Chapter 17
Power-to-Gas: A New Energy Storage Concept for Integration of Future Energy Systems

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17.1 Introduction

Energy storage is essential and well-accepted principle to SMART GRID. Currently Ontario has excess power; in 2016, $1 billion dollars of power was "curtailed" in addition to many billions sold outside of Ontario to the USA as a significant loss. In this work, power-to-gas has been shown to be one of the best alternatives for energy storage based on Ontario's grid profile. Hydrogen is generated with excess CO_2 free nuclear and wind power and used in a number of pathways. There are no real other alternatives for Ontario at this time: Best sites for pumped hydro are used now; Compressed Air Energy Storage (CAES) has little power density, on seasonal storage, efficiencies are low; and batteries have little power density and still higher cost, and repurposed batteries are not yet available in the market.

"Power-to-Gas" as a technology using commercialized electrolyzer has a lot of advantages and will be introduced below. First off, among all the currently available energy storage technologies it has the highest energy storage density, it has many different forms of storage such as compressed gas and liquefied hydrogen in storage tanks as well as storing in natural gas infrastructure, which is a great option for its storage and distribution since it efficiently uses the existing infrastructure and that brings better economic efficiency. Once they get stored, they can be stored for a long period and that allows for delay and offsetting for additional power generation. What's more power-to-gas is also a well-known clean technology because it reduces emissions, while being mixed with natural gas and it increases end-use petroleum fuels' renewable content without changing vehicle type or refueling infrastructure; more significantly when it gets combined with biogas generation more renewable

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natural gas will be developed through methanation to give lower CO_2 emission. Power-to-gas also has the ability to supply auxiliary electrical services what's more its incremental implementation property gives it the ability to adjust changing infrastructure needs. Last but not least, it has great ability in transporting energy over long distances and acting as a transportation fuel for lift trucks in the form of hydrogen, both prove its great commercialized potential [1–7].

Hydrogen as an ideal long-term energy vector can be created from many different resources such as fossil fuel, renewables, and carbon-free nuclear. The concept of "hydrogen economy" has developed in a fast face and it focuses based on the how hydrogen will be produced, distributed, and utilized in energy system. Hydrogen can be used to create electricity and has very various production pathways, when it gets used in transportation related area lower pollution and lower greenhouse gases emissions are in favor. It is well-known that the great price gap between peak and lower price hours has always been a concern for electricity markets, while the appearance of using hydrogen as an energy carrier in electrical grid solves this problem by storing energy generated by some seasonal power such as wind, solar and GHG free nuclear power and distributing them based on needs. It is obvious to see that the concept of "hydrogen economy" actually stands for an ideal fossil fuel free economy [8].

17.2 Different Alternative of Power-to-Gas Applications

Power-to-gas application can offer the most efficient usage of surplus power at all-time due to its gradual and incremental implement, and the pathways of this application are listed below:

Power to Hydrogen to Natural Gas End-users via hydrogen-enriched natural gas (HENG);

1. Power to Renewable Content in Petroleum Fuels;
2. Power to Power;
3. Power-to-gas—Seasonal Energy Storage to Electricity;
4. Power to Zero Emission Transportation;
5. Power to Seasonal Storage for Transportation;
6. Power to Microgrid;
7. Power to Renewable Natural Gas (RNG) to Pipeline ("Methanation"); and
8. Power to Renewable Natural Gas (RNG) to Seasonal Storage.

As shown in Fig. 17.1, electrolyzers are used in different pathways to convert the surplus power to hydrogen that will then be directly converted to methane with low carbon content. This low-carbon methane will go through another process to achieve higher cost and lower. Every process possesses losses, which can be accepted if the surplus electricity is required to reduce or cannot be used anywhere else. For those that have lower CO_2 emissions compared to current conventional natural gas such

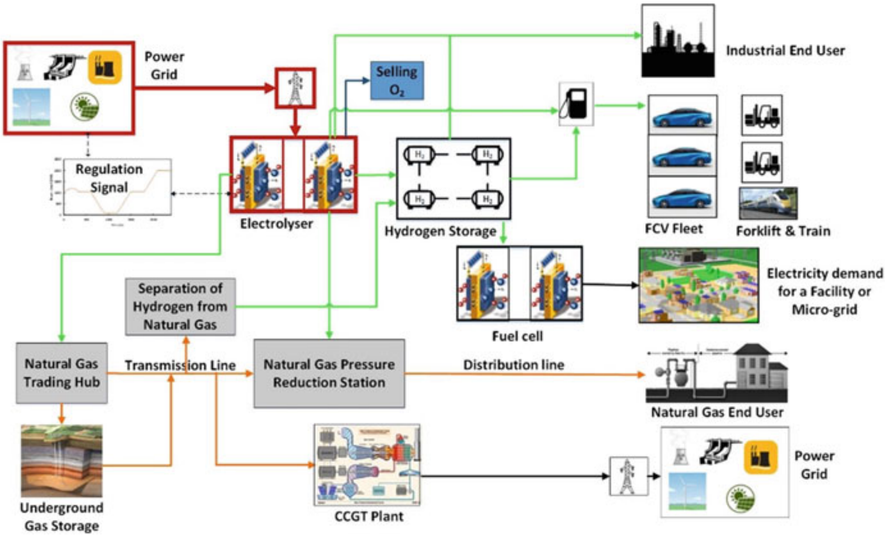

Fig. 17.1 Schematic view of Power-to-gas (adopted from Maroufmashat and Fowler [9])

as residential heat purposes, micro-CHP and large-scale gas turbine, low-carbon methane will be injected to natural gas pipeline. Either what's more it can also be used for the utilization of low-carbon transportation applications on seasonally or daily basis.

17.2.1 Power to Hydrogen to Natural Gas End-Users Pipeline Blending (HENG)

Hydrogen-enriched natural gas (HENG) can be made from decarbonizing natural gas by injecting generated hydrogen from surplus power including renewable energies to natural gas pipeline. This concept has its own limit, only when the composition of hydrogen blending to natural gas no larger than 10% the existing natural gas infrastructure or end-use equipment can function normally. HENG can be used to generate heat, electricity or as a fuel for transportation with no modification to the equipment of HENG systems due to the fact that it has lower CO_2 emissions compared to natural gas.

When this electrolytic hydrogen is injected into natural gas transportation or distribution pipelines, certain limits are required, which are between 5 and 20% based on different types of applications. Many electrolyzers and hydrogen storage tanks are required to build and install even with these concentrations. This kind of storage system has a challenging problem on its optimum capacity and many literatures suggest that this hydrogen storage system improves the performance of the whole systems even though it adds complexity and costs more to power-to-gas system.

In modern society converting diesel Class 8 vehicles to natural gas can certainly accomplish more benefits because no change needed for natural gas infrastructure and vehicles fueled with hydrogen-enriched natural gas becomes more renewable with low-carbon contents.

This pathway can show immediate effect for energy storage with minimal investment cost. What's more it does not need to shed or sell energy for loss as much to avoid high amount of Global Adjustment expenditures in Ontario.

17.2.1.1 Technology Issues Regarding the Implementation of this Pathway

One of the most significant limitations is the allowable fraction of hydrogen into natural gas pipeline. The composition has great effect on end-user systems, safety and risk issue, and durability of pipeline material and leakage of hydrogen. The end-user systems that get affected are furnaces, boilers, and power generators. They are affected by natural gas composition, type of appliances, engine and their ages with an acceptable range of hydrogen between 5 and 20%, higher composition may cost more to the system.

Compression stations and compressed natural gas tanks only have a limitation of 2% for hydrogen concentration which is small comparing to dried compressed blended hydrogen that has 20% and preferred due to higher performance. Current installed gas turbine only has a limitation up to 1%, it can be somehow increased to 5–15% if turbine gets adjusted and upgraded. Gas engine has a limitation of 2% preferably if higher concentration wants to be achieved the simple upgraded control systems shall be used [10].

Safety and risk analysis focuses on hydrogen concentration, pipeline types, material, and failure mode conditions. Comparing to large-scale coal and nuclear plants natural gas systems have a lower risk of severe accident while comparing to some renewable systems such as solar PV and wind, natural gas systems have a higher risk. Some of the risks are the possibility of ignition and the severity of explosion while close to urban areas. One of the exceptions is that during initial implementation due to low concentration of hydrogen in the natural gas system no significant risk appears. Under higher pressure and higher concentrations of hydrogen, the addition of hydrogen may cause material of pipelines degrading faster. This is mainly an issue for transmission pipelines not for steel pipelines. Hydrogen leaks 4 to 5 times faster from fittings than methane due to its lighter density. Once the concentration exceeds 20%, it will have the same order of the leakage [11, 12].

17.2.2 Power to Increased Renewable Content in Petroleum Fuels

Biofuels, typically ethanol gets blended into the distributed gasoline with the range of 5–10% in order to reduce the dependency of imported oil, promote renewable fuel industry, and reduce the carbon emissions released from cars. Under the condition of not changing the quality of the fuel itself and encounter the limitation of ethanol caused by its low energy output renewable electrolytic hydrogen can also be seen as a potential method to increase the renewable energy. Traditional petroleum fuels normally have the following stages for life-cycle emissions: crude extraction, crude transport, crude refining, petroleum fuels transportation, distribution and vehicle consumption, which all contribute to the carbon intensity of gasoline and diesel. In Ontario province unlike Steam Methane Reforming (SMR), the production of hydrogen via electrolysis has a significant low-carbon footprint but meanwhile it costs more than SMR. Well refiners will also implement electrolysis hydrogen to meet the carbon intensity reduction target regulated by government. This pathway uses power-to-gas for oil refining to reduce the carbon intensity as well as decarbonize transportation sector on the life-cycle basis without converting current infrastructure. It is also complimentary with the addition of ethanol to gasoline so that both methods of renewable content can be implemented at the same time.

17.2.3 Power to Power

Hydrogen can be converted from surplus power via electrolyzer, then pressurized, stored, and utilized through fuel cell or hydrogen gas turbine. The drawback is that it might cause potential loss of energy because of the need of fuel cells in the facility. What's more the round trip efficiency is lower than battery than battery energy storage but it is favorable in some remote applications or emergency situations, which provides extended power applications.

17.2.4 Power-to-Gas to Seasonal Energy Storage to Electricity

Produced hydrogen can be stored in the underground facility; moreover, along with natural gas storage electricity can be generated in large-scale natural gas-based power plant. This pathway can properly use wind energy in its off-season as well as for daily and weekly variation in energy demand. It is also very useful for load leveling of baseload nuclear power in Ontario.

17.2.5 Power to Hydrogen for Zero-Emission Transportation

Hydrogen can also be used as a transportation fuel, which gets compressed and stored at high pressure ranging from 300 to 700 bar for hydrogen vehicles and lift trucks. While the concentration is highly required for this application, that is the appearance of 99.995% pure hydrogen.

Using hydrogen separated via electrolysis from nuclear, hydro, wind, or solar sources as fuel to vehicles can truly achieve zero emissions. Comparing to gasoline internal combustion engine (ICE) vehicles, fuel cells vehicles using hydrogen made from natural gas still have a significantly less GHG reductions. How well hydrogen as a future transportation fuel will develop really depends on fuel cell vehicle availability and the development of hydrogen refueling stations. This pathway can integrate electrical and transport energy sectors without the need to upgrade electricity distribution systems to possibly achieve zero emission transportation in an urban area with consumers' preference. In order to improve urban air quality and associated benefits in society's health outcomes using hydrogen FCV in urban areas is a good approach. For different specific transportation applications battery electric vehicles and fuel cell vehicles can be a desirable complementary technology in both the short and long terms.

17.2.6 Power to Seasonal Storage for Transportation

Salt caverns or depleted oil and gas reservoirs can be used to store pressurized hydrogen produced from surplus power via electrolyzer. It can then be separated from other gases via Pressure Swing Adsorption (PSA) and sent to the end-users once it is needed by transportation. It has similar benefits as "Power to Hydrogen for Zero Emission Transportation" with additional benefit, that is, the hydrogen can be produced while renewable energy is plentiful and used all year round. It requires very high penetration of wind energy and baseload nuclear and large capacities of sessional energy storage.

17.2.7 Power to Microgrid

Due to the nature of the intermittency of renewable energies the mismatch between electricity grid congestion at peak demand and under-utilized excess power distribution infrastructure during off-peak hours are all great technical concerns for urban communities. Power-to-gas which stores energy in the form of hydrogen within micro grid is an alternative to utilize for variety of microgrid energy requirements such as transportation demand or to be used for community. It can also be helpful for remote off-grid communities and mining sites with larger needed storage capacities.

17.2.8 Power to Renewable Natural Gas (RNG) to Pipeline ("Methanation")

A stream of renewable natural gas made from combination of hydrogen and carbon dioxide can be mixed into natural gas distribution system, this methane production has a higher energy loss and cost but with no limitation of blending into the natural gas distribution systems comparing to simple hydrogen production. It can even be complimentary with the first pathway to inject hydrogen into natural gas pipeline up to allowable limit and convert remaining hydrogen to methane via methanation. It is not a fully developed technology occurred inside a chemical reactor, biological reactor, or natural methanation in underground storage so that the purity of carbon dioxide and the quality of synthesis methane both shall be taken into account. Sometimes if the synthetic methane has low quality an additional gas cleaning process will be needed.

Qualitative benefit of this pathway is carbon sequestration from biogas production or industrial processes such as cement production.

17.2.9 Power to Renewable Natural Gas (RNG) to Seasonal Storage

Underground storage can be used to store renewable methane (RNG) once it is produced from surplus electricity. This pathway considering methanation can be matched to an ongoing industrial or agricultural operation for carbon sequestration and independent on natural gas demand profiles.

17.3 Key Technologies in Power-to-Gas

The core technology of power-to-gas system is electrolyzer that converts electricity into fuel. Alkaline, polymer electrolyte membrane (PEM), and solid oxide membrane (SO) are all different types of electrolyzers. Comparing to the most commercial one alkaline electrolyzer PEM electrolyzer has higher potential for cost reduction, durability, and efficiency improvement in future. One of the other electrolyzers that have potential for greater efficiency gain is solid oxide electrolyzer but they require high operating temperature and still in research phase of development. Speaking of higher current density and operational flexibility in terms of dynamic response and frequency regulation that are preconditions for future capital cost reduction PEM electrolyzers have great benefits. When load should be immediately ramp up or down from the point of the normal operation the operation flexibility for the utility electricity grid becomes a key advantage of PEM electrolyzers. Meanwhile it also has the potential to provide auxiliary services that increase the technology's availability factor. If the electrolyzers can be maintained at elevated pressure it will be a benefit for future power-to-gas systems because they can reduce the compression requirement for storage systems, PEM electrolyzer is one of those while alkaline ones are not. Nowadays PEM electrolyzers are limited by the rate of hydrogen production per stack and cell lifetime, even with those limitations they are still expected to surpass alkaline technology in the near future.

The following table lists out the technical, operational, and economic information of the two most applicable electrolyzers that are alkaline and PEM electrolyzers. The information has been collected from different manufacturers' data and existing literature. Commercial or pre-commercial applications with a time frame of up to 10 years are represented by "current perspective," while the long-term planning depends on future technologies with the improvement of their cost and performance as well as a period of more than 10 years ahead [13–15].

The investment costs of alkaline electrolyzers and PEM electrolyzers are $1000 and $2000 per kW, respectively. This cost might be changed based on the specific size and thermodynamic condition and based on E&E consultant the cost of PEM electrolyzers is expected to be $1300 per kW [9].

The other important technologies considering in power-to-gas applications are hydrogen storage and compression systems. Different types of storing hydrogen exist, including underground compressed gas, metal hydride, and liquid hydrogen. Based on the applications, the type of storage may vary. The compressed gas storage is the simplest one, while the issue about the storing liquid hydrogen is boil off losses that results in limited time of storage. For long-term, large-scale energy storage, the underground hydrogen storage is desirable. The information regarding the energy storage systems are summarized in the following table (Table 17.1).

17.4 Technical and Economic Assessment of Power-to-Gas Pathways

Different pathways of power-to-gas applications are presented in the following figure (Fig. 17.2). The overall efficiencies of each pathway along with the economic benefits of them are presented in Tables 17.2 and 17.3.

Since there is a wide range of efficiencies for some technologies, the allowable range of pathway efficiency is mentioned in Table 17.2. In order to calculate the levelized cost of product, as shown in Table 17.3, the hourly Ontario electricity prices (HOEP) are used. The calculation is classified for two groups of HOEP when it is less than 2.5 cent per kW and when it is more than 2.5 per kW.

Results in Tables 17.2 and 17.3 show that in terms of economic and technical points of view, the power-to-gas pathways with hydrogen to the end-users are better options compared to other alternatives that have additional energy conversion technologies leading to more energy losses and lower efficiency and more cost.

Table 17.1 Technical and economic data for hydrogen storage, compression and purification technologies (adopted from [9])

Technology	Explanation	Efficiency		Cost (CAN per kg or kg h^{-1})		Lifetime
		Current	Long term	Current	Long term	
Low pressure hydrogen storage	3–300 kg	Almost 100% (without compression)		260–430	15	20
Compressor—for low pressure storage	Until 180 bar	88–95%	88–95%	3000	3000	20
Compressor—for refueling station	Until 700 bar	80–91%	80–91%	8700–17,000	13,000	20
Injection to pipeline compression	Including compression	95%	95%	–	–	
Underground storage	GWh to TWh (including compression)	90–95%	95%	300–350	40	30
Hydrogen purification system	PSA	80–95%	85%	4000	4000	20

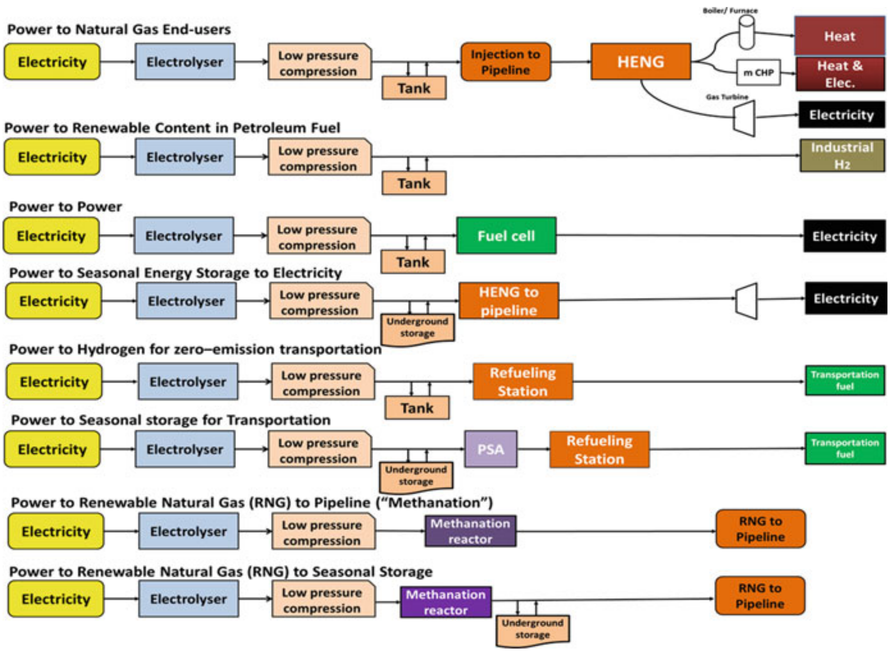

Fig. 17.2 Different pathways of power-to-gas (adopted from [9])

Table 17.2 Technical comparison of the power-to-gas pathways

P2G pathways	Technologies	Current (%)	Long term (%)
Power to natural gas end-users	Electrolyzer, low pressure hydrogen storage/compression, injection to pipeline	59–83	64–86
	To heat for residential	52–76	56–79
	To micro-CHP	40–72	55–74
	To large-scale gas turbines	18–26	23–31
Power to renewable content in petroleum fuel	Electrolyzer, low pressure hydrogen storage/compression	55–83	59–86
Power to power	Electrolyzer, low pressure hydrogen storage/compression, fuel cell	17–40	27–43
Power to seasonal energy storage to electricity	Electrolyzer, low-pressure compression, underground storage, transmission pipelines, natural gas-based power plants	16–24	22–29
Power to hydrogen for zero–emission transportation	Electrolyzer, low-pressure compression and storage, high-pressure compression for refueling station	50–79	54–82
Power to seasonal storage for transportation	Electrolyzer, low-pressure compression, underground storage, hydrogen separation technologies, high-pressure compression	36–68	43–66
Power to renewable natural gas (RNG) to pipeline ("Methanation")	Electrolyzer, low-pressure energy storage and compression, methanation reactor, gas clean-up, injection of renewable natural gas to the natural gas pipeline	40–63	45–65
Power to renewable natural gas (RNG) to seasonal storage	Electrolyzer, low-pressure compression, methanation reactor, gas clean-up, underground storage, injection of RNG to the natural gas pipeline	34–60	43–58

From technical point of view, the power to hydrogen for heat purposes and for transportation has the highest energy efficiency, which is around 50–80%. Power to power has a lowest efficiency specially when utilizing from underground energy storage. Seasonal storage can lower the overall efficiency of power-to-gas, but not more than 10% lower. Power to renewable content in petroleum fuels has an average efficiency of 68% (current) and 72% (future), while a large Steam Methane Reforming (SMR) has an efficiency in a range of over 70%. Results indicate that in future years power-to-gas can be competitive to the conventional SMR from

Table 17.3 Economic comparison of the power-to-gas pathways

$ per kWh	0 < HOEP<2.5		2.5 < HOEP<7.5	
P2G pathways	Current	Long term	Current	Long term
Power to natural gas end-users	0.15–0.27	0.02–0.04	0.19–0.37	0.07–0.1
Power to power	0.53–0.57	0.07–0.09	0.76–78	0.19–0.23
Power to hydrogen for zero–emission transportation	0.18–0.27	0.03–0.04	0.23–0.34	0.08–0.09
Power to seasonal storage for transportation	0.27–0.33	0.09–0.1	0.53–1.06	0.22
Power to renewable natural gas (RNG) to pipeline ("Methanation")	0.22–0.35	0.04–0.05	0.3–0.47	0.11–0.13
Power to renewable natural gas (RNG) to seasonal storage	0.42–0.45	0.08–0.09	0.53	0.15–0.16

technical point of view. From economic point of view, power to power has the highest cost, regarding different types of electrolyzer and fuel cell technologies; the cost is between 0.38 and 0.53 $ per kWh when the HOEP is less than 2.5 cent per kWh, while that of is 0.6 and 0.8 $ per kWh when the HOEP is more than 2.5.

The levelized cost of power to hydrogen pathways is less than the others. Seasonal storage technologies can increase cost by double. The levelized cost of product for hydrogen is around 17–29 cent per kWh, while in the long term the cost must be as low as 4–5. The reason is that the price of storage technologies will be decreased significantly in the long-term. The levelized cost of methane for natural gas vehicles is in the range of 28–41 cent per kWh. Improvements in technologies can increase the overall efficiency of power-to-gas pathways in future years that make them more economically and technically feasible for implementation.

17.5 Case Studies

Different applications of power-to-gas in different projects are summarized as below: a deterministic energy system model for the production of electrolytic hydrogen from off-peak grid and intermittent wind power is developed. The interaction of the energy system with the existing: Power grid infrastructure (in Ontario);—Natural Gas grid infrastructure (for hydrogen distribution in Ontario) is studied [1]. A Pricing Mechanism for Valuing Ancillary, Transportation and Environmental Services Offered by a Power-to-Gas Energy System is developed [16]. The benefit of accounting for uncertainty in electricity pricing and future zero-emission transportation sector by considering hydrogen demand that influence the operation of the power-to-gas energy hub is demonstrated in Ref. [17]. Benchmarking and selection of power-to-gas utilizing electrolytic hydrogen as an energy storage alternative is carried out in Ref. [17]. Decarbonizing transportation through the use of power-to-gas for oil refining operations is investigated in Ref. [18].

Assessing the feasibility of Methanation (Renewable Natural Gas) as a viable energy recovery pathway for power-to-gas energy systems and the integration of Renewable Natural Gas into the Natural Gas Distribution System as Renewable Natural Gas potential are the subjects of future projects.

17.6 Summary and Concluding Points

Power-to-Gas is a part of transition plan to sustainable low-carbon energy systems in order to respond the climate change. In this work, different potential alternatives of power-to-gas are presented and some limitations regarding the technology readiness are discussed. Hydrogen generated from clean sources of energy can be mixed with natural gas to make hydrogen-enriched natural gas to be injected in natural gas pipelines and utilized for different application. The hydrogen-enriched natural gas can be separated in to hydrogen and natural gas at the end-user to supply the hydrogen demand of transportation sector in the urban areas. Hydrogen can also be stored in underground in the existing infrastructure for seasonal energy storage. Different pathways of power-to-gas are discussed from economic and technical points of view. With this information, policy maker is able to develop energy policy transition plans and strategies towards a fossil-free economy. The use of electrolytic hydrogen from intermittent renewable energy sources and baseload nuclear power will provide needed energy storage and clean emissions free transportation fuels for the energy requirement of the future. More importantly, through the gradual implementation of electrolysis capacity, current energy needs and issues can be immediately addressed, while developing infrastructure capacity for the future.

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