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GLOBAL ENERGY LANDSCAPE

Global energy demand is projected to grow significantly in the coming decades as economies emerge and develop. Meeting anticipated demand for petroleum while accounting for the decline of current producing fields requires the addition of 64 million barrels per day (mb/d), or 4.53 terawatts, of new gross capacity before 2030 — six times the current capacity of Saudi Arabia. Further, there is no consensus in the industry that petroleum production can be sustained at >100 mb/d. Hence, enormous resources will be expended even to maintain the current fossil fuel paradigm – and that is before concerns about large transfers of wealth, price volatility, supply vulnerabilities, and climate risk from greenhouse gas (GHG) emissions.

TRANSPORTATION FUELS AT A JUNCTURE

Liquid hydrocarbon fuels have undeniable advantages in energy density, installed infrastructure, scalability, and applicability across platforms. Such fuels will remain the 'gold standard' for transportation, which indicates the importance of 'drop-in' alternatives to petroleum that can provide GHG benefits and are safe, secure, affordable, and scalable.

APPROACH

Sandia National Laboratories' Sunshine to Petrol (S2P) platform capitalizes on decades of synthetic fuel technology, in which synthesis gas, a mixture of hydrogen (H_2) and carbon monoxide (CO), is converted to hydrocarbons:

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O.$$

The needed innovation and the principal focus of S2P are on the difficult splitting reactions in which energetically spent carbon dioxide (CO_2) and water (H_2O) molecules are energized to CO and H_2:

$$2H_2O + \text{energy} \rightarrow 2H_2 + O_2;\ \text{and}\ CO2 + \text{energy} \rightarrow CO + \tfrac{1}{2}O_2.$$

These splitting reactions are made feasible using a two-step, concentrated solar driven, high-temperature, metal oxide based thermochemical cycle (TCC). A TCC divides thermodynamically unfavorable reactions into two or more favorable reactions. In essence, a TCC is a heat engine that uses heat to do chemical work of breaking bonds; hence, it converts heat energy into chemical energy. High efficiency is theoretically possible for these high temperature, thermally driven processes, especially when compared to approaches that are more conventional, e.g. biofuels or electrolysis.

CHALLENGES

All large-scale renewable energy technologies face the challenge of capturing and converting a low-density energy source into a more concentrated and usable form. For solar technologies, this translates to costs and resource limitations associated with the collection of low energy density sunlight, which makes high efficiency especially important. New energy technologies must also offer clear advantages in efficiency, cost, and/or scalability over currently available alternatives. For synthetic fuels from the sun, the only known and proven pathway would use solar-generated electricity (PV or CSP) to drive water electrolysis to produce H_2 with downstream processing to the liquid hydrocarbon.

We characterize challenges specific to S2P as Reactor-, Materials-, and Systems-related. By addressing each of these challenges, the S2P team aims to make rapid and continuous advances to improve efficiency and durability of S2P and drive down anticipated cost and resource intensity.

Reactor: Thermodynamics dictates that the two reactions of a TCC are favorable at two different temperatures. Preserving the sensible heat of the metal oxide as it cycles between high and low temperatures (recuperation) is crucial to achieve high efficiency. Other vital reactor attributes, in addition to recuperation, include: (1) inherent separation of the two products energized chemical, CO or H_2 from O_2, (2) continuous utilization of incident solar energy, (3) direct illumination of the reactive metal-oxide during thermal reduction, and (4) an independent (partial) pressure control for each half-cycle. The challenge is to design for these attributes, for desired radiative absorption and emission properties, for the gas flows and gas/surface interactions, and for durability.

Materials: The redox active materials forming the heart of the TCC must perform predictably and reliably over many thousands of cycles in an extreme non-steady-state environment. To achieve maximum efficiency, the material must meet not only thermodynamic and physical criteria, but also be designed to function in a manner that balances and maximizes incident solar flux, redox chemical kinetics (limited by thermodynamics), reactant/product species transport, and heat recuperation to maximize efficiency and chemical flux. The figure at right summarizes S2P's materials issues. The challenge is to design for all the vital attributes: thermodynamics, kinetics, ion transport, sufficient surface area, and long-term chemical and physical stability.

Systems: The TCC reactor is only a component of a larger system. Failure to appreciate the complete picture can lead to decisions that produce optimum performance at the component level, but at the expense of end-to-end system performance. The challenge is to preserve the energy of the energized reactor products into the final fuel product, including optimizing separations, gas handling, intermediate storage, and heat integration.

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