Power to Gas

Opportunities for Greening the Natural Gas System

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Study commissioned by NW Natural
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Overleaf photo:
Glomfjord, Norway 135 MW electrolyzer plant. 1953-1991. Courtesy Nel Hydrogen.

Executive Summary

Power to gas (PtG) is a means of using electricity and water as primary feedstocks to produce hydrogen or methane fuels capable of reducing the carbon footprint of delivered gas. If the power is sourced from renewable resources such as excess wind or solar energy, the resulting gas is also carbon neutral. This offers the potential to produce carbon neutral fuels when renewable resources are in good supply, leverage existing natural gas infrastructure for long-term and large-scale storage, and to use those fuels in existing power plants to provide carbon neutral power when renewable resources are in short supply.

European policies recognize the vitally important need for long-term storage of renewable energy in the natural gas infrastructure. These policies have fostered dozens of demonstration projects that are increasingly becoming full-scale commercial applications. In the US, PtG is not generally recognized as energy storage at all, and is sometimes specifically excluded in electric system storage mandates. Not only are unsupportive policies an impediment to PtG storage applications, competing electric energy storage media—such as batteries and pumped hydro storage—are prohibitively expensive for long-term bulk energy storage, and are hundreds of times more expensive than PtG storage in these applications.

The technology for disassociating water into hydrogen and oxygen with electricity was discovered more than two hundred years ago, with utility scale electrolyzers in operation since at least as far back as 1953 (see cover photo). Despite the long history of the technology, it continues to develop due to renewed interest spurred by the rise in renewable resources that can create vast surpluses of electricity that need to be stored in large quantities over long periods of time.

The commercially-produced hydrogen available today is primarily derived from natural gas and is not carbon neutral. Hydrogen produced by PtG technologies is not cost competitive with fossil-derived hydrogen or natural gas based on the energy value alone. The relatively high cost of natural gas in Europe, along with firm commitments to meeting carbon emission reduction goals, contributes to the greater level of interest in PtG there, while progress in the US has lagged significantly. Despite its higher cost in the US, PtG gas brings a host of other values that may make up for the cost difference and continued reductions in the cost of PtG technology will help make it increasingly more cost competitive.

Hydrogen can be used directly in place of natural gas in many applications. Quantities of hydrogen can be mixed directly with natural gas in pipeline systems. There are important differences between hydrogen and natural gas that limit the fractional amount of hydrogen that can be injected into gas pipelines without requiring other changes (e.g., end user burner modifications). Through methanation, hydrogen combines with carbon dioxide to make methane, the primary constituent of natural gas. The resulting methane is freely interchangeable with natural gas. The Audi Car Company has been producing carbon neutral methane in a 6 MW plant in Germany since 2013 to fuel its compressed natural gas vehicles from a carbon neutral source.

While the importance of PtG to the success of renewable energy is broadly recognized and encouraged in Europe, the general lack of recognition among policy makers, renewable advocates, and regulators in the US remains a serious impediment. There are some incentives for creating low carbon transportation fuels, but few other incentives. While the energy value of the produced gas is its primary value proposition, there are other valuable aspects of PtG that include strengthening the floor for wholesale electric market prices; providing fully dispatchable load capable of supplying grid balancing services ("ancillary services") to power grids, offering long-term storage of renewable energy; and reducing the carbon footprint of the nation's energy systems. An important challenge for PtG is gaining the policy support necessary to enable the monetization of these important aspects of the technology.

Development of PtG in North America can benefit from the rapid rise of PtG in Europe, where economies of scale and investments in research and development are causing improvements and cost reductions in the technology.

Producing carbon neutral fuels from PtG can result in multiple benefits for the gas system, the electric power system, and the environment. Among the potential benefits are:

1. Providing a viable approach to reaching carbon emission reduction goals.
2. Leveraging existing natural gas infrastructure for providing seasonal storage and distribution of renewable energy.
3. Reducing exposure to fuel price risk from volatile fossil-derived natural gas prices that may become subject to future carbon taxes or caps.
4. Expanding the market and reach of renewable power sources beyond the electric power grid to reduce carbon emissions from other energy sectors.
5. Potentially increasing disaster resilience by providing fuels from locally sourced renewable generation, without relying on interstate pipelines or roads.
6. Providing an economically feasible technology for bulk storage of renewable energy on a seasonal basis.
7. Adding flexible load to help manage both the variability and occasional large surpluses of renewable generation that occur on the electric power system, potentially putting otherwise unusable power to good use.

It is likely that PtG has a bright future in achieving these benefits. A combination of policies and historically low natural gas prices are inhibiting its development in the US today, but as the pressure to reduce carbon emissions increases, and the cost of the technology improves with scale, there will be increasing opportunities for cost-effective PtG applications in the US.

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Acknowledgments

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Power to Gas

Opportunities for Greening the Natural Gas System

by Ken Dragoon, Flink Energy Consulting

"Power-to-gas" (PtG) is the creation of gaseous fuels from electric power. It is likely to be an indispensible component of low-carbon power systems and is available commercially at an industrial scale. As the cost of electric power from renewable resources drops, the prospect of using such carbon-neutral energy to create carbon-neutral fuels capable of displacing today's dependence on fossil fuels is a tantalizing prospect for eliminating greenhouse gas emissions. This paper summarizes principal aspects of the state of this technology and its importance in reducing greenhouse gas emissions, with a focus on incorporating carbon-neutral gas into the existing natural gas grid.

The natural gas system supplies nearly 30% of all primary energy consumed in the US for heating, manufacturing, transportation, and increasingly to fuel electric power generation in a symbiotic relationship with renewable energy to meet electrical demand. Modern natural gas power plants are far more capable of adjusting to the sometimes rapid changes in output from renewable resources than many other conventional resources. Natural gas and renewable resources combined to significantly reduce carbon emissions associated with generating electric power, a trend that is expected to continue.

According to the Environmental Protection Agency (EPA), greenhouse gas emissions per unit of energy delivered from the electric power industry dropped 16% between 1990 and 2015, due to increased renewable and natural-gas-fueled generation replacing coal power. Electric power derived from natural gas resources increased from 11% of total generation to 32% in that period, and electricity from wind and solar increased from 0.1% to 5%[1].

Progress toward reducing greenhouse gas emissions is expected to continue. Although commitments to carbon emission targets at the federal level have faltered somewhat, commitments from states, local governments, and US industry are accelerating. Examples of the progress include:

- California's 2017 legislature debated setting 100% renewable sourced electric power by 2045.
- The City of Portland and Multnomah County have adopted a 100% renewable target for all city energy uses by 2050.
- Apple Computer contracted for 100% renewable energy to power its Prineville, Oregon server farm.

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1 *Inventory of Greenhouse Gas Emissions 1990-2015*, Environmental Protection Agency, 2017, page 3-16.

- The State of Oregon established the Oregon Global Warming Commission and is actively considering legislation to cap greenhouse gas emissions.

There is no reason to believe these efforts will abate, and it is no coincidence that NW Natural has adopted its own Low Carbon Pathway to reduce carbon emissions from its natural gas system 30% by 2035. Providing gas to customers with products derived from low-carbon PtG technologies could have an important role to play in meeting NW Natural's emission reduction goals in 2035 and beyond.

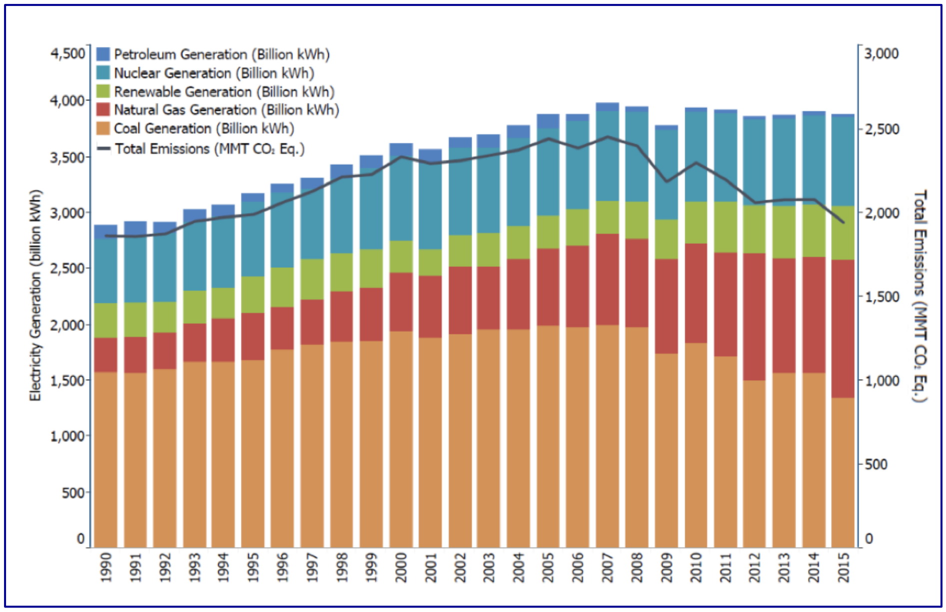

Figure 1 Carbon emissions from electricity production declining from their peak in 2007 despite relatively constant production levels. Source: EPA Inventory of US Greenhouse Gas Emissions and Sinks, Figure ES-8.

Hydrogen: the PtG Foundation

Hydrogen is the most abundant element in the universe, and along with oxygen, constitutes water. In its pure gaseous form, hydrogen burns readily in air, but unlike natural gas, its main combustion product is water rather than carbon dioxide. If by some quirk of natural history the primary constituent of natural gas produced from the ground were hydrogen, using natural gas in place of petroleum and coal would virtually eliminate carbon dioxide emissions in the energy sector.

The primary constituent of natural gas is methane, but this was not always true of the gas delivered to homes and businesses. Prior to the advent of natural gas, many cities relied on "manufactured gas" that contained a mixture of 30-50% hydrogen[2]. Even today, Hawaii's Oahu gas grid contains a significant percentage of hydrogen. In June 2017, Nel Hydrogen and H2V signed a framework agreement to provide up to 700 MW of hydrogen electrolysis

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2 *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, Melaina, Antonia, Penev, NREL 2013.

facilities to inject hydrogen directly into the French natural gas grid[3]. Hydrogen has an established history and promising future as a substitute for natural gas, and the production of hydrogen from renewable power sources is the basis for PtG pathways to reducing carbon emissions.

Producing hydrogen from electric power and water is the first step in any PtG application. The produced hydrogen can be used directly, in place of natural gas, or as a feedstock for producing other fuels such as methane—the primary constituent of natural gas.

Producing Hydrogen Through Water Electrolysis

Hydrogen can be produced by breaking water into its constituent parts through a process called electrolysis. Splitting water into hydrogen and oxygen with electricity was discovered a few weeks after the discovery of the battery more than 200 years ago. The advent of low-cost electricity from solar and wind raises the possibility of creating hydrogen from low-carbon resources. Today, commercially available hydrogen is primarily derived from processing natural gas and has a significant carbon footprint. Realizing the carbon benefit of substituting hydrogen for natural gas necessitates a low-carbon source of "green" hydrogen.

At its simplest, electrolysis is accomplished by introducing an electric current through water. As the current flows, water splits into hydrogen that forms around one of the electrodes, and oxygen that appears around the other. The process results in three important products: hydrogen, oxygen, and heat. Making use of all three products may be key to realizing the greatest value from electrolysis applications.

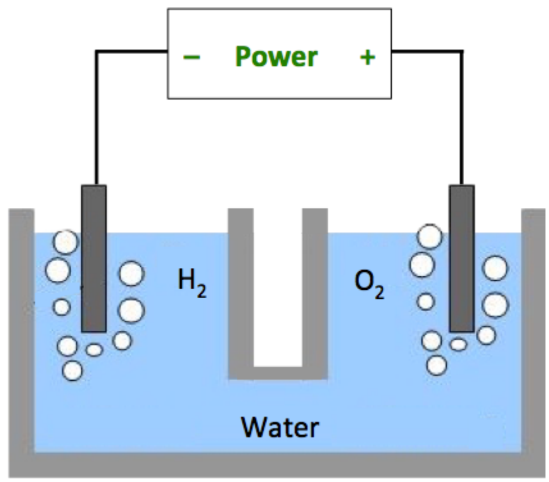

Figure 2: Basic electrolysis consists of passing direct current through water.

Modern electrolysis has come a long way, and continues to improve in both efficiency and cost. There are three categories of electrolyzers today, each with its own characteristics and potentials: Alkaline, Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis (SOE).

Alkaline Electrolysis

Alkaline electrolysis is the oldest of the three electrolysis technologies, and the closest to the simple configuration depicted in Figure 2. Alkaline electrolyzers are the least expensive, most time-tested, and currently more efficient than the other commercial electrolysis technologies. Alkaline electrolyzers introduce an alkaline chemical catalyst, usually caustic

[3] Personal conversation with Nel Hydrogen CEO Jon André Løkken. See also: *Ny Nel-kontrakt kan være starten på fransk milliardeventyr*, E24.no, June 13, 2017.

potassium hydroxide[4], into the water to improve the efficiency of the process.

While technology maturity, commercial scale, cost, and efficiency are important advantages to the technology, alkaline electrolysis has certain limitations compared with the newer PEM technology, including:

- longer startup times (>10 minutes)[5],
- sensitivity to rapid changes in input power levels,
- lower power densities that lead to relatively larger space requirements,
- produced gas at relatively low (1-15 bar) pressure[6].

Fast startup and ability to ramp quickly are positive attributes for units responding to potentially variable power from renewable resources. Most hydrogen applications require compressed gas, necessitating a compression stage that reduces efficiency and can involve additional maintenance costs.

Most of the large scale applications of electrolysis today are of the alkaline electrolyzer type. The cover photo on this report is of a 135 MW alkaline electrolyzer in Norway that was in service from 1953 to 1991. Its purpose was to use excess hydro power to produce hydrogen that was used in the production of ammonia-based fertilizer.

Proton Exchange Membrane (PEM) Electrolysis

Another technology that is gaining in importance is PEM electrolysis, based on special polymer materials that can pass protons. The membrane separates the produced oxygen and hydrogen, allowing higher pressures to develop without dangerous mixing of hydrogen and oxygen within the cell. Importantly, this technology is virtually identical to PEM fuel cells that produce electricity from hydrogen and oxygen—the basic process shown in Figure 3 is virtually reversible. Fuel cells are the power source for most hydrogen fueled vehicles, and the association with fuel cells makes PEM a target of research and development efforts.

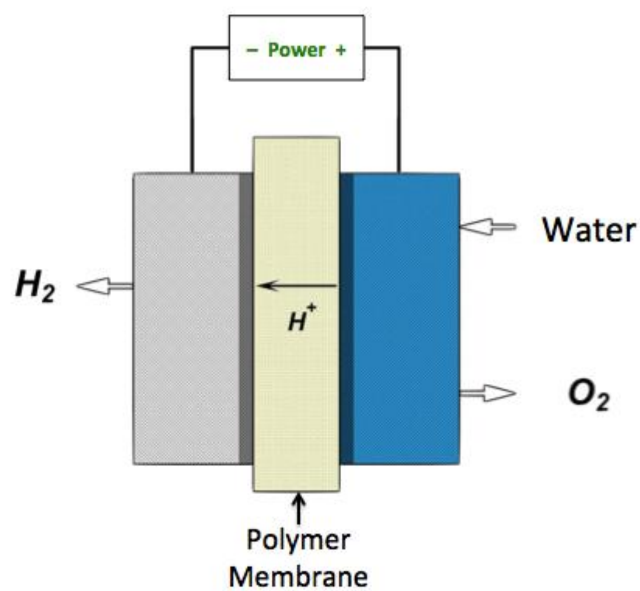

Figure 3: Basic PEM electrolysis cell. The membrane separation allows higher pressures to be developed within the cell without mixing hydrogen and oxygen within the cell.

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[4] Oregon startup company Hydrostar claims a proprietary nontoxic catalyst in their electrolysis technology.

[5] At least one manufacturer contends that fast start alkaline units are possible if established as a design criterion.

[6] Compressors can increase the pressure of the produced gas, and research is ongoing to develop alkaline electrolyzers that can produce higher pressure gas.

PEM technology has been commercialized in recent years and has several advantages over alkaline electrolyzers:

- higher power densities that have lower space requirements,
- relatively rapid startup times (<10 minutes),
- rapid response capability (sub-minute) to changes in input power levels,
- higher pressure (~30 bar) hydrogen production capability,
- potential for further development to reach higher efficiencies.

PEM electrolyzers are becoming more common, principally due to their smaller size and ability to rapidly respond to changes in output level. For example, ITM Power supplied the 500 kW electrolyzer to absorb wind and tidal generation from Eday Island resources in the Orkney Islands. The gas is compressed and transported by truck and ferry to Kirkwall, where a fuel cell converts the hydrogen back to electricity. It was the largest commercial scale PEM electrolyzer built at the time it was ordered. The manufacturer has since taken orders for 3 and 10 MW electrolyzers, and has announced plans for designing 100 MW scale devices[7].

Solid Oxide Electrolysis (SOE)

Still in the research and development phase, solid oxide electrolysis (SOE) may play a vital role in a low carbon energy economy. Both Alkaline and PEM electrolysis obtains the energy needed to split water molecules from electric power. SOE relies on a combination of electric energy and heat. There are important advantages to heat as the primary energy source because heat is generally less expensive to create and store than electric power. We already see super-surpluses of electric power from solar and wind that tend to be difficult to utilize and expensive to store. If that energy could be stored temporarily as heat, to be used at a more constant rate to create hydrogen, it could be a very inexpensive way to store and make use of renewable energy that might otherwise simply be curtailed.

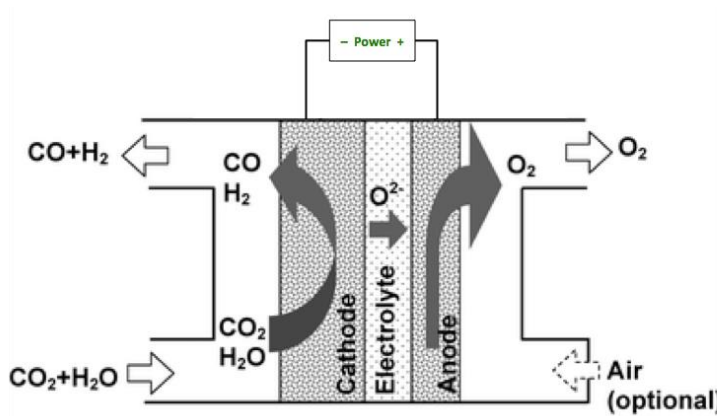

Figure 4: Solid Oxide Electrolysis. Water, potentially mixed with carbon monoxide, is introduced as high temperature (700-1,000 C) steam.

Another potential advantage of SOE is the ability to produce either hydrogen gas or a mixture of hydrogen and carbon monoxide with the addition of a carbon dioxide feedstock. The mixed gas can, in turn, be used to synthesize methane or other hydrocarbon transportation fuels. There is much optimism that SOE will proceed to commercialization in the next dozen years or so.

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[7] *100 MW Electrolyzer Plant Designs to be Launched at Hannover*, ITM-Power, 12 December, 2016.

Renewable Resources and PtG

Fully relying on solar and wind electric power to reduce carbon emissions has some significant challenges due to the variable nature of those resources. Two of the most prominent challenges are how to meet electrical demand when wind and sun are not available in sufficient quantities, and how to make economic use of the super-surpluses of power when sun and wind can supply far more power than the concurrent demand. Boom and bust cycles of renewable resource production are inevitable and must be addressed if they are to be the primary means of eliminating carbon emissions. PtG presents perhaps the only economic solution.

Power plants are often assigned a type of figure of merit called "capacity factor," which is the ratio of average output of an electric power plant (typically over a year) divided by its maximum output capability. A power plant that runs all the time at maximum output would have a capacity factor of 100%. Plants used solely to meet system peak demands may have a capacity factor of just 5-15%. Wind projects typically have capacity factors in the 25-45% range, and photovoltaic solar projects in the 15-30% range.

The capacity factor of wind and solar becomes important to systems meeting all their power requirements with such resources. Meeting the average demand necessitates 3-5 times as many megawatts of installed renewable capacity. For example, meeting a 100 MW average demand with a 20% capacity factor solar resource would require at least 500 MW of installed solar power. The peak demand of the 100 MW average load might normally be around 160 MW. As a result, there will inevitably be times when the resource is not generating enough to meet load, and other times when the production will be several times the actual demand. Systems meeting most or all their power demand with wind and solar need some means of storing the excesses and using at least some portion of them to meet the shortfalls.

To some extent, these boom and bust cycles already exist in systems with significant fractions of wind and solar power supplies. When solar and wind fall off, other resources such as hydro- and gas-fueled power plants are called on to increase their output. Under maximum renewable resource output, other resources are minimized to make best use of the available resource, and this may require exporting power to other regions. Once markets are saturated, wind and solar resources may be curtailed (i.e. turned off).

Curtailments are already occurring in significant quantities in the Northwest on the Bonneville Power Administration transmission system and in California. Curtailments typically occur in the spring when hydro, wind, and solar output can be high, and while demand for power is moderate—especially at mid-day with California solar resources, and at night in the Northwest with wind and hydro output. Such events, and lesser ones that drive wholesale power prices to very low levels (e.g. below the cost of natural gas on an energy basis), provides a potential low-cost fuel source for PtG projects. In turn, developing PtG electrical demand can play an important role in reducing the frequency and intensity of such events, effectively bolstering a floor on wholesale electrical prices, while putting the otherwise-curtailed energy to productive use.

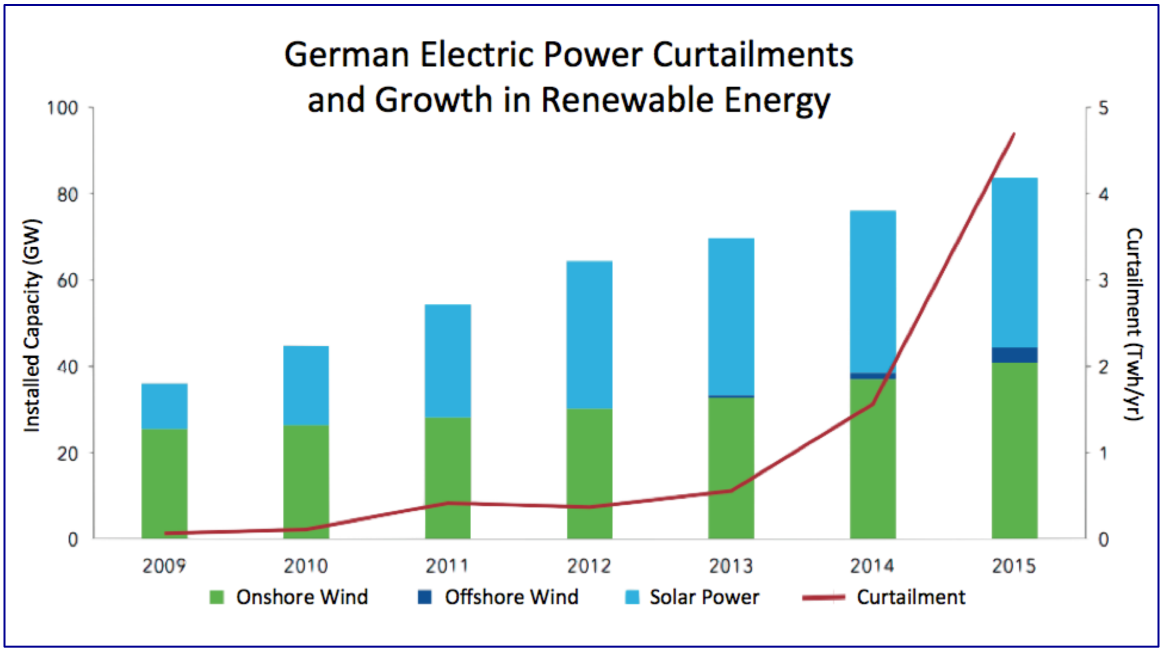

Figure 5: Energy curtailments in Germany. Adapted from: *Power-to-Gas in a Decarbonized European Energy System Based on Renewable Resources*, DNV GL for European Power to Gas, .

In 2017, California renewable curtailments will total about 350,000 MWh[8], representing roughly $10 million[9] of wholesale energy. The Bonneville Power Administration reported just under 140,000 MWh[10] of resource curtailments in 2017. All things being equal, these numbers can be expected to increase as the percentage of power coming from wind and solar increase. Figure 5 shows very rapid the rise of unusable energy with renewable resource development in Germany.

Making power grids work with large fractions of wind and solar will require some means of storing these “super-supplies” of power, and potentially returning that power back to the grid at other times when renewables are less available. Although this need to combine energy storage with renewable resources is widely recognized, the importance of PtG in that role is far less well-known.

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8 Per the October 22, 2017 California ISO Wind and Solar Curtailment Report, year-to-date curtailments were 346,520 MWh.

9 This is based on assuming an average wholesale electric power price near $30/MWh. The literal value of this energy at the time it was generated was zero or less.

10 Source: Bonneville Power Administration website, Oversupply Management Protocol Retrospective Reports, 2017.

Power System Energy Storage and PtG

Unlike other fuels, electric power is produced and consumed at virtually the same moment. If there is a large enough mismatch between supply and demand[11], the power grid can become unstable and cause widespread outages. Power system operators typically accommodate this difficult situation through vigilant monitoring and adjusting of power output levels to match demand within tolerable levels. The introduction of variable and less controllable wind and solar contributes to this difficult balancing act.

Regulators, utilities, and power system operators are responding to the increased difficulty brought by wind and solar by looking for more flexible resources—such as power plants, loads, and storage facilities that can be controlled and rapidly respond to changing power balance conditions. Several states have mandated minimum electric energy storage requirements, including California, Massachusetts, New York, and Oregon. These requirements have largely been met, or are proposed to be met, by advanced battery technologies or pumped hydro energy storage.

Pointedly not considered is the ability to use surplus electricity to produce power plant fuels—such as hydrogen, methane, and ammonia—that can be used to recover power at a later date. In other words, PtG is an important electric energy storage option that is largely left out of the conversation. For example, the Northwest Power and Conservation Council's November, 2017 "White Paper on the Value of Energy Storage to the Future Power System" contains a compendium of energy storage technologies that does not include PtG energy storage.

Another example is the Oregon Public Utilities Commission Order 17-118 in docket UM 1751, which identifies qualifying energy storage technologies as those consistent with Sandia Laboratories' *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA* (2015)[12]. That document contains the following language (p. xxv):

> "The Handbook includes discussion of stationary energy storage systems that use batteries, flywheels, compressed air energy storage (CAES), and pumped hydropower and <u>excludes thermal, hydrogen, and other forms of energy storage that could also support the grid</u>…" [emphasis added]

While, in Europe, PtG is considered a vital step toward meeting renewable energy and carbon emission reduction goals, it is not commonly accepted as an energy storage technology in the US. This suggests a greater advocacy role for PtG manufacturers and other interested stakeholders in forming energy storage policy.

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11 This discussion distinguishes between consumption and demand. Consumption is taken to be the rate at which power is consumed by a load, while demand is the amount that would be consumed if power were delivered under rated conditions of voltage, frequency, power factor, etc. Deviations in these standard conditions are evidence that supply and demand are mismatched, though consumption will match supply irrespective of the conditions.

12 There is an ambiguity in the Commission order as to which version (2016 or 2015) of the handbook it was referring. The 2016 language is somewhat broader, but affirms that hydrogen remained excluded from coverage within the text.

Why it Matters

According to the Northwest Power and Conservation Council, the region receives about 13,000 average megawatts power from fossil resources. It would take about 40,000 MW of wind generation to supplant that generation. As discussed above, when the wind comes up, the region would be hard pressed to find a place to put all that wind generation, and without additional system loads much of it would be curtailed. Another issue is how to generate the 13,000 MW over a period of several weeks when the wind could be missing altogether. The two most commonly heard answers are batteries and pumped hydro storage.

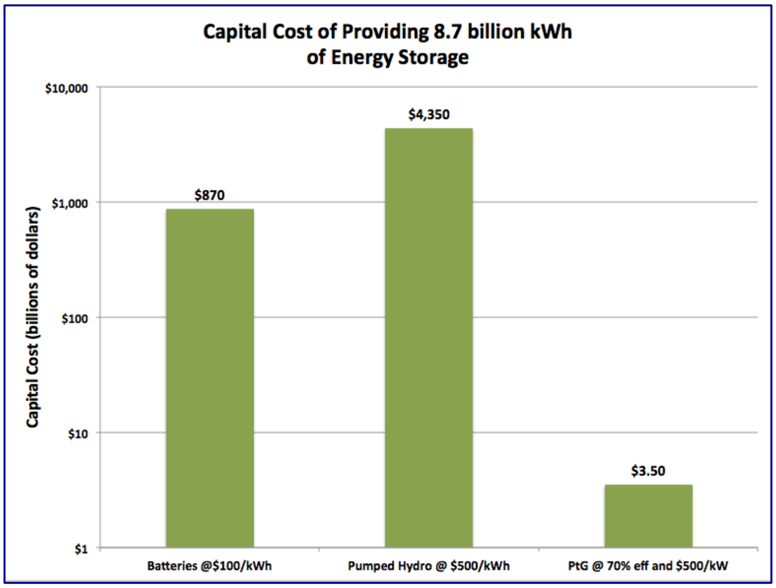

Figure 6: Capital cost comparison of energy storage technologies with PtG. Note that a logarithmic scale was used to make the PtG cost visible on the chart.

Batteries

There are a number of battery technologies available today, and improvements in cost and performance are continuing at a rapid pace. However, the cost of battery storage is largely proportional to the quantity of energy stored. If the Northwest need is 13,000 MW for a period of four weeks, the amount of energy storage required would be 8.7 billion kWh[13]. A design goal for lowering battery costs is currently around $100 per kilowatt-hour (kWh) of energy storage by 2020[14]. Assuming that goal is achieved, meeting the energy storage requirements would cost $870 billion. For comparison, this figure is roughly fifty times the current capital investment in wind and solar resources in the region.

Pumped Hydro Storage

Energy can be stored by using electric pumps to move water from a lower source to a higher elevation, and later allow the water to fall back through hydro generators to recover the electric energy. Such storage facilities are called pumped hydro storage and have long been used primarily to meet peak electric demand needs. The amount of energy that can be stored depends on the physical availability of the upper and lower bodies of water, and the

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13 This is 13,000 MWH X 1,000 kWh/MWh X 4 weeks X 168 hours/week = 8.736 billion kWh.

14 This figure is illustrative only, and generally taken to be the cost of batteries absent balance of plant and interconnection costs. However, some analysts are optimistic that the cost of batteries alone could reach $80/kWh by 2030 or earlier, so $100/kWh is used as generally indicative of plant costs as battery technology improves.

elevation difference between them. Costs can be very location specific, but the *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA* (2015) examined the costs of four hypothetical pumped storage units[15]. In terms of cost per kWh of storage, they ranged from about $500/kWh to just over $700/kWh, which is five or more times the battery costs derived above.

PtG Electric Grid Energy Storage

An alternative to storing electric energy in batteries or pumped hydro would be to use electrolyzers to produce carbon neutral fuels that can be used directly by natural gas customers or can be burned in existing electric power plants. Assuming that the power plants are on average 35% efficient in converting fuels to electric energy, and that electrolyzers are about 70% efficient in converting electric energy to gas, producing would require 35 billion kWh of electric power input. If that gas were produced over a seven month period, it would require about 7,000 MW of electrolyzer capability. Commercial utility scale electrolyzers cost about $500/kW of capability[16], resulting in a total capital cost of $3.5 billion—less than one percent of the cost of battery storage. Economies of scale would likely reduce that figure significantly if this scale development were actually pursued.

There are no currently conceived improvements in other storage technologies that can compete with PtG for addressing the renewable energy integration challenge at the highest levels of renewable deployment. In addition to providing the needed non-fossil back up for renewable generation, PtG offers power systems a potentially fully flexible and controllable load for system balancing, and an additional demand for power that is increasingly in excess supply. It offers the potential for not only increasing the usability of renewable energy, but also producing fuels for reducing carbon emissions in other energy sectors. PtG is likely an inescapable component of a truly low-carbon energy future.

PtG Pathways

Hydrogen can be biologically or chemically combined with carbon dioxide to form methane. Methane has potential advantages over hydrogen as a fuel. Foremost is that natural gas is principally composed of methane and can be used freely in place of natural gas for consumption, storage, and transportation. If the carbon dioxide is taken from the atmosphere, the process remains carbon neutral. In addition to methane and other carbon

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15 Values derived from Figure 25, p. 37, by multiplying project capacities by the graphed costs per kW and dividing by the energy storage capability (megawatts of capacity times hours of storage).

16 Various electrolyzer costs are quoted, depending on electrolyzer type, delivery pressure, and assumptions about economies of scale. Typical values fall in the $500-$1,000/kW range, for megawatt-scale 70% efficient machines. See for example *Power-to-Gas: The Case for Hydrogen White Paper*, California Hydrogen Business Council, October 8, 2015. Nel Hydrogen recently announced a 100 MW electrolyzer proposal for 450 million Norwegian Kroner, or $550/kW.

fuels, hydrogen can be chemically combined with nitrogen (predominant component of air) to form ammonia that can be used either as a fuel or for fertilizer, as was the purpose of the 135 MW Glomfjord electrolyzer in Norway pictured on the title page of this report.

As a result there are multiple pathways for PtG applications, depending upon whether hydrogen or some other substance is the ultimate product, whether the process involves purely chemical or biological processes, and what the processed substance is used for. Producing carbon neutral fuels for supplementing the electric grid is not necessarily the highest and best use of PtG potentialities, especially in the near-term. Therefore, it is worth considering some of the many PtG pathways, as illustrated in Figure 7.

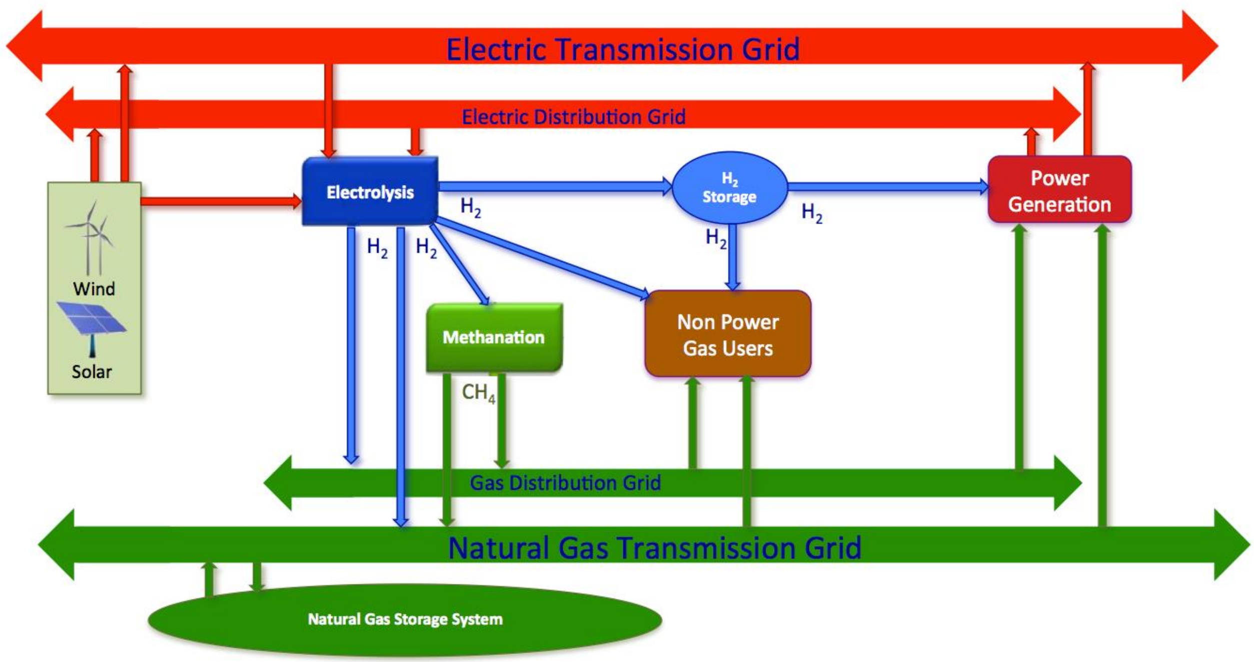

Figure 7: Representation of the many PtG pathways resulting in a variety of potential applications.

Electrolysis

Beginning with the electrolysis process, there are three general decisions to make:

- selection of electrolyzer technology type,
- source of electric power,
- disposition of the produced hydrogen (and potentially heat and oxygen byproducts).

Each of these decisions entails multiple options that are considered in greater detail below.

Electrolyzer Technology Options

As previously discussed, there are three general electrolyzer technologies, two of which are commercially available today: Alkaline and PEM. In general, megawatt-scale applications will tend toward alkaline electrolyzers that are commercially available on that scale. Applications in which fast reaction is a priority, or physical space is limiting, tend toward PEM devices. There may be cases to be made for combinations of PEM and alkaline in applications where some variability is expected. Another potential would be to pair alkaline technology with smaller scale battery storage to absorb fast fluctuations.

Electric Power Source

Electric power can be acquired through wholesale arrangements over the high voltage transmission grid, directly from utilities over the lower voltage electric distribution grid at the retail level, or directly from an on-site power source. Each of these has its own benefits and challenges.

Wholesale Market

Negative market prices driven by super-supplies of renewable energy are only accessed through the wholesale electric markets. If a PtG facility is owned or operated by an electric utility, it could receive the benefit of access to those prices; however, accessing wholesale market prices is possible for non-utility entities. In Oregon, participation of loads in the wholesale markets is provided through Direct Access legislation. The Oregon Public Utility Commission certifies energy service suppliers[17] that utilities work with for providing non-retail power service. An advantage of working with active wholesale market participants is the possibility for electrolyzers to provide other power grid services, such as rapid response and system balancing. These are potentially beneficial value streams that are typically unavailable to retail electric utility customers and may not be available through all energy service suppliers.

Retail Market

Large consumers of electric power can sometimes negotiate special deals with utilities for non-standard service. It may be possible to arrange directly with a utility for a discounted energy rate in exchange for providing flexible and interruptible load. Standard rates, even relying solely on off-peak discounted power, are likely prohibitively expensive. As renewable resources increase in importance, it is becoming more clear that utilities need to reflect unusually low wholesale prices at the retail level to promote using energy that might otherwise be curtailed as unusable. At this time, there are no state mandates for requiring tariffs that would accomplish this important function.

On-Site Generation

Co-locating electrolyzers and renewable resources has some potential advantages. Electrically connecting a renewable power source to an electrolyzer load avoids significant costs normally faced by renewable projects. These potentially include substations, high voltage transformers, purchasing transmission rights, transmission and distribution system interconnections studies, and potential capital improvements that might be required by those systems. Renewable resources are increasingly finding little ability to purchase firm transmission rights (typically required by utilities purchasing renewable energy) at any price. Demonstrating the ability of electrolyzer plants to foster new renewable resource

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[17] A list of Oregon State certified energy service suppliers is available on the Oregon Public Utility Commission website. As of this writing, the list includes 3Phases Renewables, Avangrid Renewables, Calpine Energy Solutions, Constellation NewEnergy, EDF Energy Services, and Shell Energy North America.

development without acquiring additional electric transmission rights could open the floodgates to new renewable development that would not otherwise occur.

Disposition of Produced Hydrogen

There are a myriad of potential hydrogen markets, including residential and commercial space and water heating, transportation, and manufacturing. Produced hydrogen can be intermixed with the natural gas system as pure hydrogen, or converted to methane which is completely interchangeable with natural gas. After its manufacture in the electrolyzer, the produced hydrogen has five potential dispositions:

1. The high pressure natural gas transmission pipeline system;
2. lower pressure distribution pipeline system;
3. on-site storage for later transportation or consumption;
4. further processing into methane;
5. direct delivery to consumptive uses.

Each of these is discussed in more detail below.

High Pressure Pipeline Injection

Hydrogen can be injected directly into high or low pressure natural gas pipeline infrastructure. Permissible, or technically acceptable, concentration levels depend on the system into which it is introduced. Volumes of gas in the high pressure system are great enough to be able to accept relatively high levels of production while maintaining acceptably low overall concentrations of hydrogen. This comes at the cost of higher energy and capital requirements to pressurize gas to the higher levels. The maximum acceptable concentration of hydrogen blended into the nation's natural gas system—without causing issues relating to safety, leakage, or consumption of the fuel—is reportedly in the range of 5-15%[18].

Lower Pressure Distribution Pipeline Injection

Injecting hydrogen directly into the lower pressure distribution pipeline system is less costly and more efficient than high pressure injection, but the lower volumes involved limit the scale of the injections without introducing high concentrations of hydrogen in the system. Most natural gas systems can accept concentrations of hydrogen up to a few percent without significantly affecting the transportation or use of the product. Levels as high as 20-25% may be acceptable in some systems. If NW Natural matched 10% of its annual sales with PtG hydrogen, it would represent over 500 MW of electrolyzer load, consuming the equivalent of

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[18] At "…less than 5%–15% hydrogen by volume, this strategy of storing and delivering renewable energy to markets appears to be viable without significantly increasing risks associated with utilization of the gas blend in end-use devices (such as household appliances), overall public safety, or the durability and integrity of the existing natural gas pipeline network." *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, M. W. Melaina, O. Antonia, and M. Penev, National Renewable Energy Laboratory March 2013.

about half the output of Oregon's current wind fleet[19].

Confining the injections to an isolated part of the gas grid may allow up to 100% hydrogen, depending on the customers on that segment of the system; however, it may require some engineering adjustments to gas-consuming equipment.

Hydrogen Storage

There are some applications in which hydrogen is produced and stored on-site for later transportation. Although hydrogen can be stored as a compressed gas or cryogenic liquid, compressed gas is the more common approach. Storage can be a desirable option in applications remote from natural gas systems or where the hydrogen is produced for its own special characteristics. The latter usually involves providing hydrogen to fuel cells.

Fuel cells convert hydrogen and oxygen (from the air normally) into electric power. Although fuel cells are more expensive than combustion engines for producing electric power, they are far more efficient. Often the most valuable use of hydrogen is in fuel cell hydrogen vehicles that are increasingly appearing at commercial levels in the US and abroad. Although battery electric vehicles appear to be outstripping fuel cell hydrogen vehicles, there is likely a long-term space for hydrogen vehicles on longer range, continuous operation transportation such as buses, trains, and ships.

The cost of compression and physical storage facilities must be taken into consideration. A 2005 analysis found a wide range of compressed hydrogen storage costs. The values shown in Figure 8 translate to a range of about \$6.3/kWh to \$71/kWh[20] (\$185-\$2,100 per therm) of storage capacity.

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19 Based on assuming NW Natural 2016 Annual Report sales of just over one billion therms, 70% efficiency electrolyzer technology, and Oregon wind fleet of about 3,000 MW. At today's electrolyzer costs, this represents a capital investment of between \$250 and \$500 million.

20 Expressed in the same year currency used in the original study, assuming \$1.18 per euro, and 33.3 kWh/kg hydrogen density (lower heating value).

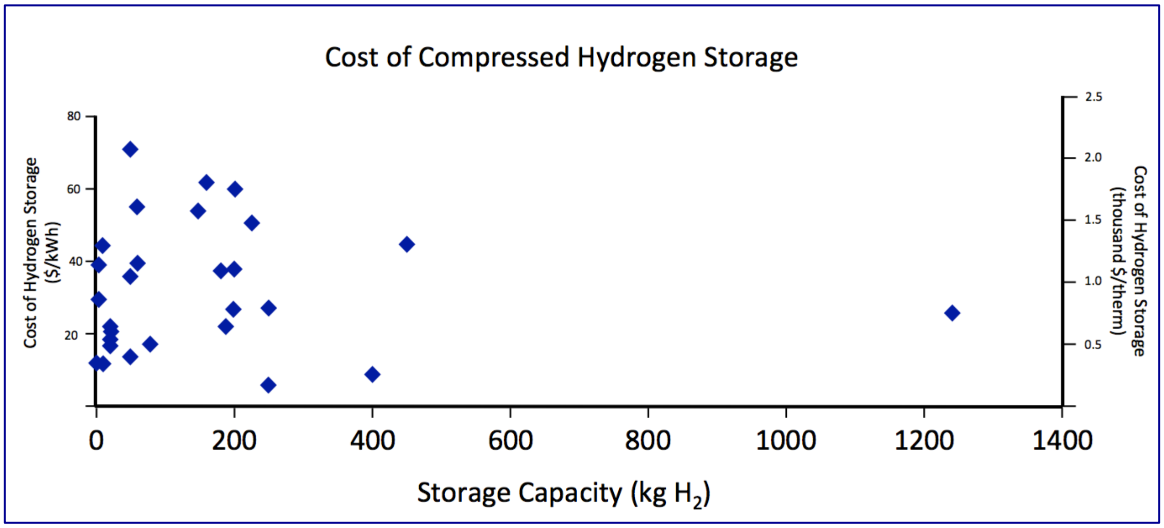

Figure 8: Capital costs quoted for compressed hydrogen storage facilities, based on a 2005 analysis. Energy units are based on lower heating value of hydrogen. Adapted from *Systems Analyses Power to Gas: Deliverable 1*, DNV KEMA, June 20 2013, Figure 23, p. 69.

Methanation

Converting hydrogen to methane makes it completely interchangeable with natural gas. Although methane releases carbon dioxide to the atmosphere when it is burned, if the source of carbon for the methanation process is scavenged from the atmosphere, the process remains carbon neutral. A source of carbon is an integral component of methanation. It can come from bio-digesters or be taken as carbon dioxide directly from biomass stack emissions. An experimental joint National Renewable Energy Laboratory (NREL), SoCalGas facility combines hydrogen with micro-organisms in a bio-reactor to produce methane[21]. The needed carbon dioxide can potentially be scavenged directly from the atmosphere itself[22].

The benefit of having a completely interchangeable form of gas comes at the expense of an additional process step with its own capital and energy costs. Nevertheless, the chemical process for combining hydrogen and carbon dioxide to form methane is known as the Sabatier process, and was developed more than a century ago. That technology is well developed and widely available, and could be employed to convert excess renewable energy to a fuel that could potentially make today's natural gas system entirely carbon neutral[23].

Direct Delivery

On-site production and consumption of hydrogen is another possibility, likely involving at

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21 See: https://www.nrel.gov/news/features/2017/undersea-microbes-provide-path-to-energy-storage.html

22 See, for example, "In Switzerland, a giant new machine is sucking carbon directly from the air," E&E News, June 1, 2017.

23 There are also greenhouse gas implications relating to leaks of methane into the atmosphere from the natural gas system that would need to be separately addressed.

least a small amount of on-site storage. Examples of this may be an on-site bio-digester for producing methane and hydrogen vehicle fueling stations. Nel Hydrogen manufacturers both electrolyzers and modular hydrogen fueling stations.

Power Generation

Electric power generation relying on PtG products can be supplied through the natural gas pipeline system, as is currently done, or rely on hydrogen stored for their use. From an environmental perspective, it hardly matters whether the carbon-neutral fuel produced is consumed directly by the power generators themselves or simply somewhere in the pipeline grid. Nevertheless, it is also possible to supply the power plants with pure hydrogen, potentially created and stored at the plant site.

Cost and Value Considerations

While the value proposition for PtG as seasonal renewable energy storage is orders of magnitude better than battery and pumped storage alternatives, the economic case for PtG hydrogen as a fuel is generally less clear. The cost calculation depends strongly on the cost of the electric power consumed and the electrolyzer utilization factor.[24] Low power prices tend to be available in the market over far fewer hours than higher cost power. The advantage of purchasing power at low-cost is offset by spreading project capital costs over fewer kilograms of produced gas. This relationship is illustrated in Figure 9 for an hypothesized electrolyzer cost. For example, the cost of produced hydrogen from zero cost power available on 20% of all hours (UF=20%) is approximately the same (~$2/kg) as purchasing $22/MWh power if available 50% of the time (UF=50%).

In addition to the cost of power and utilization rate, variables include the continuing decline in the cost and penetration of renewable resources, and economies of scale to be expected from the accelerating deployment of commercial electrolyzer technologies. Commercial PtG deployments are increasing around the world, especially in Europe. The most recent cost quote for large scale electrolyzers comes from the deal between Nel Hydrogen and C2V to provide 100 MW scale electrolyzers for $550 per kilowatt of electrolyzer capability (see reference in footnote 16).

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[24] Utilization factor is analogous to capacity factor, representing the average usage rate divided by the maximum possible usage. For example, if an electrolyzer could produce 10 tons of hydrogen in a year at full output, but only produces one ton, its utilization factor is 10%.

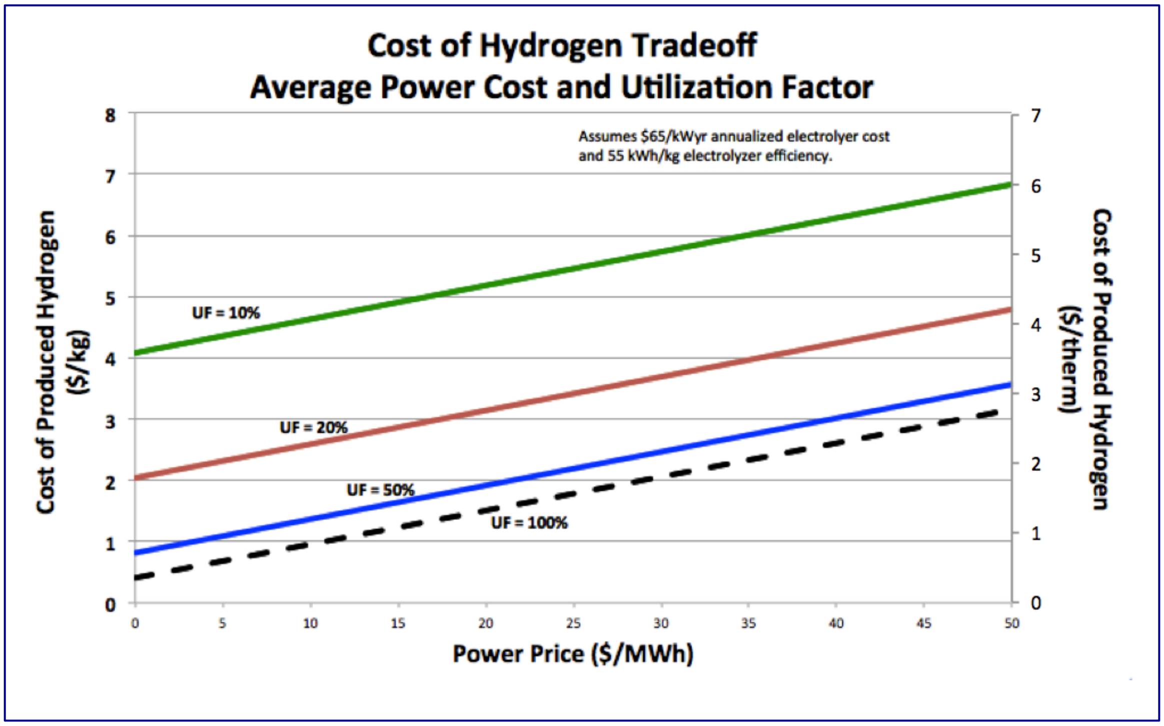

Figure 9: Tradeoff between produced hydrogen costs, average cost of power, and utilization factor.

The value of the produced gas is also an important variable to be considered along with any applicable subsidies available. For example, Oregon and California award credits for low carbon transport fuel substitutes that have a significant value today. Each credit represents a metric ton of avoided carbon dioxide emissions avoided. Recent prices have been around $50 per credit[25], that translates to about $0.54/kg ($0.47/therm) of hydrogen produced if used in standard vehicles, or $1.00/kg ($0.88/therm) in fuel cell vehicles.[26]

Electrolyzer flexibility may also be leveraged by providing balancing services to the electric grid—i.e. responding to changing power system balance by adjusting consumption on a sub-hourly (usually 5-15 minute) basis. Oxygen and heat byproducts may also be monetized. The various values may be combined to offset a significant percentage of electrolyzer costs, and substantially reduce the cost per therm of hydrogen.

25 Price quoted based on recent personal communications with Oregon DEQ staff. Oregon DEQ issues monthly Clean Fuels Program Transfer Reports containing recent month trading prices.

26 Oregon and California transportation fuel credits take account of the comparative efficiency of the fuel use through an "energy economy ratio" that is assigned to different transportation technologies. Fuel cell vehicles are more energy efficient than conventional internal combustion vehicles and would receive a higher credit. It should be noted that Oregon Dept. of Environmental Quality has not adopted an energy economy ratio for fuel cell vehicles at this time—the estimate is solely that of the author.

Water Use

The first step in any PtG process involves producing hydrogen from water and electric power. The amount of water consumed in the process becomes an obvious question. It turns out that the amount of water required is surprisingly modest. Each gallon of water can produce .48 therms of hydrogen[27], about a third of the average Oregon household's natural gas use. Put another way, if a household's gas needs were met by PtG, the extra water consumed would be about 1% (3 out of 300 gallons per day). It takes about 71.4 gallons of water to produce a megawatt-hour of hydrogen energy, about one tenth the water consumption of coal plants to produce an equivalent amount of energy.[28]

Resiliency

The Northwest is subject to extremely destructive Cascadia Subduction Zone earthquakes which may disrupt resupply of natural gas and transportation fuels for weeks or months. Without indigenous supplies of transportation and heating fuels, the state's energy security is especially vulnerable. The ability to use locally available resources (e.g. water, wind, and sun) to produce transportation fuel may be a vitally important key to improving the state's response to such events, bringing value far in excess of today's market price of fossil-based hydrogen or natural gas.

Price Volatility Risk Management

Hydrogen or methane derived from PtG processes are likely to be higher cost than their fossil-derived counterparts at today's historically low natural gas prices. There are several factors potentially mitigating the price disadvantage. The cost of PtG gas is expected to continue to drop due to increased economies of scale in manufacture, while wholesale electric prices continue to see downward pressure due to growing penetration of renewables. Large scale development of dispatchable PtG electrical loads potential provides an important cap on volatile gas prices, and strengthens a floor for wholesale electric prices. See Figure 10 for natural gas price volatility over the past ten years. Adding to that uncertainty is the growing possibility of carbon emission costs being explicitly levied on the production or sale of fossil fuels. Gas produced through PtG can be seen as a hedge against natural gas price risk, just as renewable electric power does for power consumers.

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27 A gallon of water has a mass of 3.78 kg, made up of 3.36 kg of oxygen and just .42 kg of hydrogen. One kilogram of hydrogen contains 33.3 kWh of electric energy (lower heating value), so there are (.42 kg X 33.3 kWh/kg) 14 kWh, or 0.48 therms of energy, in each gallon of water.

28 Source: Union of Concerned Scientists (UCS) web page cites 480-1,100 gallons of water consumption per MWh of coal production (100-317 gallons for once-through units). UCS conclusions based on *Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature*; Macknick, Newmark, et al; Environ. Res. Lett. 7 (2012) 045802.

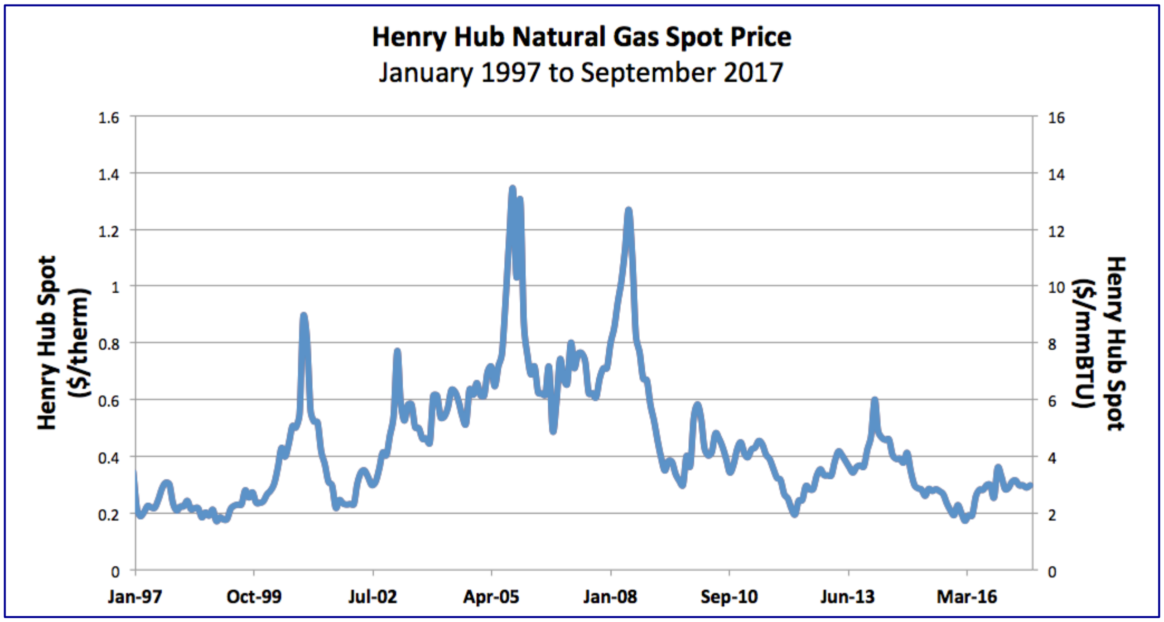

Figure 10: Historical spot market natural gas price volatility. Source: Energy Information Administration.

PtG Applications

Low gas prices in the US have hampered development of PtG projects, likely due to the historically low price of natural gas. In contrast, there are dozens of projects in Europe where natural gas is more expensive. Although most of the European installations are relatively small scale demonstration projects, utility scale developments are also being pursued. A sampling of PtG applications are offered below.

US

There are two important US projects going on today, both associated with SoCalGas, the NREL, and Dr. Jack Brouwer at the University of California, Irvine.

Advanced Power & Energy Program, University of California, Irvine

In concert with SoCalGas and research support of the NREL, UCI's Advanced Power & Energy Program is conducting research into PtG with its 60 kW PEM electrolyzer. Hydrogen from the electrolyzer is mixed with natural gas from the campus gas system and injected back into the campus system at a pressure of 400 psi (28 bar). Research goals of the facility include:

- Advance the dynamic operation of DC electrolysis.
- Advance hydrogen natural gas mixing concepts.
- Investigate pipeline hydrogen storage capabilities.
- Demonstrate efficient hydrogen production and injection into an existing natural gas pipeline—a U.S. first.
- Develop integrated PtG system concepts.
- Analyze the cost effectiveness of massive PtG energy storage.

The UC Irvine PtG system continues to operate and contribute to researching PtG technologies.

SoCalGas/NREL Bio-Methanation Project

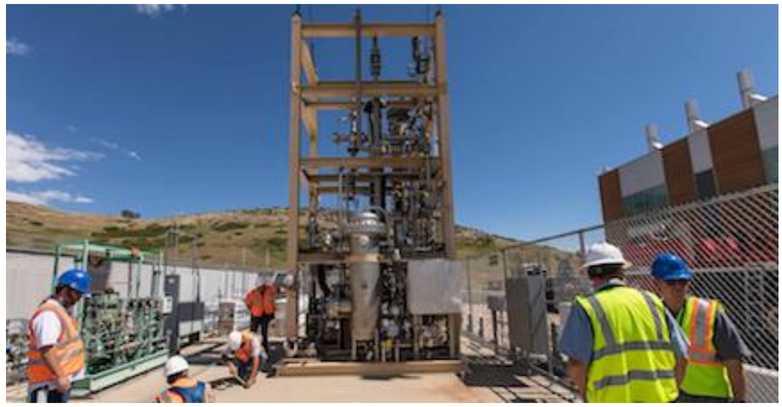
Figure 11: NREL/SoCalGas bio-methanation project. Photo: NREL.

West of Denver on the NREL campus is an experimental hydrogen methanation bio-reactor that combines hydrogen with microbes that produce methane. The microbes produce methane as they metabolize under favorable environmental conditions. The facility is roughly scaled in the 100-200 kW scale, designed to handle 2.5-5 kg per hour of hydrogen.[29] Hydrogen is produced by an electrolyzer and fed to a bio-reactor kept at 150° F (66° C) and 250 psig (18 bar). The microbes are a naturally occurring species known as *Methanothermobacter thermautotrophicus*.

Europe

Development in Europe is substantially beyond what is occurring in the US, partly due to the higher natural gas prices there, and partly due to the continent's commitment to reducing greenhouse gas emissions and the rapid development of renewable energy for that purpose. Figure 5 showed Germany's experience with increased curtailments, or conversely, the increasing need for controllable demand to absorb low-value renewable energy. Converting renewable electricity to carbon neutral fuel is recognized as a vital component to meeting European objectives. The European Commission's 2016 "Clean Energy for all Europeans" directives revised its definition of energy storage to include PtG[30]. Figure 12 maps the database of European PtG facilities taken from the European Power-to-Gas Platform. A few of those projects are described in brief detail below.

[29] Source: *Novel Power-to-Gas Tech Begins Testing in the US*, Feherenbacher, GTM, October 16, 2017.
[30] See ITM Power December 1, 2016 announcement *New EU Directives to Drive the Adoption of Power-to-Gas Energy Storage.*

Figure 12: European PtG projects. Existing projects in green, planned in yellow, and completed demonstrations in red. Adapted from European Power to Gas Platform.

Frankfurt am Main gas distribution network

Thüga Group's power-to-gas demonstration plant was the first project to inject hydrogen generated by electrolysis into a gas distribution network when it was commissioned in 2014. The 325 kW PEM ITM-Power electrolyzer converts power to hydrogen at a 77% efficiency rate according to Thüga Executive Board Chair Michael Reichel.[31]

Audi e-gas Plant, Werlte

The Audi Car Company began operating a 6 MW power-to-methane facility near Werlte, Germany in 2013. Power was contracted from wind generation to fuel an alkaline

31 Project press release: *Strom zu Gas-Anlage der Thüga-Gruppe hat alle Erwartungen übertroffen*, August 8, 2017.

electrolyzer that produces the hydrogen feeding a chemical methanation reactor. Carbon dioxide produced by a bio-mass burning plant nearby is the other main input to the plant to produce methane. The main purpose of this project was to demonstrate full scale production of carbon neutral methane for its fleet of compressed natural gas vehicles. The Werlte plant also contributes balancing services to the German electrical grid.

Audi e-gas Plant, Allendorf

Audi opened a new PtG methane production facility based on microbial methanation of carbon dioxide and hydrogen inputs. The project employs a 1.1 MW PEM electrolyzer. Audi distributes the gas through the existing German natural gas network to compressed natural gas (CNG) filling stations. The plant can produce about 1,000 metric tons of methane per year, chemically binding some 2,800 metric tons of CO2. Water and oxygen are the only by-products. Allendorf is the first industrial scale bio-methanation PtG facility in Germany.

Figure 13 Audi Allendorf bio-methane plant. Source: [Schmack Biogas GmbH](#).

Orkney Islands Hydrogen Projects

The European Marine Energy Centre (EMEC) maintains test sites for wave and tidal energy on Mainland Orkney and Eday Islands respectively. The Orkney archipelago lies 16 km off the northern coast of Scotland. Electric power reaches the islands through two 33 kV undersea cables from the mainland. The archipelago is home to substantial wind generation and is a net exporter of energy to the mainland, generating approximately 120% of the islands' power consumption. Eday Island hosts a 900 kW wind turbine and tidal energy test berths that can produce up to 4 MW of power—which is more than can be managed by the island's relatively weak grid system.

Under some conditions, the grid can become overloaded. In response, EMEC installed a 500 kW ITM Power PEM electrolyzer. Up to 500 kg of hydrogen can be stored on-site. Trucks capable of transporting 250 kg transfer the hydrogen from the Eday site to Kirkwall on Orkney Island via ferry. A 75 kW fuel cell system on the Kirkwall dock supplies auxiliary power to island ferries when they dock overnight, saving diesel emissions that the ferries would otherwise emit to power themselves. Electrolyzer and fuel cells were commissioned in September, 2017.

Plans call for the "BIGHIT" project that will add a 1 MW electrolyzer on Shapinsay, where the gas will be used to power ten hybrid hydrogen range-extended (180 mile) electric battery vans, and to heat schools.

Falkenhagen Wind-Gas Project

German utility E.ON operates several PtG projects in Germany, including the 2-MW Falkenhagen pilot plant. The Falkenhagen project reports 66 percent efficiency with off-the-shelf equipment prior to any optimization of components. The electrolyzer is able to inject gas directly into the Hamburg area gas distribution pipeline system at 25 bar, without separate compression. German pipeline regulations limit the hydrogen mix in the pipeline system to less than 10%. The project started construction in 2012 and fed more than 2 million kWh (60,000 kg, or 68,000 therms) of hydrogen into the German grid.

Aberdeen Hydrogen Bus Project

The City of Aberdeen Scotland initiated a project to purchase ten hydrogen fuel cell buses and 1 MW Hydrogenics alkaline electrolyzer to provide the fuel. Initial project funding was for 20 million pounds, with support from a range of government and granting entities. The system became fully operational in 2015, and Aberdeen announced plans to double the bus fleet to 20 buses in March, 2017.[32]

[32] *Aberdeen's hydrogen bus fleet to double as Government pledges £3m*, Ryan Cryle, Evening Express, March 17, 2017

Summary

Creating hydrogen from electricity and converting that hydrogen to methane are both well-proven technologies whose costs are declining with advances in the technology and economies of scale. Europe leads in the number of PtG facilities due to the higher cost of gas and the continent's commitment to greenhouse gas emission reduction targets. There are megawatt scale projects in Europe producing both hydrogen and methane that are designed for specific fuel uses (e.g. transportation, fuel cell electric power) and for injection into gas grids. Plans for hundred-megawatt scale projects have received funding commitments and are expected to go forward at this time.

Figure 14 September 2016 inaugural flight of the HY4, the world's first four-seater hydrogen fuel cell aircraft with a range of 750-1,500 km and maximum speed of 200 km/hr. Source: [HY4.org]

Electric utilities, regulators, and renewable resource advocates in the US are focused on the need for energy storage to accommodate the variable nature of the generation from those sources. Much of the attention is given to the range of battery technologies and pumped hydro storage. The costs of seasonal energy storage with those technologies are orders of magnitude greater than the equivalent cost of creating and storing gas through PtG in the gas pipeline system. While the ability of PtG and gas grids to provide needed storage is well recognized in Europe, it is generally neglected, and sometimes specifically excluded from energy storage discussions, policies and mandates in the US. This suggests the need for policy interventions for PtG advocates.

The economic advantage of PtG over competing bulk energy storage options is overwhelming. Nevertheless, achieving cost parity of the produced gas with conventionally produced natural gas is more difficult. Several projects have leveraged the flexibility of PtG loads to earn additional value from the power system operators. Carbon-neutral transportation fuels may be eligible for state and federal clean fuel credits that offer significant value and cost reductions. PtG can provide additional protection against risk deriving from high natural gas price volatility and price risk due to future carbon regulation. Cost of the produced gas can be expected to fall over time, with electrolyzer economies of scale and downward price pressure on wholesale electric prices due to the continual expansion of power from renewable sources.

Appendices

A. Electrolyzer Technology Comparison Chart

Source: THE POTENTIAL OF POWER-TO-GAS, ENEA, January 2016

	Alkaline	PEM	Methanation
Efficiency (HHV)	• 74 % to 78 % with H2 at atmospheric pressure • 66 % with H2 delivered at 10 bar Includes energy consumption of auxiliaries and purification unit.	Expected to be slightly higher than for alkaline electrolysis**. Commercial performance at large scale (10 MWel) to be confirmed.	79.40%
Start-up Time	• 10 to 40 minutes for cold start-up (depends on the initial temperature) • Few seconds for standby start-up (auxiliaries ready to run)	• 10 to 40 minutes for cold start-up (depends on the initial temperature) • few seconds for standby start-up (auxiliaries ready to run)	• Continuous operation of the reactor thanks to hydrogen buffer storage upstream. • Maintain the reactor at a sufficient temperature thanks to external heating or a thermal insulation of the reactor (e.g. if maintained at 250 °C the reactor can be started up in few minute
Lifetime	• 60,000 hours for the cell stack • 20 – 30 years for the rest of the full installation	• 40,000 hours for the cell stack • 20 – 30 years for the rest of the full installation	• 20,000 to 25,000 hours for the catalysts when the reactor is cycling (not yet validated in commercial conditions) • 20 years for the reactor vessel
CAPEX	Installed turnkey CAPEX at 10 bar including balance of plant, transport, installation and commissioning, excluding civil work and connection to other section of the plant: • 500 kW: 2000 €/kW • 1 MW: 1500 €/kW • 10 MW: 1000 €/kW	• In the coming years: - 10 MWe: 1000 €/kWel • 2030 - 1 MWe: 1000 €/kWel - 10 MWe: 700€/kWel • 2050 - 1 MWe: 500-550 €/kWel - 10 MWe: 350-400 €/kWel	Estimated factory gate cost of a 5 MWHHV-SNG methanation reactor (no feedback available from commercial units): • For the coming years: 1,500 €/kWHHV-SNGout*** • In 2030: 1,000 €/kWHHV-SNGout • In 2050: 700 €/kWHHV-SNGout Additional costs for balance of plant, transport, installation and commissioning: 50 % of the factory gate cost.
Maturity	Commercial, mature, economies of scale primary channel for cost reduction.	Used commercially at small scale and under commercial demonstration at large scale for power-to-gas applications (1-10 MWel). 100 MW plant in design by ITM Power.	The first generation of methanation reactors for power- to-gas application is under demonstration (e.g. Audi Werlte plant). New generation of technologies are under development (e.g. KIC InnoEnergy CO2SNG, DemoSNG projects).
OPEX	• 1-2 % of CAPEX/year (for a 10 MW electrolyzer) • 4-5 % of CAPEX/year (for a 1 MW electrolyzer) Cell Stack Replacement: Approximately 30 % of the total CAPEX every 60,000 hours of operation.	• 1-2 % of CAPEX/year (for a 10 MW electrolyzer) • 4-5 % of CAPEX/year (for a 1 MW electrolyzer) Cell stack replacement: Approximately 50 % of the total CAPEX every 40,000 hours of operation.	Cost of operation and maintenance (including catalyst replacement): • 5-10 % of CAPEX/year (for a reactor corresponding to a 10 MWel electrolyzer input)

*** Oregon Startup company HydroStar claims non-toxic alkaline electrolyzer at lower cost**
****PEM electrolyzers generate hydrogen up to 30 bar, with development efforts aimed at 80 bar.**
MWhHHV-SNG means higher heating value MWh of synthetic natural gas
kWhHHV-SNGout means higher heating value of synthetic gas output of the reactor

B. Manufacturers

Alkaline Electrolyzers	PEM Electrolyzers	Methanation Plants
ELB Elektrolyse Technik	Acta Spa	CEA
Hydrogenics	AREVA H2 Gen	Etogas
Idroenergy	H-Tec Systems	Haldor Topsoe
IHT	Hydrogenics	KIT
McPhy Energy	ITM Power	MAN Diesel & Turbo SE
NEL Hydrogen	Proton Onsite	
Teledyne Energy Systems	Siemens	

Bibliography

American Gas Association. *Average Annual Residential Consumption per Customer by State 2005-2015*. https://www.aga.org/knowledgecenter/facts-and-data/statistics/annual-statistics/energy-consumption, Accessed Nov 2017.

Antonia and Saur. *Wind to Hydrogen in California: Case Study*. NREL, Aug 2012.

Bertuccioli and Chan. *Study on development of water electrolysis in the EU*, Apr 03, 2014.

Bolinger, Seel, and Hamachi LaCommare. *Utility-Scale Solar 2016*. Lawrence Berkeley Labaoratory, Sep 2017.

California Hydrogen Business Council. *Power-to-Gas: The Case for Hydrogen White Paper*, Oct 08, 2015.

California Independent System Operator. *Wind and Solar Curtailment*, Oct 22, 2017.

Climeworks. *Climeworks launches world's first commercial plant to capture CO2 from air*, May 31, 2017.

Climeworks. *World-first Climeworks plant:*

Capturing CO2 from air to boost growing vegetables, May 31, 2017.

de Bucy, Jacques. *The Potential of Power-to-Gas*. ENEA, Jan 2016.

DNV GL for European Power to Gas. *Power-to-Gas in a Decarbonized European Energy System Based on Renewable Energy Sources*, 2016(?).

DNV GL for TKI Gas. *Power-to-Gas project in Rozenburg, The Netherlands*, May 31, 2015.

Dodge and Edward. *Power-to-Gas Enables Massive Energy Storage*. Breaking Energy, Dec 02, 2014.

Edmonds, Bill. *Presentation: Natural Gas in a Low Carbon Future*. NW Natural, Apr 2017.

Eichman, Denholm, Jorgenson, and Helman. *Operational Benefits of Meeting California's Energy Storage Targets*. NREL, Dec 2015.

Eichman, Harrison, and Peters. *Novel Electrolyzer Applications: Providing More Than Just Hydrogen*. NREL, Sep 2014.

Eichman, Josh. *Hydrogen Energy Storage (HES) Activities at NREL*. NREL, Apr 21, 2015.

Eichman, Josh. *Hydrogen Energy Storage (HES) and Power-to-Gas Economic Analysis*. NREL (Presentation), Jul 30, 2015.

Eichman, Townsend, and Melaina. *Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets*. NREL, Feb 2016.

Empa. *Synthetic natural gas from excess electricity*. ScienceDaily, Jan 06, 2014.

ENEA. *The Potential of Power to Gas*, 2016.

Environmental Protection Agency. *Inventory of US Greenhouse Gas Emissions1990-2015*, Apr 15, 2017.

Fehrenbacher, Katie. *Novel Power-to-Gas Tech Begins Testing in the US*. Greentech Media, Oct 16, 2017.

Founti, Maria. *Power-to-Gas Concept and Overview of HELMETH Project*. HELMETH, May 19, 2016.

Gandia, Sanches. *Hydrogen Production From Water Electrolysis: Current Status and Future Trends*. IEEE, Feb 2012.

Giannopoulos, Dimitrios. *Introduction/Main Features of High Temperature Electrolysis with SOEC*. HELMETH, May 30, 2016.

Grond, Schulze and Holstein. *Systems Analyses Power to Gas: Deliverable 1 Technology Review*. KEMA, Jun 20, 2013.

Helmeth Project. *High temperature electrolysis cell (SOEC)*, (undated).

Honselaar, Weidner, and Steen. *Workshop report: summary & outcomes Putting Science into Standards Power-to-Hydrogen and HCNG*. JRC Science and Policy Reports, Jan 01, 2015.

Hydrogenics. *Power-to-Gas Solution*. Hydrogenics, (undated).

Hydrogenics. *Renewable Hydrogen Solutions*. Brochure (undated).

IPHE. *Utsira Wind Power and Hydrogen Plant*. IPHE Renewable Hydrogen Report, (undated).

ITM Power. *Power to Gas Webinar*. Presentation, Jun 22, 2017.

Jentscha, Trost, and Sterner. *Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario*. 8th International Renewable Energy Storage Conference Proceedings, IRES 2013, 2014.

Joint Institute for Strategic Energy Analysis (JISEA), *Lessons Learned from Energy System Stakeholders*. Apr 2015.

Koponen, Kosonen, and Ahola. *Review of water electrolysis technologies and design of renewable hydrogen production systems Progress of Master's Thesis*, Feb 10, 2016.

Law, Steve. *NW Natural Charts a Green Energy Path*. Portland Tribune, Apr 26, 2017.

Macknick, Newmark, et al. *Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature*, Res. Lett. 7 (2012).

Mainova, Thuga, and Strom zu Gaz. *Strom zu Gas-Anlage der Thüga-Gruppe hat alle Erwartungen übertroffen* ("Thüga Group Electricity to Gas Plant Exceeded All Expectations"). Press release, August 8, 2017.

Melaina and Eichmann. *Hydrogen Energy Storage: Grid and Transportation Services*. NREL, Feb 2015.

Melaina, Antonia, and Penev. *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*. NREL, Mar 2013.

MIT. *The Future of Solar Energy: An Interdisciplinary MIT Study*, Jan 01, 2015.

National Grid. *Renewable Gas — Vision for a Sustainable Gas Network*, Jan 2010.

Nilsen and Lorentzen. *Ny Nel-kontrakt kan være starten på fransk milliardeventyr*. E24, Jun 13, 2017.

Northwest Gas Association. *2016 Gas Outlook*, 2017.

NREL. *Technology Brief: Analysis of Current-Day Commercial Electrolyzers*, Sep 2004.

NW Natural. *NW Natural 2016 Integrated Resource Plan*, (undated).

NW Natural. *NW Natural Annual Report 2016*, (undated).

NW Power and Conservation Council. *White Paper on the Value of Energy Storage to the Future Power System*, Nov 2017.

Oregon Global Warming Commission. *Oregon Global Warming Commission Biennial Report to the Legislature 2017*, Feb 2017.

Oregon Public Utility Commission. *Order Number 17-118: Implementing Energy Storage Program Guidelines*, Mar 21, 2017.

Penev, Michael. *Hybrid Hydrogen Energy Storage*. NREL (Presentation), May 22, 2013.

Pless, Arent, Logan, Cochran, Zinaman, and Stark. *Pathways to Decarbonization: Natural Gas and Renewable Energy*

Rosenfeld, Jeff. *Task 2 – Illustrative Compliance Scenarios Final Report*. ICF, May 09, 2017.

Sandia National Laboratories, *DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA*, February 2015.

Schiebahn, Grube, Robinius, Tietze, Kumar, and Stolten. *Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany*. International Journal of Hydrogen Energy, 40 4285-4294, Jan 01, 2015.

Sterner, Michael. *Bioenergy and renewable power methane in integrated 100% renewable energy systems*. Fraunhofer Thesis, Sep 23, 2017.

Thoma, Julia. *Hydrogen, A Promising Fuel and Energy Storage Solution*. NREL Continuum Magazine, Issue 4, Apr 2013.

Thomas, C. E. (Sandy). *Fuel Cell and Battery Electric Vehicles Compared*. H2Gen Innovations, Inc., Mar 27, 2009.

Veissmann. *Power-to-gas – key technology for linking different sectors*. Brochure, Feb 2017.

Weidner, Honselaar, Cebolla, and Gindroz and de Jong. *Sector Forum Energy Management / Working Group Hydrogen: Final Report*. CEN/CENELEC, Jan 01, 2016.

Weidner, Stein, de Jong, and Gindroz. *Power-to-Hydrogen: key challenges and next steps*. CENELEC (Workshop Report), May 2016.