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A comparative life cycle energy and carbon emission analysis of the solar carbothermal and hydrometallurgy routes for zinc production

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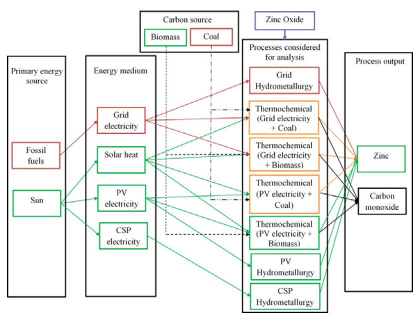
HIGHLIGHTS

- Life cycle analysis of solar carbothermal and hydrometallurgy systems for zinc.
- Comparative analysis for the pilot, demonstration and commercial scale plants.
- Solar carbothermal has higher energy requirement than solar hydrometallurgy.
- Solar carbothermal with biomass and solar power has lowest carbon footprint.
- Trade-off between carbon and energy seen.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper provides a framework to assess the viability of the solar carbothermal route for zinc production by comparing the life cycle energy demand and carbon emissions with the photovoltaic (PV), concentrated solar power (CSP) and grid driven hydrometallurgy systems. The data of the pilot-scale demonstration at Weizmann Institute of Science (WIS) is used to propose a hypothetical design of the 300 kW solar thermochemical plant at Jodhpur, India. A conceptual design of the similar scale PV, CSP, and grid hydrometallurgy plants are developed. The effect of upscaling these technologies to the demonstration and commercial levels is assessed.

On a commercial scale, the energy demand and carbon footprint of the solar thermochemical process are 2.33–4.36 MJ/kg of zinc and 0.02–0.19 kg CO_2/kg of zinc respectively. The corresponding values for the commercial-scale PV/CSP hydrometallurgy system are 2.15/2.37 MJ/kg and 0.16/0.16 kg/kg respectively. The energy demand of the solar carbothermal process is at least 9% higher than the PV hydrometallurgy system. However, if biomass is the carbon source and electricity for meeting the auxiliary load is obtained from a PV plant, then the carbon footprint of the solar carbothermal process is 82% lower than the PV hydrometallurgy system. In this case, the biomass source has an energy penalty, and hence the energy demand is 58% higher than the PV hydrometallurgy route. From a practical perspective, the use of PV/CSP driven hydrometallurgy system does not require any change in the process of commercial zinc production. Therefore, the commercial-scale adoption of the solar carbothermal route will depend on whether the 82% lower carbon footprint, with the biomass source and PV electricity, compensates for the 58% higher energy demand and complications associated with the high-temperature operation.

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Nomenclature

ΔH	heat of reaction (kJ/mol)
$A_{cathode}$	cathode area (m^2)
A_{CSP}	area of concentrated solar power plant (m^2)
A_{hel}	heliostat area (m^2)
A_{PTC}	area of parabolic trough collector (m^2)
AF_{grid}	grid availability factor (%)
A_{PV}	area of photovoltaic panels (m^2)
CED_{zinc}	cumulative energy demand of zinc (MJ/kg)
CEF_{zinc}	carbon emission factor of zinc (kg/kg)
d_{road}	distance traveled on the road (km)
d_{sea}	distance traveled on the sea (km)
DNI_{annual}	annual average direct normal insolation ($kWh/m^2/year$)
DNI_{design}	design point direct normal insolation (W/m^2)
$DNI_{CSP,design}$	design point direct normal insolation of CSP plant (W/m^2)
E_{C-CO}	net annual energy consumed from the carbon source (MJ)
E_E	energy embodied in equipment (MJ)
E_{input}	plant energy input (MJ)
$E_{input,life}$	energy consumed over plant lifetime (MJ)
E_O	annual energy consumed in plant operation (MJ)
$E_{output,annual}$	annual energy output (MJ)
$E_{output,life}$	lifetime energy output (MJ)
$E_{net-output,annual}$	net annual energy output (MJ)
E_R	energy consumed in component replacement (MJ)
EPP	energy payback period (years)
$EROI$	energy return on investment
f_{CO/CO_2}	molar ratio of CO/CO_2
F_{aux}	auxiliary load consumption factor (%)
$F_{CSP,grid}$	annual grid power consumption factor (%)
$F_{t-km,road}$	fuel consumed per ton-km on road (kg/ton km)
$F_{t-km,sea}$	fuel consumed per ton-km on sea (kg/ton km)
$FLOH_{annual}$	annual full load operating hours (h)
GHI_{annual}	annual average global horizontal irradiation ($W/m^2/year$)
H	heliostat direction cosines
I	current (A)
J	current density (A/m^2)
LHV_C	lower heating value of carbon source (MJ/kg)
LHV_{CO}	lower heating value of carbon monoxide (MJ/kg)
LHV_{HFO}	lower heating value of heavy fuel oil (MJ/kg)
LHV_{diesel}	lower heating value of diesel (MJ/kg)
m_{N_2}	nitrogen consumption rate (Nm^3/h)
m_{NG}	natural gas consumption per kg of zinc output (kg/ton zinc)
$m_{zinc/cathode}$	zinc produced per cathode (kg/h)
$m_{zincdust}$	zinc dust consumption per kg of zinc output (kg/ton zinc)
$m_{zinc,design}$	design point zinc output (kg/h)
m_{ZnSO_4/H_2SO_4}	zinc sulfate/sulphuric acid consumption rate (kg/h)
$M_{C,annual}$	annual carbon consumption (kg)
$M_{CO,annual}$	annual carbon monoxide output (kg)
M_g	mass of goods (ton)
M_{HTF}	mass of heat transfer fluid (kg)
$M_{N_2,annual}$	annual nitrogen consumption (Nm^3)
$M_{NG,CSP}$	annual natural gas consumption (kg)
M_{PV}	mass of PV system (kg)
$M_{storage}$	storage mass (kg)
$M_{zinc,annual}$	annual zinc output (kg)
$M_{zinc,annual/cathode}$	annual zinc produced per cathode (kg)
$M_{zincdust,annual}$	annual zinc dust consumption (kg)
N_{anode}	number of anodes
$N_{cathode}$	number of cathodes
n	plant life (years)
n_{zinc}	zinc output (kmol)
n_{CO_2}	carbon dioxide output (kmol)
n_{CO}	carbon monoxide output (kmol)
n_C	carbon consumption (kmol)
NE	net energy (MJ)
N_{PTC}	number of parabolic trough collectors
PLF_{CSP}	plant load factor of concentrated solar power plant (%)
PLF_{PV}	plant load factor of the photovoltaic system (%)
PLF_{plant}	plant load factor of plant (%)
PR	performance ratio
Q_{abs}	annual energy absorbed in the reactor (kWh)
$Q_{reaction}$	useful power consumed in the reactor (kW)
$Q_{reactor}$	solar input to the reactor (kW)
R	distance between heliostat and solar tower (m)
SEC_{BoP}	specific electricity consumption in balance of plant components (kWh/kg)
SEC_{EC}	specific electricity consumption in electrowinning cell (kWh/kg)
S_{hour}	storage time (h)
SEC_{N_2}	specific electricity consumption of nitrogen (kWh/kg)
SM_{HTF}	specific mass of the heat transfer fluid per unit collector area (kg/m^2)
SM_{NG}	specific mass of the natural gas consumed per unit collector area (kg/m^2)
SM_{PV}	specific mass of PV system (kg/m^2)
V	voltage (V)
W_{annual}	annual electricity consumption (kWh)
$W_{BoP,annual}$	annual electricity consumption in the balance of plant components (kWh)
$W_{cathode}$	power consumed in the cathode (kW)
$W_{CSP,annual}$	annual electricity output of the concentrated solar power plant (kWh)
$W_{CSP,design}$	design capacity of the concentrated solar power plant (kW)
$W_{CSP,grid}$	annual grid electricity consumed by the concentrated solar power plant (kWh)
$W_{EC,annual}$	annual electricity consumption in the electrowinning cell (kWh)
$W_{grid,design}$	design point power consumption from grid (kW)
$W_{load,design}$	design point electricity load of the plant (kW)
$W_{load,annual}$	annual electricity load of the plant (kWh)
$W_{LP,annual}$	annual electricity consumption in leaching and purification plant (kWh)
$W_{MC,annual}$	annual electricity consumption in melting and casting unit (kWh)
$W_{misc,annual}$	annual electricity consumption in miscellaneous plant components (kWh)
$W_{N_2,annual}$	annual electricity consumed in the nitrogen production plant (kWh)
$W_{O,annual}$	annual electricity consumed in the plant (kWh)
$W_{PV,design}$	design rating of the photovoltaic plant (kW)

Subscript

	atmosphere
aux	auxiliary
e	east
hel	heliostat
$misc$	miscellaneous
n	north

Greek symbols

$\eta_{atm,hel}$	atmospheric transmittance efficiency of heliostat field (%)
$\eta_{atm,TR}$	atmospheric transmittance efficiency of tower reflector (%)
η_{cos}	cosine efficiency (%).