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POTENTIAL HIGH-TEMPERATURE INDUSTRIAL PROCESS HEAT APPLICATIONS FOR CONCENTRATING SOLAR TECHNOLOGY IN SOUTH AFRICA

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ABSTRACT

South Africa has the largest and most developed economy and the highest energy consumption on the continent. 72% of the primary energy is provided by coal, making South Africa the leading carbon dioxide emitter in Africa and the 13th largest in the world.

As the amount of South Africa's proved crude oil reserves is very small, synthetic fuels derived from coal and natural gas in its coal-to-liquid and gas-to-liquid plants make up roughly 90% of the country's domestic petroleum production. However, just one third of the total petroleum demand can be met by the production and the other two third has to be imported and processed in the local oil refineries.

Using Concentrated Solar Thermal (CST) technology, especially solar tower systems, could have the potential to substitute fossil fuels by solar energy, as South Africa is exposed to one of the highest direct normal irradiance (DNI) in the world.

There are several technologies able to deliver high temperature heat. They differ by heat transfer media, system temperature and the system pressure. Direct or indirect heat storing allows a high solar share while an easy hybridization with fossil fuels guarantees 100% availability.

One promising technology, for example, uses small ceramic particles as heat transfer and storage media. The particles can be heated up to 1000°C and later be used for production of hot air.

A very simple and therefore robust technology uses ambient air which is heated up to 750°C for direct use in a pre- heating process or storing the heat in regenerator storage.

Another technological approach uses the rejected heat of a solarized gas turbine with temperatures up to 650°C as process heat. The benefit of such a system is the combined generation of electricity and heat. Storage can be included at the pressurized side allowing high solar share or by using a regenerator on the hot exhaust stream.

The diversity of processes and consumers requires an individual selection of the technology and a layout adapted to the specific consumer needs. The paper presents the different available technologies to show the potential using CST for process heat using air with temperatures above 600°C.

INTRODUCTION

South Africa has the largest and most developed economy in Africa and has at the same time the highest energy consumption on the continent. 72% of the primary energy is provided by coal, making South Africa the leading carbon dioxide emitter in Africa and the 14th largest in the world [1].

Especially in terms of diversifying primary sources of energy and emissions minimization, concentrating solar thermal (CST) is thought to be a promising technology as South Africa is exposed to one of the highest direct normal irradiance (DNI) in the world. Moreover, no significant land use constraint is apparent and materials for building CST plants are mostly readily available [2]. Furthermore, CST plants allow a very high share of local value generation and therefore jobs.

CST plants for electricity production are already well established in South Africa: while 200 MW of CSP are currently under construction and further 200 MW are approved to begin construction this year, another 200 MW is expected to be announced. According to the latest update of the draft IRP 2010-2030 Update Report the CST capacity is increased from the current allocation of 1,200 MW to 3,300 MW by 2030 [3].

Considering the given political framework in South Africa and since much research is already focused on CST as electricity generation, this paper emphasizes potential high-temperature process heat applications for CST systems.

NOMENCLATURE

CST	Concentrated Solar Thermal
DNI	Direct normal insolation
EAF	Electric Arc Furnaces
PSA	Plataforma Solar de Almería, Spain
SNL	Sandia National Laboratories
DLR	German Aerospace Center

According to Vannoni et al. [4] the highest share of high-temperature heat demand is found within the chemical, the non-metallic minerals and basic metals sector. Looking on Figure 1, these specific industries currently consume also the most energy in South Africa's industrial sector.

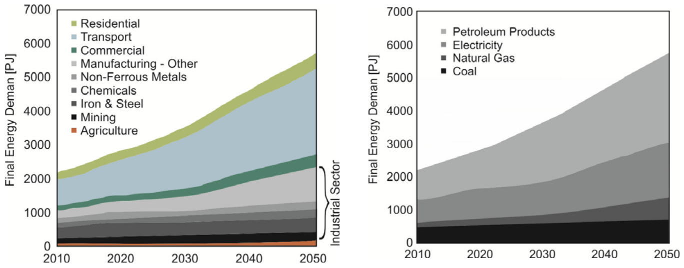

Figure 1: Projected demand for the SA economy by sector (left) and different energy carriers (right) [5].

PROCESS HEAT APPLICATIONS IN SOUTH AFRICA

Oil Refineries

As the amount of South Africa's proved crude oil reserves is very small, synthetic fuels derived from coal and natural gas in its coal-to-liquid and gas-to-liquid plants make up roughly 90% of the country's domestic petroleum production [1]. However, just one third of the total petroleum demand can be met by the production and the other two third has to be imported and processed in the local oil refineries. Although the petrol retail price is regulated by the government its calculation is strongly dependent on the international crude oil spot prices.

Furthermore fuel use for the transport and residential sector is predicted to increase considerably due to the growth of economy and population wealth [5]. The demand for petroleum products will more than double until 2050 as predicted in Figure 1. To meet this increasing demand and the plan of the government to implement new, tighter fuel standards by 2017 South Africa's refineries must be continuously adapted [1].

With about 485,000 barrel per day South Africa has the second largest crude oil distillation capacity on the continent [1]. The average energy use of an oil refinery lies between 1 – 4 GJ per ton crude oil [6]. This results in a constant consumption of ~800-3200MW$_{th}$ or 7.2-28.8TWh$_{th}$/a. Solar resources at the refinery locations are in a DNI range from <1600 to 2100kWh/a.

The energy for the refinery processes is supplied by natural gas if available or comes from the crude oil itself as in the case of the Chevron refinery in Cape Town.

A major question for cost-effectiveness is the further use of the intermediate oil products which are at the moment burned in the refinery. LPG can be either exported or sold at high prices to domestic households in order to satisfy their cooking and heating needs. Refinery gas could potentially be converted to H_2 or a high value liquid hydrocarbon. Moreover, combined heat and power generation is also imaginable as most refineries are already equipped with a steam turbine system to generate electricity. Excess electricity could be sold to the grid, eventually leading to an overall cost reduction of the final petroleum products.

Reducing the high fossil fuel usage in oil refineries by integrating a CST system seems therefore a promising way to meet the increasing demand in the transport sector and simultaneously fulfill the government's objective to secure energy supply, retain its affordability and create jobs. Reducing the imported energy streams would make macroeconomic sense as well as potentially save money for the companies as crude and oil product prices are high and volatile.

Electric Arc Furnaces

Solar preheating of educts for Electric Arc Furnaces (EAF) used for the production of steel and ferroalloys like ferrochrome is another potential high value solar process heat application. Preheating saves an electric kWh for every solar thermal kWh introduced into the process and is therefore potentially very cost-effective. Preheating and pre-reducing the educts with off-gases from the furnace and the high ferroalloy melting temperatures like for example 1350°C-1675°C for FeCr [7] limit the energy contribution from solar due to the high temperatures required. But even a small solar contribution can be an interesting market due to the South African production capacity of about 5Mt/a of ferroalloys [8]. With an electricity use of 3.1-4.5MWh$_{el}$/t for ferrochrome [9] as the main product this results in ~1.8-2.6 GW$_{el}$ baseload consumption or 16-23TWh$_{el}$/a. Assuming only a 20% solar electricity saving, the 2013/2014 average Eskom electricity price of 0.706ZAR/kWh$_{el}$ [10] and a project lifetime of 25 years this represents a market of 54-79 billion ZAR or 3.9-5.7 billion € at current exchange rates. The solar resource at the South African plant locations is in the DNI range of 1900-2500kWh/a, at which a solar heat price of 0.7ZAR/kWh$_{th}$ seems achievable. Further advantages like higher production capacities of the furnaces and reduced environmental impact are not valued in the calculation.

PARTICLE TECHNOLOGY

The first extensive evaluation of solid particles for solar applications was performed and published by Sandia National Laboratories (SNL) in the 1980s, e.g. [11, 12].

Sand-like ceramic particles have been identified as appropriate heat transfer medium. These particles are usualy used in large quantities in oil industry and therefore available in sufficient amount and with acceptable prices (prices comparable to molten salt expected).

The schematic view of a solar tower system with particles as heat transfer and storage medium is shown in Figure 2. The mirrors in the heliostat field concentrate the direct solar radiation onto the top of a tower, where the receiver is located.

In a direct absorbing particle receiver (like the falling particle or centrifugal concept) the solar radiation is absorbed directly by the particles. The heated particles are collected and transported to a hot storage.

On demand, the hot particles can be used to generate hot air by an efficient direct contact heat exchanger with temperatures up to 750°C. The cold particles are stored in the cold tank before they are transported again to the receiver. If no sun is available a fossil back-up heater that is implemented in the particle cycle, can provide the heat to provide firm capacity.

Solid particles do not have a lower operation temperature limit, compared to the solar salt that will freeze below a temperature of about 260 °C. The upper temperature limit for the particles is far beyond the maximum temperature for solar salt and other indirect receiver concepts (e.g. tube receiver) that are limited by the maximum operational temperature of the structural material. Particle outlet temperatures in excess of 1000°C can be achieved with ceramic particles.

Simulation results indicate receiver efficiencies in excess of 90% at design point and for a high flux centrifugal receiver even yearly receiver efficiency in excess of 90% [13, 14].

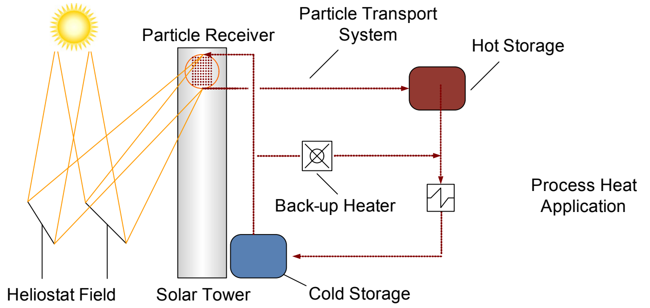

Figure 2: Solar tower system with particle receiver

Receiver

Actually, various particle receiver concepts are under investigation by different research institutions.

Two concepts are presented more in detail within this paper, the falling particle and centrifugal receiver concept.

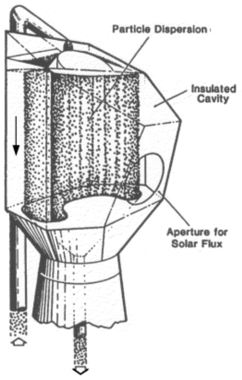

Figure 3: Falling particle receiver [12]

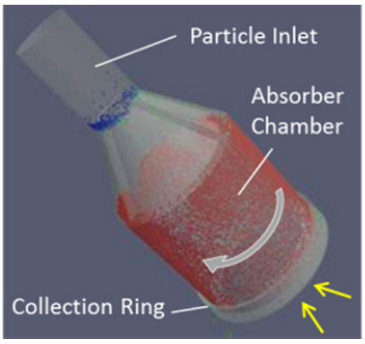

Figure 4: Principle of centrifugal receiver

Sandia National Laboratories proposed a falling particle curtain located in a cavity with a sideway aperture [11] (Figure 3). If the particles in the receiver fall down gravity driven, this is called a falling particle receiver. The concentrated solar radiation enters the cavity and is directly absorbed in the particle film. Recently research activities were restarted within the SunShot Initiative [15].

To enhance the receiver performance a face-down cavity was proposed [16]. The falling particle curtain is located in an insulated hollow cylinder with an aperture facing down towards the ground to reduce convective losses.

Centrifugal receivers are currently in the focus of DLR development (Figure 4) [14, 17]. The main part of the centrifugal receiver is a rotating, insulated metallic cylinder. At the top the particles are fed into the receiver. The particles are pressed against onto the inner wall of the cavity by centrifugal acceleration. They form a dense particle film which moves towards the aperture. The concentrated solar radiation enters the cavity and is directly absorbed in the particle film. Gravity impels the particle layer to move downwards to the aperture. The hot particles are collected in a ring that is located around the aperture and are then transferred to the subsequent particle circulation.

Storage

One of the key advantages of solid particles is the inherent storage capability. The heat is stored directly in the particles, which are collected in an insulated storage bin. The storage density can be high because of the high heat capacity of the particles of over 1200 J/kgK at 800°C [11] and the possibility of high temperature spread between hot and cold state.

Advantages/ Disadvantages/ Risks

Particle receivers offer a high potential for competitive high-temperature heat supply. The particle system provides significant advantages compared to the stat of the art, like molten salt, air or steam receivers. However, the development of the particle system is still at its beginning and several technical risks must be addressed.

Advantages are:

- High temperature capability up to 1000°C
- High heat storage capacity (high heat capacity and high temperature spread)
- Particles are available in large-scale quantities
- Costs for particles are comparable with Solar Salt
- High receiver efficiency due to direct absorption
- No freezing, therefore no additional efforts for trace heating, like for molten salt system.

Disadvantages and risks are:

- High temperature components, especially transport system and heat exchanger, are not yet commercially available
- Effects of high temperature corrosion and abrasion have not been assessed in detail so far
- Quantity and influence of fines that will be generated by abrasion are not known yet. Absorption of the concentrated solar radiation by dust could significantly reduce the receiver efficiency
- Fines from abrasion or from outside could cause problems (e.g. sintering) in the particle cycle

OPEN VOLUMETRIC RECEIVER TECHNOLOGY

The open volumetric receiver technology can be used to heat a gaseous non-pressurized fluid, usually ambient air, to temperatures of about 700°C. In a solar thermal power plant this hot air is used to heat the convective boiler of a conventional steam cycle. In the same way the hot air can be used to feed a process heat application.

The thermal energy of the hot air can also be transferred to a parallel regenerator storage filled with solid material and stored as sensible heat. A parallel fossil back up heater can provide firm capacity. Figure 5 shows the scheme of the concept.

Figure 5: Solar tower power plant with open volumetric receiver technology

Receiver

In the open volumetric receiver the concentrated radiation is absorbed in the depth ("in the volume") of a porous absorber structure which is cooled by air flow parallel to the direction of irradiation. The idea of the volumetric receiver principle is to have a large inner surface for absorption of radiation and heat transfer to the fluid while exhibiting only a small front surface to the ambient (Figure 6). This reduces the radiative losses and allows using air as heat transfer fluid in combination with high solar flux densities. The ratio of the inner heat transfer surface to the front surface is usually between 50 and 500 [18, 19].

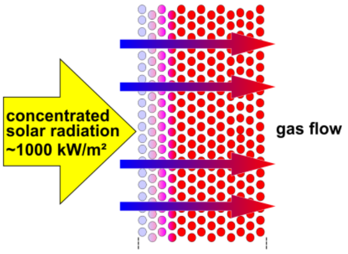

Figure 6: Principle of the volumetric absorber.

Figure 7: State of the art ceramic receiver modules in the 3MW test receiver.

Two main lines of absorber materials have been investigated in larger detail so far: the metal wire mesh and the ceramic honey comb.

The open volumetric receiver with wire mesh absorber was developed by Fricker in 1983 and tested successfully on the Plataforma Solar de Almería (PSA) in 200 kW scale in 1986 and in 2.5 MW scale in 1993. The receiver reached an average air outlet temperature of 700°C at an average flux density of 300 kW/m² and a thermal efficiency of 79 % [20]. The absorber was a knitted mesh of Ni-Cr steel wires of 0.12 mm thickness.

The open volumetric receiver technology with ceramic honeycomb absorber structures was developed by DLR since 1992 in several steps [18, 20]. The current state of the art is a monolithic SiSiC honeycomb of 2mm channel width and 0.8 mm wall thickness. A receiver covered with modular absorber elements of this kind was tested successfully on the PSA in 200 kW scale in 2001 and in 3 MW scale in 2003 (Figure 7) [18]. An average air outlet temperature of up to 750°C at an average flux density of up to500 kW/m² and a thermal efficiency of about 75% was reached [20]. The maximum local material temperature reached values above 1000°C. A solar tower power plant in 1.5MWe scale based on this receiver technology is operated since 2009 as test and demonstration plant in the German town Jülich, close to Cologne [21].

Other structures and materials for volumetric absorbers were also investigated, such as ceramic and metallic foams, metal sheets, printed ceramics and ceramic fiber mats [19, 22]

Storage

The regenerative storage system consists basically of a non-pressurized vessel filled with solid storage elements, e.g. a packed bed of rocks, ceramic spheres or saddles, or layers of Cowper stones or other porous bricks [23, 24].

The storage which is connected in parallel to the receiver is charged by the fluid flowing in one direction (usually top to bottom) and discharged by flowing in the reverse direction. Due to the large internal surface area the heat is transferred to the storage material in a small section of the volume where the thermocline zone is formed which separates the sections of high and low temperature.

Two solar heat storage systems of this kind have been built and tested until today and still exist. One is the storage of the 3MW test plant on the PSA which uses ceramic spheres as inventory material. The other is the storage of the solar tower in Jülich, a vessel of 120m³ filled with monolithic honeycomb bricks of Alumina porcelain. This storage is designed to operate between 680°C and 120°C (i.e. the upper and lower process temperature of the boiler) and is able to run the steam plant for 1.5h under nominal rate.

Due to the usage of non-pressurized ambient air as heat transfer fluid the open volumetric receiver technology is especially suitable for hybridization, i.e. combination with another heat source, usually from combustion of fossil or regenerative fuels. This allows providing heat independently from the day/night cycle and weather conditions, e.g. for 24/7 operation. The simplest way of hybridization is firing of gaseous or liquid fuels directly inside the hot air duct downstream of the receiver [25, 26]. More flexibility in terms of fuel type and operation strategy is gained by operating the combustion in a parallel flow to the receiver and mixing both streams before reaching the consumer. Accordingly, the waste heat flow from a gas turbine is also well suited to combine with the solar heated air.

Advantages/ Disadvantages/ Risks

The open volumetric receiver technology has several advantages especially for the usage as a process heat source:

- Ambient air as heat transfer fluid
- Simple and robust design of receiver and storage components
- Good operability
- Suitability for hybridization

On the other side there are some disadvantages:

- Moderate thermal efficiency (as compared to e.g. molten salt receivers)
- Limited scalability
- Parasitic power consumption in the air blower

SOLAR GAS TURBINE SYSTEMS

Direct introduction of solar energy into a Brayton cycle using solar tower systems enables a highly efficient conversion of the solar energy. Instead of using a combined cycle the high outlet temperature of the turbine can be used for process heat applications. The solar energy can be introduced by preheating of the compressor discharge air by a pressurized receiver before it enters the combustor of the gas turbine.

Receiver

There are two main receiver concepts which have been developed and demonstrated in the past. Tubular receivers (Figure 8) use several parallel metallic absorber tubes located in cavity. Due to the limited heat transfer capability of air as heat transfer medium such receivers have to deal with high material temperatures and are thus limited to outlet temperatures of about 800°C. As the heat transfer is strongly depending on the fluid velocity within the absorber tubes, a relatively high pressure drop must be accepted for an economic design.

The so-called volumetric pressurized receivers use a porous absorber structure located in an insulated pressure vessel. The heat transfer takes place gradually in depth of the volumetric absorber structure, where also the solar radiation is gradually absorbed. A pressurized quartz window is used to introduce the solar radiation. Due to the fact that the receiver can't be built at any desired size, for high power levels it is necessary to connect several receivers to a cluster (Figure 9). For a complete coverage of the focal spot, secondary concentrators with hexagonal entrance aperture in front of the receivers must be used.

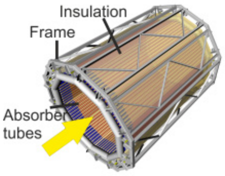

Figure 8: Tubular receiver

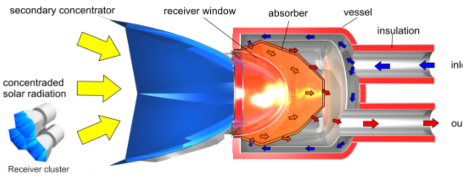

Figure 9: Volumetric pressurized receiver

The SOLGATE project demonstrated the pre- heating using a combination of tubular and pressurized volumetric receivers in combination with a gas turbine [27].

The receivers delivered 1 MW_{th} with an outlet temperature of 1030°C at 7 bar_{abs} pressure.

Within the SOLUGAS project a tubular receiver heating air from 330°C up to 800°C with a thermal power of 3.12 MW and a pressure drop of 250 mbar was developed and successfully tested [28, 29]. The receiver is a prototype (with reduced mass flow) for a commercial system using the Mercury-50 4.6 MW_{el} turbine.

In [30] a tubular receiver design was presented to pre- heat the compressed air of a 4.6 MW_{el} turbine from 330°C up to 800°C, at 10 bar_{abs} and a pressure drop of 250 mbar. A receiver efficiency of 80% and higher could be reached by closing the aperture by a non-pressurized transparent quartz window.

To reach the turbine inlet temperature of 1170°C the air is heated up in the burning chamber of the turbine using fossil fuel. In addition to 8.4 MW_{th} of solar power, fuel power of 7.83 MW_{th} is needed for design point operation of the plant. This leads to a reduced solar share but guarantees a stable power generation without additional back up heaters.

Storage

The turbine exhaust temperature of 650°C can then be used directly for process heat application without storage and heat exchanger. This configuration needs a higher amount of fossil power for all other time points than the design point, if the process heat is needed constantly as the turbine is running in fossil-only mode in non-solar situations.

Introducing a regenerator storage (Figure 10) can increase the solar share when the gas turbine is mainly operated during when solar power is available. The thermal power for the process heat application is then reduced, but available for longer time periods.

A pressurized thermal storage, located in parallel to the receiver, allows increasing the solar share and could deliver the full thermal power of the turbine exhaust heat (Figure 11).

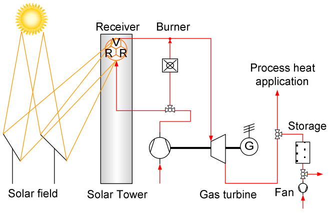

Figure 10: SGT with pressure-less storage

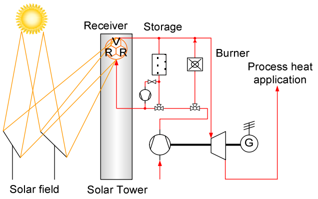

Figure 11: SGT with pressurized storage

Advantages/ Disadvantages/ Risks

The advantages of solar gas turbines for process heat are:

- Inherent hybridization (combustor already integrated)
- Combined generation of electricity and heat
- Several concepts allow flexible adaption to customer needs (no storage, pressureless or pressurized storage)

Disadvantages of such systems are:

- Low solar share (especially without storage)
- High costs and safety risk for solar pressurized receiver
- More complex due to turbine and receiver operation

CONCLUSIONS

South Africa has the highest consumption of energy on the continent. As the amount of South Africa's proved crude oil reserves is very small, synthetic fuels derived from coal together with coal based electricity production lead to the situation that 72% of the primary energy is provided by coal.

Using Concentrated Solar Thermal (CST) technology, for electricity production is already well established in South Africa, as South Africa is exposed to one of the highest direct normal irradiance (DNI) in the world. Several industries consume a large amount of high temperature process heat. Especially the substitution of liquid fuels could be economical as they can be either exported or sold at high prices to domestic households.

The paper presents three solar thermal technologies that could have the potential to substitute fossil fuels by solar high temperature process heat.

The particle technology is able to produce hot air up to 800°C using high efficient direct absorbing receivers together with efficient direct contact heat exchanger and simple storage.

A simple, robust and proven technology is the open volumetric receiver system, able to produce hot air with temperatures up to 750°C. Storage can be included using a regenerator pressure less storage.

Solarized gas turbine systems are able to produce electricity and process heat up to 650°C at the same time. Storage can be included on the pressure less side or by integration between receiver and turbine.

All systems presented solar thermal systems allow the integration of back up heaters to guarantee firm capacity.

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