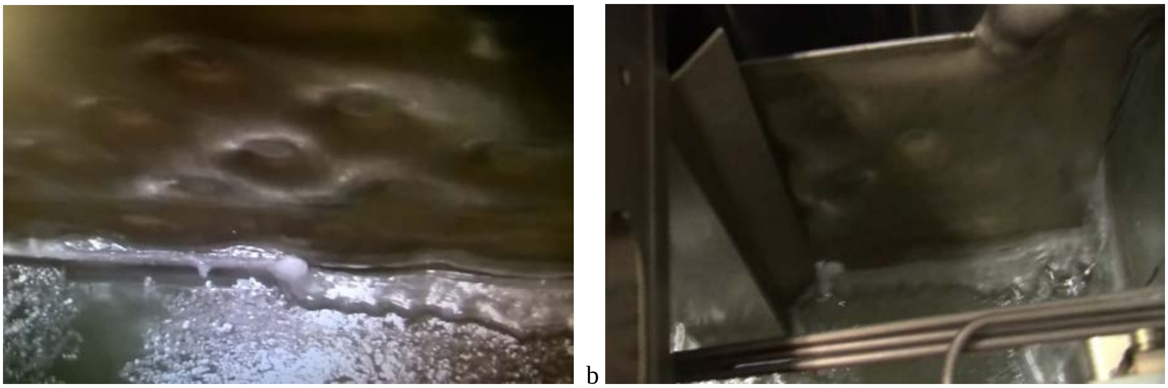

Fig. 5. (a) and (b) increasing layer of unscraped salt at the front sides of the cooling plates due to heat losses.

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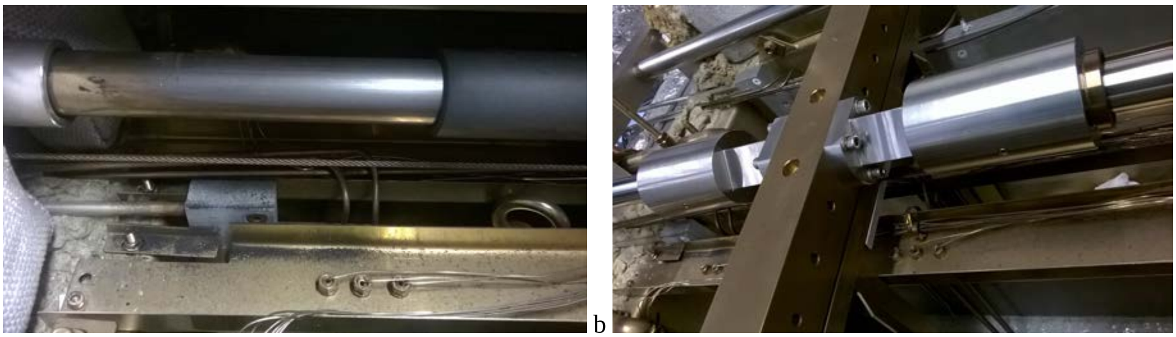

Fig. 6. (a) bronze bushes with abrasive wear; (b) stainless steel ball bushings.

The bearings for the scraper slide are critical due to the high temperature environment. Bronze bushes used in the linear scraper mechanism turned black after couple of tests, vibration lead to abrasive wear between the bushes and shaft (see Fig (a)). The linear scraper often vibrated at the beginning of scraper movement and shortly before it stopped completely. Therefore, slide bushes were replaced by stainless steel ball bushings (Fig (b)). However, these also left scratch marks on the shaft, once again leading to abrasion.

Re-design of the linear scraper mechanism is shown in Fig. The mounting is changed from a central slide to a portal frame, supported by four ball bearings. Two bearings each are guided in a track on each sides of the storage. For exact positioning in relation to the cooling plates, two bearings each are mounted in the middle of the traversal trusses, and guided along the middle track. The cooling plates are also fixed by this support frame, so there can be no relative movement due to thermal expansion, keeping the gap between scraper and cooling plate constant. The support frame is fixed to the storage containment, so the cooling plates can be fixed to the containment bottom without risking relative movement. The number of scrapers is doubled and they are fixed to the traversal trusses. By doubling the number of scrapers, each scraper will only move along half of the cooling plate length. This allows for more varieties of scraper velocity and momentum.

The scrapers have a telescope mechanism and a radial form at the lower tip. When the solid layer, caused by heat losses through the bottom of the containment, reaches the lower tip of the scraper, it can move upwards, reducing the momentum from sliding along the solid layer noteworthy. Through this measure it is expected that storage discharge will not be hindered.

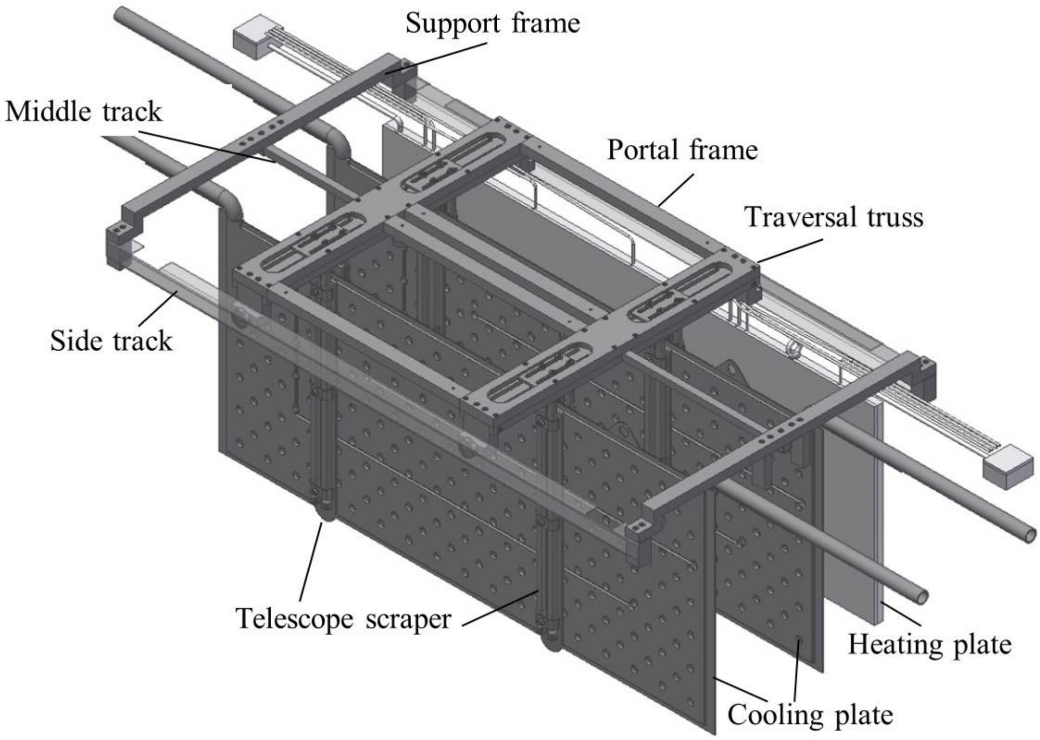

Fig. 7. Re-design of linear scraper mechanism with support frame

In parallel measures for coating of the cooling plates by nanotechnology or any other means are investigated to eliminate adhesion of the solidifying salt on the metal surface. First tests with Vermiculite are currently conducted. If a suitable coating is found, the linear scrapers will only be needed to stir the slurry and move the solid particles away from the heat exchanger surface, reducing parasitics considerably.

3. Conclusions

Germany's future energy system, based on mostly fluctuating renewable energy technologies, requires new infrastructure and new system architecture. Integration of storage technologies and the synergetic coupling of electricity and heat sector will become mandatory. Smart grids, decentralized as well as supra-regional, including decentralized and large scale storage capacities will be necessary for security of energy supply.

Power-to-heat will become one important module within the system architecture of smart grids. Power-to-heat with high temperature heat storage will improve the value of this concept. The process heat sector has a huge potential for reduction of CO2-emissions, also requiring high temperature heat storage solutions.

Feasibility of the innovative high temperature latent heat storage concept with moving scrapers was demonstrated with a first prototype, showing advantages of the active over the passive concept. In this proof of concept, several aspects have been identified for improvement. With the presented re-design of the linear scraper mechanism, an essential reduction of friction of the bearings and scrapers will be achieved. The new electric heating concept, based on thick film technology, is a good solution for best heat distribution with low material inventory with an option to apply the heater structure on the cooling plates. Investigation of coatings for the cooling plates, to reduce or diminish adhesion between PCM and heat exchanger surface, are still under way.

References

[1] Fh IWES, SUER, and Fh IFAM, "Power-to-Heat zur Integration von ansonsten abgeregeltem Strom aus Erneuerbaren Energien abgeregeltem Strom aus." Agora Energiewende, 2014.

[2] D. Laing, U. Nepustil, D. Lodemann, K. Keil, and R. Sivabalan, "POWER-TO-HEAT - INNOVATIVE CONCEPT FOR LATENT HEAT STORAGE WITH DIRECT ELECTRICAL CHARGING," in 9th International Renewable Energy Storage Conference (IRES 2015), 2015, pp. 1–7.

[3] A. Energiebilanzen and A. E. Energien-statistik, "4. Primärenergieverbrauch in Deutschland 2013 (13.828 PJ*)," 2013. .

[4] D. Laing, T. Bauer, N. Breidenbach, B. Hachmann, and M. Johnson, "Development of high temperature phase-change-material storages," Appl. Energy, vol. 109, pp. 497–504, 2013.

[5] D. Laing-Nepustil, U. Nepustil, R. Sivabalan, and D. Lodemann, "Innovative PCM Storage as Power-to-Heat Unit for Process Heat Applications," in ISES Solar World Congress 2015, 2015.