Synergy

Commercializing Solar Fuels within Today's Markets

Can a solid foundation for the future adaptation of solar fuels be built today? Component technologies developed to efficiently generate fuel from sunlight are finding innovative pathways to commercialization in established markets.

Introduction

Designing, building, and commercializing a device that mimics photosynthesis and efficiently stores solar energy in the chemical bonds of a fuel is one of the greatest challenges in chemistry.[1] Decades ago, the first fundamental electrochemical discoveries essential to solar fuel generation were made: light-driven water splitting at a TiO_2 electrode[2] and conversion of CO_2 into methane and ethylene on a copper surface.[3] Since then, researchers from around the globe have significantly improved the mastery of each discrete component of solar fuels, such as charge transfer at semiconductor electrodes, water oxidation catalysis, and CO_2 reduction. Although these seminal works laid a foundation, a chasm exists between academic research and the realization of an economically viable device that generates fuel directly from solar energy. We propose a strategy that commercializes the discrete components of solar fuels rather than attempting to launch directly into a full liquid fuel value chain. This strategy would shorten the gap between lab and market by commercializing smaller-scale, higher-value applications of each component, which could then be integrated into a higher-volume, lower-cost supply chain over time.

With the existing availability of abundant low-cost fuels, there is little incentive to adopt new, large-scale energy technologies that pose considerable upfront technical and economic challenges. Understanding this barrier, we recognize that market innovation in solar fuels will most likely arise evolutionarily rather than revolutionarily.[4] As such, there are benefits in creating alternative minimum viable products ready for today's markets instead of solely focusing on the pursuit of an all-in-one device to replace fossil fuels. This strategy enables early innovation, mitigates risks associated with individual technologies by testing them on a commercial scale, and brings products to market independently of future policy decisions. As fossil fuel markets change, these mature component technologies can be procured cheaply off the shelf and integrated into an economically viable solar fuel device (Figure 1).

Clear and practical hurdles must be overcome for the commercialization of solar fuels.[5,6] These challenges have been highlighted in recent commentaries by Hammarström[7] and Bolsen et al.[8] In our view, effective solutions can start today and will connect three themes: academia, policy, *and* industry, all taking steps to bring a minimum viable product to customers.

Examples of Minimum Viable Products for Solar Fuels

Today, many industries use products and processes that could be replaced with alternatives that are based on technologies developed by solar fuel researchers. If the solar fuel components can be implemented at equal or lower cost than conventional solutions, then these markets represent realistic near-term value propositions, a few examples of which are shown in Table 1.

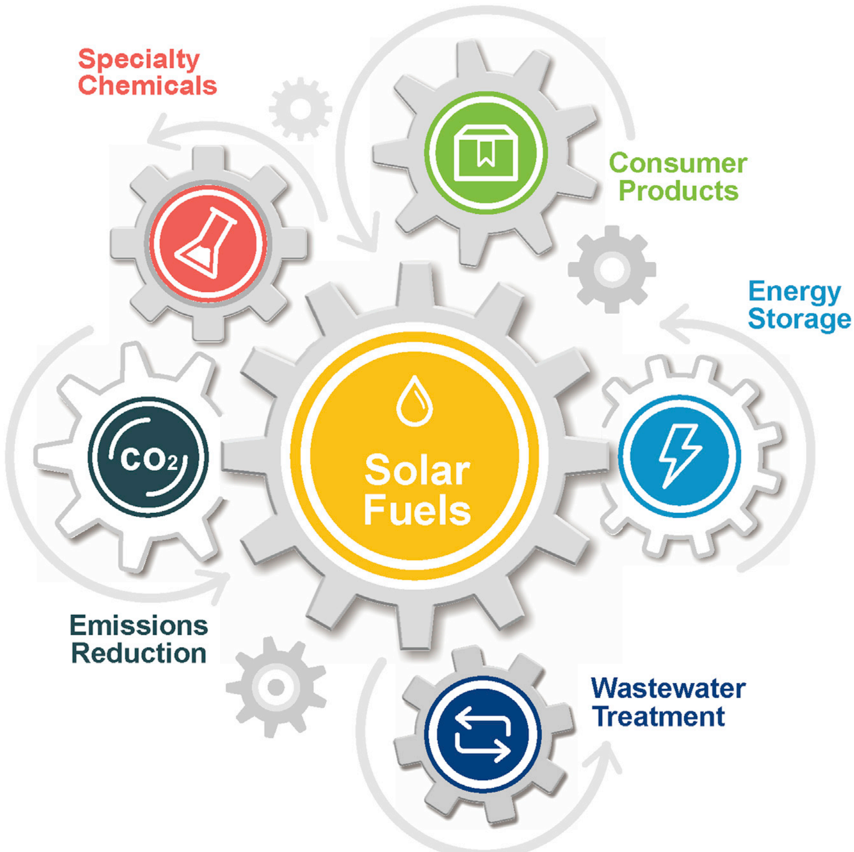

Figure 1. Driving Toward a Solar Fuel Market
Component technologies in solar fuels can drive innovation in established industries, address pain points, and validate market behavior on commercial scales (examples are shown). In turn, these collectively lower the barrier to creating a larger solar fuels market.

Neither metal refining nor wastewater treatment has yet derived much benefit from research directed at improving the stability and activity of electrochemical oxidation catalysts, and there is room to improve and further translate relevant research to these applied fields. Newer, low-cost water oxidation catalysts can be used to oxidize small organics in wastewater treatment[9] or to prevent anodic corrosion of electrodes in metal refining and electroplating. The latter requires stable catalysts that transport electron holes to water at a rate faster than redox corrosion of their underlying support. These topics are strong research areas in solar fuels. Water oxidation occurs in processes such as zinc refining, producing millions of tons of O_2 per year to provide electrons for metal reduction. In this industry, anodic corrosion of the oxygen electrode is a common pain point. Explaining the utility of water oxidation catalysts as corrosion inhibitors can enable customers in the electrorefining market to take advantage of the decades of academic improvements.

The onsite production of gases is another market segment that provides significant opportunities for solar fuel technologies. Today, onsite electrochemical production of hydrogen from water represents a multi-billion-dollar market. The corresponding market potential for the commercialization of reduced CO_2 products could be even larger, given the wider range of products and valuable intermediates that can be made: carbon monoxide (CO), methane, ethylene, ethanol, formic acid, etc. In

Table 1. Potential Target Applications for Entry into Commercial Markets with Respect to Specific Solar Fuel Research Sectors

Solar Fuel Chemical Processes	Near-Term Market Examples
Water oxidation	protection against anodic corrosion
	wastewater treatment
	life support
CO_2 reduction	on-site generation of specialty gas
	generation of modular products
	CO_2-derived plastics
H_2 evolution	on-site hydrogen generation
	compressed or pressurized hydrogen
CO_2 adsorption	greenhouses
	cement production

one example, the onsite production of gases from CO_2 could reduce the cost of transport for small to medium-sized applications, where conventional large-scale thermochemical synthesis of these gases from fossil fuels is not practical. Ethylene is used in fruit-ripening facilities and for refrigeration, and CO is used as a reducing agent in a range of specialty chemical processes, such as pharmaceuticals. Islands with limited natural gas resources are evaluating methane production from CO_2 either in a single catalytic step from CO_2 or by combining electrochemically produced H_2 and CO_2 in hydrogenation schemes, such as the well-studied Sabatier reaction.

For solar fuels, a critical economic driver will be the cost of capturing CO_2. A capture cost of \$100 per ton of CO_2 translates to approximately \$1.00 per gallon of fuel,[10] which was nearly the wholesale cost of gasoline in February 2016 (\$1.046 per gallon; \$1.625 per gallon in February 2017).[11] Hence, \$100 per ton of CO_2 leaves little room for the capital and operating costs of conversion to fuel. Early efforts for industrial carbon capture have been plagued by cost overruns, so more real-world capture projects are necessary to drive down costs. Air-capture projects are now being used to enhance the CO_2 concentration in remote greenhouses, and pairing industrial CO_2 capture with the high-margin applications in the preceding paragraph would allow for more cost tolerance in early deployments.

Challenges and Opportunities

The solar fuel industry faces many challenges beyond technology development. One major hurdle is access to capital. Investments at the peak of the clean-tech bubble in the early 2000s resulted in significant stigma to investing in those technologies today, and this in turn forced small businesses to find non-traditional ways to raise funding. One potential method that has been realized is deriving available funds from a combination of sales-generated revenue in one of the aforementioned niche applications, contract research, and/or small investments from partners, collectively termed "bootstrapping" in the entrepreneurial world. Other resources that can be leveraged by solar fuel innovators are entrepreneurial fellowships and support programs, such as Cyclotron Road at Berkeley Laboratory, Chain Reactions Innovations at Argonne National Laboratory, Innovation Crossroads at Oak Ridge National Laboratory, Breakout Labs, and for later-stage start-ups, Elemental Excelerator. These provide funding, mentorship, and access to networks of investors and industry contacts. Additionally, small-business research grants from federal agencies can help to provide funding for technologies aligned with a specific agency's research needs. National facilities, such as the Molecular Foundry user facility at Lawrence Berkeley National Lab and others around the world, can provide in-kind support to help develop novel technologies. Even then, solar fuel companies still have an extremely difficult time attracting investment capital. This makes it even more important to find profitable value propositions rather than start with the generation of low-cost fuels. Another challenge that is often overlooked by solar fuel researchers is manufacturing: cost, reproducibility, quality control, automation, etc. As such, early partnerships with industry to bring costs down by simultaneously innovating on both the research and development and manufacturing sides can provide a clearer path to commercialization.

Despite the currently poor venture-funding climate in clean tech, a solar fuel market could well be on the horizon. Public awareness of increasing atmospheric CO_2 concentrations, especially internationally, has driven the organization of prizes, grants, and other incentives for the development of technologies in this area. Incentive prizes, which often exist independently of government funding, have a track record of spurring innovation[12] and creating new markets. The Ansari XPRIZE is an excellent example—a $10 million purse enabled competitors to raise more than $100 million in private follow-on funding. Many competitors are part of today's $1 billion private space-travel industry. Along the way, the regulatory environment for space exploration was improved to incentivize private firms. The NRG COSIA Carbon XPRIZE and Emissions Reduction Alberta (ERA) Grand Challenge are poised to do the same to accelerate the creation of a solar fuel and carbon market with similar success. The Carbon XPRIZE is a $20 million global competition to develop breakthrough technologies that will convert CO_2 emissions from power plants and industrial facilities into valuable products, and the ERA Grand Challenge is a CAD$35 million multistage event that supports technologies that convert CO_2 into useful products.

Conclusions

The growing worldwide concern regarding climate change, coupled with exponential cost reductions of the components of a solar fuel device, provides strong indications for the eventual deployment of solar fuels at a large scale. That lead time will be shortened if the constituent chemical innovations find early pathways to market. This will mitigate the risks that the individual processes in solar fuel generation face and will enable subsequent commercialization of a fully integrated device. This is a tried-and-true strategy for many other industries, and we are bringing it to the attention of the solar fuel research community.

We believe that moving fundamental solar-fuel-related research from basic-research laboratories into market-ready technology can be accomplished in the near term. Entering non-traditional markets with a minimum viable product and growing incrementally to discover larger potential opportunities is a promising pathway forward. Although policy and academia will always be major players to get us to a solar fuel economy, industry and early-stage companies must also play a role by scaling components of the technology in the immediate term. Entrepreneurs from around the world are eager to bring these technologies from the lab to industry, and their success will be driven by market forces.

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