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WHITE PAPER

THE ROLE OF SOLID OXIDE TECHNOLOGY IN THE HYDROGEN ECONOMY: A PRIMER

May 2021

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EXECUTIVE SUMMARY

Hydrogen's time has arrived. As countries commit to net-zero emissions goals, the need for hydrogen is becoming clear. The market is developing rapidly, with a twenty-fold increase in the pipeline of announced projects over the past 18 months. While many technologies exist for hydrogen production, the market will be led by the technology that wins on cost, efficiency, scalability, flexibility and zero-carbon production.

Zero-carbon hydrogen is produced through electrolysis, with three key technologies: alkaline, proton-exchange membrane (PEM), and solid oxide electrolysis. Bloom Energy is the global leader in solid oxide technology, combining advantages of scale and flexibility with much higher production efficiency and a supply chain that relies on readily available materials. Solid oxide technology can play a competitive role in a broad variety of hydrogen production scenarios, including utilizing excess renewables, integrating with large-scale sources of heat from industrial processes and nuclear reactors, as well as innovative ways to reform natural gas or biomethane. This flexibility opens up global end-use markets including steel and chemical manufacturing, long-haul transportation, and fully-firmed wholesale power.

This white paper describes the growing momentum in hydrogen and the inherent advantages of solid oxide electrolysis.

Five Key Takeaways:

1. Solid oxide technology is widely recognized in the academic literature as a key hydrogen technology, especially due to its potential to generate the lowest cost of hydrogen compared to PEM and alkaline. Jack Brouwer, the Director of the National Fuel Cell Research Center at UC Irvine summarizes these advantages well: "Solid oxide electrolyzers hold the greatest potential to generate low-cost green hydrogen because of their superior efficiency, rapidly declining costs, and scalability.[1]"

2. Bloom is the clear solid oxide leader, with greater trailing twelve months revenues than our six largest competitors combined. Our experience and scale mean we already have a low cost point for our electrolyzer product currently under development, and our costs are dropping more than twice as fast as other electrolyzers.

3. Market momentum continues to build for hydrogen, with over 25 GW of projects announced in the last 6 months alone. Bloom has recently announced an exciting project with Idaho National Labs to demonstrate the efficiency advantages of integrating our electrolyzer with a heat source.

4. Detailed analysis for three illustrative cases shows how solid oxide technology can play a critical role in decarbonization:

   — **Electrolyzing renewable electricity to produce hydrogen:** The largest announced electrolysis deployments will be coupled with dedicated renewable projects. Solid oxide can handle intermittency of renewables by being kept in hot standby, producing hydrogen at a lower levelized cost than PEM and alkaline, due to a competitive capex cost and an efficiency advantage.

   — **Producing hydrogen from nuclear power:** Solid oxide electrolyzers can have an approximately 31% efficiency advantage over PEM and alkaline when paired with a source of waste heat which can be used to offset some of the electricity demand. Nuclear energy is a good example of a source of low cost power and waste heat. Currently ~22% of nuclear power plants in the US are unprofitable. However, installing an electrolyzer onsite with a nuclear plant creates a new revenue stream by enabling the operator to sell power when wholesale electricity prices are high and hydrogen when electricity prices are low. This can improve plant profitability and secure their role in the energy transition. This application is gaining momentum, with Bloom partnering with Idaho National Labs to test our high temperature electrolyzer with waste heat utilization.

   — **Decarbonizing Steel Manufacturing:** Hydrogen is seen as a key component in decarbonizing sectors like steel manufacturing. Steel-making alone contributes 8% of global CO_2 emissions due to carbon-intense production methods: every ton of steel releases ~1.7-2 tons of CO_2.

5. A clear pathway exists to cost-competitive solid-oxide based hydrogen solutions. Across these use cases – as well as others not detailed here – projected cost declines in our electrolyzer hardware and input power costs show the potential to move the hydrogen economy into the mainstream over the next 5 years

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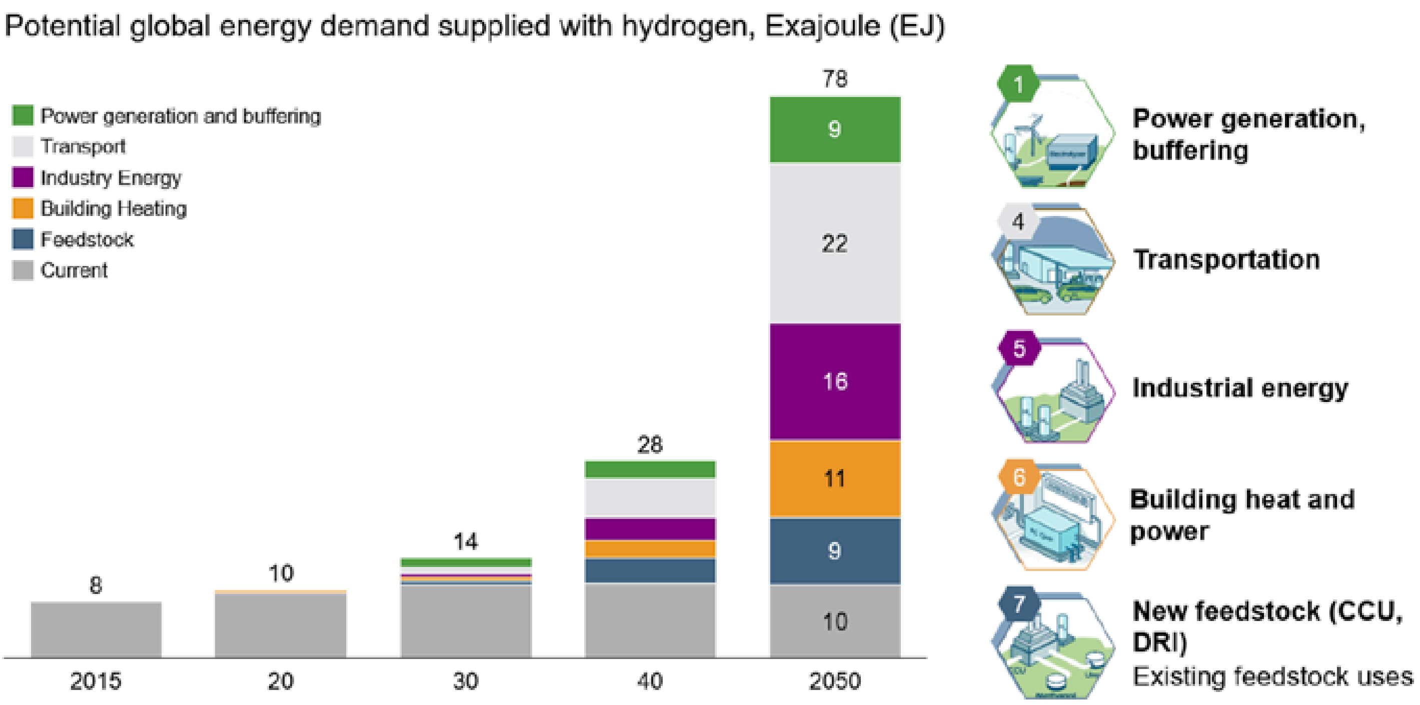
[1] See: https://delawarebusinessnow.com/2020/07/bloom-shares-soar-as-company-enters-south-koreas-hydrogen-market/

1 HYDROGEN'S GROWING MOMENTUM

Sixty-six countries have committed to net-zero emissions goals in the coming decades. Governments increasingly recognize the need for hydrogen as a complement to intermittent renewable power, strengthening the policy tailwinds for hydrogen projects. Several have announced explicit hydrogen investment targets, subsidy schemes, and regulatory frameworks. The EU has committed to build 40 GW of electrolyzers this decade, an investment of roughly €24B, and is considering importing another 40 GW from countries such as Morocco that have lower hydrogen production costs. Korea's Green New Deal commits to 200,000 hydrogen-powered vehicles and 450 refueling stations by 2030. California's Low-Carbon Fuel Standard has spurred early momentum in the US, and the new Biden administration has made hydrogen a key element in its plans to fight climate change, with the goal that green hydrogen become cost competitive with conventional sources within the decade.

According to Hydrogen Council[2], hydrogen will likely play six key roles in the energy transition: chemical feedstock for ammonia and methanol; transportation (especially long haul trucking); process heat for cement and other industrial processes; building heat; new feedstock for processes like steel production and synthetic fuels; and power generation (providing flexibility to the grid). Together, these could comprise 18% of final energy demand by 2050.

EXHIBIT 1: HYDROGEN'S ROLE IN GLOBAL DECARBONIZATION[3]



[1] The Hydrogen Council is a large industry group that has used McKinsey to create a widely-cited report on the hydrogen market; many equity research teams have relied on it to write positively on the sector.

[2] Hydrogen council, "Scaling Up"

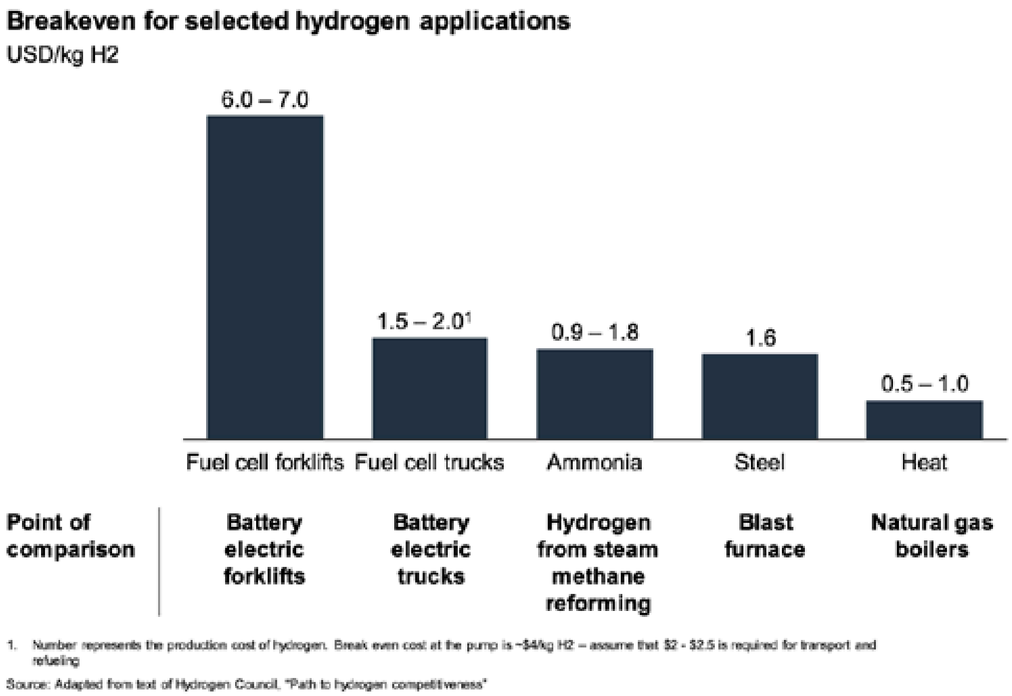
This hydrogen can be produced in three ways:

- **Conventional production:** hydrogen is produced by steam methane reforming (SMR) of natural gas feedstock to produce hydrogen and carbon dioxide. Most hydrogen is produced this way today, but it is not carbon-neutral.
- **Electrolysis:** hydrogen is produced by converting water and electricity into hydrogen without any carbon dioxide emissions. Any zero carbon source of electricity such as wind, solar, hydro or nuclear power produces carbon-free hydrogen.
- **SMR with carbon capture:** hydrogen is produced when carbon capture and sequestration is added to conventional SMR production. If biogas is used instead of natural gas, carbon negative hydrogen can be produced.

The latter two methods are attracting the most attention today, as governments and businesses focus increasingly on solutions that enable the full decarbonization of the global energy economy. The remainder of this white paper examines the role of solid oxide technology – in particular, Bloom's leading solid oxide capabilities – as a critical tool in the coming energy transition.

The breakeven cost for hydrogen (i.e., the point at which it can compete economically with its alternatives) varies as a function of application and geography. Some applications like fuel cell vehicles are small by total addressable market but already "in the money" today. Larger applications like trucking, ammonia production, steel production, and as fuel for heating generally all break even at or below $2/kg in Europe, or $1/kg in the US. For example, the green and grey hydrogen breakeven price for a greenfield ammonia plant would be ~$1.2/kg in the US and $2.1/kg in Spain.[4] Of important note is that these values are on an unsubsidized basis; efforts in Europe around a contract-for-differences incentive to subsidize carbon free hydrogen change this picture dramatically, as would the per-kg hydrogen subsidy currently under discussion in Washington, DC.

EXHIBIT 2: BREAKEVEN HYDROGEN COST FOR SELECTED APPLICATIONS: RANGE REPRESENTS US TO EU[5]



High range represents "early breakeven geographies" like Europe and Japan

Low range represents "late breakeven geographies" like the US

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[4] Gate landed prices for natural gas in Jan 2021: US: $3.35/MMBTU, Spain: $7.83/MMBTU and ~$30/tCO_2 EU ETS

[5] Adapted from text of Hydrogen Council, "A Path to Cost Competitiveness."

2 WHY BLOOM ENERGY, AND WHY SOLID OXIDE?

2.1 Bloom's hydrogen roots

Bloom's hydrogen story started over 20 years ago, when Bloom's founders chose solid oxide technology for NASA's first planned mission to Mars. This flight-ready hardware used electrolysis to make hydrogen from solar power and, in "reversible" operating mode, generated power from that hydrogen.

This solid oxide technology became Bloom's core "Energy Server" product platform back on Earth. Demonstrations in 2005 produced both hydrogen and power. As the hydrogen market had not yet emerged, our systems instead recycled the produced hydrogen back into the system to boost efficiency and reduce emissions. We still operate in this mode across our fleet today.

However, the quickly improving economics of the hydrogen market are now beginning to enable real solutions at scale. Bloom is therefore leveraging its 15 years of experience, scaled-up solid oxide platform, and strong hydrogen intellectual property (including 19 patents) to create uniquely differentiated solutions for customers interested in hydrogen solutions today.

2.2 The solid oxide advantage

Different types of electrolyzers have different attributes. Solid oxide electrolyzers have comparable capex to PEM and alkaline electrolyzers, a faster learning rate, and higher efficiencies. Solid oxide also has a higher efficiency than PEM and alkaline due to its higher operating temperature. The chart below details the findings of a comprehensive "expert elicitation" study of the three key electrolyzer technologies:

TABLE 1: MAIN CHARACTERISTICS OF "GENERIC" ALKALINE, PEM, AND SOLID OXIDE ELECTROLYZERS[6]

Attribute	Alkaline	PEM	Solid oxide
Electrolyte	Aqueous potassium hydroxide (e.g., Nafion)	Polymer membrane	Yttria stabilized Zirconia
Cathode	Ni, Ni-Mo alloys	Pt, Pt-Pd	Ni/YSZ
Anode	Ni, Ni-Co alloys	RuO2, IrO2	LSM/YSZ
Stack efficiency (kWh/kg)	48 - 63	48 - 58	36[7] - 46
Operating temperature (°C)	60 - 80	50 - 80	650 - 1000
System response	Seconds	Milliseconds	Seconds
Stack lifetime (hours)	60,000 - 90,000	20,000 - 60,000	9,000 - 70,000[8]
Uninstalled capex cost today ($/kW)	$500 - $1000[9]	$700 - $1400[5]	~$900[10]
Capex learning rate (%)	9%[11]	13%[7]	28%[6]
Maturity	Mature	Commercial	Demonstration

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[6] O. Schmidt, et. al. Future cost and performance of water electrolysis: An expert elicitation study. International Journal of hydrogen energy.

[7] Assumes waste heat integration.

[8] Range represents academic literature; Bloom's demonstrated stack lifetime in fuel cell mode is approximately five years (43,800 hours); see the white paper titled "A Primer to Understanding Fuel Cell Power Module Life" available here: https://www.bloomenergy.com/sites/default/files/bloom-energy-a-primer-to-understanding-fuel-cell-power-module-life_0.pdf

[9] IRENA, Green hydrogen cost reduction, 2020

[10] Bloom hydrogen investor day. Nov 2020. The higher input rating alone for an electrolyzer drops the cost dramatically vs. the same platform running in fuel cell mode.

[11] Hydrogen Council

Consistent with (and in some ways in addition to) the above, Bloom's solid oxide platform enjoys strong differentiation in the fast-growing hydrogen market, with four significant advantages:

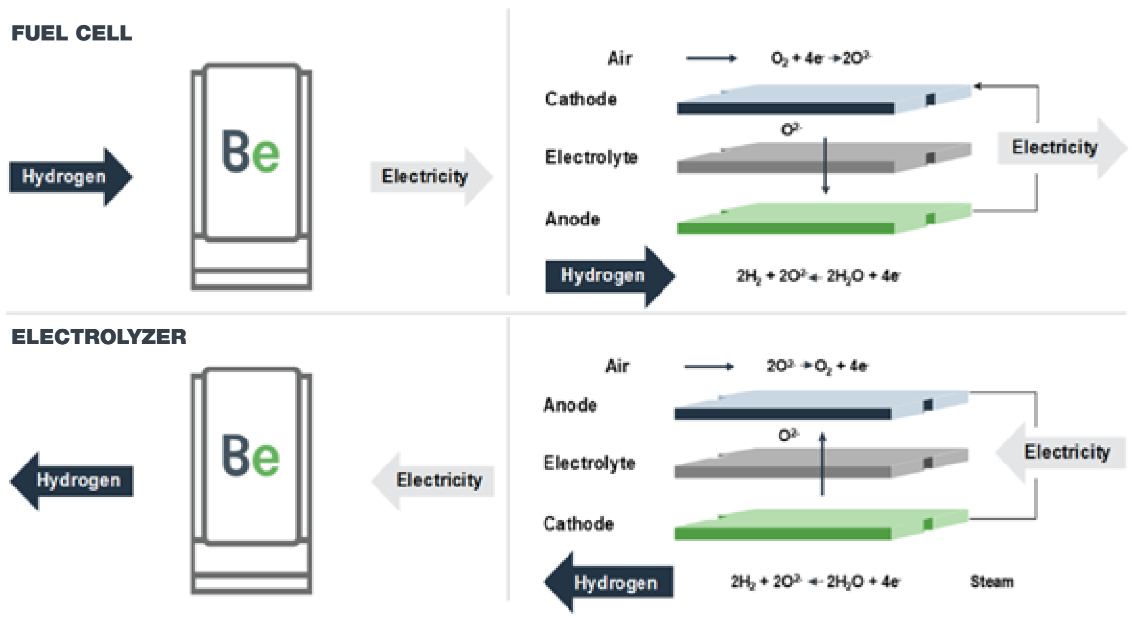
Higher efficiency. The high temperature of SOEC's electrochemical reaction (700-900°C for SOEC compared to less than 100°C for alkaline and PEM) leads to a fundamental efficiency advantages - more hydrogen is produced per unit of electricity input. This efficiency is a major driver of hydrogen production cost. In situations where SOECs can be integrated with a source of low- or zero-cost waste heat (e.g., in industrial production, or when sited alongside nuclear power plants), this efficiency advantage increases even further.

Faster capital cost declines. Bloom's solid oxide platform has demonstrated a steeper learning curve[12] than the other technologies, due to our low cost materials set that enables continuous process and technology improvements to reduce cost. Based on these improvements, we have seen a 28% learning rate over the last decade. Put another way, every time our cumulative production has doubled, our hardware costs fell by 28% (on average). This steep learning curve is twice as fast as the learning curves of alkaline and PEM technologies. This dynamic has led to an average product cost decline of 10-15% per year, or approximately 60% since 2015.[13]

A flexible platform with many hydrogen applications. Bloom's core solid oxide platform can be used in many different applications. Bloom's fuel cells operate on hydrogen (or other fuels) to make zero carbon electricity. Bloom's electrolyzers can use wind, solar (including solar thermal), hydroelectric, or nuclear electric to create hydrogen. The platform can also generate hydrogen in fuel cell mode by reforming nonhydrogen fuel (like natural gas or biogas). To ensure that this process emits zero carbon, Bloom can equip the platform with a proprietary, low-cost carbon capture and storage (CCS) module that separates the reformed hydrogen from the CO2, allowing permanent underground storage of the CO_2. Adding biogas to this process is compelling from a sustainability perspective because it creates a carbon-negative solution via "bio-energy carbon capture" (BECCS).

> **"Solid oxide electrolyzers hold the greatest potential to generate low-cost green hydrogen because of their superior efficiency, rapidly declining costs, and scalability. Achieving zero emissions in many sectors will depend upon making massive amounts of renewable hydrogen. Because Bloom is the market leader in solid oxide technology, I am very encouraged by [Bloom's hydrogen announcements]."** [1]
>
> **—Jack Brouwer, the Director of the National Fuel Cell Research Center at UC Irvine**

EXHIBIT 3: FUEL CELL AND ELECTROLOYZER OVERVIEW



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[12] Learning curves, a tool widely used in energy to chart cost reductions, refers to the percentage change in costs per cumulative doubling of production volume.

[13] See https://s22.q4cdn.com/122868703/files/doc_presentations/2021/01/Bloom-Energy-December-2020-Analyst-DaySlideFixJan24.pdf, page 8.

This platform approach enables many applications; we detail a few of them below. From a competitive standpoint, our versatility creates a virtuous cycle, as each application increases production volume and manufacturing scale, in turn lowering production costs. As costs fall, our competitive position grows stronger, opening more opportunities. This creates a "flywheel effect" as the volume-up-cost-down cycle builds long-term competitive advantages in terms of scale economics.

Scale and experience. Bloom has reached scale by growing revenues at a 30% CAGR over the last decade. As a result, our fleet today now is now over half a gigawatt (GW).[14]

This scale has generated the resources to invest heavily in RD&D – some $1 billion to date. This scale also translates into deep experience operating the fleet. For example, Bloom has developed significant technical insights by generating over 800 billion cell hours in the field, which is one reason our stack lifetimes have increased so much in the past decade. We view this competitive advantage as difficult to replicate without similarly significant operations at scale.

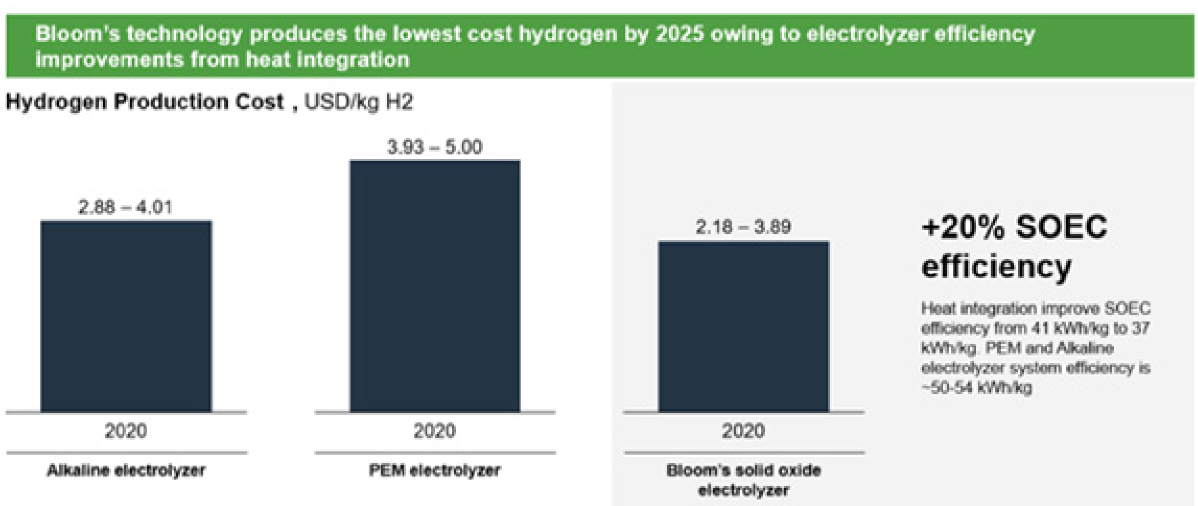
This commercial field experience in fuel cells directly transfers to our hydrogen products, as we can utilize the same core platform, supply chain, manufacturing process, partners, and advanced remote software monitoring across all of our products and applications. Our experience as a developer of fuel cell projects, in addition to our role as an OEM, provide us with the skill sets required to target markets, engage customers with turnkey solutions, model and finance projects, deliver develop profitable projects to investors, and target the most profitable opportunities for ourselves and our customers.

2.3 Levelized Cost of Hydrogen Modelling and Results

The intrinsic attributes of the solid oxide technology, coupled with Bloom's scale and experience, can lead to competitive production costs of hydrogen today and significantly lower costs in the next 5 – 10 years. In assessing hydrogen production technologies, we use a common industry concept of the "levelized cost of hydrogen" (LCOH). LCOH captures all cost drivers over the lifetime of the electrolyzer, including electricity, amortized capex and install costs, and operations and maintenance. Exhibit 4 shows the modeled results for the projected LCOH -- from now until 2030. We also sensitize the model by using a range of key model inputs (see the sidebar below). One of the ways in which we do this is by varying electricity prices (from $0.02/kWh to $0.04/kWh).

Despite the fact that our own performance may vary in some cases than those cited by the study (e.g., our capex cost announcements are 10% lower than cited by the paper, and our demonstrated fuel stack life 4x that described by the study), the model results show that solid oxide can be the lowest cost way to produce hydrogen. This is especially true in applications that utilize waste heat.

EXHIBIT 4: LEVELIZED COST OF HYDROGEN (USD/KG) FROM PEM, ALKALINE, AND SOLID OXIDE ELECTROLYZERS WITH A VARIETY OF ASSUMPTIONS[15]



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[14] Fuel cells are typically rated in terms of output power, whereas electrolyzers are much rated higher as they are sized in terms of input power. The differential between the two means that our fleet's size in electrolyzer terms would be over 1 GW. This also explains why our SOFC costs translate into much lower per kW costs when operated in electrolyzer mode.

[15] See Table A1 in the Appendix for detailed assumptions.

Calculating levelized cost of electricity

Some of the most important levelized cost of hydrogen drivers include:

- **Levelized cost of input electricity:** There is often a tradeoff between very cheap electricity from renewables at a relatively low capacity factor (for example wind PPAs in SPP, MISO, and ERCOT are being signed below $20/MWh) and relatively expensive, uninterrupted grid electricity.
- **Electrolyzer efficiency:** Electrolyzer efficiency determines the amount of electricity required to produce hydrogen. Efficiency reporting is best communicated in kWh/kg – often stack and system efficiency are cited separately. Waste heat recovery is a key efficiency booster than can help solid oxide electrolyzer improve their efficiency advantage over PEM and alkaline.
- **Electrolyzer capex and install cost:** The uninstalled capex and the installation costs of an electrolyzer also contribute to the cost of hydrogen. As the cost of this equipment falls, so too does the unit cost of hydrogen. A second-order impact is the cost to finance the equipment, as measured by the weighted average cost of capital (WACC) of a project.
- **Capacity factor of the input power:** The capacity factor of the power source is important because it plays a strong role in the utilization, or load factor, of the electrolyzer. Optimizing capacity factor is often a tradeoff between running fewer hours a day, which minimizes electricity opex (e.g. power is often cheaper at night), and maximizing capital productivity.
- **Operations and maintenance costs, including stack replacement:** Operations and maintenance are usually estimated to be ~3-10% per year of total installed capex. Stack replacements are a less important cost driver, as a subsegment of O&M. Stack replacements often happen 5-10 years after install (depending on operating conditions), meaning they benefit from the aggressive cost declines in electrolyzer capex, and the discount rate further minimizes costs incurred years after project start
- **Tax incentives, property taxes and insurance:** These typical project variables can affect project economics and tend to be more highly localized and project-specific.

To calculate the LCOH for a given project, we leverage our significant project development experience permitting, designing, constructing and selling projects to date based on our platform. Our project models utilize the above set of costs and input variables, and then solve for the required LCOH required to deliver the asset owner or project investor the target rate of return.

3 DEMONSTRATING THE SOLID OXIDE ADVANTAGE WITH THREE USE CASES

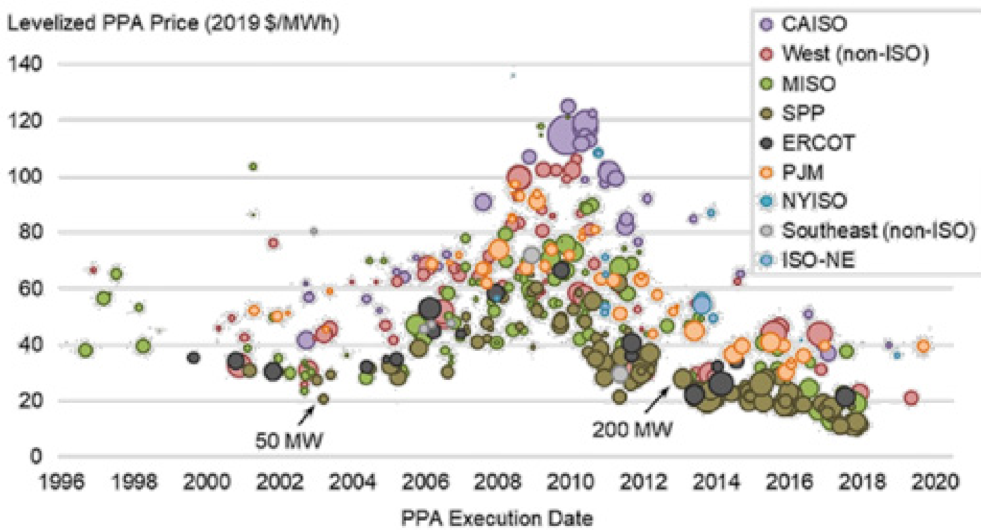
The three use cases laid out below demonstrate the advantages of solid oxide in a number of interesting ways:

3.1 Electrolyzing renewable power to produce green hydrogen

Falling renewable power costs are one of the main drivers of hydrogen cost declines. Over the next 10+ years, giga-scale renewable-based projects will make up the largest portion of announced hydrogen production capacity.

Access to less expensive renewable power can help enable low cost hydrogen. As an example, US wind PPAs are consistently being signed for under $20/MWh today (Exhibit 5), with potential for even lower costs in the coming years.

EXHIBIT 5: LEVELIZED WIND PPA PRICES



Source: Berkeley Lab, FERC

Despite popular misconceptions, all three of the major electrolysis technologies can be paired with renewables. Solid oxide electrolyzers, for instance, have a long startup time, but they can be kept in "hot standby" to respond to the load profile of renewables. Key system components for renewable integration include:

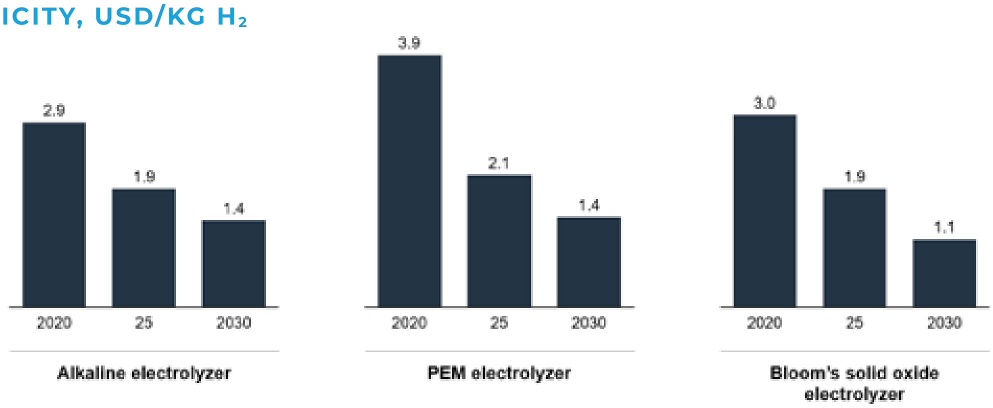
1. **Insulation to keep electrolyzer hot when not operating**; as part of operating the SOEC at high temperature, thermal management is a key system design element to minimize the heat loss and use the available heat as efficiently as possible. This design strategy couples well with the intermittency approach of keeping the units in a hot standby mode which enables the system to be brought back up to operating conditions rapidly with minimal energy expense.

2. **Software and controls to help predict when renewable loads will change, enabling response in advance of same**; the SOEC is inherently capable of responding to demand changes and with advanced controls algorithms, has no issues with typical profiles with today's renewables.

3. **Integration with energy storage to level out loads**; increase the capacity factor of the electrolyzer and match the cost of storage to H_2 production capacity requirement, installed renewable and electrolyzer capacity.

Based on projections of Bloom solid oxide electrolysis capex vs. other technologies, we model that solid oxide electrolyzers can establish a cost advantage over renewable-coupled PEM and alkaline electrolyzers by 2025 and drop to ~$1.2/kg by 2030, an estimated 20% advantage compared to PEM and a 25% advantage vs. alkaline.[16]

EXHIBIT 6: HYDROGEN PRODUCTION COSTS FROM RENEWABLE ELECTRICITY, USD/KG H_2



[16] See Table A1 in the Appendix for detailed assumptions.

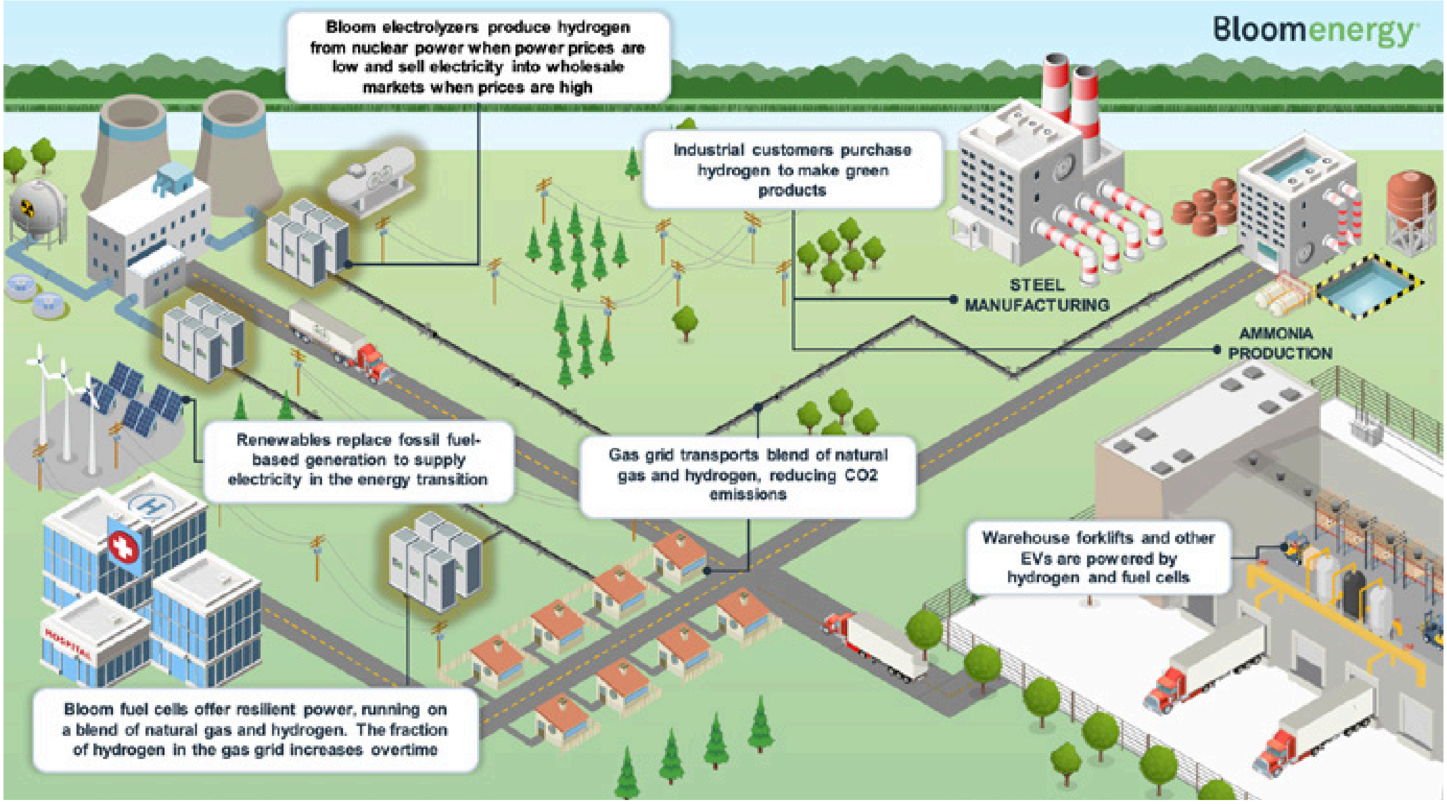
3.2 Producing hydrogen from nuclear power

Nuclear plants' economics are increasingly challenged by the growth of low-marginal cost renewables and by stagnating electric demand. In some markets, such as the SPP in the US, wholesale power prices are already below $20/MWh more than 50% of the time. As wholesale prices drop, more and more nuclear power plants are faced with the decision to curtail generation or operate at a loss.

A 2018 study by the Union of Concerned Scientists found that more than a third of plants in the US, ~22% of total US nuclear generating capacity, were unprofitable or scheduled to retire.[17] While merchant operators typically face more competitive markets conditions, more than half of the economically challenged plants were in regulated markets. Profitability challenges could be further compounded if natural gas and renewable prices remain low while nuclear operating costs rise.

Hydrogen can help change these plants' strategic outlook and viability. Nuclear power's abundant low-cost power can be utilized at off-peak times to produce some of the cheapest and cleanest hydrogen in many markets. And solid oxide electrolysis technology, which becomes even more efficient than alternatives when paired with a source of waste heat like nuclear power, can be a critical component to achieving such competitive cost levels.

EXHIBIT 7: NUCLEAR POWERED HYDROGEN PRODUCTION SCHEMATIC



With waste heat integration, solid oxide electrolysis can produce hydrogen at an LCOH of ~$1.2/kg by 2030, competing favorably against hydrogen and non-hydrogen energy alternative for many applications. When power prices are at $22-$28/MWh – the hydrogen strike price[18] - or lower (potentially up to 50% of the time in some markets), producing hydrogen at these expected 2030 cost levels is the more lucrative choice for a plant operator. Importantly, hydrogen from nuclear power likely has a near term cost advantage vs. hydrogen generated from wind and solar and will remain competitive with wind and solar, even if wind and solar hit very low LCOEs at ~$10/MWh.

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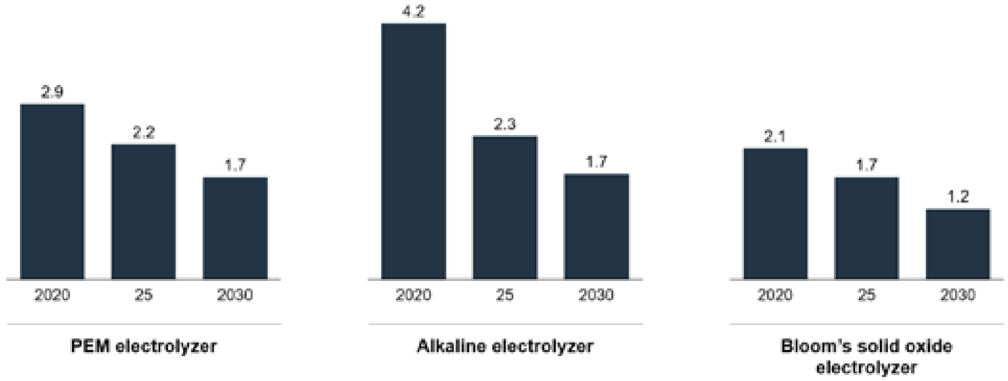
[17] Union for Concerned Scientists, "The Nuclear Power Dilemma Declining Profits, Plant Closures, and the Threat of Rising Carbon Emissions"

[18] Detailed explanation of hydrogen strike price in the appendix

EXHIBIT 8: COST TRAJECTORY OF HYDROGEN PRODUCED FROM NUCELAR POWER

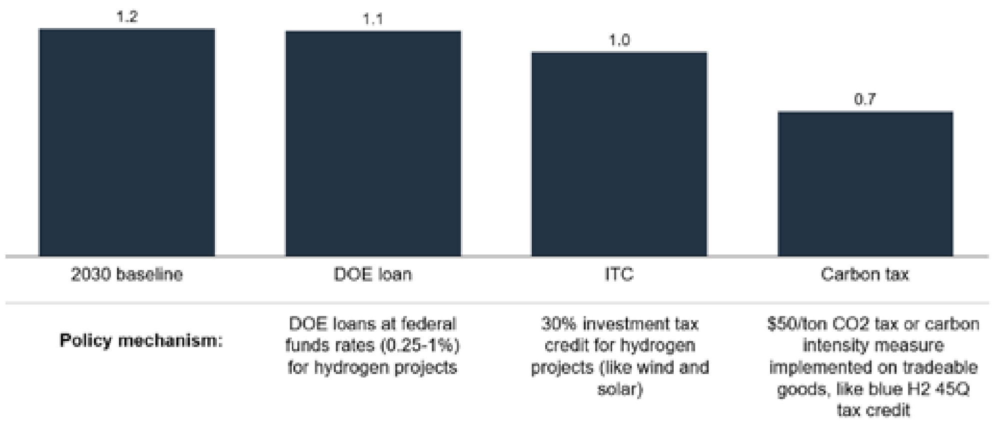


Policy interventions could accelerate the attractiveness of this use case. A 30% installation tax credit on the electrolyzer (similar to the levels in the US in the early days of solar), a \$50/tCO_2 tax credit (similar to the current US 45Q carbon sequestration credit), and a government loan guarantee to support financing (as the US DOE has often done for other new applications) would be sufficient for this to occur (Figure 9).

These electrolyzer installations would be very large, though not unreasonably so when compared to announced electrolysis mega-projects in Europe and Asia. Securing stable revenue streams for the hydrogen would require signing up multiple hydrogen offtakers. The average large ammonia plant (~500,000 tons of ammonia p.a.), for example, requires a volume of hydrogen input that would be produced by ~500 MW of electrolyzers, whereas the average nuclear plant produces 1,000 MW or more of power.[19]

The application is gaining momentum. In the US, Xcel, APS, and First Energy are all part of a consortium to trial hydrogen integration with nuclear plants. As noted above, Bloom is now partnering with Idaho National Labs to demonstrate the potential of this kind of electrolysis with heat integration. Finally, EDF in France has issued RFPs for electrolyzers coupled with nuclear power plants.

EXHIBIT 9: IMPACT TO 2030 SOEC HYDROGEN PRODUCTION COST WITH DIFFERENT POTENTIAL POLICY SUPPORT MECHANISMS (USD/KG)



[19] Based on Yara's announcement of green ammonia project at the Porsgrunn plant.

A note on waste heat integration with solid oxide electrolysis: Waste heat integration is one of the main advantages of solid oxide electrolyzers, boosting system efficiency from ~42kWh/kg to ~36 kWh/kg[20] and substantially improving the levelized cost of hydrogen. Potential sources of waste heat include production processes for steel, glass, aluminum, cement, and lime. Waste heat from nuclear power plants, however, is more attractive since they are also a source of low marginal cost electricity (as low as $20/MWh). Additionally, nuclear waste heat is close to the ideal temperature for solid oxide electrolysis (>600°C), is abundant in its availability, and comes from plants that are often close to hydrogen demand. For example, the Waterford 3 Nuclear Generating Station is ~40 miles from CF Industries' Donaldsonville Nitrogen Complex, which is one of the largest ammonia production facilities in North America.

3.3 Decarbonizing Steel Manufacturing

Hydrogen is seen as a key component in decarbonizing sectors that require high heat and/or stored fuel. Steel-manufacturing alone contributes 8% of global CO_2 emissions due to carbon-intense production methods. Because of this, there is growing momentum around clean steel breakthrough technologies that can lead to a zero-carbon steel making process by 2030.

Steel is primarily made via two routes: the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and Direct-reduced iron-Electric Arc Furnace (DRI-EAF) route. In a place like Europe, BF-BOF is a cheaper technique but has a higher carbon intensity. Switching to a DRI (Direct Reduced Iron) – EAF process creates an opportunity to replace fossil fuels in the DRI process with hydrogen. This transition will require retooling and an investment in new technologies. The investment, however, will create the most dramatic reduction in the CO_2 emissions of steel manufacturing.

In North America, DRI-EAF is used almost exclusively, due to relatively cheaper fuel and electricity costs. In this market, the retooling expense is less dramatic than the European market.

Similar to the waste heat integration discussed in the nuclear section of this whitepaper, SOEC is a superior electrolyzer technology thanks to efficiency pickup from electrolyzing steam. The heat generated from the furnace can be used to create steam, lowering the amount of electricity required for hydrogen production.

Achieving decarbonization goals will require investments in the hardest to abate industries because they are also some of the most intensive emitters of CO_2. Because these businesses are often low-margin and require long term investments in capital equipment, they will also require policy incentives to accelerate the adoption of low or zero carbon techniques. The EU Green Deal, for example, has encouraged European steel producers to begin testing technologies for carbon-reduced steel, many of which most have a hydrogen focus. The new policy framework by the European Commissions has a 1 trillion EUR investment budget until 2030 across 5 major action areas, including "Climate-neutral & circular economy" which specifically addresses steel as a key industry. Coupled with the price of CO_2, the European market is likely to emerge as a leader in low carbon steel manufacturing. The most immediate opportunities, however, may come from the Canadian market. The carbon trading market (carbon tax ramping up to C$170/t$CO_2$ by 2030), coupled with the existence of DRI-EAF manufacturing, makes the Canadian market a highly attractive near term opportunity for the hydrogen transition of steel manufacturing.

4 CONCLUSION

The decarbonization trend has accelerated over the past year, and it has become clear that hydrogen solutions are critical to fully eliminating CO_2 from the global energy system.

Given Bloom's leadership role in solid oxide technology and fuel cells broadly, we are deeply confident in our ability to leverage our scale, experience, continued cost improvements and core efficiency advantages to delivery high value add solutions to our customers demanding cost-effective, low to no carbon solutions.

Our significant experience in energy project development has led us to a number of very interesting high-scale hydrogen projects, some examples of which we detail above. With this focus on practical and economic solutions for our customers, we remain very optimistic about our advantages in the critically important, increasingly relevant hydrogen economy.

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[20] https://reader.elsevier.com/reader/sd/pii/S1364032119302928?token=7BC7102B1F376CD1266B4981F172918AF96303F3A6409246927C16E59875E582296C372D6040BAB494F417D6C60B8CA9&originRegion=us-east-1&originCreation=20210510184706; https://www.sciencedirect.com/science/article/pii/S0360319917339435

5 APPENDIX

TABLE A1: COST AND PERFORMANCE ASSUMPTIONS FOR ALKALINE, PEM, AND SOLID OXIDE ELECTROLYZERS

Product	ALK	PEM	SOEC
Year	2020	2020	2020
Cost Build			
Cost ($/kW)[21]	$716	$1,227	$917
Margin	30%	30%	30%
Price ($/kW)	-	-	$1,192
Install ($/kW)[22]	-	-	$110
Total Upfront Price ($/kW)	$931	$1595	$1,302
Starting system efficiency (kWh/kg)[23]	54	52	36.5 - 41.5
Capacity Factor	50%	50%	50%
Electricity Costs	$0.02 - $0.04	$0.02 - $0.04	$0.02 - $0.04
O&M (Annual $/kW)	$36	$61	$69
O&M (% of Equipment Price)[24]	5.0%	5.0%	7.5%
Cost of Capital	7.00%	7.00%	7.00%
Cost of H_2	$2.88 - $4.01	$3.93 - $5.00	$2.99 - $3.89
Learning Rate[25]	9%	13%	24%[26]

Assumptions used to calcualte levelized cost of hydrogen in Figure 4.

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[21] PEM and alkaline capex numbers from Yates, et. al. “Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis” SOEC numbers from Nov 2020 investor day

[22] Install costs assumed to be included in SOEC install cost assumed to be 12% of capex. DOE “Final Report: Hydrogen Production Pathways Cost Analysis (2013 – 2016)”

[23] PEM and alkaline efficiency ranges from above citation. SOEC range from (1) Wang et. al. “Power-to-fuels via solid-oxide electrolyzer: Operating window and techno-economics” to (2) Schmidt et. al. “Future cost and performance of water electrolysis: An expert elicitation study”

[24] PEM and alkaline assumed to be 5% based on expert interviews. Additional data point from, NREL, “Cost-Competitive Electrolysis-Based Hydrogen Under Current U.S. Electric Utility Rates.” SOEC number calculated from, “Final Report: Hydrogen Production Pathways Cost Analysis (2013 – 2016)”

[25] Hydrogen council, “A path to hydrogen competitiveness”

[26] Historical learning rate for Bloom SOFC is 28%, here we conservatively assume 24% in the future

TABLE A2: LEVELIZED COST AND ASSUMPTIONS FOR GREEN H_2 COUPLED ELECTROLYSIS

Product	ALK			PEM			SOEC		
Year	2020	2025	2030	2020	2025	2030	2020	2025	2030
Cost Build									
Cost ($/kW)	$716	$398	$307	$1,227	$515	$352	$917	$485	$229
Margin	30%	30%	30%	30%	30%	30%	30%	30%	30%
Price ($/kW)	-	-	-	-	-	-	$1,192	$631	$298
Install ($/kW)	-	-	-	-	-	-	$110	$84	$61
Total Upfront ($/kW)	$930	$517	$399	$1,595	$670	$457	$1,302	$715	$359
Starting stack efficiency (kWh/kg)	54	54	54	52	52	52	41.5	41.5	41.5
Degradation (% per 1000 hours)[27]	0.08%	0.08%	0.08%	0.18%	0.18%	0.18%	0.55%	0.55%	0.55%
Capacity Factor	50%	50%	50%	50%	50%	50%	50%	50%	50%
Electricity Costs	$0.02	$0.015	$0.01	$0.02	$0.015	$0.01	$0.02	$0.015	$0.01
O&M (Annual $/kW)	$36	$20	$15	$61	$26	$17	$69	$36	$17
O&M (% of Equipment Price)	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	7.5%	7.5%	7.5%
Cost of Capital	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Cost of H_2	$2.88	$1.85	$1.36	$3.93	$2.06	$1.41	$2.99	$1.85	$1.06
Learning Rate[28]	9.0%			13.0%			24.0% equipment (install 11%)		

Assumptions used to calcualte levelized cost of hydrogen in Figure 6.

[27] Assumes 4,000 hours of operation a year with degradation values from Yates, et. al. “Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis” SOEC numbers from Nov 2020 investor day

[28] Assumes 6 GW in 2025, and 40 GW in 2030 for each technology, PEM and Alkaline equivalent to hydrogen council estimates

TABLE A3: LEVELIZED COST AND ASSUMPTIONS FOR ELECTROLYSIS COUPLED TO NUCLEAR POWER

Product	ALK			PEM			SOEC		
Year	2020	2025	2030	2020	2025	2030	2020	2025	2030
Cost Build									
Cost ($/kW)	$716	$398	$307	$1,227	$515	$352	$917[29]	$485	$229
Margin	30%	30%	30%	30%	30%	30%	30%	30%	30%
Price ($/kW)	-	-	-	-	-	-	$1,192	$631	$298
Install ($/kW)	-	-	-	-	-	-	$110	$84	$61
Total Upfront ($/kW)	$930	$517	$399	$1,595	$670	$457	$1,302	$715	$359
Starting stack efficiency (kWh/kg)	54	54	54	52	52	52	36.5	36.5	36.5
Degradation (% per 1000 hours)	0.08%	0.08%	0.08%	0.18%	0.18%	0.18%	0.55%	0.55%	0.55%
Capacity Factor	40%	40%	40%	40%	40%	40%	70%	50%	50%
Electricity Costs*	$0.012	$0.012	$0.012	$0.012	$0.012	$0.012	$0.02	$0.014	$0.014
O&M (Annual $/kW)	$36	$20	$15	$61	$26	$17	$69	$36	$17
O&M (% of Equipment Price)	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	7.5%	7.5%	7.5%
Cost of Capital	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Cost of H_2	**$2.86**	**$2.20**	**$1.67**	**$4.18**	**$2.34**	**$1.73**	**$2.14**	**$1.68**	**$1.15**
Learning Rate[28]	9.0%			13.0%			24.0% equipment (install 11%)		

Assumptions used to calcualte levelized cost of hydrogen in Figure 8.

*Nuclear levelized cost of hydrogen analysis takes into consideration that nuclear operators will face a tradeoff between selling electricity and producing hydrogen. The decision to sell electricity versus produce hydrogen is based on a wholesale electricity price floor below which the hydrogen produced has more value than the electricity that was used to produce it would if sold in wholesale markets. This hydrogen "strike price" is calculated by dividing a set market price for hydrogen ($1/kg hydrogen is assumed) by the electrolyzer's efficiency (~36-42kwh/kg with and without benefits of heat integration, respectively). When wholesale prices are above this hydrogen strike price (~$22-25/MWh), economically rational nuclear power plant operators would prefer to sell electricity. Below this price, the hydrogen produced will have more value.

To reflect this dynamic, this analysis uses the averaged 2019 SPPSOUTH_HUB Day Ahead Price below the hydrogen strike price to inform cost and capacity factor of hydrogen production. At a strike price of $25/MWh, the corresponding electricity cost proxy is ~$20/MWh with a capacity factor of ~70% (calculated percent of hours in a year below strike price). At a strike price of $22/MWh, the corresponding electricity cost proxy is ~$14/MWh with a capacity factor of ~50% (calculated percent of hours in a year below strike price).

This sub-production cost strike price average is used as a proxy electricity cost in LCOH calculations rather than the true marginal cost of production for nuclear power plants (~$20/MWh for top performers). This is done to reflect the fact that economically rational operators are in principle losing money whenever they sell electricity into wholesale markets below their marginal cost of production and/or hydrogen strike price. Thus, this reduced electricity cost proxy reflects the opportunity cost on the part of nuclear operators and lowers the overall levelized cost of hydrogen.

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[29] Assumes heat integration is done at no additional capex