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Review—Engineering Challenges in Green Hydrogen Production Systems

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Today, hydrogen (H_2) is overwhelmingly produced through steam methane reforming (SMR) of natural gas, which emits about 12 kg of carbon dioxide (CO_2) for 1 kg of H_2 (~12 kg-CO_2/kg-H_2). Water electrolysis offers an alternative for H_2 production, but today's electrolyzers consume over 55 kWh of electricity for 1 kg of H_2 (>55 kWh/kg-H_2). Electric grid-powered water electrolysis would emit less CO_2 than the SMR process when the carbon intensity for grid power falls below 0.22 kg-CO_2/kWh. Solar- and wind-powered electrolytic H_2 production promises over 80% CO_2 reduction over the SMR process, but large-scale (megawatt to gigawatt) direct solar- or wind-powered water electrolysis has yet to be demonstrated. In this paper, several approaches for solar-powered electrolysis are analyzed: (1) coupling a photovoltaic (PV) array with an electrolyzer through alternating current; (2) direct-current (DC) to DC coupling; and (3) direct DC-DC coupling without a power converter. Co-locating a solar or wind farm with an electrolyzer provides a lower power loss and a lower upfront system cost than long-distance power transmission. A load-matching PV system for water electrolysis enables a 10%–50% lower levelized cost of electricity than the other systems and excellent scalability from a few kilowatts to a gigawatt. The concept of maximum current point tracking is introduced in place of maximum power point tracking to maximize the H_2 output by solar-powered electrolysis.
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Green hydrogen (H_2), which is produced from low-carbon renewable sources including water and renewable energy, is indispensable for our energy and environmental sustainability.[1–4] H_2 can serve as a storage medium for intermittent solar and wind power, enabling longer-term (typically weekly) storage beyond daily storage by batteries.[5,6] It can provide a fuel for fuel cells in transportation, which is particularly important for long-haul heavy-duty trucking as an electric truck requires a massive battery and long charging times. It can also act as an agent to convert captured carbon dioxide (CO_2) to a hydrocarbon (e.g., methanol) as a sustainable fuel for buildings, transportation, and industries, or as a sustainable feedstock for other synthetic hydrocarbons such as plastics.[7]

This paper presents an analysis on some of the engineering challenges and opportunities in integrating renewable energy with electrolytic hydrogen production. The analysis will focus on intermittent solar and wind power. Hydro power is dispatchable and currently used in electrolytic H_2 production as part of the electric grid mix. On the electrolyzer side, the analysis will focus on alkaline and polymer electrolyte membrane (PEM). Solid-oxide electrolyzers operate at an elevated temperature of 700 °C–900 °C, which represents a unique case for integration, i.e., maintaining the high temperature on a 24/7 basis with intermittent solar and wind power is a challenge that alkaline and PEM electrolyzers do not share. In addition, the analysis will focus on large-scale water electrolysis systems from a megawatt to a gigawatt, as these are the scales required for green H_2 production but such large scales present significant challenges that smaller-scale systems do not encounter.

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Carbon Dioxide Emissions from Hydrogen Production Processes

Today hydrogen is overwhelmingly produced by steam methane reforming (SMR) of natural gas. The complete conversion of methane in natural gas to H_2 is given below:

$$CH_4(g) + 2H_2O(g) \rightarrow 4H_2(g) + CO_2(g) \quad \text{[R-1]}$$

although there are multiple steps involved in this overall reaction. SMR is carried out with high-temperature (700 °C–1,000 °C) and pressurized steam (3–25 bar), which requires energy to produce. The total equivalent carbon dioxide emissions from the SMR process are close to 12 kg of CO_2 per kilogram of H_2 produced (kg-CO_2/kg-H_2),[8,9] which include about 9 kg-CO_2/kg-H_2 direct emissions from the SMR process and up to 3 kg-CO_2/kg-H_2 equivalent emissions from upstream methane leakage. While 12 kg-CO_2/kg-H_2 is lower than 19 kg-CO_2/kg-H_2 for the coal-to-H_2 process,[9] it is still very high compared to solar- and wind-powered water electrolysis.

Water is a carbon-free source of hydrogen, which is abundant and renewable. Although less popular, there are three commercial processes to produce H_2 from water and grid power:[10] alkaline, polymer electrolyte membrane, and solid oxide electrolysis. The overall reaction for water electrolysis is:

$$2H_2O(aq) \rightarrow 2H_2(g) + O_2(g) \quad \text{[R-2]}$$

where H_2 is produced at the cathode and O_2 at the anode in an electrolyzer. These electrolytic processes do not directly emit carbon dioxide, but they require a huge amount of electricity, 50–60 kWh of electricity to produce 1 kg of H_2 excluding transmission losses.[10] The problem is that the grid is generally "dirty." In the U.S., over 60% of the grid power is derived from fossil fuels.[11] Generating 1 kWh of electricity in the U.S. emits on average 0.42 kg of CO_2 at power plants.[12] This carbon intensity translates into 23 kg-CO_2/kg-H_2 with grid power, nearly double the CO_2 emissions of the SMR process. The increased CO_2 emissions are due to the extra steps to convert natural

Table I. Carbon dioxide emissions for four different hydrogen production processes.

H_2 production process	Steam methane reforming	Grid-powered electrolysis (U.S.)	Solar-powered electrolysis	Wind-powered electrolysis[14]
CO_2 emission in kg-CO_2/kg-H_2	12	23	2.1	0.68

gas to electricity and then use the electricity to produce H_2, instead of directly converting natural gas to H_2.

The situation is different in some countries such as Norway and Sweden where the electric grid is already quite clean or low carbon. Typically those countries have abundant hydro power. When supplemented by nuclear and/or wind power, grid-powered water electrolysis makes perfect sense there. In general, the CO_2 emissions for grid power must be below 0.22 kg-CO_2/kWh to compete with the SMR process and substantially lower to derive environmental benefits, as 55 kWh/kg-H_2 $\times$ 0.22 kg-CO_2/kWh = 12 kg-CO_2/kg-H_2. This fact means that the U.S. must reduce the CO_2 emissions of its grid power by at least 50% for any environmental benefit from grid-powered electrolytic H_2 production.

Much greener hydrogen can be achieved if electrolysis is powered directly by renewable energy sources such as solar, wind, and/or hydro power. Take solar power as an example, which is arguably the "dirtiest" renewable energy source. It requires about 3 kWh of electricity to produce a 1-Wp (watt peak) solar module.[13] Solar manufacturers rely on the same electric grid as other manufacturers, so the electricity they use has the same carbon intensity, i.e., a 1-Wp module is equivalent to 1.26 kg of CO_2 emissions at power plants in the U.S. On the other hand, the 1-Wp module generates on average 30 kWh of electricity over its 25-year lifespan, or the CO_2 emissions for solar electricity are 0.042 kg-CO_2/kWh. With solar-powered electrolytic H_2 production, the CO_2 emissions are 2.1 kg-CO_2/kg-H_2. With wind and hydro power, the CO_2 emissions should be lower than 2 kg-CO_2/kg-H_2.[14] Table I summarizes the carbon intensity of different processes for H_2 production.

While the motivation for green hydrogen is clear, the technology for large-scale water electrolysis from solar and wind power has yet to be developed. Hydro power does not suffer from intermittency, and it has been applied to green H_2 production as part of the grid mix since the 1920's with the Norsk Hydro/alkaline technology. This paper will focus on wind and solar power for electrolytic H_2 production.

Current Electrolytic Hydrogen Production Systems

Today most commercial electrolyzers for hydrogen production take alternating-current (AC) power from the electric grid, but the cell stacks operate on direct-current (DC) power. To match the AC power, all the supporting components in today's electrolyzer systems such as the pumps are AC components. Efforts are required if one decides to run the entire electrolyzer system on DC power.

For large-scale electrolyzers over 1 MW, high-voltage AC power typically exceeding 100,000 V is required as input to the electrolyzer site. The high voltage minimizes the resistive losses from transmission, as the current required to deliver 1-MW AC power at 400 V_{rms} is 2,500 A_{rms}. Most electrolyzers today operate at 200 V or 400 V DC. In either case, a large-scale electrolyzer requires a step-down transformer to convert the high-voltage AC power to low-voltage AC and then a rectifier to convert the low-voltage AC power to 200-V or 400-V DC before delivering it to the cell stacks. Therefore, there are two power conversions on the electrolyzer side:

- High-voltage AC to low-voltage AC.
- Low-voltage AC to low-voltage DC.

It is reminded that each time power is converted or conditioned, there is a power loss associated with that conversion/conditioning. There is also a monetary cost associated with the power conversion/conditioning device.

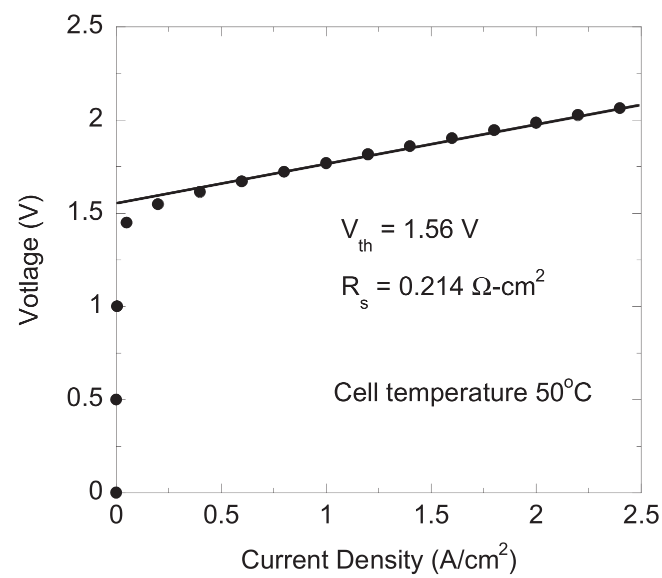

Figure 1. Polarization curve of a commercial PEM hydrogen cell operating at 50 °C.

A large-scale electrolyzer for hydrogen production today contains several cell stacks in a parallel connection. Each stack contains 100–200 hydrogen cells in a serial connection, where the hydrogen cell is the basic building block for electrolyzers. As an example, Fig. 1 shows the polarization curve, i.e., the current-voltage relationship, for a commercial PEM hydrogen cell with a 7-mil perfluorosulfonic acid membrane operating at 50 °C. There are two features in Fig. 1 that are common for both alkaline and PEM hydrogen cells:

- The cell requires a turn-on voltage, below which the current is practically zero.
- Beyond the turn-on voltage, the current-voltage relationship is largely linear.

For system design and simulation, the following equation represents the current-voltage relationship of the cell[15]:

$$V_{cell} = V_{th} + I_{cell} \times R_{cell} \quad \text{[E-1]}$$

where V_{cell}, I_{cell}, and R_{cell} are the voltage, current, and resistance of the hydrogen cell, and V_{th} the turn-on voltage. For the hydrogen cell in Fig. 1, the turn-on voltage is 1.56 V $cell^{-1}$. In Fig. 1, the current is given in current density J_{cell} with a unit of A/cm^2 and the resistance in specific resistance R_s with a unit of Ω-cm^2. The relationships between R_s and R_{cell} and between I_{cell} and J_{cell} are: and

$$R_s = R_{cell} \times A \quad \text{[E-2]}$$

$$I_{cell} = J_{cell} \times A \quad \text{[E-2]}$$

where A is the area of the cathode in the hydrogen cell.

When n hydrogen cells are serially connected in a stack, the current-voltage relationship for the stack is:

$$V_{stack} = n \times V_{th} + I_{cell} \times n \times R_{cell} \quad \text{[E-3]}$$

With m stacks parallelly connected in an electrolyzer, the current-voltage relationship for the entire electrolyzer system is:

$$V_{system} = n \times V_{th} + m \times I_{cell} \times n \times R_{cell} \quad \text{[E-4]}$$

It is possible that a large-scale electrolyzer requires more than one rectifier, and equation E-4 applies to the m stacks powered through one rectifier.

The largest electrolyzer for hydrogen production today is a few megawatts. To scale up the electrolyzer to a gigawatt , one can, in principle, do the following:

- Increase the area of the cathode in the hydrogen cell to increase its current. A larger cathode area does not change the current density as the cell voltage is more or less fixed to about 2 V $cell^{-1}$. Today the typical cell current is between 2,500 A and 5,000 A, so each cell requires 5–10 kW to drive. For example, the Giner ELX 225 kW cell stack has a nominal current of 3,750 A.[16] Conversations with electrolyzer manufacturers suggest that in the future, over 10,000 A $cell^{-1}$ can be expected.
- Increase the number of cells per stack to increase the stack power. Today most stacks contain 100–200 cells, so a single stack requires as low as 0.5 MW $stack^{-1}$ and as high as 2 MW $stack^{-1}$ to drive. Solar modules can withstand a maximum system voltage of 1,500 V, so one can imagine a stack of 750 hydrogen cells for 1,500 V. A 1,500-V 10,000-A stack would require 15 MW to power.
- Increase the number of stacks in an electrolyzer system to increase the system power. Today a typical megawatt-scale electrolyzer has between 1 and 20 stacks and designs for larger systems have been developed. If a system has 100 1,500-V 10,000-A stacks, the system power would reach 1.5 GW!

However, there remain significant engineering challenges to come up with a gigawatt-scale electrolyzer, as some of the approaches above are already maxed out to the limitations of today's technology.

Wind-Powered Electrolytic Hydrogen Production

Wind turbine generators produce AC power, whereas solar photovoltaic (PV) arrays output DC power. Therefore, some of the challenges that wind-powered water electrolysis systems encounter are different from solar-powered systems.

Wind-powered electrolytic hydrogen production systems require three power conversions, two on the electrolyzer side:

- High-voltage AC to low-voltage AC.
- Low-voltage AC to low-voltage DC.

And one on the wind turbine side:

- Low-voltage AC to high-voltage AC.

The last conversion arises because the output voltage of wind turbine generators is typically in the 600–700 V_{rms} range. A step-up transformer is thus necessary to bring the low-voltage AC power up to high-voltage AC. Moreover, a dedicated transmission line from the wind farm to the electrolyzer site is likely needed to deliver wind power for two reasons:

- In most cases, the current grid does not have the capacity to accept and deliver additional power of a megawatt to gigawatt scale, without an expensive grid upgrade.
- Through a "dirty" grid, it is impossible to produce greener H_2 than steam methane reformed H_2. This fact is true for most countries.

Co-locating a wind farm with an electrolyzer is preferred to reduce both the cost and the power loss from long-distance power transmission.

One advantage of wind-powered electrolytic hydrogen production is that the power electronics are largely available. Today large-scale electrolysis from megawatt to gigawatt is carried out to produce several raw materials including caustic soda, aluminum, copper, and zinc.[17] The electrolyzers for those materials all take AC power from the grid, i.e., those megawatt to gigawatt transformers and rectifiers are readily available for large-scale wind-powered electrolyzers.

There is a major difference between grid-powered electrolysis and direct wind- or solar-powered electrolysis, i.e., the intermittency of wind and solar power. According to the U.S. Energy Information Administration,[18] the capacity factor of utility-scale wind turbine generators in 2020 is 35.3%, so a wind-alone electrolyzer produces 65% less hydrogen than a grid-powered electrolyzer running on a 24/7 basis. The capacity factor for large-scale solar PV systems is even lower at 24.2%. The low capacity factors contribute to the high cost of green H_2.

One approach to improve the capacity factor of the electrolyzer is to combine wind power with solar power.[19,20] Wind power and solar power are often complementary temporally, so a wind and solar hybrid hydrogen production system may achieve a capacity factor of 50%. One engineering challenge here is how to couple intermittent AC power with intermittent DC power for DC electrolyzers. Another challenge is how to properly size the wind generator, PV array, and electrolyzer for a specific location to maximize the system capacity factor and minimize the upfront system cost.

Beyond 50%, other renewable or low-carbon energy sources are needed such as hydro and/or nuclear power. Here storage of wind and solar power through hydrogen is excluded as an option for improving the capacity factor of the electrolyzer. One could use H_2 produced from wind or solar power to generate electricity through a fuel cell, and then produce H_2 with this electricity at night. This does not seem like a smart choice due to the power losses associated with the additional conversions from H_2 to electricity to H_2. There is nothing to be gained by such an approach except less H_2. Wind- and solar-powered H_2 production can be used for many applications such as storage of intermittent wind and solar power, long-haul heavy-duty trucking, and conversion of captured CO_2 to a hydrocarbon, but not for production of H_2.

Solar-Powered Electrolytic Hydrogen Production

Solar power is projected to overtake wind power soon and become the leading renewable energy source of the future.[21] The largest solar PV systems today exceed 2 GWp.[22,23] Without a cost-effective and scalable technology for PV-powered electrolytic hydrogen production, those large-scale solar systems are backed with only battery storage systems.[23] The discharge time for various batteries is limited to a few hours for daily storage, but hydrogen enables weekly storage.[24]

Driving large-scale electrolyzers with solar power presents significant engineering challenges. Since PV arrays output DC power and electrolyzers take DC power, there are several possibilities to integrate solar power with electrolysis including:

- DC to AC and then back to DC.
- DC to DC without going through AC.

It is reminded that a traditional PV system always contains power electronics for maximum power point tracking (MPPT). MPPT ensures that a PV system always outputs the maximum available PV power under any irradiance and/or load conditions. For a grid-tied system, the DC-AC inverter performs MPPT. DC-DC coupling requires the DC-DC power converter to perform MPPT.

DC-AC-DC for PV-powered hydrogen production.—Today the only feasible approach to drive a large-scale electrolyzer with solar power is through an AC grid (Fig. 2). To quantify, let us assume a 10-MW electrolyzer. Four PV arrays of 3 MWp each are needed to

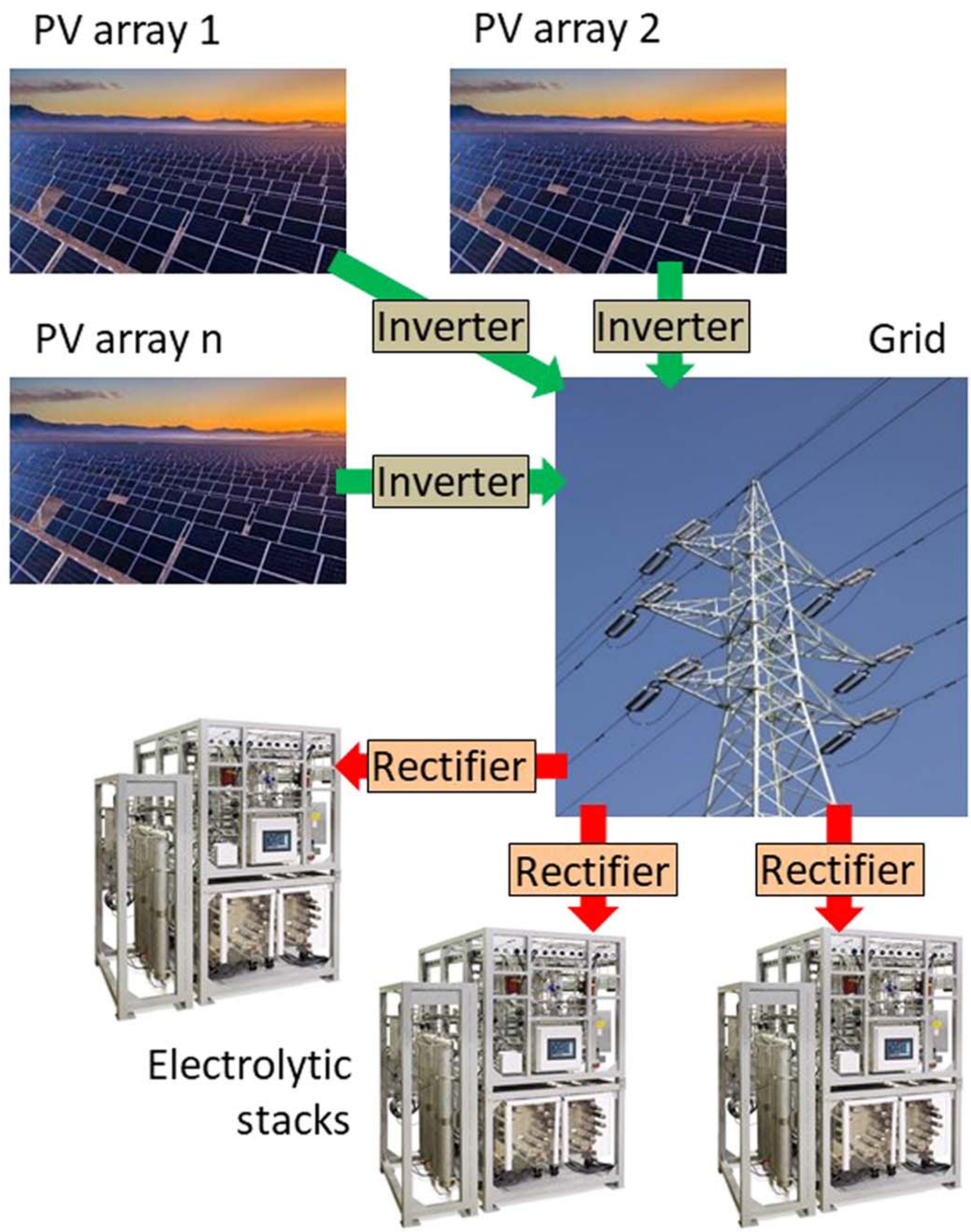

Figure 2. Today's approach for solar-powered electrolytic hydrogen production through an AC grid.

provide about 12 MWp of solar power for the electrolyzer. The reason for the multiple solar arrays is that the largest inverter available on the market today is about 3 MW. The low-voltage DC solar power (typically around 500 V) is first converted to low-voltage AC by the inverters. If the power loss through the inverters is 10%, 12-MWp DC power provides about 11-MWp AC.

Once the DC solar power becomes AC, the rest of the power system looks essentially the same as for wind-powered electrolyzers. The outputs of the four inverters go through a step-up transformer that converts the low-voltage AC power to high-voltage AC. The electric grid accepts the AC power peaked at 11 MW and delivers it to the electrolyzer site, where the high-voltage AC power is converted back to low-voltage AC (200–400 V_{rms}) through a step-down transformer. The low-voltage AC power is then rectified back to DC for the DC electrolyzer. The transformers and rectifiers all incur power losses. If the combined power loss by the transformers and rectifiers is 10%, the 11-MWp AC power is now reduced to 10-MWp DC for the 10-MW electrolyzer.

There are four power conversions in the DC-AC-DC approach. Two on the PV array side:

- Low-voltage DC to low-voltage AC with MPPT.
- Low-voltage AC to high-voltage AC.

And two on the electrolyzer side:

- High-voltage AC to low-voltage AC.
- Low-voltage AC to low-voltage DC.

Again, a dedicated transmission line from the solar farm to the electrolyzer site is likely needed for the same reasons as for wind-powered electrolyzers.

Short-distance power transmission can employ a low voltage with a high current, for a limited transmission loss. Therefore, co-locating a solar farm with an electrolyzer brings out the opportunity to eliminate the power conversions between low-voltage AC and high-voltage AC, making two power conversions possible for DC-AC-DC based water electrolysis, one conversion on the PV array side:

- Low-voltage DC to low-voltage AC with MPPT.

And one on the electrolyzer side:

- Low-voltage AC to low-voltage DC.

Therefore, co-locating a solar farm and an electrolyzer has the potential to reduce both the power loss and the upfront system cost over those systems relying on long-distance power transmission.

DC-DC for PV-powered hydrogen production.—There is another approach to drive large-scale electrolyzers with solar power, i.e., through DC-DC coupling, which is a major opportunity for electrical engineers as large-scale solar-powered DC-DC electrolyzers do not exist today.

There are several methods to implement the DC-DC approach. One is through a high-voltage DC transmission line. In this method, there are two power conversion or conditioning steps on the PV array side:

- MPPT for low-voltage DC.
- Low-voltage DC to high-voltage DC.And one on the electrolyzer side:
- High-voltage DC to low-voltage DC.

The advantages of this method seem marginal as it cuts down the four power conversions for the DC-AC-DC approach to three. Moreover, high-voltage DC transmission[25] is a new technology as high-voltage AC transmission has been in practice for over 100 years.

The DC-DC approach does allow a much simpler system, in principle, when the solar farm and the electrolyzer are co-located. Like the DC-AC-DC approach, co-location can eliminate the power conversions between low-voltage DC and high-voltage DC, making one power conversion possible for DC-DC based electrolytic hydrogen production. All it requires is a DC-DC power converter between the PV array and the electrolyzer, which also performs MPPT. Such a system has been demonstrated at small scales for individual homes,[26–28] with a lower power loss and a lower upfront system cost than relying on long-distance power transmission.

However, it is technically difficult to scale up the DC-DC power converter to a megawatt to gigawatt scale. The largest DC-DC power converter on the market today is only 500 kW, the Dynapower model DPS-500 battery charge controller.[29] This scale is far smaller than the typical electrolyzers today, 1–10 MW. The Dynapower DPS-500 outputs 1,000 V and 500 A, which represents a mismatch to the input of the electrolyzers, 200–400 V and 2,500–5,000 A.

Solar-powered large-scale electrolysis requires a high-current DC-DC power converter because the hydrogen output by electrolysis depends on the number of electrons supplied. Every H_2 molecule produced requires two electrons to the cathode:

$$2H^{+} + 2e^{-} \rightarrow H_2(g) \qquad \text{[R-3]}$$

as long as the voltage stays above the turn-on voltage. High-current power converters present a new, unique engineering challenge. First, there would be significant resistive losses due to the high current. Moreover, the only way to have a 10,000 A power converter today is to connect many matched power transistors in parallel as each transistor can handle only a tiny fraction of the total current. It is expensive to find a large number of matched power transistors, and more transistors mean more chances of transistor failure thus a shortened lifespan of the power converter. Practically anything beyond a few thousands of amperes is highly unlikely. Large-scale solar-powered electrolytic H_2 production through a DC-DC power converter is likely limited by power electronics to about 1 MW per converter.

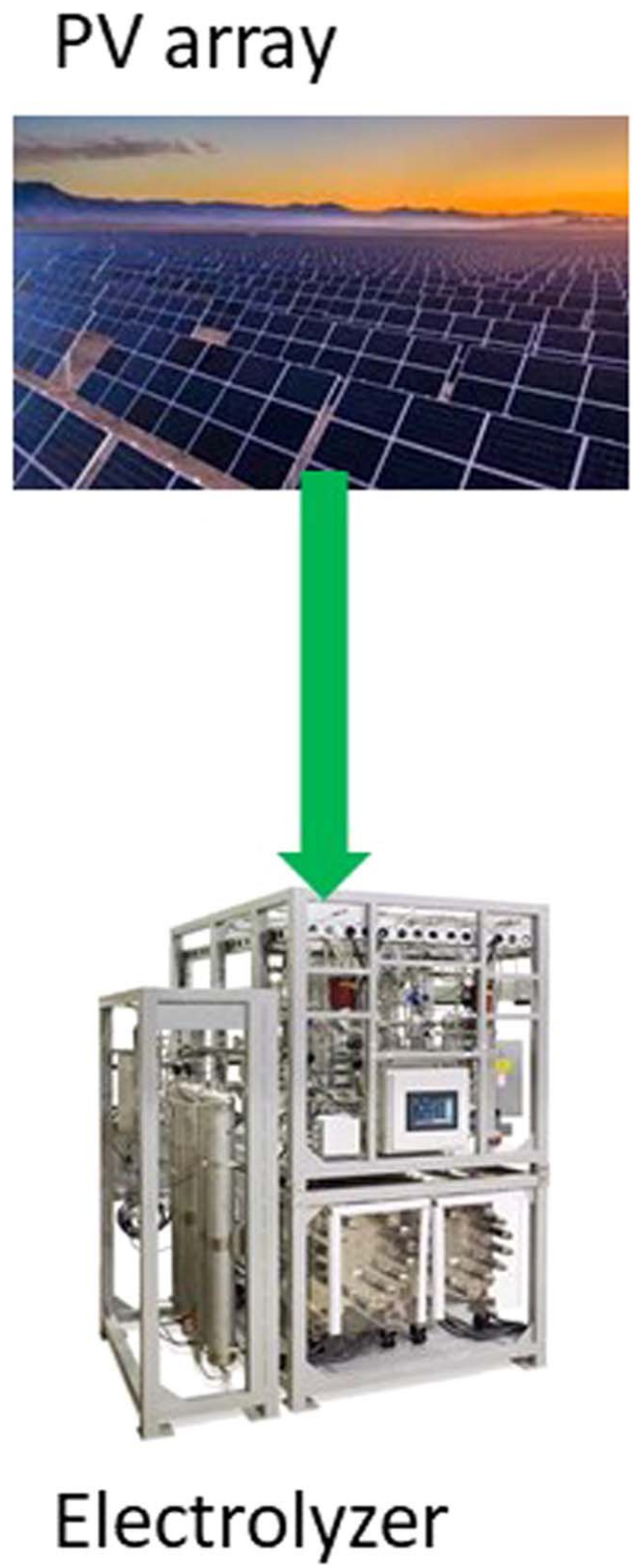

Figure 3. Direct coupling through co-locating PV array and electrolyzer for green hydrogen production.

Direct coupling for PV-powered hydrogen production.—Co-locating the solar farm and the electrolyzer introduces another opportunity, i.e., direct coupling between the PV array and the

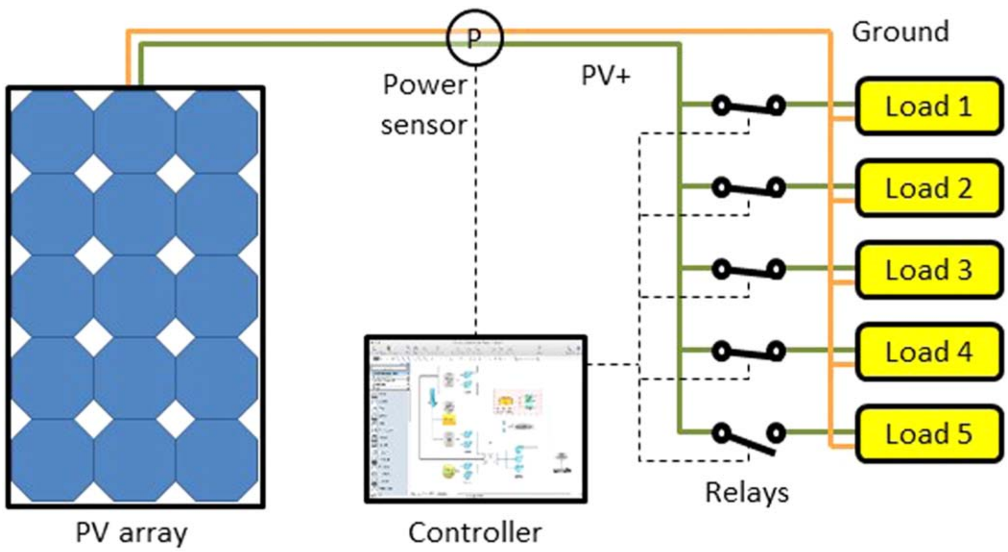

Figure 4. The basic, stand-alone load-matching PV system with five loads.[34]

electrolyzer.[30] The output of a solar array can be directly connected to the input of an electrolyzer without any power electronics in between (Fig. 3), although proper designs of the PV array and/or the electrolyzer are required to achieve voltage and power matching between them.[31,32]

Let us examine the state-of-the-art half-cut monocrystalline passivated emitter rear contact (PERC) solar modules as an example. A module with 120 half-cut PERC cells outputs 310 Wp under the standard test conditions (AM 1.5 and 25 °C).[33] At the maximum power point, the module outputs a voltage of 33 V and a current of 9.4 A. With the operating voltage of a hydrogen cell around 2 V $cell^{-1}$, each solar module can, in principle, drive 16 or 17 serially-connected hydrogen cells in a stack. For a typical stack of 3,000 A and 400 V, a solar array consisting of 12 modules in a string for 396 V and 319 strings in parallel for 2,999 A is required to power it, i.e., 3,828 solar modules for a 1.2-MW stack. For a 1,500-V 10,000-A stack, each string can have 45 solar modules in series for 1,485 V and 1,064 strings in parallel for 10,002 A. In this case 47,880 solar modules would be connected for one stack of 1,485 V $\times$ 10,002 A = 14.9 MW.

While direct coupling represents a simple system topology for solar-powered electrolysis, it suffers from a low system efficiency of about 90%,[15] i.e., about 10% of the maximum available PV power from the solar array is lost due to the mismatch between the solar array and the electrolyzer. Nevertheless, it is a worthy approach if no better approach is available, considering the higher power losses and additional system costs associated with a transmission line and the technical barriers to a high-current DC-DC power converter.

Direct coupling with load management for PV-powered hydrogen production.—A directly-coupled system for solar-powered electrolytic hydrogen production can be much more efficient if load management is incorporated.[34,35] Such a system can exceed a 99% power efficiency without a traditional power converter for MPPT, i.e., less than 1% of the maximum available PV power is lost and over 99% of the maximum available PV power is delivered to the loads. The load-matching PV system performs MPPT by matching the power demand of the loads with the maximum available PV power. This is achieved by changing the number of loads connected to the solar array.

The basic, stand-alone load-matching PV system is illustrated in Fig. 4. Five loads are shown in Fig. 4 but the system can have fewer or more loads if needed. There are different methods to implement this basic system for water electrolysis:

- A stand-alone system with no power exchange with an electric grid.
- A grid-feeding system allowing PV power to feed into the grid when needed.
- A grid-backed system allowing grid power to drive hydrogen production when needed.
- A grid-integrated system allowing power to flow in both directions.

Here only the stand-alone system will be explained for a better understanding.

A couple of features are essential for the load-matching PV system:

- The system has more than one load for load management. For water electrolysis, each load is a cell stack. The Nel Hydrogen M500 and the Teledyne Titan EL-1400 each offers two loads or two cell stacks.
- The system contains no power converter for power conversion or conditioning. Instead, it digitally delivers PV power to a load through a relay, i.e., the power is either on or off for a load.
- The loads, when connected to the PV array, are connected in parallel, i.e., the combined resistance of all the connected loads decreases with more connected loads.
- The system has a microcontroller that connects or disconnects a load through a relay based on the information provided by the power sensor for MPPT.

Figure 5 illustrates the basic control algorithm for MPPT in the load-matching PV system.[36] The power sensor first measures the power delivered to the currently-connected loads. The microcontroller then switches, i.e., connects or disconnects, a load so the system has a different number of connected loads. The sensor measures the power delivered to the new set of connected loads, and the microcontroller compares the two measured powers. If the new power is lower than the old power, the microcontroller undoes the switched load, and the system goes back to the original number of connected loads. If the new power is higher than the old power, the microcontroller keeps the switched load so the system has a different number of connected loads now. In either case, the algorithm starts over again and will continue until the maximum power point is found.

Figure 6 presents a load-line analysis for the load-matching PV system with three electrolytic loads which explains how the system performs MPPT through load management.[35] When the solar irradiance increases, the blue current-voltage curve of the PV array gradually shifts up. The three red load lines in Fig. 6 represent one,

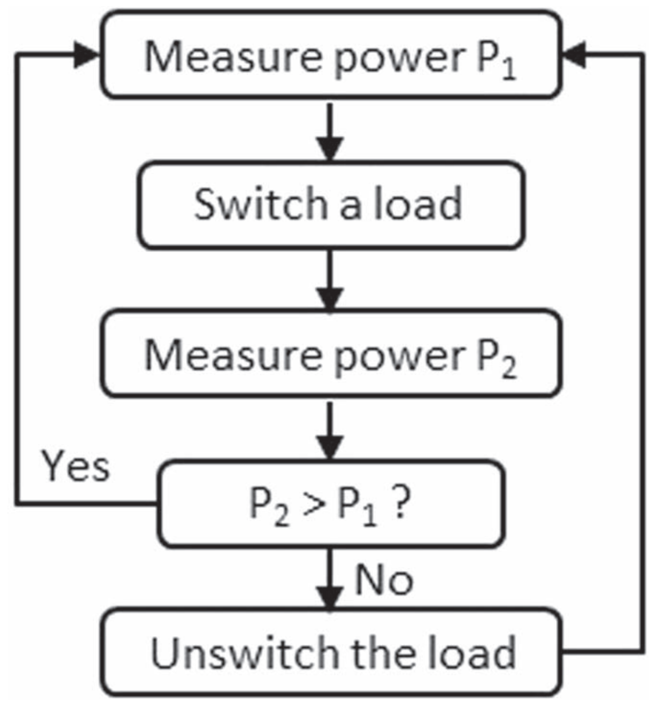

Figure 5. The basic control algorithm for MPPT through load management in PV systems with multiple loads.[36]

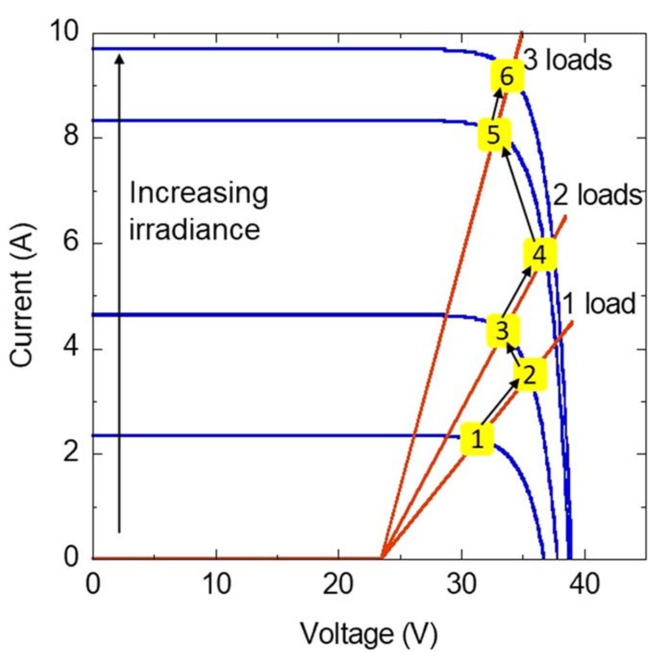

Figure 6. load-line analysis for a load-matching PV system with three electrolytic loads.[35]

two, or three loads connected to the PV array, and the system can operate only along these red straight lines. At point 1, load 1 is connected to the PV array. At this moment, the load resistance is smaller than the characteristic resistance of the PV array so the system is on the left side of the maximum power point. As the irradiance increases, the PV array resistance decreases and the operating point of the system moves along the 1-load line, passes through the maximum power point, and reaches point 2. At this moment, the load resistance is larger than the PV array resistance. The system cuts the load resistance in half by connecting load 2 in parallel with load 1, jumping from point 2 to point 3. This critical point is referred to as a switch point. The optimal switch point for a maximum system power efficiency occurs when the power delivered to n + 1 loads, P_{n+1}, is equal to that of n loads, P_n:

$$P_n = P_{n+1} \quad \text{[E-5]}$$

The system then operates along the 2-loads line until it reaches the next switch point, and so on. When the irradiance decreases, this process occurs in reverse and loads are disconnected from the PV array one by one.

The load-matching PV system with electrolytic loads is efficient. Both static and dynamic simulations suggest that the daily-averaged system power efficiency is over 99% with just four electrolytic loads, and increasing the loads from four to six marginally improves the system power efficiency by less than 0.5%.[35,37] With a nearly 50% increase in the electrolyzer cost from four stacks to six stacks, a load-matching PV system with four electrolytic loads is more cost-effective. Compared to those systems relying on long-distance power transmission, this load-matching system is about 25% better in efficiency alone, from about 80% to over 99%.

The elimination of the traditional power converter underlies the efficiency, cost, and scalability advantages of the load-matching PV system over all the other systems discussed in this paper. Instead of three or four power conversions through a DC or AC transmission line, the load-matching system involves zero power conversion. As shown in Fig. 4, the PV power feeds directly into the loads without any power conversion or conditioning. Therefore, any power loss and component cost associated with power conversion/conditioning are eliminated in the load-matching PV system. Without a power converter, the upfront system cost is reduced by about 10% over a DC-DC power converter-based system, based on the cost of the inverter in today's PV systems.[38] Compared to those systems relying on long-distance power transmission, the load-matching PV system is estimated to reduce the upfront system cost by about 30% from the long transmission line, transformers, rectifiers, and power converters. In addition to the cost benefits, the load-matching PV system offers a close to 100% efficiency. DC-DC power converter-based systems have a typical efficiency of about 90%, so the load-matching PV system reduces the levelized cost of electricity by about 20%. Compared to those systems through long-distance power transmission, the levelized cost of electricity is estimated to be reduced by about 50%.

Moreover, the elimination of the traditional power converter makes the load-matching PV system easily scalable from a few kilowatts for an individual home to a gigawatt for a large-scale solar farm, or anywhere between. Once the cell and stack are defined, an obvious route to scale up the system is to add more loads.[34,35,37] There is no fundamental limitation to how many loads the system can manage, so the number of loads can vary between 2 and, say, 500 if needed. It is reminded that the size of a traditional solar PV system is defined by the power rating of the power converter. This is why a traditional PV system with an inverter is limited to about 3 MWp.

Table II compares the different integration approaches for solar-powered electrolytic hydrogen production systems. The number of power conversion required for each approach has been discussed in this paper. To estimate the power losses for each approach, it is assumed that:

- Each power converter (DC-AC inverter and DC-DC converter) incurs a power loss of about 10%.
- Transformers and rectifiers incur a power loss of about 3% each.
- Power transmission losses are distance-dependent and here transmission losses are excluded.
- Direct coupling without load management incurs a power loss of about 10%.[15]

Table II. Comparison of different integration approaches for solar-powered electrolyzers.

Power System	Long-haul AC	Co-located AC	Long-haul DC	Co-located DC	Directly-coupled	Load-matching
Power conversions	4	2	3	1	0	0
Power loss	20%	13%	30%	10%	10%	1%
Power rating	MW to GW	kW to GW	kW to MW	kW to MW	kW to MW	kW to GW

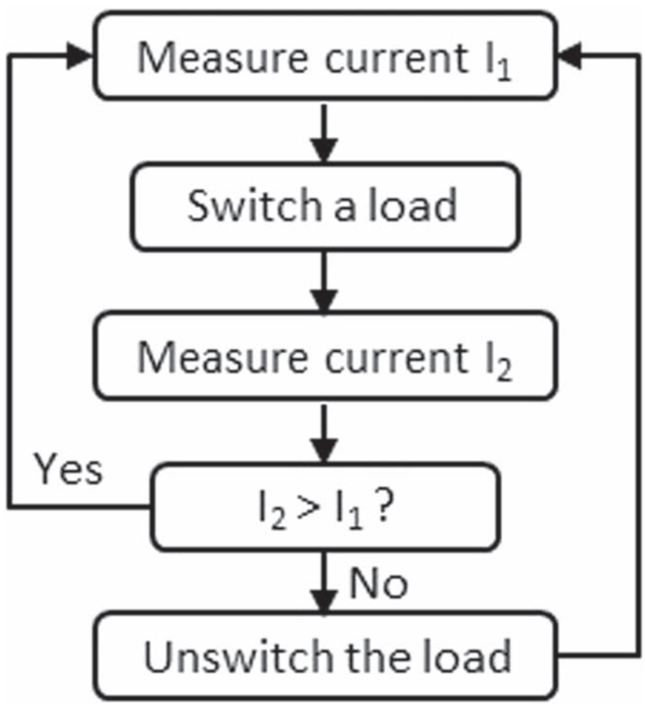

Figure 7. The basic control algorithm for MCPT through load management in PV systems with multiple loads.

For power rating, it is reminded that if a system requires a DC-DC power converter to interface with an electrolyzer, the converter is likely limited to about 1 MW due to engineering challenges in high-current DC-DC converters.

This load-matching PV system is not without limitations to its size. The system voltage or stack voltage is currently limited to 1,500 V as this voltage is the maximum that a solar module can withstand. The current through a stack or a cell is defined by the relay, which is limited to tens of thousands of amperes. At the system level, there is no fundamental limitation on the number of loads a system can have, but there is a practical limitation, i.e., the resistive losses in the electrical wiring. A large solar farm can occupy multiple acres, and we need to run long, large copper bars to collect a large current. The resistive losses increase with larger PV arrays and eventually become unbearable (or the amount of copper required becomes unbearable). A quantitative analysis is needed to understand this limitation.

Maximum current point tracking.—The prevailing wisdom in the solar community is that intermittent PV power must be conditioned to maximize the power output, and various MPPT techniques have been developed and incorporated into the power converter.[39] This power conditioning is required in most cases. In fact, the power rating is the first parameter to consider when designing PV systems.

Electrolysis represents a different case. Here it is the current, not the power that matters more. As Reaction R-3 shows, each hydrogen molecule produced by electrolysis requires two electrons supplied to the cathode. To maximize the H_2 output from a solar-powered electrolyzer, a maximum current point tracking (MCPT) technique is required. However, all the power converters in today's PV systems incorporate a MPPT algorithm by default, which is not suitable for solar-powered electrolysis.

Of note is that the load-matching PV system in Fig. 4 can easily be modified to perform MCPT. A current sensor replaces the power sensor in Fig. 4 to measure the current delivered to the loads, and only a few small changes are needed for the control algorithm in Fig. 5 to perform MCPT. As shown in Fig. 7, the MCPT algorithm compares the currents before and after a load is switched to track the higher current. This algorithm will continue until the maximum current point is found.

Conclusions

An analysis is presented on integration approaches for large-scale direct solar- and wind-powered electrolytic hydrogen production systems. While wind-powered electrolyzers can take advantage of the current megawatt to gigawatt industrial electrolyzers, there are more questions about large-scale solar-powered electrolyzers. Several approaches for solar-powered electrolysis are discussed: (1) DC-AC-DC coupling between a PV array and an electrolyzer; (2) DC-DC coupling without AC; and (3) direct DC-DC coupling without power electronics. Some of the conclusions include: (1) co-locating a solar or wind farm with an electrolyzer for a lower power loss and a lower upfront system cost than long-distance power transmission; (2) a directly-coupled system with load management for a significantly lower levelized cost of electricity and excellent scalability than all the other systems in this paper; and (3) a MCPT technique in place of MPPT for solar-powered electrolyzers to maximize the H_2 output. The analysis also concludes that the carbon dioxide emissions for grid power must fall below 0.22 kg-CO_2/kWh for grid-powered water electrolysis to achieve lower CO_2 emissions than the mainstream SMR process for H_2 production.

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