

How to Make Clean Hydrogen AWSM: The Advance Water Splitting Materials Consortium

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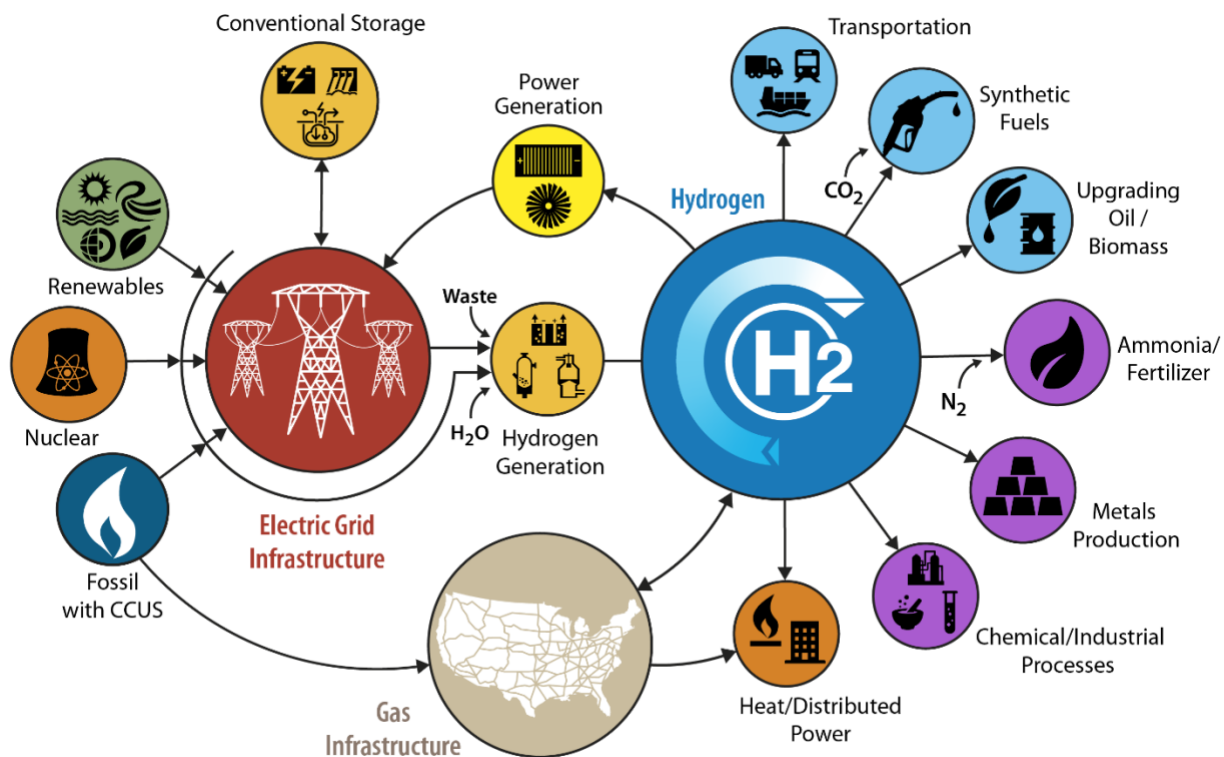
Keywords: clean hydrogen, advance water splitting materials, AWSM, Hydrogen Energy EarthShot, Hydrogen Shot, H2@Scale, anion exchange membrane electrolysis, proton exchange membrane, solid oxide electrode cell, photoelectrochemical, solar thermochemical, hybrid, decarbonization, low temperature electrolysis, high temperature electrolysis

Clean hydrogen is a carbon-free energy carrier that can be produced from water and sustainable energy sources such as wind, solar, and nuclear. Hence, clean hydrogen is considered one of the best ways to not only decarbonize the energy supply system but address the zero-emission challenges specific to large-carbon emitting industries that are difficult to separate from fossil fuels (e.g., heavy-duty trucking, load-following electricity, iron, steel, and cement). To help achieve the Biden Administration's energy goal of a 100% clean energy economy and net-zero emissions by 2050, several tens of millions of metric tons of clean, low-cost hydrogen will be needed annually. U.S. Department of Energy (DOE) recently launched the Hydrogen Energy EarthShot ("Hydrogen Shot") which aims to reduce the cost of clean hydrogen to \$1 per 1 kilogram in 1 decade.¹ H2@Scale (Figure 1) is a DOE initiative that supports the Hydrogen Shot goals to enable drastic decarbonization by scaling up low-cost clean hydrogen production, transport, storage, and utilization.² Clean hydrogen can power the grid, generate heat, be stored as an energy carrier, or be used to decarbonize multiple industrial sectors that are currently major contributors to emissions. Some examples of these sectors are transportation, ammonia/fertilizer production, synthetic fuels, metal refining, and chemical/industrial processes. In summary, large-scale, low-cost hydrogen production from diverse domestic resources can enable an

economically competitive and environmentally beneficial future energy system across multiple sectors.

The HydroGEN Advanced Water Splitting Materials (AWSM) Consortium was established in 2016 as part of the Energy Materials Network (EMN) under the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office to enhance the performance, improve the durability, and reduce the cost of clean hydrogen production technologies, and it is helping to advance the H2@Scale vision. HydroGEN (www.h2aws.org) is DOE EMN consortium comprised several U.S. national laboratories focused on accelerating the materials research and development (R&D) of all emerging advanced water splitting pathways for clean, sustainable, and low-cost hydrogen production. The four early-stage, clean hydrogen production technologies that HydroGEN concentrates on are: low temperature electrolysis (LTE), high temperature electrolysis (HTE), photoelectrochemical (PEC), and solar thermochemical (STCH) water splitting. HydroGEN fosters cross-cutting innovation using theory-guided applied materials R&D, leverages world-class expertise and capabilities at the national labs, and encourages collaboration among industry, universities, and national labs.

This article describes the basics of these advance water splitting technologies, outlines their advantages and disadvantages, and identifies the material R&D needs.



Low Temperature Electrolysis (LTE)

Low temperature electrolysis directly converts electrons to hydrogen through electrochemical water splitting.³ Compared to other electrolysis types, low temperature systems (< 100°C) are more mature industrially and allow for input flexibility, operation at high current density, and long-term durability. This LTE area includes three separate technologies: (1) *liquid alkaline (LA)*, (2) proton exchange membrane or polymer electrolyte membrane (*PEM*), and (3) anion exchange membrane or alkaline electrolyte membrane (*AEM*) systems.

LA electrolysis is the most developed of the three technologies with a long history of industrial use. It consists of two electrodes (anode and cathode) separated by a diaphragm operating in a liquid supporting electrolyte, typically concentrated potassium hydroxide (Figure 2a). The diaphragm can be a polymer stable at high pH, not conductive, and porous, such as polysulfone, polyvinyl, polycarbonate, tetrafluoroethylene, and polyethylene. Advantages to the technology are primarily centered around cost, where the high pH enables platinum group metal (PGM)-free catalysts and improved durability that would not be feasible in an acidic environment. Disadvantages exist, however, and include the large footprint, low current density due to the larger physical distance between electrodes, and cost (both the cost to compress

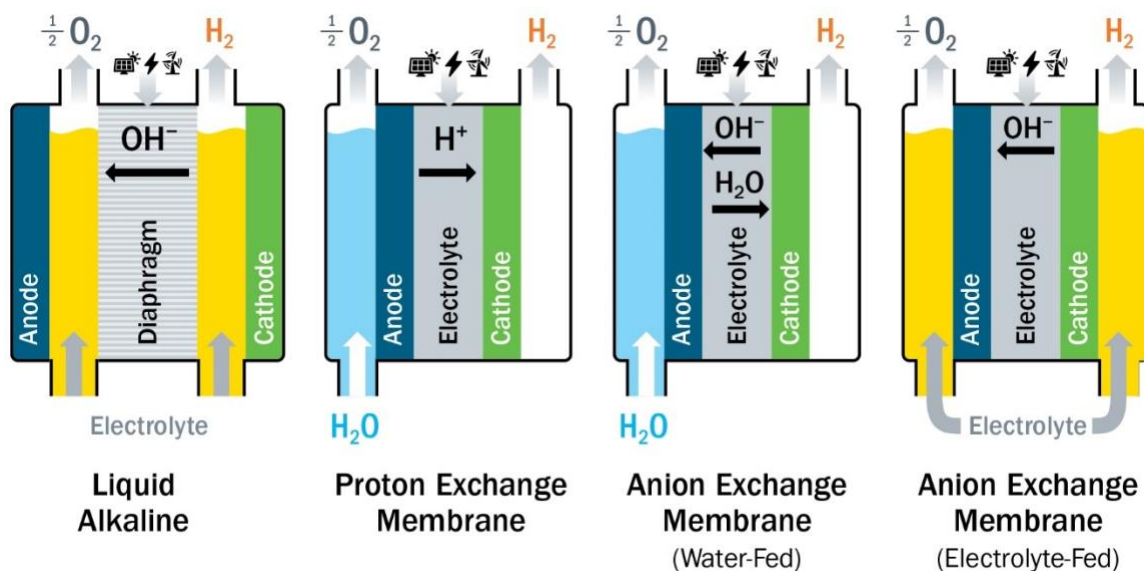
hydrogen downstream and maintenance costs associated with the caustic electrolyte). *LA electrolysis* under atmospheric conditions usually operates at constant load and has a slower response time due to the large cell size. *LA electrolysis* can be operated under variable load, but it would be pressurized, more compact (faster response time), and needs to balance with crossover issues that can decrease cell efficiency.

For *proton and anion exchange membrane-based systems*, the electrodes physically contact a polymeric membrane to form a membrane electrode assembly, and the zero-gap approach can improve performance by minimizing the electrode distance and ohmic loss (Figure 1b-d).

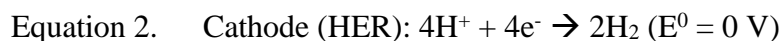
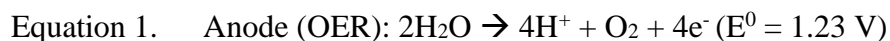
In *PEM electrolysis systems*, the membrane is typically Nafion™ (a perfluorosulfonic acid membrane), and the two electrodes are typically platinum (supported) at the cathode for hydrogen evolution reaction (HER, Equation 1) and iridium oxide at the anode for oxygen evolution reaction (OER, Equation 2). The catalysts are traditionally at loadings of milligrams per square centimeter. The thickness of the PEM can vary from 10 μm to 250 μm, depending on the membrane chemistry and other factors. Thin membranes are better for minimizing ohmic loss, while thicker membranes are better for lower crossover (resulting in higher cell efficiency) and are more durable (higher mechanical membrane stability). Development of new or improved membranes that allow for full liquid hydration operation and differential pressure, with minimal hydrogen crossover, are needed. Compared to liquid alkaline systems, PEM electrolysis has a shorter commercial history but allows for a significant increase in performance or current density, hydrogen compression at the device with back pressure, and a smaller footprint. The need for PGM catalysts and component coatings (on porous transport layers and separators between cells in a stack), however, can increase cost, and their scarcity is a concern.⁴ Electrocatalyst development in PEM systems has historically focused on materials discovery through admetals and *ex situ* oxide content. Under-explored areas in materials integration (including supports, morphology, and structure) may be useful to improve performance and lessen load requirements.⁵ Additionally, long-term durability issues arise when targeting low-cost hydrogen production, both through intermittent power inputs and anticipated PGM catalyst loading reductions.^{6,7}

Compared to other LTE technologies, *AEM electrolysis systems* have less commercial history and are in a developmental phase, but they share similarities with both LA and PEM

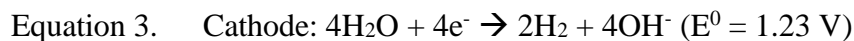
electrolysis. As with PEM systems, AEM electrolyzers use a zero-gap approach, but the membrane conducts hydroxide (Figure 2c and 2d, Equations 3 and 4), as opposed to protons. As with LA electrolysis, AEMs create a high pH environment, which enables PGM-free catalysts and component coatings.⁸ Operation in AEM electrolysis depends on whether the intent is to replace LA- or PEM-based systems. For a liquid alkaline replacement, supporting electrolyte (e.g., hydroxide, carbonate) is supplied to both the anode and cathode and operation is at balanced pressure (Figure 2d). For a PEM electrolysis replacement, water is supplied to the anode and wicks through the membrane to the cathode where hydrogen evolution occurs (Figure 2c). In a water-fed AEM electrolyzer, hydrogen can be compressed through backpressure. Recent component advancements have enabled high performance, particularly in AEM electrolysis with supporting electrolytes, although maintenance of the caustic electrolyte may add to production cost.^{9,10,11} While efforts and progress have also accelerated water-fed AEM electrolysis systems, performance and durability have generally been lower than both the supporting electrolyte-fed AEM- and PEM-electrolysis systems, particularly when normalized to membrane thickness.¹²



PEM water electrolysis:



AEM or LA water electrolysis:



Equation 4. Anode: $4\text{OH}^- \rightarrow + 2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^-$ ($E^0 = 0 \text{ V}$)

High Temperature Electrolysis (HTE)

HTE has received extensive interest in the past 20 years as a high-efficient water splitting technology for hydrogen production, where the energy demand may be reduced because the Joule heating during HTE may be used in the water splitting processes at high temperatures.¹³ The high temperature operation decreases electricity consumption, offset by high heat demand, which can become a cost-driver as low-cost external heat coming from nuclear, solar, and other sources are available. In addition, operating at high temperatures favors the reaction kinetics and enable the use of less noble (less expensive) materials such as nickel and conductive oxides, rather than platinum, as electrocatalysts.¹⁴

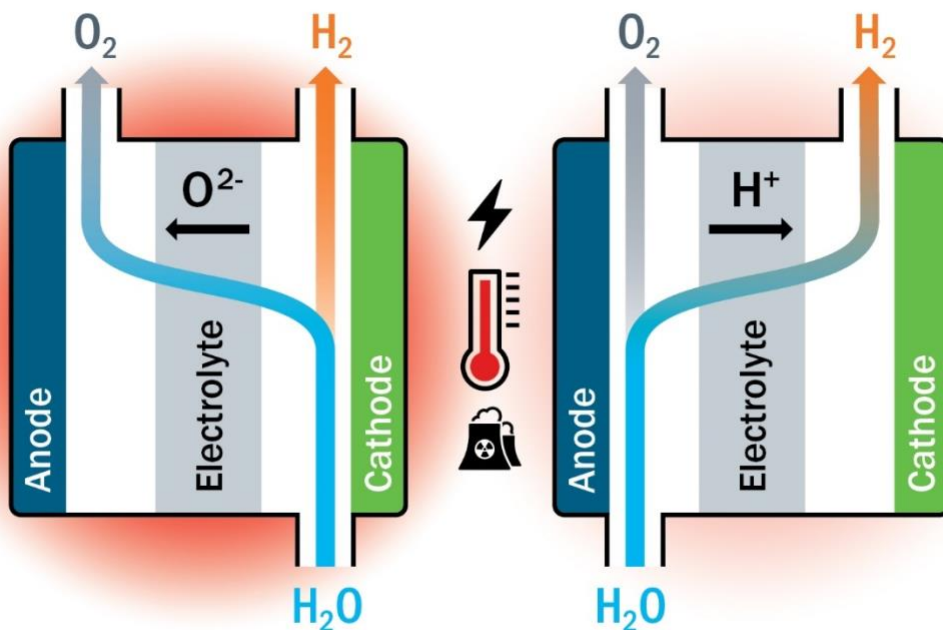
HTE is often referred to as solid oxide electrolysis cells and stacks (SOECs). It is also known as ceramic ion-conducting steam electrolysis system and emerges from the development of solid oxide fuel cells (SOFCs). SOEC is a reverse/regenerative mode of SOFC, producing hydrogen instead of generating electrical power.¹⁵ There are two primary types: oxygen-ion conducting SOEC (o-SOEC) and proton conducting SOEC (p-SOEC). The SOEC type is based on the charge carrier. Figure 3 shows the working principle for both SOECs. An SOEC normally consists of three layers: a hydrogen electrode (cathode), an air/oxygen electrode (anode) and a solid oxide electrolyte. In o-SOEC, steam is fed into the porous cathode. When a voltage is applied, the steam moves to the cathode-electrolyte interface and is reduced to form hydrogen (H_2) and oxygen ions (O^{2-}), which are conducted through the dense solid electrolyte (Equation 5). The electrolyte must be dense enough to allow the oxygen ion to pass through. At the electrolyte–anode interface, the oxygen ions are oxidized to form pure oxygen gas (Equation 6). In p-SOEC, steam is fed to the anode and is oxidized to generate oxygen gas and protons (Equation 7). Protons conduct through the solid electrolyte and form pure hydrogen gas at the cathode (Equation 8).

An *o-SOEC* is the more mature of the two technologies and typically runs between 700–850°C.¹⁶ The most common electrolyte in *o-SOEC* is yttria stabilized zirconia (YSZ) or scandia stabilized zirconia (ScSZ) due to their excellent ionic conductivity, high strength, good chemical stability, and compatibility with other components. Ni-cermet, and (La, Sr) $\text{MnO}_{3-\delta}$ (LSM) or (La, Sr) $\text{CoO}_{3-\delta}$ (LSC) or (La, Sr)(Co, Fe) $\text{O}_{3-\delta}$ (LSCF) are typical hydrogen and oxygen electrode

materials, respectively.¹⁷ At the current stage, all material systems for o-SOEC and related integration have been widely studied and developed, making the o-SOEC technology poised for widespread commercialization.¹⁸ The most challenging need to be addressed is to develop more durable o-SOEC systems with remarkable cost reduction to allow cost-effective scale-up and high-throughput manufacturing processes to be exploited and implemented.¹⁹

p-SOEC is an emerging technology under HTE and operates at intermediate temperatures of 400–600°C by employing barium zirconate, barium cerate, or combined compositions as the solid electrolyte.²⁰ Lower operating temperatures can significantly improve the cell/stack durability, minimize stack sealing problems, enable the use of less expensive materials (e.g., ferritic stainless steels for interconnect), and improve response to rapid start-up and repeat thermal cycling needs. Furthermore, *p*-SOEC can inherently overcome the problems that o-SOEC encounter, including the mixture of hydrogen and steam, severe delamination of electrodes at high current densities, and partial oxidation of the nickel-based electrode. While these remarkable merits exist, there are still tremendous research efforts needed to address challenges related to materials in *p*-SOEC (e.g., the benchmarking materials for each component) together with the integration requirement for the prototype demonstration at large scale.^{21,22}

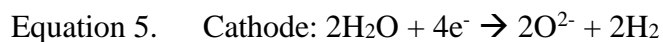
As the high cost of ceramics is recognized as one of several big challenges in the SOEC technology, a new cell configuration—metal-supported SOEC—shows its unique advantages in that it can reduce the use of ceramics considerably while offering better mechanical strength and sealing efficiency.²³ Certainly, fabrication requires further investigation to improve the cell performance and reduce the cost, ensuring that it can be leveraged by both o-SOEC and *p*-SOEC technologies.²⁴



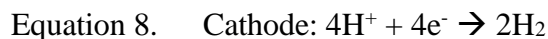
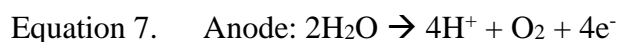
**Oxygen-Ion Conducting
Solid Oxide Electrolysis Cell**

**Proton Conducting Solid
Oxide Electrolysis Cell**

***o*-SOEC:**



***p*-SOEC:**



Photoelectrochemical (PEC) Water Splitting

PEC hydrogen production is a direct conversion and one-step process, which integrates light harvesting, photovoltage generation, and water splitting components into one system. The advantage of this technology is lower cost and significantly less complexity with respect to other advanced technologies for hydrogen production. The challenges are centered around the development of durable and efficient materials. In simple terms, PEC is similar to LTE—the main difference being that PEC utilizes sunlight as “power” and LTE uses electrons.

In PEC hydrogen production, semiconductors and catalysts aid the formation of hydrogen through the conversion of solar energy into chemical energy. In this process, light is absorbed by semiconductor materials and in turn generates enough photovoltage to split water autonomously

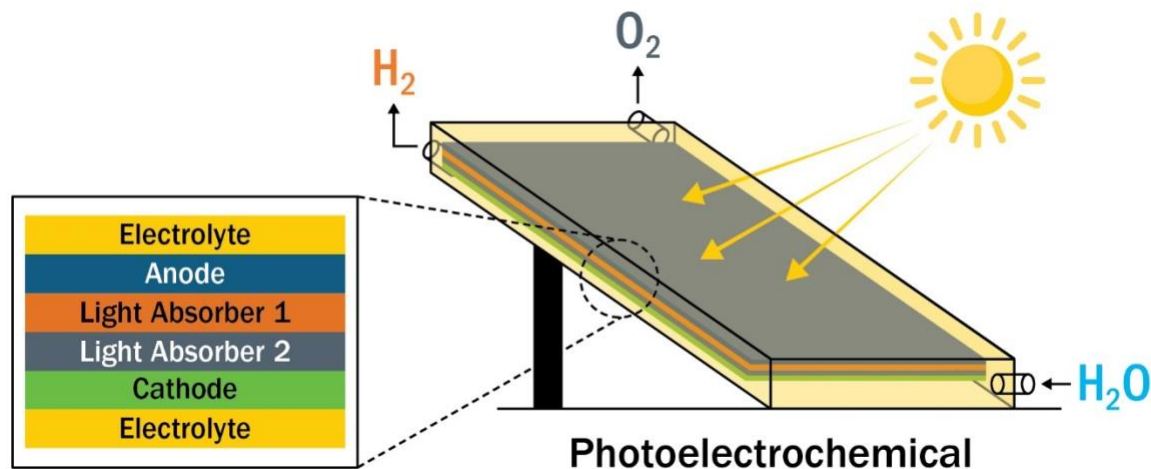
into hydrogen and oxygen (Equation 9). To understand the architecture of a PEC device and the need for semiconductor and catalyst materials, one should consider the energetics of the hydrogen production reaction. The thermodynamic potential to form H₂ from water is about 1.23 V, which in practice becomes ~1.7 V due to the kinetics of the water splitting. These high voltages can be generated by appropriate semiconductors, which absorb light and generate and excite electron-hole pairs with an associated photovoltage that can be used for catalyzing water splitting. The magnitude of the photovoltage that a semiconductor can generate is directly related to the band gap of the material and interfacing multiple semiconductors together (multijunction) is a route to providing an even higher photovoltage. Specifically, a multijunction is a stack of multiple light absorbing layers (e.g., Figure 4, light absorbers 1 and 2), which ensure the generation of a sufficient photovoltage to autonomously perform the water splitting reaction. Additionally, a semiconductor's ability to produce hydrogen (oxygen) depends on the relative position of its conduction (valence) band with respect to the reduction (oxidation) potential of water. For this reason, usually p-type semiconductors are used at the cathode side, and n-type semiconductors are used at the anode side. Upon light illumination, the band bending allows for minority carriers to flow at the semiconductor's surface and to be utilized in the water splitting reaction. Semiconductors often need to be integrated with catalysts that can lower the kinetic barriers of the water splitting reaction and enable the charge transfer to the reaction site. Specifically, HER catalysts are used at the cathode, whereas OER catalysts are used at the anode. The fabrication of optimized functional interfaces between semiconductors and catalysts ensures efficient charge transfer. Importantly, optimal interfaces ensure PEC device performance and durability to the strongly reducing (oxidative) reaction conditions and to the extreme acidic (basic) pH used for hydrogen (oxygen) production.

There are four types of PEC systems: two based on single (type-1) or dual (type-2) waterbed colloidal suspensions, and two based on multijunction photovoltaic materials that are immersed in a water-based electrolyte (type-3, Figure 4) and that are additionally part of a solar concentrator system and pressurized (type-4).²⁵ Variations of these configurations, which include vapor-fed devices, are also possible and have shown promise, especially for operation under near-neutral pH conditions. Importantly, a membrane or gas separator is often used in these devices to keep H₂ and O₂ separated, thus ensuring safety as well as efficiency and enhanced collection ability of the products of interest. Figure 4 illustrates the schematic of a type-3 device

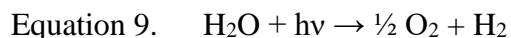
with two light absorbers interfaced with the OER (anode) and HER (cathode) catalysts. The device is immersed in electrolyte.

While PEC catalyst materials are usually similar to the ones used in LTE (e.g., HER: Pt, PtRu, and OER: IrO₂), there are several semiconductor material candidates: silicon, metal oxides, nitrides, as well as II-VI and III-V semiconductors.²⁶ More recently, lead halide perovskites have also debuted as promising materials in the field, though their stability in aqueous environments still represents a major barrier.²⁷ To date, the use of III-V multijunctions have demonstrated the most potential due to the generation of a high photovoltage.

While the technological impact of the PEC approach is still in its infancy, great strides have been made in this field in the past few years. State-of-the-art PECs using III-V semiconductors show a calculated solar to hydrogen (STH) efficiency of ~19%.²⁸ The main challenges for PEC systems are the overall efficiency, defined as the actual STH performance, and the durability of the system. Life cycle analysis has pointed to these two parameters as the major contributors to the technological impact of PEC devices.²⁹ Thus, the development of stable and efficient semiconductor/catalyst architectures is of fundamental importance in this field. To address these issues, research has focused on the development of protective coatings. TiO₂, GaN, and MoS₂ are some of the coatings that have shown great promise in the field. Interestingly, recent development in theoretical approaches allow for the prediction of novel efficient yet stable compounds that can be synthesized and tested and can provide promising routes for future development.^{30,31} In addition, the utilization of *in situ* and *operando* characterization techniques allows for studying corrosion mechanisms and material transformations under operating conditions.³² Specifically, the latter approach can allow for the rational design of protection strategies of efficient yet unstable semiconductors, which open new opportunities in the field. Providing a stable device with high STH is key to success in this field.



PEC water splitting:



Solar Thermochemical (STCH) Water Splitting

Thermochemical cycles for producing hydrogen by splitting water are categorized thematically by the number of reactions required to complete the cycle and by the method of treatment (i.e., purely thermochemical or hybridized approaches that invoke electrochemistry to complete reaction steps within the cycle).^{33,34} Examples of three common cycle chemistries are illustrated in Figure 5, and detailed chemistries for others that have been proposed or demonstrated at various scales from laboratory to small pilot can be found in seminal works dating from 2003.^{34,35,36,37} Akin to the breadth of the chemical processing industry, many hundreds of cycles have been considered with the notion that concentrating solar power³⁸ or nuclear power provides carbon-free energy to drive net endothermic water splitting chemistries yielding clean hydrogen without ambiguity as to how energy is sourced. The principal advantages to thermochemical water splitting cycles are lower costs because precious metal catalysts and/or materials are not needed, and that these concepts can be industrialized to large scales much like modern petrochemical enterprises.

The two-step metal oxide cycle is conceptually the simplest. The far-left illustration in Figure 5 shows how concentrating solar-thermal energy is used to raise the temperature of a redox-active oxide (MO_x) to a point where O₂ will spontaneously evolve from the material; temperatures in excess of 1500°C are common. At that moment of oxygen evolution, solar energy is directly converted into chemical energy now carried by the reduced compound MO_{x-1}.

In the second part of the process, the reduced oxide is exposed to H₂O at conditions where an oxygen atom is spontaneously stripped from the water molecule and put back into the oxide leaving behind H₂ and completing the cycle. There are several manifestations of two-step cycles where the oxidation state of a single element within the compound is manipulated during the process. Binaries like CeO₂, SnO₂, and oxides of Zn group metals have demonstrated a high degree of water splitting efficacy.³⁹ A select group of more complex oxides comprised of ternaries, quaternaries, and quinarys have also proven useful.^{40,41,42} When reduced, the compounds may stay solids, as in the non-volatile MO_x cycles, or can change from solids to liquids or vapors depending on the temperature and desired cycle conditions.

STCH water splitting:

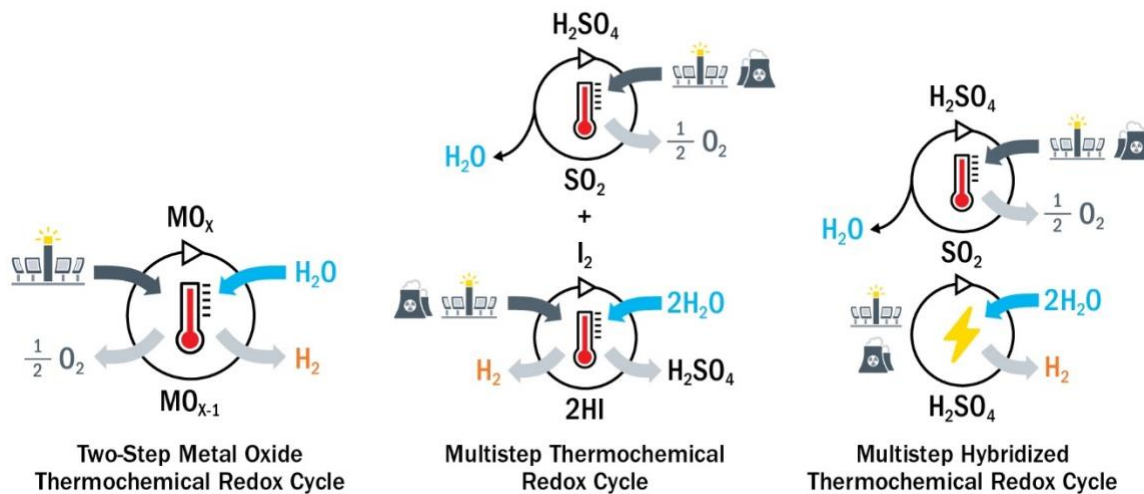
Equation 10. Oxygen Evolution Reaction: $\text{MO}_x + \text{heat} \rightarrow \frac{1}{2} \text{O}_2 + \text{MO}_{x-1}$

Equation 11. Hydrogen Evolution Reaction: $\text{MO}_{x-1} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{MO}_x$

Multistep cycles, be they purely thermochemical like the sulfur-iodine example shown in Figure 5 (center illustration) or hybrids like the sulfuric acid example shown in Figure 5 (far-right illustration), are more complicated and involve several chemical species participating in reaction schemes that net water splitting. And as with a two-step process, the redox active elements, sulfur and iodine in these examples, remain within the cycle requiring only water and carbon-free energy to be inputted. Furthermore, hybridized approaches that use electrochemistry to promote oxidation or reduction of chemical species other than water operate at voltages below 1.23 V.^{32–34,43} Process complexity arises because the reaction network invariably cycles through multiple chemical species interacting in multi-phase environments housed within different chemical unit operations such as reactors and separators. The principal advantage to multi-step cycles when compared to a two-step cycle is a lowering of the process temperature at the expense of added complexity.

To summarize, thermochemical routes for producing hydrogen via water splitting span an extremely large concept space full of opportunities to advance the art. Interest in these cycles stems from the belief that these chemistries can be industrialized and brought to market at extremely large scale, much like the petrochemical or commodity chemicals industries. To achieve this goal, advancements are required in research focused on understanding the behavior of materials in extreme environments (e.g., materials subject to harsh chemical and thermal stresses), as well as finding novel methods for improving the efficiency of separations in harsh

environments. Discovery of new materials and/or chemistries for thermochemical cycles (including hybrids) offers an opportunity to exploit advancements in high performance computing, computational material science, *ab initio* theory, and fundamental science targeted at developing an atomistic understanding of redox processes.



Summary

Large-scale production of low-cost, clean hydrogen production is an important near-to-longer term strategy to decarbonize the energy systems and industry sectors. While DOE-funded efforts to bring near-term water splitting technologies like *PEM electrolysis* and *o-SOEC* to commercialization are currently underway, emerging water splitting technologies such as *AEM electrolysis*, *p-SOEC*, *PEC*, and *STCH* are crucial to ultimately advance all pathways to clean hydrogen. Climate change is an existential issue, and it is critically important that R&D in these AWS technologies accelerate to meet the Hydrogen Energy EarthShot goal of \$1 per 1 kg clean hydrogen in 1 decade, and realize a decarbonized energy future.

Acknowledgements

The authors gratefully acknowledge research support from the HydroGEN Advanced Water Splitting Materials Consortium, established as part of the Energy Materials Network under the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen Fuel Cell Technologies Office, under contract number DE-AC36-8GO28308 to the National Renewable Energy Laboratory (NREL), contract number DE-AC07-05ID14517 to the Idaho National Laboratory, contract number DE-AC02-05CH11231 to the Lawrence Berkeley National Laboratory (LBNL), and U.S. Department of Energy's National Nuclear Security Administration contract number DE-NA0003525 to Sandia National Laboratories, multi-mission laboratories

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Journal of Power Sources Advances, a guest editor for *Frontier in Materials*, *Frontier in Chemistry*, *Journal of Physics: Energy*, and *Journal of Materials Research*. Dr. Ding holds several adjunct/affiliated faculty positions at University of Louisiana at Lafayette, University of South Carolina, New Mexico State University, and University of Idaho. Dr. Ding is a recipient for INL-EEST Leadership award in 2021, Asian American Most Promising Engineer of the Year 2020, and Federal Laboratory Consortium Far West Awards in the category of Outstanding Technology Development in 2019. Prior to joining INL, he was senior materials engineer at Redox Power Systems in Maryland. Dr. Ding received his doctorate in material science at the University of Science & Technology of China, where he also earned a bachelor's in materials chemistry. He was a postdoctoral fellow at West Virginia and the National Energy Technology Lab in Morgantown, W.V. (2009–2010) and at Georgia Institute of Technology (2010–2014). His current research interests include natural gas upgrading, high temperature water electrolysis, advanced manufacturing, CO₂ capture and conversion, ammonia electrosynthesis, fuel cells, and electrocatalysis. He may be reached at Dong.Ding@inl.gov, and his ORCID iD is <http://orcid.org/0000-0002-6921-4504>.

Dr. Tony McDaniel is a principal member of the technical staff at Sandia National Laboratories and holds a PhD in chemical engineering from the University of California, Los Angeles. His research experience spans a range of topical areas important to functional materials and their application to developing technologies for energy storage and conversion. These include complex oxides used in the production of hydrogen by thermochemical water splitting and high temperature electrochemical processes. He has authored or coauthored over 100 peer reviewed papers and technical reports



(<https://scholar.google.com/citations?user=RSCJe88AAAAJ&hl=en&oi=ao>). Dr. McDaniel is the solar thermochemical technology lead for HydroGEN Advanced Water Splitting Materials Consortium (h2awsm.org), which is a U.S. DOE Energy Materials Network consortium dedicated to advancing the technology readiness level of renewable hydrogen production. Through HydroGEN and other programs, he manages multidisciplinary teams comprised of U.S. national laboratories and universities in collaborative R&D settings focused on developing and demonstrating technologies for sustainable solar fuels.

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Captions

- Figure 1. DOE H2@Scale vision (<https://www.energy.gov/eere/fuelcells/h2scale>) showing the flexibility of hydrogen to couple diverse domestic resources to multiple sectors and how large-scale, low-cost hydrogen can enable affordable, reliable, clean, and secure energy system. H2@Scale supports the DOE Hydrogen Energy EarthShot goal of \$1 per1 kilogram of clean hydrogen in 1 decade.
- Figure 2. Schematics of different low temperature electrolysis (LTE) systems. From left to right: (a) liquid alkaline (LA) electrolysis, (b) proton exchange membrane or polymer electrolyte membrane (PEM) electrolysis, (c) anion exchange membrane or alkaline electrolyte membrane (AEM) water-fed electrolysis and (d) AEM electrolyte-fed electrolysis. Carbon-free electrons from nuclear, solar and wind power can be coupled with these LTE systems.
- Figure 3. A schematic of two types of SOECs: oxygen ion conducting SOEC (o-SOEC, left), and proton conducting SOEC (p-SOEC, right). o-SOECs typically operate at 700–850°C, while p-SOECs operate at intermediate temperatures of 400–600°C. Nuclear plants, solar, and other sources can supply the carbon-free electrical and thermal energy to these SOECs to split water and produce hydrogen.
- Figure 4. Schematic example of a PEC (type-3) device. The figure illustrates the simplified structure (left) of a PEC panel illuminated by the sun (right). The PEC device structure includes two light absorbers: a n-type semiconductor at the anode and a p-type semiconductor at the cathode for oxygen and hydrogen production, respectively. The two semiconductors should provide a photovoltage > 1.7 V to drive spontaneous water splitting and are interfaced with OER and an HER catalysts. The device is immersed in

an electrolyte and produces hydrogen and oxygen upon light illumination. A membrane or a separator can be used to aid product separation and ensure safety of the device. The device can be fed water (H_2O) in a recirculated manner and hydrogen (H_2) and oxygen (O_2) are collected separately.

- Figure 5: Schematic showing exemplar thermochemical cycles for the three classes of water-splitting redox chemistries. Far left is the simple two-step metal oxide cycle, center is the multistep cycle, and far right is the hybridized cycle that invokes an electrochemical step other than direct water electrolysis. Water and energy are the only inputs into these systems, and hydrogen and oxygen are the only outputs. All other chemical species are transformed and regenerated within the redox cycle. Nuclear plants, solar and other sustainable power sources supply the carbon-free energy inputs to these cycles to split water and produce clean hydrogen.