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Major Goals: "Solar Fuels Generation: PV and Electrolysis Workshop" was held at the University of Delaware to identify R&D needs to develop systems for the generation of fuels and industrial chemicals based on renewable resources with a particular focus on photovoltaic (PV) driven electrolysis for the production of H2. The following research areas were identified as important opportunities or "pinch points" that should be addressed to help accelerate a transition towards a renewable hydrogen future: 1) Advanced electrolyzer designs, catalysts, and membranes; 2) Design and control of microgrid systems consisting of multiple generators including fuel cells, storage, and controllers; 3) Leveraging 'free' electricity from PV and wind facilities experiencing curtailment due to grid-capacity to generate H2; and 4) potential use of CO2 as feed stock for fuels generation. These areas are described below as short to long term needs.

Accomplishments: The workshop focused on evaluating the current state of PV/EC technology and identifying challenges and opportunities in two critical areas: 1) systems optimization and 2) PV and EC design. Invited two speakers, representing the Department of Energy (DOE), national laboratories, industry, and universities, provided the current status of research and development and stimulated discussions on the merits and challenges of obtaining high production capacities using the proposed PV/EC approach. In addition to H2 fuel generation and conversion, there was discussion of CO2 conversion. This is a newer and much less-well explored area. It has greater technical challenges associated with both the kinetics of CO2 reduction and electrolyzer device-level implementation, but also has great promise to generate a wider range of fuels and chemicals and to reduce CO2 concentration in the atmosphere.

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Solar Fuels: Pathway to a Sustainable Future

Abstract

"*Solar Fuels Generation: PV and Electrolysis Workshop*" was held at the University of Delaware to identify R&D needs to develop systems for the generation of fuels and industrial chemicals based on renewable resources with a particular focus on photovoltaic (PV) driven electrolysis for the production of H_2. The following research areas were identified as important opportunities or "pinch points" that should be addressed to help accelerate a transition towards a renewable hydrogen future: 1) Advanced electrolyzer designs, catalysts, and membranes; 2) Design and control of microgrid systems consisting of multiple generators including fuel cells, storage, and controllers; 3) Leveraging 'free' electricity from PV and wind facilities experiencing curtailment due to grid-capacity to generate H_2; and 4) potential use of CO_2 as feed stock for fuels generation. These areas are described below as short to long term needs.

Introduction

This white paper is an outcome of the "*Solar Fuels Generation: PV and Electrolysis Workshop*" held at the University of Delaware on March 7 and 8, 2016, where leading experts convened to discuss the potential of solar fuels generation using photovoltaic (PV) and electrolyzer technologies. A list of the panelists who contributed to the discussion that informed this white paper and their affiliations is contained in Appendix A. Both commercial PV and electrochemical (EC) technologies have been available for decades, and their combination represents an attractive means of converting renewable electricity into storable "solar fuels", such as hydrogen, for carbon-free dispatchable electricity. In contrast, the current method to obtain H_2 is from reforming methane, which leads to a very large CO_2 footprint for the otherwise clean burning fuel.

The workshop focused on evaluating the current state of PV/EC technology and identifying challenges and opportunities in two critical areas: 1) systems optimization and 2) PV and EC design. Invited speakers, representing the Department of Energy (DOE), national laboratories, industry, and universities, provided the current status of research and development and stimulated discussions on the merits and challenges of obtaining high production capacities using the proposed PV/EC approach. In addition to H_2 fuel generation and conversion, there was discussion of CO_2 conversion. This is a newer and much less-well explored area. It has greater technical challenges associated with both the kinetics of CO_2 reduction and electrolyzer device-level implementation, but also has great promise to generate a wider range of fuels and chemicals and to reduce CO_2 concentration in the atmosphere.

There are two approaches for solar-driven electrolysis of H_2O: 1) the PV cell can be integrated into the EC cell as a monolithic package with sunlight in and H_2+O_2 out; or 2) the PV module can be external to the electrolyzer. Technical challenges for the first approach include materials compatibility, corrosion, optical losses, system design over very large area for collection of products, and the inability to independently control current-voltage delivery to the EC cell. These are well known issues and have been the focus of research over the past 2 decades, with slow but steady progress, which can lead to a commercially viable technology. The second approach could be implemented today with commercially available PV and EC technologies that can be incorporated into systems for H_2 generation and storage, allowing dispatchable generation of electricity from fuel cells. While not optimized for cost or performance, there is an existing demand that could be met with today's technology and costs. There are systems-level design and integration issues, e.g. impedance matching the high voltage low current PV output to the low voltage high current electrolyzer, hardware and software to interface the solar and wind generators, electrolyzer, H_2 storage, fuel cell and the grid operator to allow synchronization of the optimum times for generating H_2 from renewable versus grid electricity and generating electricity from stored H_2. This includes optimizing the sizes and parallel/series connections of PV or wind/electrolyzer/fuel cell/storage units. The cost and performance of the electrolyzers can be improved through development of polymer or proton electrolyte membrane (PEM) materials. Finally, to gain acceptance by utilities, a system-level benefits and costs analysis, as well as policies that incentivize load-shifting and grid services, are required.

Below are examples of research projects that would advance the commercialization and performance of PV/EC systems:

A. Diversion of excess grid deployed PV to H_2 generation

Increasingly, PV and wind installations are losing revenue and wasting energy due to grid-enforced curtailment when their output exceeds the local grid capacity or load. This is caused by two factors. First, intermittent renewable sources like PV and wind are not dispatchable, which can cause them to over-supply the local grid depending on weather and local load, neither of which are controllable. Second, in the case of PV, falling module prices have encouraged increasing the DC/AC ratio of the plant (more PV relative to the inverter capacity). The increasing use of single axis trackers compounds this problem by generating more energy per installed kW. Thus, instead of wasting energy that cannot be accepted into the grid, a near term opportunity would be electrochemically converting it to H_2 fuel and storing for later. This approach is being widely discussed in Europe, where PV and wind curtailment is a bigger problem. A recent analysis of charging batteries with curtailed energy estimated that a 20 MW installation in California could provide 2 MWh of otherwise wasted energy per day on many days per year depending on weather and grid capacity [1]. A key advantage of such a system is that the energy is free. A key disadvantage is that curtailed energy occurs randomly and for short duration. Thus, a system powered solely on curtailed energy will have a low utilization. This could be compensated for by also operating the electrolyzer with lower-cost off-peak nighttime electricity, either from wind or conventional sources. The H_2 could be stored on site to meet peak demand on a cloudy or windless day, or to provide other grid services (see below). It could also become ‘green-gas’ for injection into an existing natural gas pipeline ‘grid’. Development of this type of application to meet immediate needs will grow the solar fuels industry, leading to economies of scale that will open up other applications, including the acceleration of the use of H_2 for transportation. Immediate demonstration projects using existing technology at various scales would identify cost performance trade-offs, including environmental benefits.

B. Energy management, transmission and distribution systems

A recent report from NREL co-written by one of the panelists (Harrison) considered the technical abilities of today's commercially available electrolyzers [2]:

"Electrolyzers acting as demand response devices can respond sufficiently fast and for a long enough duration to participate in energy management on the utility scale and at end user facilities. Furthermore, electrolyzers can be operated to support a variety of grid applications while also providing hydrogen for industrial processes, transportation fuel, or heating fuel…. Based on the findings, the authors recommend that electrolysis devices be considered in the planning and selection process for supporting end-user energy management, transmission and distribution system support, and wholesale electricity markets. Their operational flexibility and the variety of potential systems configurations in which they can be included make them an ideal candidate from a technical point of view."

This near-term strategy will provide multiple services to both the grid operator, including frequency stability and spinning reserves, and the end-user, avoiding demand charges, load shifting, taking advantage of time-of-use rates, while operating with a wide range of fluctuating and transient inputs as might occur from renewable energy sources [2]. Early implementation is already occurring using batteries. This application of electrolyzers and fuel cells needs to be compared to conventional battery storage.

C. Advanced Electrolyzer Components and Design

Currently two types of low temperature water electrolyzers are commercially available, alkaline and PEM electrolyzers. The properties of PEM electrolyzers, namely fast power-up response times and high operational current densities, make them the likely best candidates for application to renewables-driven H_2 systems, where spikes in energy input would be fully utilized. Furthermore, PEM electrolyzers can safely operate across the full nominal current density range as the membrane attenuates O_2 and H_2 gas crossover. Units can operate at increased pressure to deliver a pressurized H_2 product, reducing needs for downstream compression and storage, and differential pressure devices are available, avoiding potential hazards related to handling compressed O_2. However, PEM electrolyzers are limited by relatively high capital costs and materials limitations, including membrane stability and electrocatalyst selection for use with acidic PEMs. Mid to long-term needs to improve performance of PEM electrolyzers include, 1) development of low cost, earth-abundant, high performance catalysts, 2) development of high performance catalytic assemblies with ~monolayer metal loadings, e.g. nano-structured films, core-shell approaches, or use of high performance support materials, 3) improved membrane properties to assist catalyst selection and design, including development of high performance alkaline membranes, and 4) improved stability of membranes to increase electrolyzer lifetimes, to allow high temperature operation and reduce requirements for very high quality input H_2O, and 5) improved electrolyzer performance through design modifications to decrease ohmic losses and allow high pressure and temperature operation.

D. Integration and control: Microgrids

An integrated system with a significantly reduced carbon footprint consisting of generators (electrolyzer, PV, wind, fuel cell), accumulators (batteries, H_2 storage), and controllers (inverters, charge regulators, flow controllers) to form a microgrid should be developed to evaluate the performance and to identify optimum system configurations. High reliability microgrids are well-suited for use at data centers, emergency response stations, hospitals, or remote military bases. Microgrids can function in a grid connected or grid independent mode. A back-up fossil fuel generator would increase the reliability of meeting loads to 100% at relatively low cost. Fuel cells have recently been incorporated as part of state-of-the-art microgrids. University of CA at San Diego has a 2.8 MW fuel cell as part of a campus wide 42 MW research microgrid which also includes solar and natural gas. Boeing recently delivered an experimental solid-oxide fuel cell for a microgrid at a Navy base in California [3]. The design and control of microgrids with PV, batteries and fuel cells has been analyzed [4,5]. A review of economic value of hybrid microgrids concluded [6]:

"*Fuel cell systems can provide a significant benefit to residential households with regards to energy usage. The study supports the idea that the concept of net metering can be applied outside of the traditional renewable energy sources successfully, making it particularly relevant in microgrid settings where multiple on-site generation technologies may be available*".

The excess heat generated by the fuel cell can provide heat to the on-site host, thus increasing the overall value of the microgrid by adding a CHP function. Further improvements are needed in components and algorithms which interface to and optimize the energy source, storage, electrolyzer, and user demand. Even when grid connected, microgrids allow for a high fraction of self-consumption, thus preventing grid congestion and taking loads off-line during high demand. They can provide energy reliability for their host, and for the grid as well, and support cybersecurity goals.

Successful near to mid-term demonstration of microgrids will require complex control, integration and decision making about energy sources. Thus, there is a need for acquiring and analyzing data, controlling energy flow from several sources, and maybe controlling demand as well (e.g. cycling the HVAC during summer afternoon). Presently off-the-shelf electronics, sensors, and software for high level system integration and direct coupling between PV and electrolysis are not available. As with all the applications, economies of scale and new manufacturing processes/approaches will be essential for cost-effective implementation at medium scales.

E. Critical Analysis of Capture of CO_2 for Fuels

With the field in its infancy there are many opportunities for the development and improvement of CO_2 capture and systems for converting feedstock CO_2 to useful chemicals. We note that some CO_2 electrolyzer issues will be similar to those encountered for water electrolysis. It is expected the growing knowledge base for H_2 electrolyzers will assist the development of CO_2 electrolysis technologies. Long-term areas of fundamental research must include 1) development and analysis of cost and energy effective CO_2 capture systems, including simple CO_2 recovery and adsorbate regeneration, 2) development of efficient and high specificity electrocatalysts for CO_2 reduction, 3) improved understanding of CO_2 chemistry and identification of possible other CO_2-related chemical pathways or feedstock chemicals, including bio-inspired approaches, and 4) analysis and design of possible CO_2 electrolyzer architectures and materials to allow high unit performance and lifetimes, decreased costs, and simple low cost and low energy liquid product separation.

Summary and Future Directions

The conference primarily focused on identifying the R&D needs for the generation of fuels and industrial chemicals based on PV driven electrolysis. The research required to implement solar-driven fuel production consists of development of new catalysts and membranes, coupled with advanced electrolyzer designs, and microgrid systems for H_2 generation, incorporating storage and fuel cell technologies. Since large-scale deployment is most likely many years down the road, prototypical near-term applications installed at moderate scale (<100 kW) can provide operational data and act as test beds for different components and control and integration algorithms. This will lead to greater confidence and awareness of PV-generated H_2 matched with fuel cells for on-grid and off-grid generation. This in turn will justify support for investment in: 1) commercial fuel cell and PV/EC production, 2) component level integration strategies, and 3) fundamental research on EC cells to improve performance, lower cost, and increase operational lifetime. The goal of this white paper is to stimulate discussion among researchers, industry partners and funding agency decision makers. Development and integration of the diverse multidisciplinary range of the technologies required would be best achieved by a DOE-sponsored university-based hub/center consisting of universities, national labs and industry partners.

Acknowledgements

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Appendix A: List of Panelists

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