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Development of a solar fuels roadmap for South Africa

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Abstract

South Africa is heavily reliant on fossil fuels for energy. Fortunately it has an excellent solar resource which, through solar fuels or high temperature solar applications offers the potential to reduce carbon dioxide emissions, to increase energy security and to optimize fossil fuel resource use. Solar fuels can be defined as solar derived thermochemical processes and can include energy carriers (hydrogen, synthesis gas and liquid fuels), chemical or material commodities (metals, lime, and cement) or thermo-chemical storage. South Africa is developing a "*Roadmap to Solar Fuels*" under the guidance of local and SolarPACES experts. This papers aims to provide an overview of the drivers and the process of developing a "*Roadmap to Solar Fuels*" for South Africa. It will also provide feedback on workshops and interactions with industry and government role players and will provide an overview of the specific solar fuels opportunities that exists for South Africa that can be explored further.

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Keywords: Solar Fuel; High Temperature Solar Applications; CSP; South Africa; Synfuels;Road map;

1. Introduction

The success of Concentrated Solar Power (CSP) for electricity production is largely due to the creation of an international market, spearheaded by the Spanish feed-in tariff supported by other feed-in tariffs, portfolio standards

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(as in the USA) and bidding for pre-determined allocations (as in South Africa). CSP has in a decade established a significant contribution to renewable electricity generation worldwide.

The SolarPACES Task II: Solar Chemistry Research would like to see this success replicated in the Solar Fuels and High Temperature Solar Application (HTSA) arena. The technology of using concentrated solar heat to drive endothermic chemical reactions is as old as CSP technology: both had their roots in the oil crisis in the 1970's.

The process to be followed is the development of an international roadmap to Solar Fuels. The first step involved the targeting of two specific countries, Australia and South Africa. In 2012 the SolarPACES ExCo approved a project "*Roadmap to Solar Fuels – Strategy for Industry Involvement and Market Penetration*" to develop road maps for solar fuels for Australia and South Africa. The rationale behind this is that both countries are carbon-rich and solar-rich. By way of explanation, of the thirty largest world economies (measured by GDP) Australia has the highest ratio of CO_2 emissions to total primary energy supply (TPES) with a value of 3.23 tonnes CO_2/toe, while South Africa is in 4^{th} place with 2.60 tonnes CO_2/toe [1].

In the first phase of the "*Roadmap to Solar Fuels*" (June 2012 to July 2013) potential interested industries (primarily from the oil, gas, and coal sectors) and responsible governmental representatives were identified and a "Road Show" of written documents and oral presentations were prepared to illustrate the CO_2 mitigation and market potential of specific solar fuels (e.g., syngas; liquid fuels). These presentations were then presented by SolarPACES experts in workshops with interested high-level industrial and governmental representatives. Subsequently the development of a "Roadmap to Solar Fuels" was initiated by local and external SolarPACES experts together with the identified industries and other interested bodies.

In the second phase of the "*Roadmap to Solar Fuels*" (October 2013 to September 2014) follow on workshops and meetings were held with interested industries, government, and academia for the definition and preparation of a comprehensive roadmap concept and document in the two selected host countries. In addition screening analyses are planned to identify the most promising options for solar fuels and development of a country-specific "Roadmap to Solar Fuels". Links between interested industries and potential technology providers will also be established.

Based on successful results of Phase 2, a third phase is planned where the roadmap concept will be proposed for the benefit of other countries (e.g., China, India), involving different industries and various solar fuels or materials production technologies.

The aim of this paper is to describe the process and the outcomes of developing a Roadmap for Solar Fuels for South Africa and will be structured as follows:

- South African solar fuels history
- Overview of South Africa
- Overview of solar fuels and HTSA opportunities for South Africa
  - The global state of the art
  - Solar fuels and HTSA opportunities in South Africa
    - Reduction/avoidance of electricity consumption (Aluminum Smelting)
    - Reduction of carbon intensity of fossil fuels
    - Calorific lift of fossil feedstocks by solar "upgrading"
    - Reducing carbon intensity of cement
- Conclusion

Nomenclature

CO_2	Carbon Dioxide
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
CTL	Coal-to-Liquids
DOE	South African Department of Energy
DST	South African Department of Science and Technology
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit

GTL	Gas-to-Liquids
HTSA	High Temperature Solar Applications
HYSA	Hydrogen South Africa
ICAO	International Civil Aviation Organization
NWU	North-West University
PV	Photovoltaic
R&D	Research and Development
SANEDI	South African National Energy Development Institute
SETRM	Solar Energy Technology Road Map
SHC	Solar Heating and Cooling
SolarPACES	Solar Power and Chemical Energy Systems
TPES	Total Primary Energy Supply
toe	tons oil equivalent

1.1. Solar fuels definition

Solar fuels can be defined as solar derived thermochemical processes and may include:

- **Energy carriers:** conversion of solar energy into chemical fuels that can be stored long term and transported long-range. The two dominant processes are the production of hydrogen by water splitting (a carbon-free process) and the production of synthesis gas (syngas) from carbonaceous feedstock(s), which may be used directly or transformed into liquid fuels.
- **Chemical or material commodities:** use of solar energy for processing energy-intensive, high temperature materials i.e. metals, lime, and cement.
- **Thermo-chemical storage:** storing of solar energy in chemicals such as sulfur, hydrogen and ammonia.

2. South African solar fuels history

The development of Solar Fuels and other High Temperature Solar Application (HTSA) related research is a relatively new field of activity in the solar technology area in South Africa. A focus on HTSA was initially built into the Hydrogen South Africa (HYSA) business plans of 2009 and 2010. These were submitted to the South African Department of Science and Technology (DST) by the national Council for Scientific and Industrial Research (CSIR) and North-West University (NWU), they called for funding to support research on high temperature solar water splitting and solar steam reforming of methane.

South Africa's Department of Energy (DOE) and DST have recently launched a project to develop a Solar Energy Technology Road Map (SETRM). The SETRM is intended to serve as a living strategic plan to assist government to understand the solar opportunity and to guide toward helping the diverse community of stakeholders involved in the South African solar industry to set and achieve tangible goals over the coming 40 years - with an important interim milestone of 2030.

This roadmap has been prepared to present South Africa with a strategic plan to develop its abundant solar resource capacity to address current and future energy demand needs. The purpose of the SETRM is to provide a comprehensive, aligned, achievable and time bound strategic plan that will help guide: policy and regulatory development; government and industry adoption of technology; national manufacturing sector strategy and related investment; education and skills programme development; innovation, research and development; and the overall diffusion of solar technologies in the country and within the broader Southern African region.

Furthermore, the objective of the SETRM is to develop a clear, comprehensive, and prioritized implementation plan (i.e. roadmap) for the development and diffusion of concentrated solar power; solar photovoltaic (PV) technologies; solar heating and cooling (SHC) technologies; and high temperature solar energy technologies in South Africa. This is in order to progress toward reduced energy use; carbon emissions, distributed electricity generation, expanded independent power production and electricity supply to the national grid, and the reduction of reliance on fossil fuels. The SETRM is being finalized at present and will provide inputs into the SolarPACES "*Roadmap to Solar Fuels*".

2.1 1st SolarPACES "Roadmap to solar fuels" workshop in Potchefstroom

Through the SolarPACES program, South Africa is beginning to engage with global leaders involved with solar fuels research and development. On the 14th and 15th of February 2013, a SolarPACES solar fuels workshop was convened by NWU and CSIR at the NWU's Potchefstroom campus and various industry and government role players attended. The objective of the workshop was to:

- Identify potential industrial and governmental players for a broader local consortium,
- Communicate experiences from the various solar chemistry and solar fuels activities taking place around the world for the last two decades, and
- Create awareness of the potential of solar as an energy source for production of fuels, chemicals and material commodities.

SolarPACES experts from Germany, Switzerland, Australia and Israel presented first-hand information on different solar fuels technologies and their CO_2 mitigation and market potentials.

Additionally, this workshop was intended to create inputs towards a country roadmap for solar fuels. The rationale behind the project is that while CSP, PV and SHC are all international industries that have benefitted from favorable renewable energy policies that are being promulgated worldwide, solar fuels have not yet garnered the same acceptance nor support and a "roadmap" would help popularize the potential of wider use for these technologies. The workshop was well attended (43 people) with 8 persons from various government departments, 15 persons from industry and 14 persons from research institutions and academia.

The following outcomes were observed from the workshop:

- Attendees were not aware of work being done worldwide on solar fuels.
- South Africa can advance rapidly using previous and existing solar fuels research and development (R&D) in the SolarPACES community as base.
- Consensus from attendees was also that South Africa needs a research facility for solar fuels.

The following areas were listed as potential priority application opportunities for Solar Fuels and HTSA in South Africa:

- Production of solar fuels through solar reforming of methane to produce synthesis gas (Dry reforming using CO_2 and steam reforming).
- Solar calcination of $CaCO_3$ to CaO for cement industry.
- Solar melting of aluminum and other metals to reduce electricity demand on the grid.
- Solar water splitting to generate hydrogen.
- Solar gasification of coal and other feedstock such as biomass etc.
- Solar steam augmentation for coal fired power plants.
- Reduction of metal oxides for large scale grid electricity energy storage batteries.
- Mining and metals application (drying of slurries and possibly melting).

3. Overview of South Africa

South Africa consists of nine provinces as shown in Fig. 1 and has borders with Namibia, Botswana, Zimbabwe and Mozambique. South Africa's coal reserves are in the Limpopo and Mpumalanga provinces. Some recent natural gas resources have been found in Mozambique and Namibia and are being explored. South Africa also has a potential shale gas resource in the Karoo that is being explored.

Fig.1. Map of South Africa

3.1 Demand drivers

A number of key drivers exist in South Africa that assists in the motivation of investigating solar fuels and HTSA further:

3.1.1 Climate protection

South Africa has committed to an emissions trajectory (peak, plateau and decline) at COP15 in Copenhagen and subsequently in the National Climate Change Response White Paper. Additionally South Africa is planning to implement a carbon tax in 2015, which will penalize emitting entities. Approximately 30 percent of SA liquid fuel demand is met by Coal-to-Liquids (CTL) and Gas-to-Liquid (GTL) plants, with CO_2 emissions one third that of Eskom (a 40 GW electrical grid run 90 percent on coal). In additional the international aviation industry is facing pressures to reduce its carbon footprint, the most obvious example of which is the European Union (EU) carbon penalty for aviation. The aviation industry has no viable means of reducing its carbon footprint other than through biofuels or carbon-lean synfuels.

3.1.2 Energy security

The South African electricity supply has been under pressure since late 2007, when load shedding had to be applied to ensure stability of the grid. This pressure is not expected to be reduced until the construction of the giant Medupi and Kusile power stations are completed. South Africa spends 75 percent of its entire energy spend on liquid fuels balance of payments to foreign suppliers. However, the 30 percent local CTL and GTL fuel production provides some cushioning with respect to balance of payments (but at significant emissions cost). Additional local fuel production would reduce the liquid fuel trade deficit. The lifting of the moratorium on shale gas exploration by the South African government as well as discussions regarding conventional gas infrastructure make examination of solar fuels application to gas of particular interest. Also, the use of solar in the power generation mix will significantly diversify supply. Increased synfuels production (using solar reforming of methane with either H_2O or CO_2) offsets the liquid fuels national balance of payments. Displacing electricity through solar fuels could reduce electricity consumption in the metals industry for aluminum foundries and zinc galvanizing plants.

3.1.3 Optimization of fossil resource use

Combining fossil fuels with solar provides an opportunity to extend the life of fossil fuels and also optimize the value obtained from them. Fig. 2 shows the Direct Normal Irradiation (DNI) map for South Africa and it is clear that the excellent solar resource which makes CSP and HTSA attractive in South Africa. The solar resource for Gauteng (the province containing Pretoria and Johannesburg) is equivalent to that of Spain (2,000kWh/m^2/year), while the Northern Cape solar resource (2,800kWh/m^2/year) rivalled only by Chile. The indicative geographical spread of various required feedstocks as well as potential HTSA applications where existing industries are in operation have also been indicated on the map in Fig. 2.

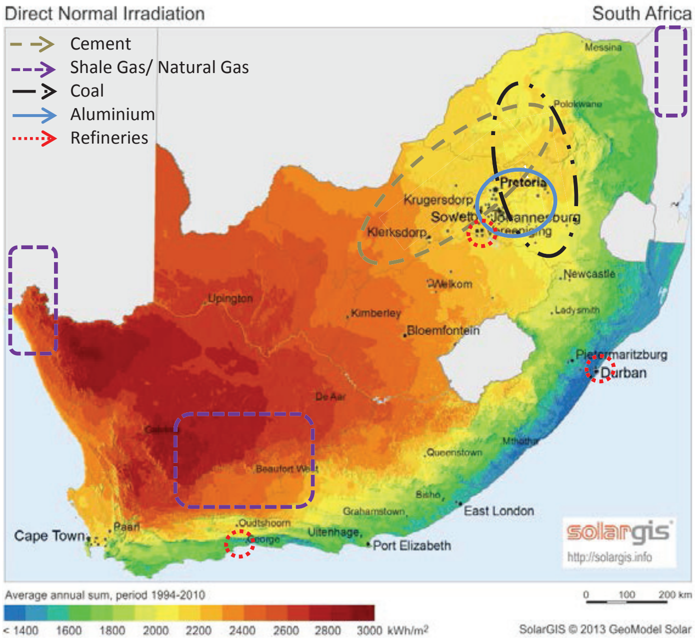

Fig.2. DNI Solar Resource for South Africa [2]

4. Overview of solar fuels and HTSA opportunities for South Africa

In this section an overview will be provided of the global state of the art. This will show that solar fuels and HTSA applications are being developed and are achieving maturity. The opportunities for South Africa will then be listed and discussed briefly.

4.1 The global state of the art

Solar fuels and HTSA related activities have been researched for the past few decades. In the latest SolarPACES Annual report (2011) [3] more than twenty active research projects are listed globally. Through these projects the following technical achievements have been realised:

- Solar steam reforming of methane has been demonstrated at 200kW level in a tubular reactor and at 400kW level in a volumetric reactor.
- Solar steam gasification of carbonaceous solid feedstocks has been performed at 500kW for petroleum coke, 1,000 kW for biomass and at 200kW for low rank coal, industrial sludge, sewage sludge and tyre chips.
- Solar dry reforming of methane has been performed. Level is unknown, but unlikely to be above 10kW.
- Solar thermal Hydrogen production has been performed at 100kW level.

4.2 Solar fuels and HTSA opportunities in South Africa

Given the fact that various solar fuels and HTSA technologies are being developed worldwide and are being scaled up to industrial sized demonstration projects the next section discussed the opportunities for these application in more detail.

4.2.1 Reduction/avoidance of electricity consumption (Aluminum Smelting)

As opposed to carbon-free generation of electricity as in CSP and PV, HTSA is similar to SHC in that consumption of electricity in industrial processes is reduced or avoided. In the case of HTSA the industrial processes concerned are particularly energy-intensive [4, 5].

One of the industries that are experiencing significant pressure is the aluminium foundry industry. South Africa has some 44 aluminium foundries, of which 34 are concentrated in Gauteng. Installed capacity in terms of aluminium die-cast ingot melt in South Africa is 77,000 tonnes per annum (equivalent to 23GWh/a for latent and sensible heat excluding heat losses). Including aluminium recycling for preparation of ingots doubles this energy requirement.

The use of concentrated solar energy to melt a portion of the aluminium has the potential of substantially reducing the electricity consumption in the foundry industry. Initial estimates suggest that of the order of US$10 million in electricity consumption could be saved per annum in the foundry industry alone.

The German Aerospace Centre (DLR) has successfully demonstrated the melting of 2kg batches in a proof-of concept rotary kiln since 2001. Preliminary examination of the melt shows high purity compared with conventional melt. The available solar radiance in Gauteng (described earlier in this paper) makes it suitable for such activities. DLR is keen to collaborate with South Africa in this. Eskom, CSIR and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) have agreed to fund and perform the feasibility study portion of the project, which if promising could lead to a full project.

4.2.2 Reduction of carbon intensity of fossil fuels

With solar fuels and HTSA the climate and energy security drivers can be applied to the domains outside that of the electricity grid: namely that of hydrocarbon fuels.

4.2.2.1 Reduction of carbon intensity of carbon-rich synthetic fuels (synfuels)

About one third of South African liquid fuel demand of some 610,000 barrels a day is met by the Fischer-Tropsch (FT) derived fuels: 150,000 barrels a day by Sasol, mostly using the CTL process and a further 45,000 barrels by PetroSA at a refinery in Mossel Bay a day using the GTL process by PetroSA. This contributes significantly to the country's fuel balance of payments: a potential annual bill of US$22.3 billion is reduced by about a third to US$15.1 billion, a saving of US$7.2 billion. This comes at a large carbon penalty, however: Sasol's Secunda plant is the world's largest single-point source of CO_2.

While combustion emissions of petrol (20.1 gCeq/MJ) and diesel (21.1 gCeq/MJ) remain the same irrespective of source the upstream emissions are highly source-dependent [6]. CTL fuels have emissions in the band of 20.7-28.6 gCeq/MJ which displays higher upstream emissions than any other source except the upper band for oil shale (13-50 gCeq/MJ), and five times higher than conventional petroleum (5.6 gCeq/MJ for petrol and 4.4 gCeq/MJ for diesel). The upstream emissions for GTL synfuels lie in a band of 7.1-9.5 gCeq/MJ, about 1.6 times that of conventional petroleum. Future carbon taxes will therefore certainly affect the South African FT industry in a significant way, CTL more than GTL.

The reason the difference between the upstream emissions of CTL, GTL and conventional oil is the first two, being FT processes, have a precursor process. The second step of the two-step process, the endothermic generation of the synthesis gas (syngas: CO and H_2) from steam (H_2O) and the feedstock (CH_4 or C), requires energy from the first feedstock combustion step:

GTL:

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O + \text{heat} \quad (1)$$

$$CH_4 + H_2O + \text{heat} \Rightarrow CO + 3H_2 \quad (2)$$

CTL:

$$C + O_2 \Rightarrow CO_2 + \text{heat} \quad (3)$$

$$C + H_2O + \text{heat} \Rightarrow CO + H_2 \quad (4)$$

As can be seen in steps (1) and (3) for each process, in the case of GTL, the product gas by mass is roughly half water vapor and half CO_2, while for CTL the exhaust is all CO_2, explaining the difference in upstream emissions for the two processes.

Now in solar fuels processes, the necessary heat required to drive the endothermic reactions to generate the syngas (gasification for coal and steam reforming for methane) can be supplied by concentrated solar energy instead of from the combustion of fossil feedstock (the combustion steps (1) and (3) shown above). This means that feedstock use can be reduced to produce the same amount of syngas (synthesis gas: CO and H_2), and CO_2 production can be practically eliminated in the syngas generation step, as the combustion step is removed:

GTL: $CH_4 + H_2O + \text{concentrated solar heat} \Rightarrow CO + 3H_2$

CTL: $C + H_2O + \text{concentrated solar heat} \Rightarrow CO + H_2$

While research is ongoing to find practical methods to gasify coal using solar heat for CTL, solar steam reforming of methane (for GTL) has been carried out by every major experimental concentrating solar laboratory globally. The process works, with different reactor designs producing syngas at different efficiencies.

Cost comparisons can be made and admittedly, the quick financial analysis does not take into account that the solar steam reforming of methane is a batch-wise process, while conventional steam reforming of methane is a continuous process. That said, the initial cost analysis indicates that solar-assisted GTL should be profitable without subsidies, although less profitable than conventional GTL. The application of a carbon tax further supports the case for investigating solar-assisted GTL.

4.2.2.2 Recycling captured CO_2: Production of carbon-lean synfuels for aviation industry

As has been discussed earlier, upstream carbon emissions can be practically eliminated in synfuels production, if combustion heat is replaced with concentrated solar heat. It is also possible to reduce the downstream, or combustion, emissions by reducing the fraction of fossil carbon in fuels, so that some of the combustion emissions may be regarded as carbon neutral. This is of great importance for the commercial aviation industry which is under pressure to reduce its carbon footprint. An example of this is the planned EU carbon tax for commercial airliners, which led to tensions with China and the United States of America. After pressure, the EU suspended its proposed tax in March 2013 for airlines flying intercontinental routes until the International Civil Aviation Organization (ICAO) rules on the matter. Internal flights within the EU will continue to be liable for their emissions, however.

Kerosene fuel and the gas turbine power plants represent the highest power-to-weight density system combination practicable, and are therefore standard for long-haul airliners. The engines and airframes are already highly efficient, and it is not expected that carbon savings per passenger mile will improve by more than about 5 percent. The only alternative for commercial aerospace to reduce their carbon footprint is to switch to carbon-neutral fuels, almost exclusively biofuels.

Solar fuels can help this situation in the following way. Reforming of methane does not have to be done with steam, it can also be done with CO_2, known as “dry reforming”:

$$CH_4 + CO_2 + \text{concentrated solar heat} \Rightarrow 2CO + 2H_2$$

In the product gases, half the carbon originates from the fossil CH_4, and half from the CO_2. If the CO_2 was captured from fossil fired power station flue gasses or from a CTL or GTL plant, it can be regarded to have been recycled: the fossil feedstock is burnt once; the carbon is used twice, and then emitted once, which differs from business as usual in that a feedstock combustion and CO_2 emission step is avoided. Of course, if the methane is biological rather than fossil in origin, all the emissions can be considered carbon neutral.

While the previous section showed that solar-assisted GTL (using steam reforming) would in all likelihood be profitable, solar-assisted GTL using CO_2 reforming requires the capture of CO_2 The use of amines to capture CO_2 will impose an energy penalty of 61-75 USD/tonne CO_2. The introduction of the proposed carbon tax, as well as the fact that an aviation fuel plant would provide a ready market for the recovered CO_2, would incentivize large-scale emitters of CO_2 such as Eskom and Sasol to consider carbon capture.

4.2.3 *Calorific lift of fossil feedstocks by solar "upgrading"*

Solar reforming/gasification of carbonaceous feedstocks can reduce carbon intensity of synfuels and the syngas could also be used as a fuel in its own right [7]. The equations for methane are repeated for convenience:

Steam reforming: $CH_4 + H_2O$ + concentrated solar heat $\Rightarrow CO + 3H_2$

Dry reforming: $CH_4 + CO_2$ + concentrated solar heat $\Rightarrow 2CO + 2H_2$

The calorific value (LHV in kJ/mol) of the products of equations (5) and (6) are higher than the starting methane:

$$\frac{\text{calorific value of the products}}{\text{calorific value of methane}} = \frac{\Delta h_{CO}+3\times\Delta h_{H_2}}{\Delta h_{CH_4}} = \frac{283.24+3\times244}{802.34} = 1.265 \quad (5)$$

$$\frac{\text{calorific value of the products}}{\text{calorific value of methane}} = \frac{2\times\Delta h_{CO}+2\times\Delta h_{H_2}}{\Delta h_{CH_4}} = \frac{2\times283.24+2\times244}{802.34} = 1.314 \quad (6)$$

Repeating the exercise for coal (represented here as pure carbon C):

Coal steam gasification: $C + H_2O$ + concentrated solar heat $\Rightarrow CO + H_2$

Coal dry reforming: $C + CO_2$ + concentrated solar heat $\Rightarrow 2CO$

As with methane, the calorific value (LHV in kJ/mol) of the products of equations (7) and (8) are higher than the starting carbon:

$$\frac{\text{calorific value of the products}}{\text{calorific value of carbon}} = \frac{\Delta h_{CO}+\Delta h_{H_2}}{\Delta h_{C}} = \frac{283.24+244}{393.696} = 1.339 \quad (7)$$

$$\frac{\text{calorific value of the products}}{\text{calorific value of methane}} = \frac{2\times\Delta h_{CO}}{\Delta h_{C}} = \frac{2\times283.24}{393.696} = 1.439 \quad (8)$$

In other words, the increase in the calorific value of methane in solar reforming using steam or CO_2 increases by a quarter and by a third respectively; and for solar gasification of carbon the respective increases in calorific value are a third and half for steam and CO_2 respectively.

The benefit of this can be illustrated by the example of shale gas being exploited in the Karoo (an area with good DNI see Fig.2) for base load power generation (hopefully efficiently, by burning in a gas turbine topping cycle of a combined cycle power station). Since the product gases of solar methane reforming have higher calorific value than the starting methane, the following is true:

1) The rate of consumption of the methane would be reduced for as long as the sun shines.
2) The carbon emissions per kWh would be reduced.
3) The availability of power would not be affected by the solar availability.

4.2.4 *Reducing carbon intensity of cement*

The role of the cement industry in carbon emissions internationally is described by the Intergovernmental Panel on Climate Change (IPCC) Chapter 3.1 of their document "Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories" [8]:

"Cement is an important construction ingredient around the world, and as a result, cement production is a significant source of global carbon dioxide (CO_2) emissions, making up approximately 2.4% of global CO_2 emissions from industrial and energy sources. ...

Carbon dioxide is released during the production of clinker, a component of cement, in which calcium carbonate ($CaCO_3$) is heated in a rotary kiln to induce a series of complex chemical reactions (IPCC Guidelines). Specifically, CO_2 is released as a by-product during calcination, which occurs in the upper, cooler end of the kiln, or a precalciner, at temperatures of 600-900°C, and results in the conversion of carbonates to oxides. The simplified stoichiometric relationship is as follows:

$$CaCO_3 + heat \Rightarrow CaO + CO_2$$

... CO_2 is also emitted during cement production by fossil fuel combustion. ... The clinker is then removed from the kiln to cool, ground to a fine powder, and mixed with a small fraction (about 5%) of gypsum to create the most common form of cement known as Portland cement. Masonry cement is generally the second most common form of cement. Because masonry cement requires more lime than Portland cement, masonry cement generally results in additional CO_2 emissions."

From the above, it is clear that there are two CO_2 emission sources in cement production, which would require different mitigation strategies:

1) The combustion of fossil fuels to provide the energy and temperature for the endothermic reaction. Reducing these emissions can be achieved by:
    a. Reducing the carbon intensity of the fuel used or;
    b. avoiding fuel combustion by using solar heat directly.
2) The CO_2 released by the chemical conversion of $CaCO_3$ to CaO. Reducing these emissions would require capturing the CO_2 and
    a. Recycling it in the fuel used or;
    b. sequestering it.

Option 1a) would require moving to a fuel with a higher hydrogen content, which would lead to a higher water vapour fraction and lower CO_2 fraction in the exhaust emissions. In South Africa, coal is very widely used as fuel in cement clinker kilns due to its low cost relative to other fuels. If shale gas were to become available at a suitable price, this would be appropriate.

Option 1b) would require a solar reactor of some description. ETH and PSI of Switzerland have together developed a rotary, multi-tube kiln heated by concentrated solar radiation. The CO_2 reduction potential over a state-of-the-art lime plant is calculated to be 20 percent.

Option 2a) would be possible if methane were the fuel used in the kiln, using the processes described above for Recycling captured CO_2: Production of carbon-lean synfuels for aviation industry. Theoretically, coal can be gasified with CO_2, but a suitable reactor would have to be developed.

5. Conclusion

Awareness of the potential of the application of solar fuels has been created in industry and government during the first two phases of the "Roadmap to Solar Fuels" project for South Africa. Potential solar fuels and HTSA applications that have been identified for South Africa include: production of solar fuels through reforming of methane to produce synthesis gas (Dry reforming using CO_2 and steam reforming); solar calcination of $CaCO_3$ to CaO for cement industry; solar melting of aluminum and other metals; solar water splitting to generate hydrogen and solar gasification of coal and other feedstock such as biomass etc.

These potential solar fuels and HTSA applications were mapped to verify available solar resource as well as feedstock availability. Given the excellent solar resource that South Africa has and the potential availability of gas the prospects of solar fuels and HTSA looks very promising. Planning is underway to develop an implementation plan and strategy to proceed with required research and development, human capital development and the establishment of experimental facilities to mature and scale up the envisaged solar fuels technologies for South Africa.

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