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# Approaches to accommodate resource variability in the modelling of solar driven gasification processes for liquid fuels synthesis

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ABSTRACT

The vast majority of present commercial gasification and liquid fuels synthesis plants operate continuously and at steady-state because this mode of operation offers lower cost, higher product quality, higher efficiency and larger scale than their batch-process counterparts. They also employ a large number of components, each with their own thermal inertia, which interact together to carefully control the composition and flow-rate at each stage in the process. Hence, any variability in the operation of any one component has a flow-on effect to influence the net cost and performance of the system. For this reason, the reliable modelling of a solar driven gasification process requires accounting both for the full variability of the solar resource not only in the gasifier, but also for all of the downstream components. Since a change in thermal input to the gasifier will influence either the throughput or composition of the product gases, the reliable modelling of the entire process is a challenging task. The development of models to account for the variability of the solar resource for solar gasification processes has, to date, been done most effectively with pseudo-steady models. These assume that all temporal changes are sufficiently slow to allow performance to be modelled as a time-series of steady-state processes, which can then be used with a time-series of historical DNI. Here we review the various approaches that have made previously to account for solar resource variability. We also directly compare the difference between steady-state and pseudo-dynamic approaches with different temporal resolution. This highlights the need to account for resource variability as a first-order effect, since the estimated size and costs of a system modelled in this way differs dramatically from that calculated with an assumed capacity factor. The two main approaches that have been proposed to date to accommodate solar variability are the use of large amounts of syngas storage, which requires further development if it is to become cost effective, or through hybridisation, which offers a cost-effective path to steady-state operation at the expense of a lower solar share. However, further work is required to develop and characterise downstream processing plant for transient operation before the performance of other solar-only liquids fuel synthesis processes can be modelled reliably.



## 1. Introduction

Although it is well established that concentrated solar thermal energy (CST) has significant potential to provide a low-carbon alternative to liquid fossil fuels through high temperature thermal processes such as gasification, termed "solar gasification" (Piatkowski et al., 2011), it is only more recently that the effect on these processes of solar resource variability has been assessed. Solar gasification offers the potential to convert a greater portion of the carbonaceous fuel to syngas, a mixture of hydrogen and carbon monoxide, than is possible with conventional gasification by displacing the carbonaceous fuel that is otherwise burnt in air or pure $O_2$ to drive the endothermic reactions (Fletcher, 2001; Kodama et al., 2002; Kodama, 2003; Steinfeld, 2005; Z'Graggen et al., 2007; Piatkowski and Steinfeld, 2008, 2011; Piatkowski et al., 2009, 2011). It therefore enables the chemical storage of solar energy in the syngas product up to 21% for a hybrid process (Kaniyal et al., 2013a) and a calorific upgrade of up to 33% relative to the calorific value of fuels such as biomass or coal (Piatkowski and Steinfeld, 2011; Wieckert et al., 2013a). The syngas produced from a solar gasifier has the potential to be converted to high value transportation liquid fuels via a range of processes, including Fischer-Tropsch (FT), methanol to gasoline (MTG) and methanol

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**Nomenclature**

| | |
|---|---|
| $A$ | area |
| DNI | direct normal irradiance ($W/m^2$) |
| F(t) | time dependent |
| $I$ | solar insolation ($W/m^2$) |
| $Q$ | heat flow (J) |
| $\dot{Q}$ | heat flow rate (W) |
| $SM$ | solar multiple |
| $T$ | temperature (°C) |
| $T_o$ | ambient temperature (°C) |
| TDO | time-dependent optical efficiency |

*Greek letters*

| | |
|---|---|
| $\eta$ | efficiency |
| $\Phi$ | solar ratio |
| $\varphi$ | latitude |
| $\delta$ | solar declination |
| $\sigma$ | Stefan-Boltzmann constant ($J/m^2\,K^4$) |

*Subscripts*

| | |
|---|---|
| aa | atmospheric attenuation |
| aper | aperture |
| cos | cosine (for optical efficiency) |
| coll | collector |
| cpc | compound parabolic concentrator |
| d | design |
| DNI | direct normal irradiance ($W/m^2$) |
| itc | interception of sunrays at aperture |
| l | loss |
| o | other |
| opt | optical |
| rec | reactor |
| ref | reflectivity |
| req | required |
| sb | shading and blocking |
| sol | solar |

to dimethyl ether (DME). However, the FT process is best established at large scale and is now also commercially available at smaller scale (Fleisch, 2014). The FT synthesis process is selected in the present review because most analysis with solar processes has been done with the process, and because it allows production of "drop-in" commercials such as FT diesel and kerosene that can be used with existing infrastructure and engines. For example, FT diesel has a high cetane number and zero sulphur or aromatics, which has advantages over both conventional diesel and liquid fuels produced from direct liquefaction process (Robinson, 2009). In addition, the FT diesel can be used in existing diesel infrastructure and engines. Gasification is a complex process, so that the endothermic gasification reactions are affected by any variability, such as occurs with the intermittent and variable nature of the solar resource. This variability leads to changes to the flow-rate and/or composition of the syngas product in a way that typically reducing the syngas quality. Such variability, in turn, typically reduces the efficiency of the downstream liquid fuels synthesis process, which is designed to be operated at a steady state operation and is extremely sensitive to the process variability (Deshmukh et al., 2010). However, the status of understanding of these various influences is yet to be systematically reviewed.

Previous reviews of solar gasification have identified two broad categories of solar gasifiers (Puig-Arnavat et al., 2013):

**Directly irradiated reactors:** Here the carbonaceous feedstock is directly exposed to the concentrated irradiation. This enables a higher reaction temperature and achieves a higher efficiency than the indirect counterpart, but at the expense of lower reliability due to the need for a window; and

**Indirectly irradiated reactors:** Here the heat from the concentrated irradiation is transferred to the reaction zone via an opaque wall. This approach suffers lower performance than the directly irradiated reactors but comes with a higher reliability.

Previous reviews of solar gasifiers have also identified different methods to transport the feedstock through the gasifier, notably packed bed, vortex flow and fluidised bed (Piatkowski et al., 2011; Puig-Arnavat et al., 2013; Alonso and Romero, 2015). However, while these reviews have considered the gasifiers themselves and shown the production of syngas to be technically viable, much less is known about the technical viability of the overall process of liquid fuels synthesis, which requires the solar gasifier to be integrated into a liquid fuels production plant. In particular, no previous review has been performed on the influence of resource variability or of methods to account for it in the overall system of a solar driven gasification process follow by a liquid fuels synthesis process.

Over the years, a number of approaches have been developed with which to account for solar resource variability. The first of these is to assume that the variability only influences plant performance through a capacity factor, allowing a single steady-state model to be used for the performance across the entire year (Hertwich and Zhang, 2009). This approach ignores any influence of variability on start-up and shut-down losses, reduction in performance of the downstream plant and incomplete conversion. However, although it is logical to conclude that this approximation is inevitably a crude, the extent of this uncertainty has yet to be evaluated. The second is the pseudo-steady state approximation (Kaniyal et al., 2013a,b, 2016; Kueh et al., 2015; Guo et al., 2015, 2017). This assumes that the changes to the thermal input from the solar concentrating and any upstream storage systems are sufficiently slow that each component in the system can be assumed to operate at steady-state. Given that no solar fuels synthesis plant has been built or operated for a significant period, no data are available with which to fully evaluate these influences. Nevertheless, some data are available for components of these models. Hence, a review of the various approaches that have been implemented to date is warranted to better establish the state of the art, identify current best practice and also the need for further work.

In light of the above summary, the aims of the present review are:

1. To review previous approaches that have been made to account for variability of the solar resource on the solar gasification process;
2. To undertake a preliminary and independent estimate of the significance of key parameters in the pseudo-dynamic approximation that has been developed to date, namely with regard to the influence of the time-varying efficiency of the solar field, for variations in flow-rate and composition of the syngas from the gasifier and of any start-up losses; and
3. To assess the role of hybrid CST and autothermal gasification technologies both in advancing understanding of these effects and in establishing the technology.