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A review of solar thermochemical processes



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ABSTRACT

This paper reviews development in the field of solar thermochemical processing by considering experimental demonstrations, reactor technology development, thermodynamic, economic and life cycle analyses. The review then builds on these aspects and compares various solar thermochemical processes. Solar upgrading of carbon feed has been demonstrated on pilot scale. It is observed that for the thermochemical cycles, only iron and ceria based redox pair have been demonstrated on pilot scale. For industrial applications, solar thermochemical production of zinc, upgrading of landfill gas and organic waste have been demonstrated on pilot scale. However, long term performance data of these pilot plants is not reported in literature.

Thermodynamic comparison reveals that the processes involving upgrading of carbon feed have energy and exergy efficiency at 50–90% and 46–48% respectively. Multistep thermochemical cycles operating at 900–1200 K have energy efficiency of 34–38%. Metal oxide redox pair based thermochemical cycles operating at 1900–2300 K have energy and exergy efficiencies of 12–32% and 20–36% respectively. Methane reforming and lime production processes have chemical efficiencies of 55% and 35% respectively and have demonstrated better performance than other solar thermochemical processes. A few processes like solar gasification of solid carbon feed have demonstrated lower chemical efficiency of around 10% even at pilot scale. The hydrogen production cost for solar upgrading of fossil fuels is estimated at 3.21–6.10\$/kg and is lower than thermochemical cycles at 7.17–19.26\$/kg and CSP driven electrolysis at 3.15–10.23\$/kg. It is observed that there is limited actual data and significant uncertainty in cost. Under these circumstances, it is recommended that initial screening of processes be done by net energy, material and life cycle analysis.

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Abbreviations: 3DOM, three dimensionally ordered macroporous; ANU, Australian National University; ASR, automobile shredder residue; ASTERIX, advanced steam reforming in heat exchangers; CAESAR, catalytically enhanced solar absorption receiver; CAS, Chinese Academy of Sciences, Beijing; CC, combined cycle; CDS, carbon dioxide splitting; CERTH, Centre for Research and Technology Hellas; CFC, catalytic filamentous carbon; CFD, computational fluid dynamics; CNRS, Centre National de la Recherche Scientifique; CoMETHy, Compact Multifuel-Energy to Hydrogen converter; CPC, compound parabolic concentrator; CPERI, Chemical Process Engineering Research Institute; CR, concentration ratio; CR5, counter rotating ring receiver/reactor/recuperator; CSIRO, Commonwealth Scientific and Industrial Research Organization; CSP, concentrated solar power; CuCl, copper chloride; DIAPR, direct irradiated annual pressurized receiver; DLR, Deutsches Zentrum für Luft- und Raumfahrt; DMR, dry methane reforming; DSS, direct sewage sludge; EAFD, electric arc furnace dust; EU, European Union; ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development; ENEXAL, Energy Exergy Aluminium; ETH, Eidgenössische Technische Hochschule, Switzerland; FB, fluidized bed; GAST, gas cooled solar tower; GE, gasification efficiency, the total mass of product gas/the total mass of dry feedstock; GHG, greenhouse gas; GRAFSTRR, gravity fed solar thermochemical reactor/receiver; HFSS, high flux solar simulator; HTGR, high temperature gas cooled reactors; HV, heating value; HYP, hydrogen yield potential; HyS, hybrid sulphur cycle; HYTHEC, hydrogen thermochemical cycles; IER-UNAM, Instituto de Energías Renovables de la Universidad Nacional Autónoma de México; IRR, internal rate of return; IS, industrial sludge; IU, Inha University, Korea; JAERI, Japan Atomic Energy Research Institute; KIER, Korea Institute of Energy Research; LCA, life cycle analysis; LFR, linear fresnel reflector; LHV, lower heating value; LRK, low rank coal; MoSTAR, molten salt tubular absorber reformer; MWCNT, multiwalled carbon nanotubes; MWSF, megawatt solar furnace; NHR, no heat recovery; NREL, National Renewable Energy Laboratory; NU, Niigata University, Japan; PROMES, processes, materials and solar energy laboratory; PSA, Plataforma Solar de Almería; PSI, Paul Scherrer Institute, Switzerland; PTC, parabolic trough collector; PV, photovoltaics; ROCA, rotating cavity; RPM, revolutions per minute; S2P, sunshine to petrol; SAC, South African Coal; SB, sugarcane baggase; SBG, solar biomass gasification; SCG, solar coal gasification; SCORE, single coil reformer; SCWG, supercritical water gasification; SF, solar furnace; SuF, sundrop fuels; S-I, sulphur-iodine; SNL, Sandia National Laboratory; SMR, steam methane reforming; SS, sewage sludge; SSMR, solar steam methane reforming; STDM, solar thermal decomposition of methane; STEP, solar thermal electrochemical production; STP, scrap tyre powder; TDM, thermal decomposition of methane; TIT, Tokyo Institute of Technology; UCB, University of Colorado Boulder; UT-3, University of Tokyo-3 (calcium bromine cycle); WHR, with heat recovery; WGS, water gas shift; WIS, Wietmann Institute of Science; WS, water splitting; YSZ, Yttria Stabilized Zirconia

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1. Introduction

Conventional industrial processes depend on hydrocarbon resources for producing fuels like hydrogen/syngas and commodities like metals, lime etc. These industrial processes are highly energy and carbon intensive. The issues of fossil fuel depletion and climate change have resulted in development of solar industrial process solutions. Concentrated solar technology offers the option of converting solar energy into thermal, electrical and chemical forms. While conventionally concentrated solar energy is used for process heat and power generation applications, using it to drive chemical reactions is interesting. Processes that make use of solar heat to drive high temperature endothermic chemical reactions are known as solar thermochemical processes.

Fig. 1 shows the trend in publications on solar thermochemical processes from 1974 to 2014. The results are obtained from Scopus. After the 1973 oil crisis, efforts were directed to shift from hydrocarbon to a hydrogen economy. In this context, research on thermochemical splitting of water for hydrogen production was initiated. High oil prices and the threat of oil embargo, ensured that focused research on solar thermochemical processes kept momentum for about a decade. With the stabilization of the oil

market, there were very few publications for next one and half decade. With emphasis on climate change, interest in solar thermochemical processing was again renewed in mid-2000 and the total number of publications have been increasing.

1.1. Solar systems for high temperature thermochemical research

From a research perspective, solar thermochemical processes are first demonstrated in an indoor environment to understand the process dynamics and reactor performance. This is achieved by use of a high flux solar simulator (HFSS) [1,2]. Fig. 2 shown the picture of a HFSS facility at German Aerospace Center (DLR), Germany [3]. HFSS provides an artificial source of concentrated solar energy where the spectral distribution can be matched with that of sun. In this arrangement, xenon or argon lamps are placed at focal point of a highly reflective ellipsoid reflector and deliver concentrated radiant energy on the target. The HFSS facility is housed at many solar thermochemical research centres across the world viz. ETH and PSI (Switzerland), DLR (Germany), University of Minnesota (USA) etc. The HFSS facility at PSI, Switzerland consists of an array of ten electrically heated xenon arc lamps that can provide upto 50 kW of radiative power on the target, with average

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