Introduction

This article will examine the confluence of two policy trends – ushering a hydrogen economy to supplant hydrocarbons and spurring energy storage to fast-track the integration of renewables into the power grid – both in the context of ensuring a faster transition to a clean energy future. Given the breadth and expansiveness of the first policy and its global resurgence (heralded by many as the *Hydrogen Comeback!*), the first part of this article will provide an overview of the potential pervasiveness of this inexhaustible non-polluting fuel and the multitude of applications it lends itself to. The second part will zero in on one particular application: hydrogen energy storage in the context of the power grid.

Part I – The Hydrogen Economy

1. Overview

Named by French chemist Antoine Lavoisier in 1783 from the Greek “hydro” and “genes” meaning “water” and “born of,” hydrogen is the smallest, lightest and most abundant element in the universe. It is a critical building block of all organic chemistry, not only the basis of life but nearly all commonly used forms of energy.

In pure form, hydrogen (H₂) is a relatively convenient fuel and store of energy. It has many physical characteristics that are similar to natural gas, which is widely used for heating and cooling, in industrial processes and in transportation. The key difference between hydrogen and natural gas is that when hydrogen is burned it produces steam instead of CO₂ which is a greenhouse gas and key source of global warming.
Why then is this seemingly perfect fuel not already used more widely? The main reason is that hydrogen does not appear freely by itself in nature. Hydrogen is usually found combined with oxygen (in water) or with carbon (such as in natural gas). Freeing the hydrogen from these other elements to create pure hydrogen takes energy, which in turn causes pollution, and often costs more money than the value of the newly created hydrogen.

However, policies to curb greenhouse gases, advances in hydrogen technology and, importantly, growth in renewable energy, are making hydrogen more attractive economically and environmentally, in turn making it a viable contributor to decarbonizing the economy.

By 2050, widespread adoption of hydrogen could contribute to nearly 20 percent of the greenhouse gas abatements needed to limit global warming to two degrees Celsius. The transportation sector would benefit meaningfully from daily oil consumption going down by 20 million daily barrels (out of a total of 100 million daily barrels of oil consumed globally) and hydrogen could help meet nearly 20 percent of electricity demand.

The hydrogen market today is a $145 billion market growing at 25 percent p.a. By 2050, this could be a $2.5 trillion per year industry creating more than 30 million jobs per year.

2. Hydrogen Technology

2.1. How is Hydrogen Produced?

Today, the world produces approximately 55 million metric tons of hydrogen. This hydrogen is produced in principally two ways:

- **Steam methane reforming**: breaking down natural gas or other molecule that has bonded hydrogen using heat or other energy. The most common way to do this is the use of steam to break down natural gas in a process called steam methane reforming.

- **Electrolysis**: breaking down water by running an electric current through it. This process is called electrolysis.

The chart below (next page) provides a schematic overview of hydrogen production.
Most of today’s methods are relatively expensive due to the high capital cost of the equipment needed to break the water or natural gas molecules but also due to the meaningful quantity of energy that is needed to run these processes. The two principal production processes are described in more detail below.\[5\]

2.2. Steam Methane Reforming

Steam methane reforming is a chemical process which can be used to produce hydrogen on a large scale. In it, natural gas, a fuel that has become increasingly cheap due to the advent of horizontal drilling and the hydraulic fracking of shale gas deposits, is split into its constituent atoms of carbon and hydrogen.

Steam methane reforming consists of two phases. In the first phase of the process, natural gas (methane or CH\(_4\)) and very high temperature steam (H\(_2\)O) are combined (i.e. reformed) to produce syngas. This syngas contains carbon monoxide (CO) and hydrogen (H\(_2\)). In a second phase, the carbon monoxide reacts further with steam to produce carbon dioxide (CO\(_2\)) and additional hydrogen.

The resulting syngas consists of hydrogen and carbon dioxide and is then filtered to extract the purified hydrogen. In total, for every molecule of natural gas, this reaction produces one molecule of carbon dioxide and two molecules of hydrogen.

Steam methane reforming is the most common and cheapest way to make pure hydrogen. However, it has two major drawbacks.
• **Cost:** hydrogen produced via steam methane reforming is still relatively costly compared to natural gas. It costs approximately three times as much (on an energy equivalent basis) as the value of the natural gas it replaces. At current natural gas prices of approx. $1.80/mmBtu\[6\] the cost of hydrogen would be approximately $5.40/mmBtu, making it not competitive.

• **Potential emissions:** steam methane reforming, in its current format, still produces the same amount of carbon dioxide, a greenhouse gas, as the combustion of natural gas.\[7\] In addition, any leakage of natural gas used in steam methane reforming, further contributes to global warming since natural gas (methane) itself is also a very potent greenhouse gas.

Another type of methane reforming, trigeneration, also uses a reforming process but it does not require additional hydrocarbon fuel to create heat and steam. Instead, this technology uses the heat and steam by-product or waste energy from power production occurring within the same system to split the hydrogen from carbon in the natural gas molecules. This method is environmentally friendlier than traditional steam methane reforming but it is not renewable since it still leads to the emission of carbon dioxide.

Approximately 95 percent of hydrogen currently produced is via carbon-based methods like steam methane reforming.

2.3. **Electrolysis**

In electrolysis, water (H\(_2\)O) is split into its two constituent elements, oxygen (O\(_2\)) and hydrogen (H\(_2\)), by passing an electric current through the water.\[8\] The resulting oxygen is a breathable gas that can be released into the air or sold as pure oxygen for industrial or other uses. The resulting hydrogen can be used as fuel.
Historically, electrolysis of water was the most commonly used method of hydrogen production but the increasing production of natural gas over the last 40 years (initially as a by-product of oil extraction but more recently for its own purposes) has led to increase usage of steam methane reforming.

However, since 2010, as the cost of electricity has decreased together with the cost of constructing electrolyzers, hydrogen produced by electrolysis is becoming increasingly competitive.

3. The Color of Hydrogen

Though hydrogen is colorless, it is often described as grey, blue or green. The difference between these types of hydrogen is related to the environmental footprint of its production process.

As mentioned above hydrogen has the benefit of being a clean burning[10] fuel that does not emit carbon when it is combusted or when it is used to create electricity in a fuel cell.[11] However, the production of hydrogen itself is a process that requires significant amounts of energy which in turn can, depending on the technology used, have varying degrees of environmental impact.
• **Grey Hydrogen**: Grey hydrogen is hydrogen produced from a hydrocarbon such as natural gas in a process where carbon dioxide or other greenhouse gases are emitted into the atmosphere. While in some cases, such as trigeneration, this type of hydrogen production can be marginally better than the direct use of the hydrocarbon, this process still has considerable negative environmental impacts. Grey hydrogen, however, is still the cheapest form for hydrogen production with a cost around $1.85/kg.\[12\]

• **Blue Hydrogen**: In blue hydrogen, hydrogen is still produced from a hydrocarbon such as natural gas but the carbon dioxide that results from the production process is captured for utilization and storage (CCUS) in a way that avoids the emission of greenhouse gases. Due to the cost of CCUS, the cost of blue hydrogen is appreciably more expensive than grey hydrogen.

• **Green Hydrogen**: Green hydrogen is produced via electrolysis with electricity from renewable energy sources such as wind and solar. In this case, the hydrogen is produced without the consumption of hydrocarbons or the release of greenhouse gases into the atmosphere. Green hydrogen is more expensive with a cost of around approximately $4 to 6/kg.

Recent interest in hydrogen, such as the European Union’s Hydrogen Strategy\[13\] unveiled in July 2020, is largely driven by the cost reductions in the production of green hydrogen. In the last several years, the cost of green hydrogen has roughly halved and the costs are anticipated to drop by another 60 percent by 2030.\[14\]

The key drivers for these declines are the decreasing costs of renewable energy as well as cost declines for electrolysis infrastructure. The cost of renewable energy has declined by 80 percent since 2010\[15\] to about $20/MWh, making it often cheaper than electricity produced by conventional, carbon-emitting methods. In addition, electrolysis capacity is being added rapidly with approximately 1 GW of announced capacity and the expectation that total electrolysis capacity will increase 55-fold by 2025.\[16\] Further, the imposition of carbon taxes or higher carbon prices, would further improve the competitive position of green hydrogen relative to grey hydrogen.

As a result of these trends, the two key impediments to wide-scale production of hydrogen from electrolysis (i.e., environmental burden and cost) are increasingly being surmounted, leading to strong interest in hydrogen as a key to decarbonizing the broader economy.

4. End Uses for Hydrogen

4.1. A Wide Array of End Uses

Hydrogen has a wide variety of end uses. Broadly, hydrogen can be used either as a fuel (i.e. it is consumed to create electricity or heat) or it can be used as a storage (i.e., it can retain energy for long periods which can be released on demand later on.). From this end usage point of view,
it resembles both natural gas and fuels such as gasoline which also can act both as a fuel or as a store of energy. Unsurprisingly, many of the end-uses of hydrogen are similar to natural gas and gasoline, and it is the displacement of those carbon-based energy carriers that will make hydrogen a key component of decarbonizing the economy.

The key end uses of hydrogen can be categorized as follows:

- A transportation fuel
- A storage mechanism and fuel for the electricity industry
- A fuel for heating commercial and residential buildings
- A high energy fuel for industrial processes
- A feedstock for industrial processes

Currently about 66 percent of hydrogen is consumed by industrial processes where it is used as a feedstock in oil refining, ammonia (for fertilizers) and methanol production (largely for plastics). Hydrogen is also used as a fuel in certain high energy industrial processes such as steel-making and aluminum smelting.

In this paper, the use of hydrogen in industrial processes is not considered in depth. In those applications the choice of hydrogen over the alternatives such as natural gas is a commercial and technical decision with relatively little consideration given to regulatory issues and which has relatively little impact on infrastructure development outside of those specific industrial ecosystems.

4.2. How is Hydrogen Used?

Hydrogen can be used as a fuel in two ways: combustion and via fuel cells.

- **Combustion**: In combustion, hydrogen is burned in a way similar to the burning or combustion of natural gas or fossil fuels. In this process, the hydrogen is burned or combined with oxygen which releases heat and can create motion. The key difference with burning hydrogen versus natural gas is that in case of hydrogen, only water or steam is released instead of carbon dioxide and other greenhouse gases. Several types of combustion engines, including vehicle engines and turbines used for power generation, can handle hydrogen.

- **Fuel Cells**: In fuel cells, hydrogen is combined with oxygen and, as a result, creates an electric current. This process is, in effect the reverse of electrolysis. As with combustion, this process creates energy (in the form of electricity) and water or steam. A diagram of a fuel cell is shown below.
4.3. Hydrogen as a Transportation Fuel

Transportation today emits approximately 20 percent of all global greenhouse gases. To achieve climate goals, transportation will also have to be meaningfully decarbonized. The two key paths to decarbonizing transportation are via battery electric vehicles and fuel cell electric vehicles as long as that electricity or hydrogen is produced from renewable sources.

Battery electric vehicles have, in recent years, gained in popularity as car manufacturers have produced light vehicles that are practical and reasonably economic alternatives to vehicles with internal combustion engines. However, battery energy storage is only feasible for light vehicles due to the very low energy density of battery energy storage systems (less than 1 MJ per kg) compared to gasoline (45 MJ per kg).

For medium duty and heavy duty vehicles, battery electric technology is insufficient due to the relatively short range that vehicles have in these applications. For trucks and buses, the combination of hydrogen fuel with fuel cells is an increasingly viable alternative. The main reason for this is the high energy density of hydrogen which is up to 120 MJ per kg compared to gasoline (45 MJ per kg).

Due to the higher density of hydrogen, fuel cell electric trucks have ranges of up to 750 miles compared to up to 300 miles for equivalent battery electric vehicles. The additional benefit of fuel cell electric trucks compared to battery electric trucks is that the fueling times for hydrogen trucks is 10 to 15 minutes, which is comparable to diesel, and a fraction of the time it takes to charge battery electric trucks.
The key challenge to the deployment of hydrogen-based transportation is the lack of a widespread hydrogen refueling network. Leading manufacturers of fuel cell electric vehicles, such as Nikola Motors and Hyliion are planning to roll out networks of hydrogen fueling stations but this will take several years and may cost between $12bn and $20bn to reach sufficiently wide coverage across the United States alone.\[22\]

4.4. Hydrogen for the Power Industry

Hydrogen can be beneficial to the electric power industry in two ways:

- Long duration storage
- Fuel for combustion in peak plants

In the storage use-case, hydrogen is produced via electrolysis using renewable electricity. That hydrogen is then stored until it is needed. At that moment, it is converted, via a fuel cell into electricity again and discharged onto the electric grid.

*Figure 1. Hydrogen electrical energy storage and dispatch scenario*

*Figure 4. Hydrogen Electrical Energy Storage and Dispatch Scenario.*\[23\]

Increasing renewable energy penetration will both necessitate the need for energy storage as well as create a favorable environment for hydrogen production.

First, due to the intermittency of and fluctuations associated with renewables, energy storage will be needed to act as a buffer that can absorb the volatility created by renewables. Electrolysis, which produces hydrogen, and fuel cells, which produce electricity, can act as storage technology to efficiently and effectively absorb these shorter term fluctuations in ways that are very similar to other battery energy storage technologies such as lithium ion batteries.
However, hydrogen has the additional benefit that it can efficiently act as long duration storage for hours, days or weeks, or even seasonal storage when it is stored in above ground storage tanks or underground salt caverns.

Second, as renewable energy production increases, the cost of renewable, carbon free energy is declining making the production of green hydrogen increasingly economic. As a result of these two trends, hydrogen-based energy storage has the potential to become economic by 2030. [24]

Hydrogen can also be used as a fuel for combustion turbines in both combined cycle and peaking applications. In this use-case, the hydrogen is burned in a gas turbine just like natural gas, with the key difference being that only water vapor is produced rather than carbon dioxide. Recent generations of gas turbines, such as General Electric’s H-class turbines have been designed to operate on hydrogen.

### 4.5. Hydrogen as a Heating Fuel

Hydrogen can also be used as a fuel for heating buildings. While buildings that rely on hydrogen for heating will need to be retrofitted with hydrogen boilers or will need fuel cells to convert the hydrogen into electricity for electric heating, the infrastructure to transport, distribute and handle natural gas can be modified to handle hydrogen.

The key challenges to using hydrogen in the current natural gas infrastructure are:

- **Pipeline integrity:** hydrogen can, in a process known as hydrogen-environment embrittlement, lead to lower fracture toughness, crack propagation resistance, and ductility (as measured by reduction in area) which increases the fatigue crack growth rates for pipeline steels and their welds.

- **Flow rate:** due to the lower energy density by volume of hydrogen compared to natural gas, a greater volume of hydrogen is needed to deliver the same amount of energy to end users. This requires higher pressure and, as a result, adjustments or replacements of equipment such as valves, connectors and meters. [25]

- **Leaking:** Hydrogen is smaller than natural gas and, as a result can permeate seals and plastic pipes leading to three times the leakage of hydrogen compared to natural gas. Because, hydrogen is non-toxic this is not a problem at lower levels but a higher concentration, this can lower the risk of fire or explosion.

There are two potential but both partial solutions. The first is to (re)combine hydrogen with carbon dioxide to produce methane (CH$_4$), in a process call methanation. To the extent that this CO$_2$ is captured from other industrial processes, thereby avoiding, emissions, the process is, at a minimum, environmentally neutral.
A second solution is to blend hydrogen with natural gas. Currently, natural gas in pipelines already contains a certain percentage of hydrogen (up to 10 percent). In quantities of up to 20 percent, most of the existing natural infrastructure can safely handle hydrogen and certain portions of the current natural gas infrastructure can accommodate up to 50 percent hydrogen. By blending hydrogen into natural gas, the environmental footprint of pipeline gas will be mitigated by reducing the amount of carbon dioxide released by end processes that use pipeline gas. However, it will only partially contribute to the reduction of greenhouse gases.

Ultimately, whether hydrogen will be used as a heating and transportation fuel or for power storage and generation, depends first, and in large part, on the ability to overcome the costly hurdle that is hydrogen production. Government initiatives can help overcome such hurdles by, *inter alia*, enacting the appropriate incentive schemes and creating an investor-friendly regulatory framework. Such initiatives can be overarching and direct, such as the European Union’s Hydrogen Strategy mentioned above.

But even in the absence of a concerted top-down hydrogen initiative, Congress has enacted federal income tax incentives relating to hydrogen (such as for example an investment tax credit for stationary commercial fuel cells[26] which can utilize hydrogen, a tax credit for certain refueling infrastructure[27] which contemplates hydrogen as an alternative fuel, a performance-based tax credit for alternative fuel motor vehicles[28] which also contemplated hydrogen as an alternative fuel, a federal credit against the alternative fuel excise for liquefied hydrogen fuel used or sold for use in a vehicle[29], and an investment tax credit applicable to residential hydrogen fuel cells[30]).

Interestingly, a shift is also perceptible in certain sectors where policies are being revisited to account for potential hydrogen-based or hydrogen-related investments, suggesting a stealthy market penetration by this odorless, colorless fuel. One such indirect policy shift is taking place in the US power sector and could help bring about a hydrogen economy by spurring demand for hydrogen energy storage.

**Part II – A Shift Toward the Hydrogen Economy in US Energy Storage Policy**

According to the EIA, 869MW of power capacity—representing 1,236MWh of energy capacity — from large-scale battery storage were in operation in the United States in 2018, up from seven battery storage systems that accounted for 59MW of power capacity a decade ago. More than 90 percent of large-scale battery storage power capacity was provided by lithium-ion batteries.[31]

This growth starts to look staggering given the limited number of existing legislative and regulatory incentives currently in place to promote energy storage investments; there are also growing concerns around the safety, supply chain risk, degradation, and operational flexibility limitations of lithium-ion batteries.

i. Federal Energy Regulatory Commission

At the federal level, energy storage benefited from a landmark ruling by the Federal Energy Regulatory Commission (FERC) in 2018: FERC Order 841 was heralded as not only transformative of the energy storage industry but was also seen as the single most important act in facilitating the energy transition in the United States.[32] FERC Order 841 modifies FERC’s regulations and instructs regional transmission operators and independent system operators (independent entities that have functional control of, but do not own, a significant portion of the transmission system in the United States) to redesign wholesale electricity markets to allow distributed and behind-the-meter energy storage resource to participate in such markets and provide capacity, energy, and ancillary services.

FERC’s view is that opening the markets to all types of energy storage resources will help accelerate the development of innovative technological energy storage solutions, clearing the path for a greener power grid.

On July 10, 2020, the United States Court of Appeals in the District of Columbia denied petitions challenging Federal Energy Regulatory Commission Order 841 (FERC Order 841) on jurisdictional grounds suggesting this policy is likely here to stay.[33]

ii. Investment Tax Credit and IRS Rulings

Energy storage has also benefited from the energy investment tax credit (ITC) under section 48 of the Code in instances where storage facilities are paired with a renewable energy project:

In one private letter ruling,[34] the Internal Revenue Service (IRS) allowed an ITC for a storage facility retroactively added to resolve a transmission issue and allow the producer to shift the time of transmission from off-peak to on-peak hours and give the wind farm more control over the flow of electricity. Importantly, the IRS noted that the addition of storage was necessary for full functionality of the project.

In another instance, the IRS highlighted four storage-related benefits: (i) the ability to store electricity generated by day for use during off-peak hours, with any unused electricity being sold back to the grid, (ii) the ability for producers to decrease the amount of energy they provide to the grid in situations where the amount produced fluctuates rapidly (as is required by most electric grids) and store the excess energy for later use (eliminating waste), (iii) the ability to ensure a more stable flow of electricity to the grid (which is particularly difficult for wind and solar developers), and (iv) the ability for consumers to limit their peak usage.[35] Even though taxpayers are not permitted to rely on private letter rulings (except to the extent addressed to them), the latter could be a preliminary indication of the agency’s view towards storage.
iii. Department of Energy

For its part, the US Department of Energy has launched the Energy Storage Grand Challenge[36], a program to speed up the advancement of energy storage technologies, with the goal of strengthening the domestic manufacturing supply chain and becoming independent of foreign resources for critical materials.

Hydrogen energy storage could fall within the framework of such a policy (which is likely motivated by energy security considerations) as it can be wholly-produced in the United States without the use of raw materials currently controlled by China (51 percent of the global total of chemical lithium, 62 percent of chemical cobalt and 100 percent of spherical graphite — the major components of lithium-ion batteries – are currently controlled by China).[37]

iv. States

Finally, there are several energy storage initiatives at the state level with various goals, including for example, Massachusetts (1,000 MWh by 2025), California (1,325 MW by 2024), Arizona (3,000 MW by 2030), New York (1,500 MW by 2025), and New Jersey (2,000 MW by 2030).[38]

2. Lithium-Ion limitations

The energy storage market is currently dominated by lithium-ion batteries despite the limitations of the technology. However, as alluded to in Part I, lithium-ion batteries have a shorter discharge time and shorter lifetime or lesser number of cycles, making hydrogen storage an attractive alternative.[39]

As a result, or perhaps as part of a broader policy trend, there are now several standalone legislative initiatives either focused on or drafted specifically to include hydrogen energy storage, whereas previously, such initiatives were designed to cater primarily to other aspects of the renewable economy.


i. Federal Tax Incentives

Earlier this year, the US Congress House of Representatives passed the Growing Renewable Energy and Efficiency Now (GREEN Act).[40] which included an extension of the ITC to include energy storage technology. If passed by the US Senate and signed into law, the ITC for energy storage would allow taxpayers to claim a credit of the cost of qualified energy property, through the end of 2024. The ITC would then phase down to 26 percent at the end of 2025 and 22 percent at the end of 2026. Energy storage technology is described as using batteries and other such technology to store energy for conversion to electricity and has a minimum capacity of 5 kWh, or to store energy to heat or cool a structure.[41]
This is a positive development for hydrogen storage as previously, the Energy Storage Tax Incentive and Deployment Act of 2019 which would have extended the ITC to “equipment which receives, stores and delivers energy” (and included hydrogen among the technologies specified) was not included in the 2020 non-defense appropriations package. And in any event, changes in the US administration, especially if buoyed by a change in the control of Congress, are likely to result in increased support for hydrogen applications whether in the context of the GREEN Act or otherwise.

ii. State Level

In addition, several states have recognized that fuel cells can be an integral part of their emissions reduction plans and have directly included them as eligible technologies in their Renewable Portfolio Standards (RPS), whether unconditionally (e.g., Connecticut, Delaware, Indiana, New York, Maine, North Carolina, Ohio) or to the extent they are fueled from renewable sources (e.g., Hawaii, California, Colorado, Massachusetts, New Jersey, New Mexico, New Hampshire).[42]

iii. FERC

Also worth mentioning is an intriguing development in the form of a Notice of Proposed Rulemaking (NOPR) issued by FERC on October 15, 2020. The NOPR proposes to allow Solid Oxide Fuel Cell systems with integrated natural gas reformation to be eligible for qualifying facility (QF) status under the Public Utility Regulatory Policies Act of 1978, as amended (PURPA). QF owners enjoy various benefits including (i) the ability to “put” their energy output to the interconnected utility at the utility’s avoided costs in certain instances, and (ii) the exemption from most FERC regulations as well as certain state regulations.

In the NOPR, FERC explains that the by-product of a fuel cell’s production of electricity is heat and steam, some of which is then used in the steam-methane reformation process to convert more methane into hydrogen, which a fuel cells uses, in combination with oxygen from the air, to produce electricity. FERC also points out that similar to more “traditional” cogeneration QFs, Solid Oxide Fuel Cell systems with integrated natural gas reformation equipment generate two forms of useful energy – electricity, on the one hand, and thermal energy used to produce hydrogen.

FERC thus expressly recognizes the efficiency of fuel cells and emphasizes their ability to convert chemical energy into hydrogen to electric energy without combustion.[43]

The NOPR is an example of the type of niche incentives for hydrogen applications – instead of a perhaps easier one-size-fits-all credit that would incentivize hydrogen development - and may presage additional ones by FERC in the near future, especially in light of recent changes to the US administration.[44]

Conclusion
Hydrogen can play a key role in decarbonizing our economy and contributing to achieving the goal of slowing and eventually reversing man-made global warming. It is versatile; it can be used as a fuel, a form of storage and as a feedstock. It is inexhaustible and, if produced with renewable energy, it does not create greenhouse gases. With the appropriate investments in infrastructure, it is also safe.

Today, hydrogen is being held back by its relatively high cost, but as shown by the major drop in the cost of solar and wind generation technology over the last 10 years, that can change rapidly. As with renewables, the powerful combination of strong governmental support and the resulting investment by private capital will lead to increased production capacity and innovation, which, in turn, would drive down the cost of producing hydrogen by 50 percent by 2030.\[45\]

Regulatory barriers are likely to be relatively modest. Much of the regulatory framework to accommodate battery energy storage, created over the last several years, will be directly applicable to hydrogen-based storage and we are seeing an emerging trend of niche legislative and regulatory incentives for hydrogen applications which, if continued, suggest that hydrogen could potentially even supplant lithium-based storage.

A hydrogen economy was envisioned as far back as 1875 when one of Jules Verne’s characters \[46\] imagined what would happen when the world has exhausted its coal deposits: “I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.” Luckily, it seems the world will not wait for coal to run out before we “shall heat and warm ourselves with water.”

\[1\] Hydrogen Council, 2017

\[2\] Hydrogen Council, *Hydrogen scaling up: A sustainable pathway for the global energy transition*, November 2017

\[3\] There are other, less common methods, such as partial oxidation, thermal decomposition and photolysis, that are not described here.


\[5\] For purposes of this paper, direct water splitting and cracking are not discussed.

\[6\] Average price at Henry Hub as quoted on the NYMEX. Data retrieved from the US Energy Information Administration.

[8] https://chem.libretexts.org/Courses/can/intro/16%3A_Oxidation_and_Reduction/16.7%3A_Electrolysis%3A_Using_Electricity_to_Do_Chemistry


[16] Hydrogen Council, 2020


[22] Hyliion and Nikola investor materials.


[25] 1 High Heating Values per unit of volume are for Methane 40MJ/m3, for Hydrogen 13MJ/m3


[27] Section 30C of the Code.
[28] Section 30B of the Code.

[29] Section 6426 of the Code.


[34] https://bracewell.com/insights/coming-out-dark-energy-storage-and-renewable-tax-credits


[37] https://www.eesi.org/papers/view/energy-storage-2019#4

[38] https://www.eesi.org/papers/view/energy-storage-2019#1

[39] Introduced as part of the Moving Forward Act, H.R. 2.

[40] Section 102(d)(5) of the GREEN Act.


[44] Hydrogen Council, 2020

[45] Jules Verne, L’Ile Mysterieuse, published by Hetzel, 1875, as cited in George A. Olah, Alain Goeppert, G.K. Surya Prakash, Beyond Oil and Gas: The Methanol Economy, published by Wiley-