Hydrogen Electricity Generation and Water Consumption Comparisons

Interim Report

Prepared by

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Disclaimer and Foreword

The report was prepared using the best available information in public resources on the various energy processes. The water consumed in energy processes is variable and technology dependent. The numbers shown in the report may differ from the actual plant numbers based on the technology variation being used. Water withdrawn is the total volume removed from a water source. A portion of this water is returned to the source and is reusable. Water consumed is the volume of water removed for use and not returned to its source. In this report, water consumption numbers are presented.

This Interim Report will be finalized by February 1, 2022, by adding description of process variability, comparison of a few more technologies and a complete bibliography.

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Executive Summary

Utah's fuel mix is changing. On a global basis, hydrogen is one of the emerging technologies. On a statewide basis, unique Utah resources can be leveraged in support of the emerging hydrogen technologies. Water consumption of electricity generation is a critical consideration for decision-making in Utah.

Electricity generation from hydrogen has three overall components: production, storage and (power) generation. Options for hydrogen production include steam methane reforming (SMR), coal gasification and electrolysis. Historically, SMR has been the most common process for producing hydrogen with coal gasification much less common. Electrolysis is the production process currently most associated with green hydrogen (very low to zero carbon dioxide emissions). Long-term storage is often desired for hydrogen applications. Utah's salt caverns offer a unique solution to the storage component of electricity generation from hydrogen. While not yet in place on a large-scale, power plants for hydrogen are anticipated to be very similar to power plants using natural gas.

The quantitative impacts to the state of Utah's water cycle were studied for a variety of conventional, renewable and hydrogen energy generation processes. Figure below shows the resulting water consumption of the electricity generation processes studied in this report. If hydrogen is generated using electrolysis, it is produced without any carbon dioxide generation.

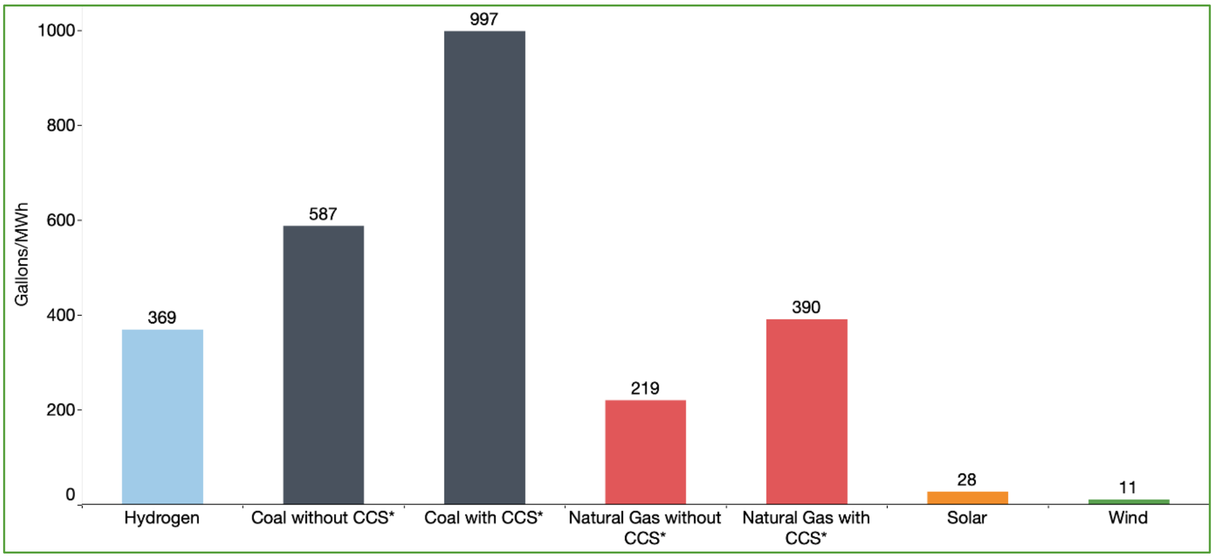

FIGURE: LIFE CYCLE WATER CONSUMPTION FOR VARIOUS GENERATION OPTIONS (*CCS REPRESENTS CARBON CAPTURE AND SEQUESTRATION). HYDROGEN IN THE ABOVE DIAGRAM IS PRODUCED BY ELECTROLYSIS USING RENEWABLE ENERGY.

Note that, in the figure above, carbon capture and sequestration (CCS) is included for both the coal and natural gas generation options shown. From a carbon perspective, CCS is required for an equivalent comparison with carbon-free power generation.

Nationwide, a number of coal-fired power plants are being transitioned to natural gas. The water consumption for a natural gas power plant is typically less than half that of a coal fired power plant. Hydrogen serves as an energy storage medium for excess renewable energy. In the hydrogen life cycle, excess renewable energy is converted to hydrogen which is stored and used during peak demand to generate electricity. The water consumption for hydrogen life cycle steps shown in the figure include water required for production of renewable energy (solar/wind), for electrolysis and long-term storage and for combustion to generate electricity. Water required for just the power plant operation component of the hydrogen life cycle is expected to be the same as or less than water required for the operation of a natural gas power plant.

Background and Introduction

Based on the data from the Energy Information Administration, coal fueled 61% of Utah's total electricity net generation in 2021 and natural gas accounted for 24%. Almost all of the rest of Utah's in-state electricity generation came from renewable energy sources, primarily solar power. Coal accounted for almost 75% of the fuel source used for electricity generation in Utah in 2016. Thus, the fuel mix for generating electricity is changing to ensure generation of low-carbon electricity.

Hydrogen is one of the emerging generation options for low-carbon electricity. For example, in the summer of 2021, the U.S. Department launched an initiative to reduce the cost of green hydrogen to $1 per kilogram of hydrogen by 2031. For an overall context, the expansion of the hydrogen economy is conceptualized in Figure 1.

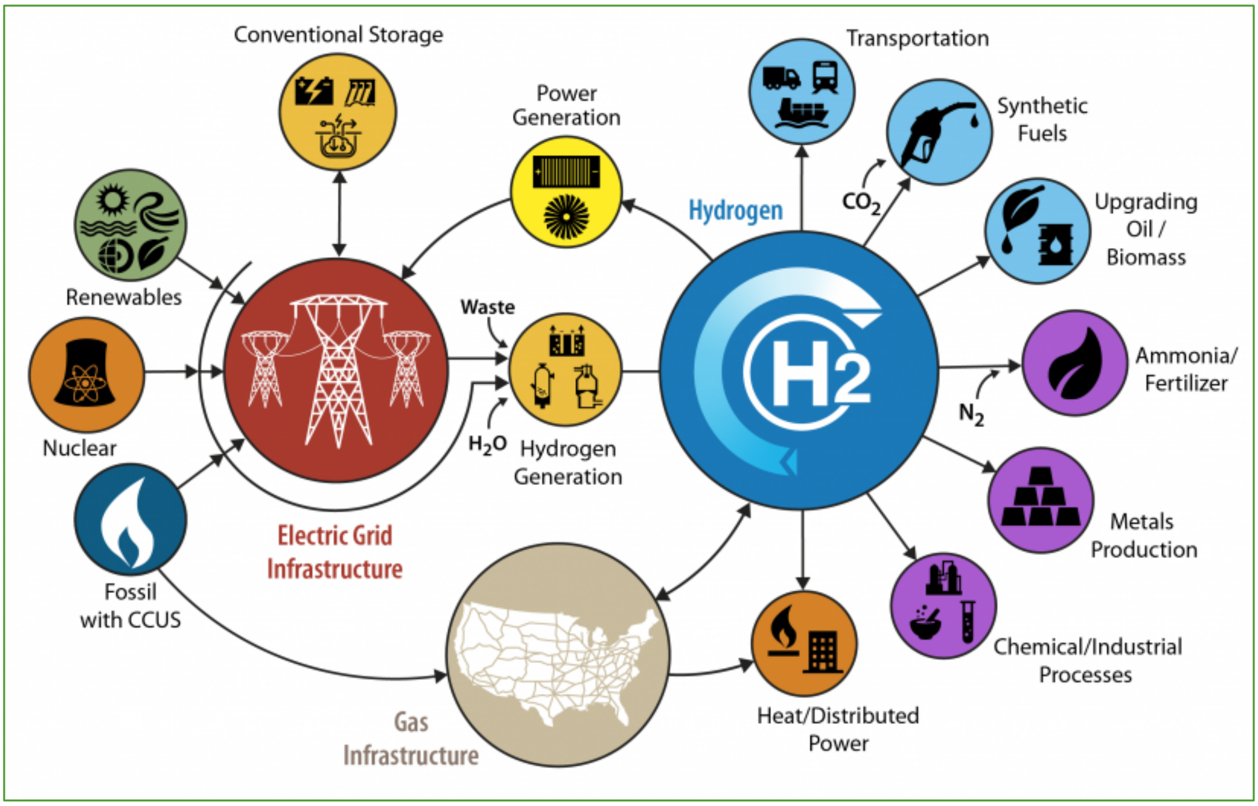

FIGURE 1: VARIOUS COMPONENTS OF THE HYDROGEN ECONOMY (FROM THE U.S. DEPARTMENT OF ENERGY)

Water is both used and produced in a number of hydrogen-related generation processes. This study first quantifies the amount of water usage for hydrogen production and consumption. For example, almost all of the hydrogen currently used in industrial processes is generated using methane steam reforming (SMR) process. SMR and its impact on water resources is included in this study.

This study considers the use of water for power in the context of water use for other conventional fuels – coal and natural gas. This study includes non-standard use of coal – coal gasification to produce hydrogen apart from the standard coal combustion. The use of water to generate 'green' hydrogen is also considered. Green hydrogen uses renewable forms of energy – solar and wind. Thus, the study will include water usage in producing electricity using wind and solar.

Hydrogen Electricity Generation and Water Use

Description

Figure 2 diagrams electricity generation from hydrogen. In summary, electricity generation from hydrogen has three components: ***production***, ***storage*** and ***electricity/power generation***. (As explained in this section, production can be achieved in various forms. Figure 2 represents production through the combined application of renewables and electrolysis.) Each component of the electricity generation from hydrogen is considered in this section.

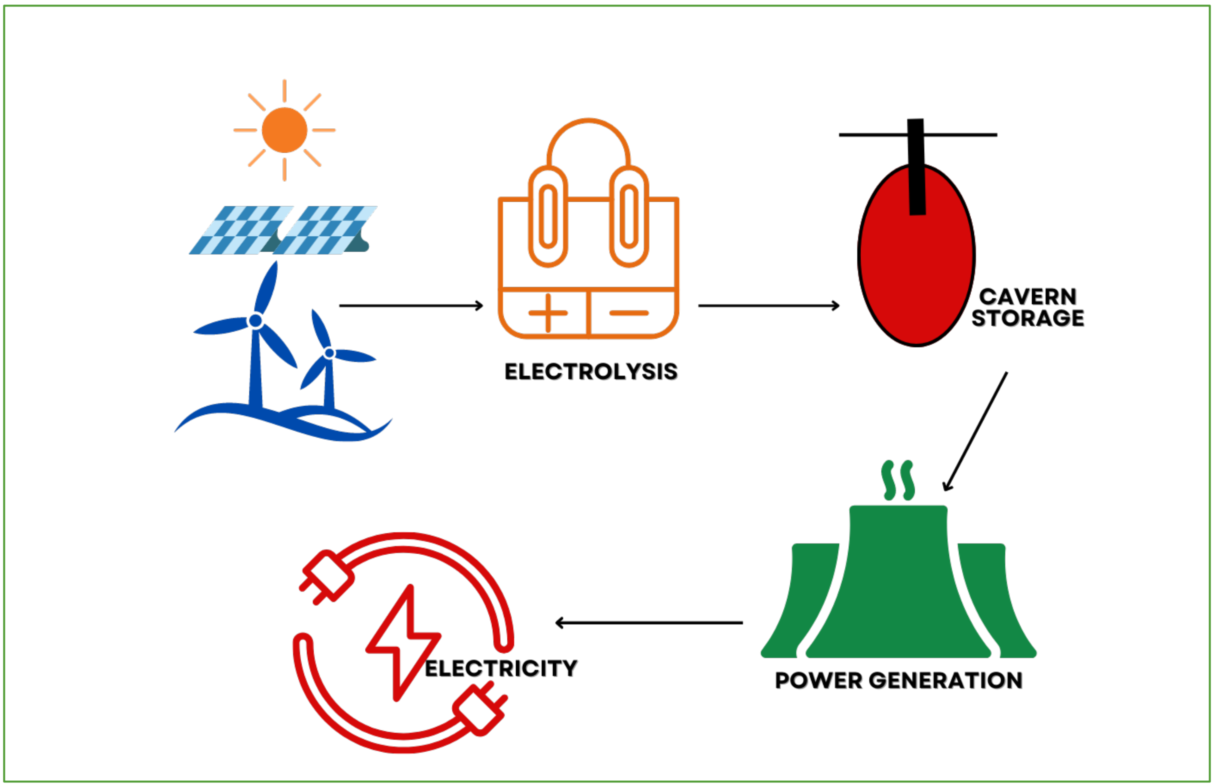

FIGURE 2: HYDROGEN ENERGY GENERATION PROCESS

Hydrogen Production

Hydrogen is not a primary fuel. Hydrogen may be produced from fossil fuels or from water by electrolysis. The concept of using hydrogen as a secondary fuel for transportation and for generating electricity has been discussed to accelerate the adoption of low carbon energy technologies. The increased attention that hydrogen energy has received in recent years is a result of the decreased cost of renewables. Hydrogen has a large energy density by mass but has very low energy density by volume. Hence, the energy per unit volume of hydrogen is much lower compared to liquid fuels or even natural gas.

Production pathways from fossil fuels and possible other solid feedstocks are shown in Figure 3. Hydrogen has been produced in large quantities for industrial use. The most common process for producing hydrogen is steam methane reforming (SMR). Hydrogen is used for the treatment of crude oil to remove sulfur, nitrogen and harmful metals. These hydrotreatment processes make production of clean diesel and gasoline possible.

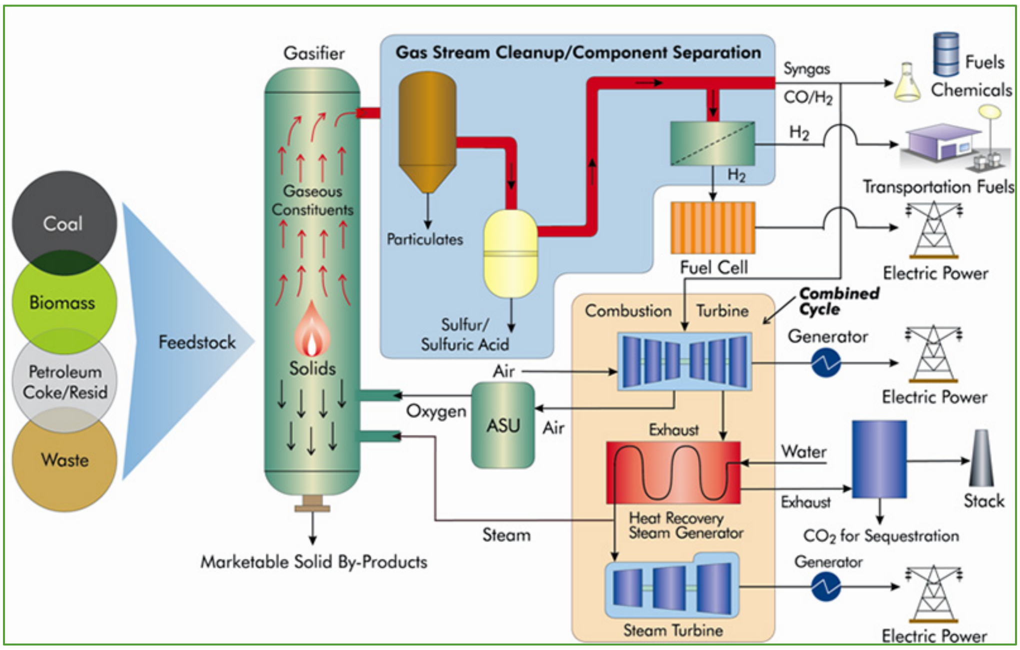

FIGURE 3: HYDROGEN PRODUCTION PATHWAYS. FROM THE U.S. DOE REPORT DOE/NETL-2022/3241.

Steam Methane Reforming

Steam methane reforming (SMR) is the most commonly used process for hydrogen production. It is a high-temperature process of methane with steam to produce hydrogen and carbon dioxide. There are other variations of the process. Autothermal reforming using partial oxidation of methane to supply the energy required for steam reforming which is highly endothermic (energy consuming process). Reactions that characterize steam reforming are shown below.

$$\text{Steam Reforming: } CH_4 + H_2O \rightarrow CO + 3H_2$$

$$\text{Water gas shift reaction:} CO + H_2O \rightarrow CO_2 + H_2$$

$$\text{Overall Reaction: } CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

The overall reaction indicates that *stoichiometrically*, SMR requires 4.5 times as much water as produced hydrogen by mass. All of the water consumption intensities are normalized to gallons of water per megawatt hour of energy produced. The theoretical minimum for steam methane reforming is 36 gal/MWh. The process of steam reforming will also require water for steam production and system cooling. How the process is managed affects water consumption. As a result, the total amount of water used for generating hydrogen by steam reforming varies. A reliable number for water consumption by steam reforming is 125 gal/MWh.

Coal Gasification

Coal gasification uses reactions of coal, oxygen and steam to produce hydrogen and carbon monoxide. A water gas shift reaction may be used to produce additional hydrogen and carbon dioxide. Coal gasification process is significantly more complicated than natural gas SMR and there are only a few hundred commercial/semi-commercial/demonstration facilities around the world. Complexity of a conceptual coal gasification plant is shown in Figure 4.

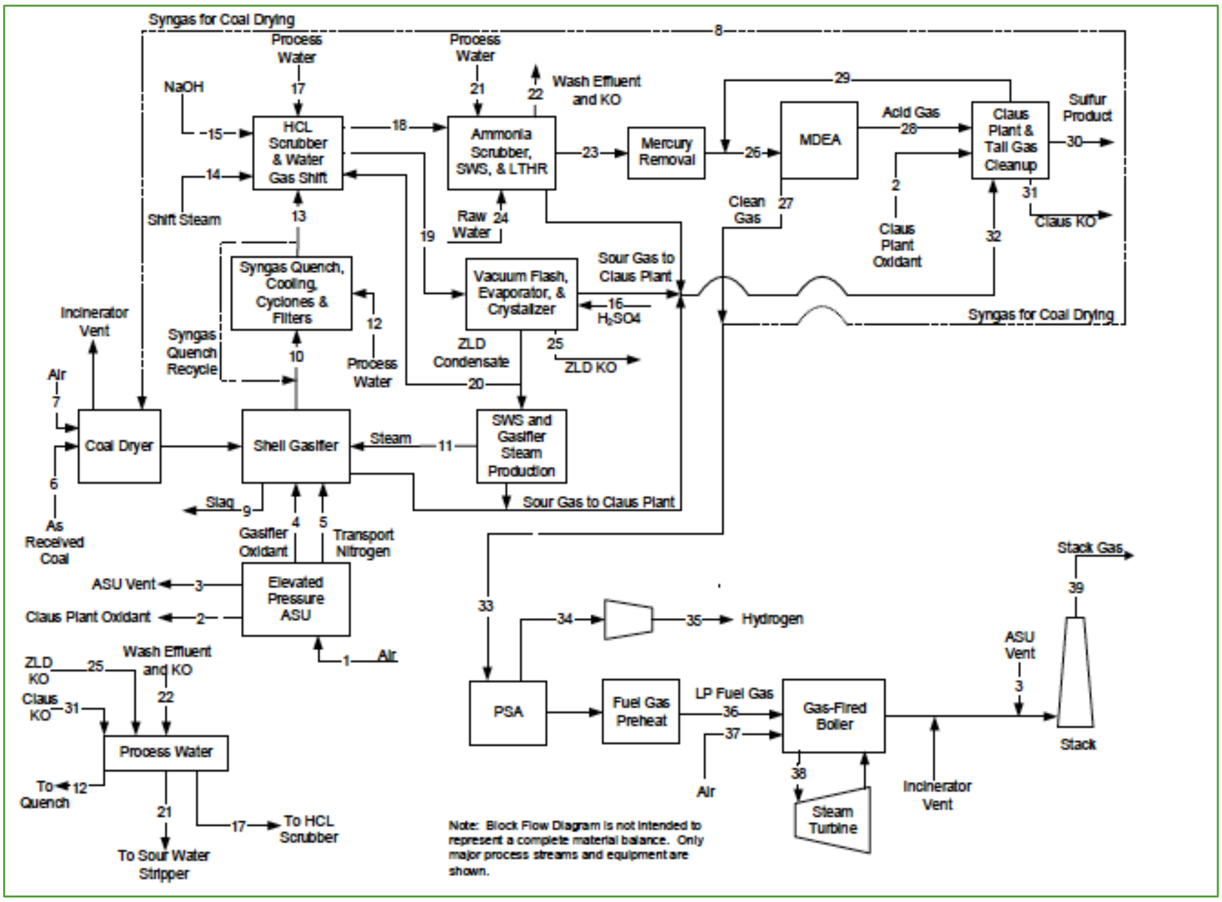

FIGURE 4: COAL GASIFICATION PROCESS FLOW DIAGRAM. DOE/NETL-2022/3241.

Water consumption for coal gasification is described in a detailed US Department of Energy's 2022 Report. For the plant shown in Figure 5, the water consumption is found to be about 165 gal/MWh.

Electrolysis

In electrolysis, electrical energy is provided to the electrolyzer. A schematic is shown in Figure 5. Reactions are described by:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

$$4H^+ + 4e^- \rightarrow 2H_2$$

$$\text{Overall Reaction: } 2H_2O \rightarrow O_2 + 2H_2$$

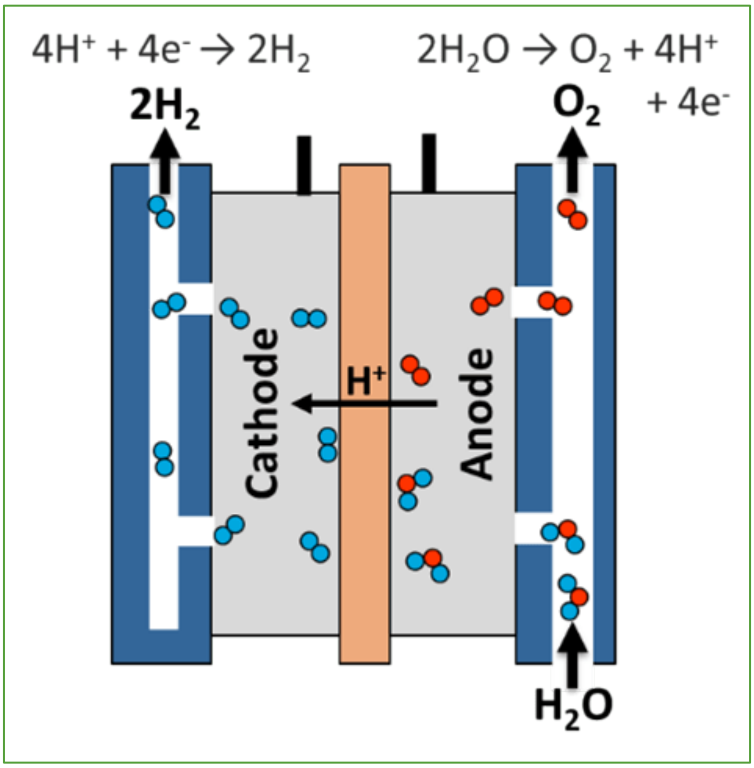

FIGURE 5: ELECTROLYSIS OF HYDROGEN. FROM U.S. DOE.

The stoichiometric water requirement of water for hydrogen production is 71 gal/MWh. It is recognized that there are several types of electrolysis systems. A proton exchange membrane electrolysis system is Shown in Figure 6.

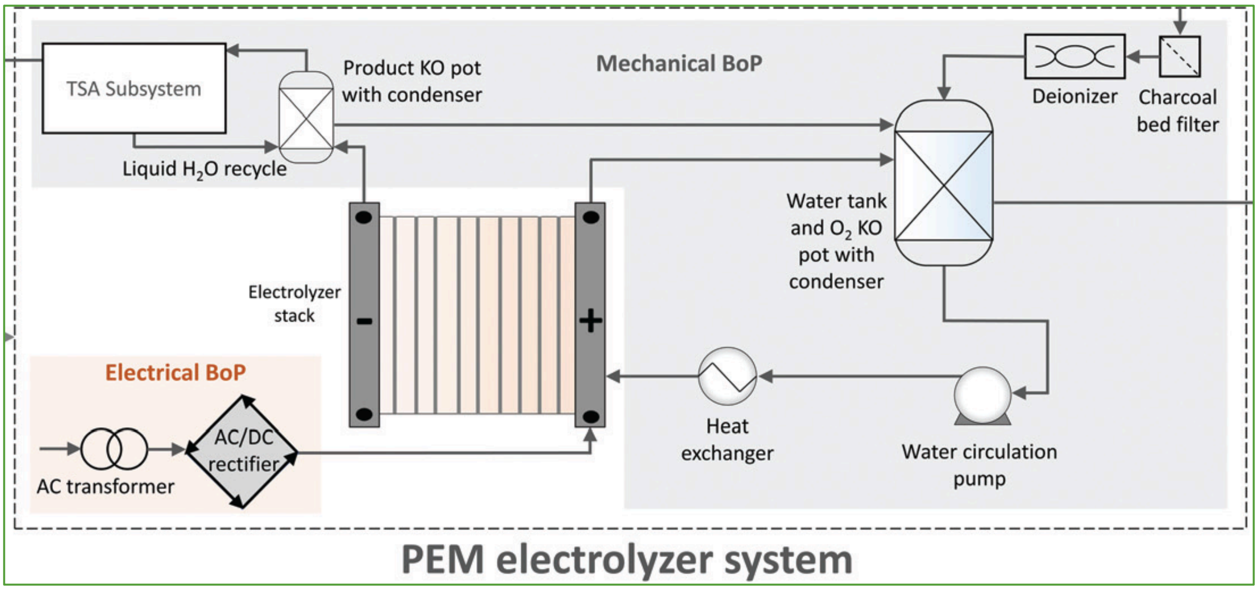

FIGURE 6: PROTON EXCHANGE MEMBRANE ELECTROLYSIS SYSTEM. FROM ENERGY ENVIRON. SCI., 2021, 14, 4831.

Water consumption for the overall electrolysis process and associated plant/facility is expected to be 4.1 gal/kg of hydrogen or 123 gal/MWh.

Comparison of water requirements for the three processes are compared in Figure 7. It should be pointed out that both coal gasification and steam methane reforming produce carbon dioxide, whereas electrolysis does not.

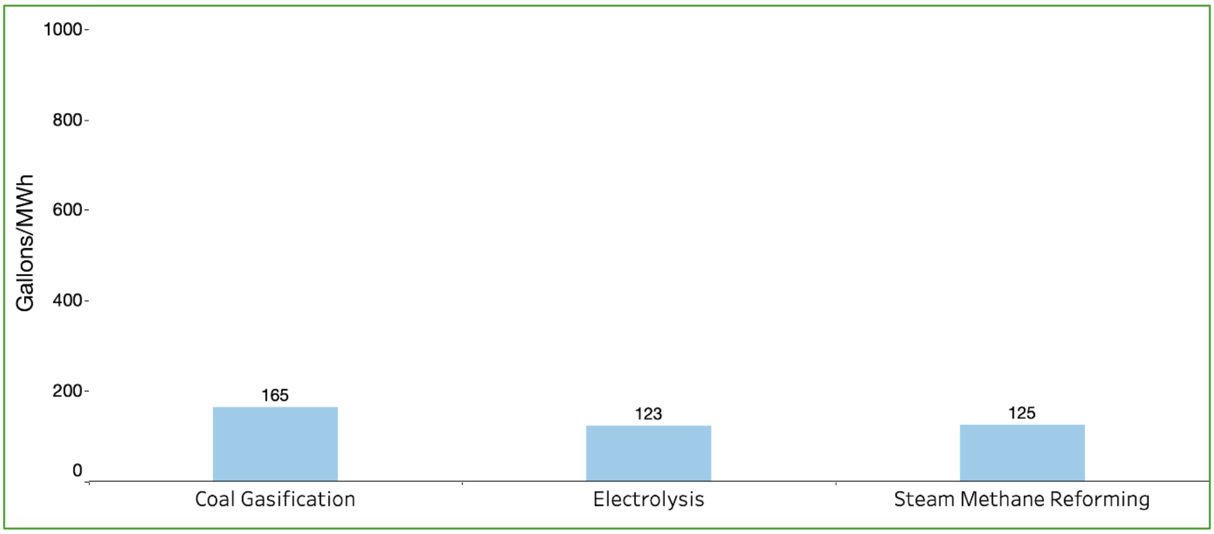

FIGURE 7: COMPARISON OF WATER CONSUMPTION FOR HYDROGEN PRODUCTION METHODS

Hydrogen Storage

Hydrogen produced may be used to for industrial use, transportation or for generating electricity via fuel cells and hydrogen turbines. A number of storage options and technologies are being developed. In most cases, long-term storage of hydrogen is desired. Salt caverns have been used for petroleum and petroleum product storage successfully. In fact, the strategic petroleum storage of millions of barrels of crude oil and petroleum products is inside large salt caverns on the Louisiana coast. A salt cavern is shown schematically in Figure 8. Salt cavern storage is considered to be the most viable option for long-term commercial-scale storage of hydrogen.

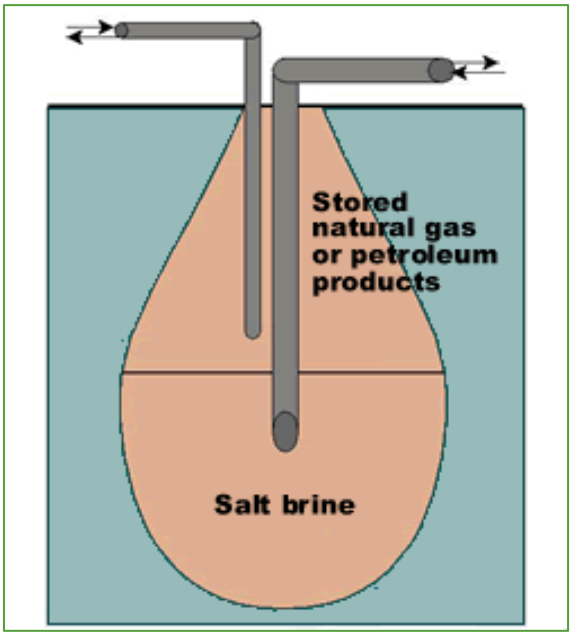

FIGURE 8: SALT CAVERN SCHEMATIC

Salt Caverns may come in various shapes and the storage may be at different depths. Salt is leached out using fresh water, and in creating the salt cavern there is 'one-time' consumption of water.

Salt dome storage of petroleum or natural gas that is currently practiced. Hydrogen storage is planned in salt domes created using a similar technology. Once salt caverns are created they last over several decades. Using a set of reasonable assumptions, and the use of four caverns over a 50-year period, the water intensity was calculated at 15 gallons/MWh.

Electricity from Hydrogen

Large-scale hydrogen power plants are not in operation. The power plants are similar in nature to natural gas power plants. A hydrogen power plant water consumption will depend on the cooling type employed. When considering the water consumption related to the operation life cycle stage for a hydrogen power plant, the water consumption is expected to be similar to that of natural gas. That is, 210 gal/MWh. Thermal conversion efficiencies of combined-cycle natural gas plants are about 60%. Efficiencies of plants with hydrogen as fuel are expected to be higher because of higher temperatures. Commercial hydrogen power plants are just beginning to be built and there is not a lot of data on hydrogen power plants. It is safe to assume that hydrogen power plants will have at least the efficiency of natural gas power plants or higher.

Water Consumption

The life cycle of energy generation is categorized into three stages: fuel cycle, operation and power plant. Summarizing the information from above, Figure 9 displays the hydrogen generation life cycle.

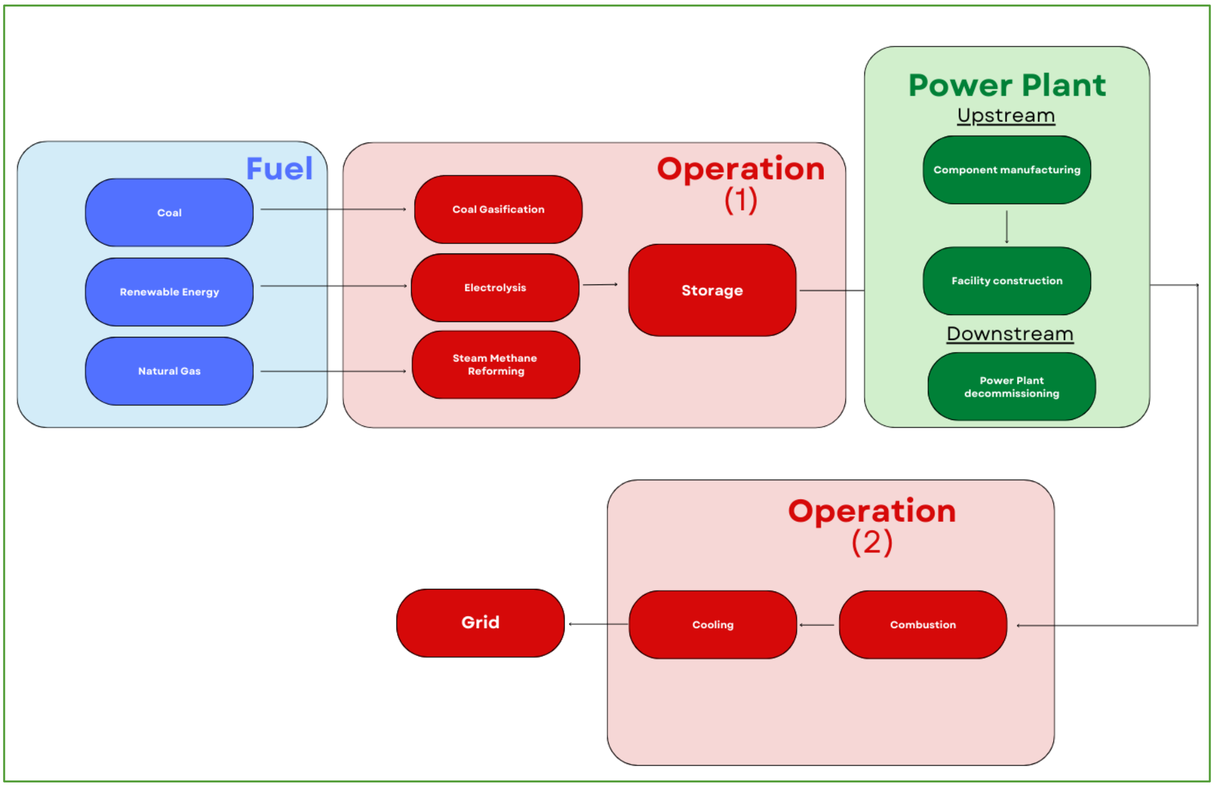

FIGURE 9: LIFE CYCLE FOR GENERATION FROM HYDROGEN

Summarizing the information presented previously in this report, Figure 10 displays water consumption for each of life cycle stage related to electricity generation by hydrogen - as well as the total life cycle of generation from hydrogen. The life cycle stages for the Figure 10 reflects the components of "green" hydrogen generated using renewable energy fuel and electrolysis production. Note that water consumption is defined as water not returned to the source of the water following use/application. The water consumption (in gallons) is normalized based on the electricity generated (in megawatt-hours).

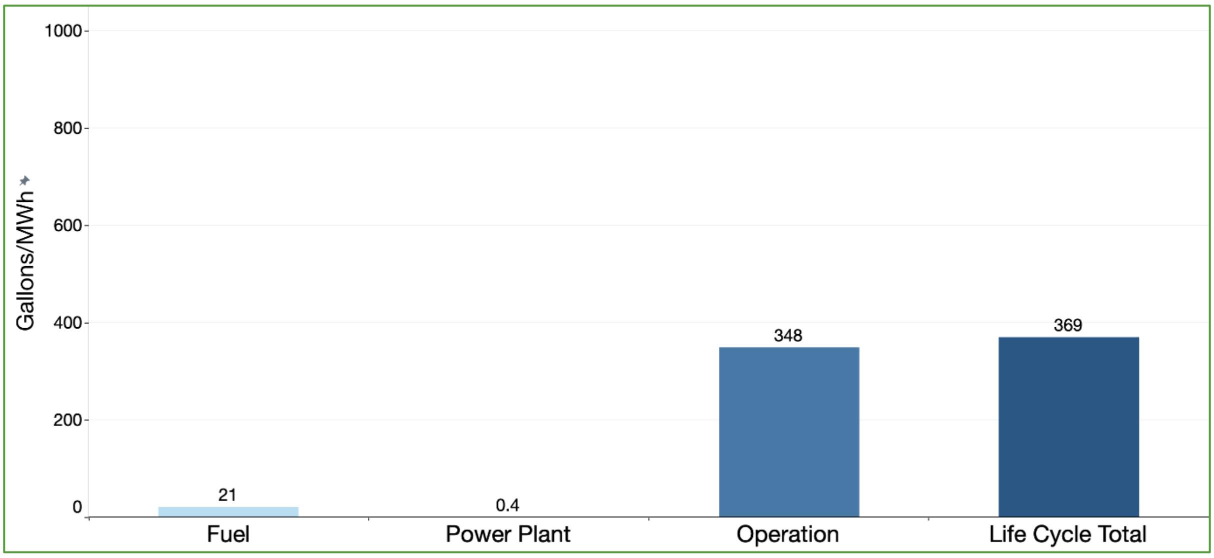

FIGURE 10: HYDROGEN GENERATION WATER CONSUMPTION. OPERATION INCLUDES ELECTROLYSIS, STORAGE AND COMBUSTION.

Water Consumption Comparisons

Conventional Electricity Generation and Water Consumption

Coal

Basic Generation Description

As shown in Figure 11, the life cycle of electricity generation from coal begins with mining and continues through to the point of generation, including steps for transportation, combustion, and plant construction/operation/decommissioning in the cycle. Pulverized coal (PC) is the most common technology for energy generation from coal. The process of using pulverized coal in a combustion power plant consist of burning coal to produce steam using a pulverized coil boiler. A steam turbine is then connected to a generator to produce electricity.

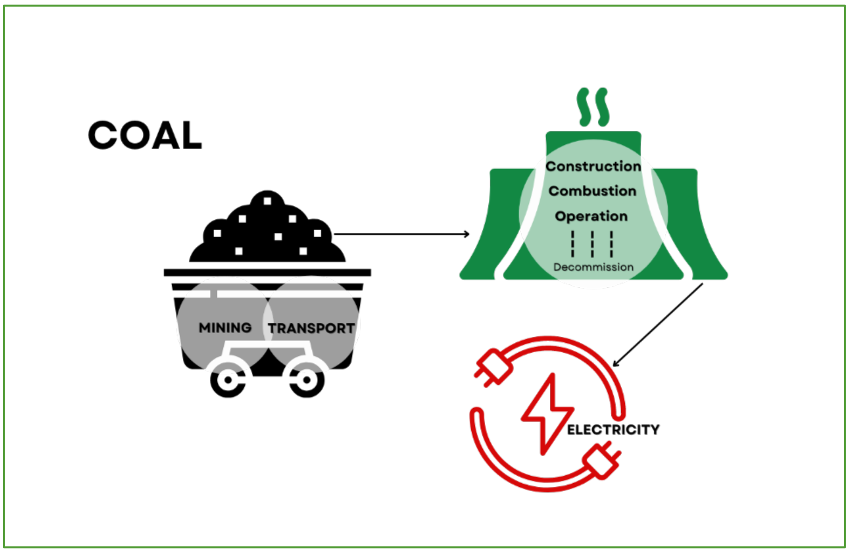

FIGURE 11: COAL GENERATION PROCESS

Water Consumption

The life cycle of energy generation is categorized into three stages: fuel cycle, operation and power plant. Figure 12 displays the coal generation life cycle.

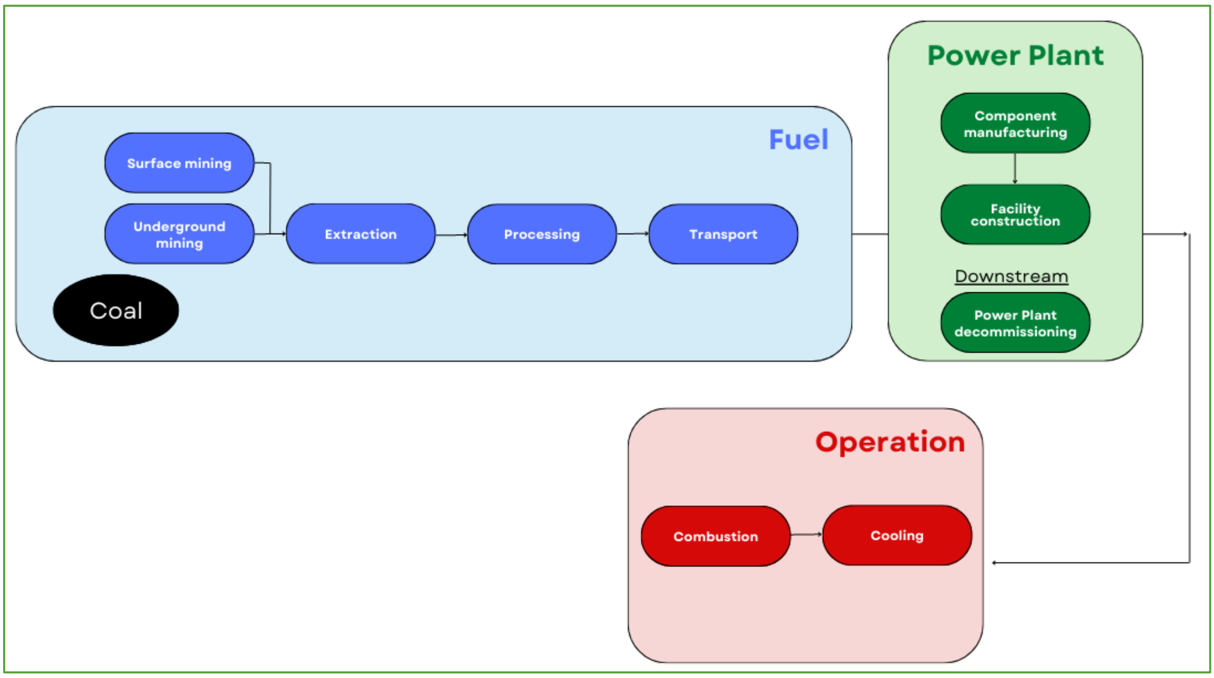

FIGURE 12: LIFE CYCLE FOR GENERATION FROM COAL

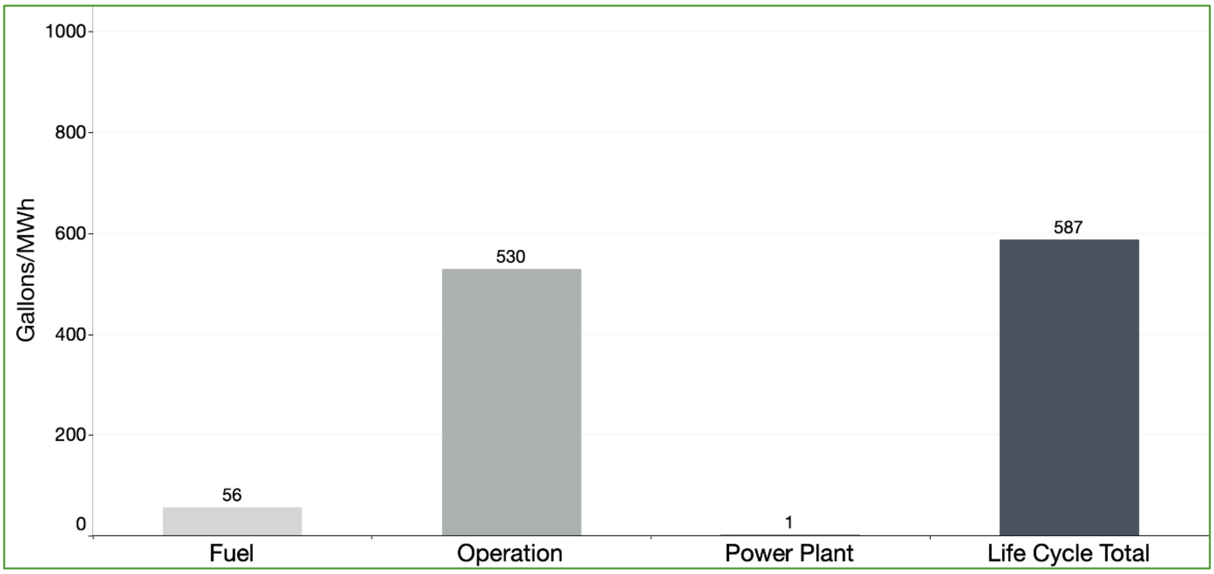

FIGURE 13: COAL GENERATION WATER CONSUMPTION

Figure 13 displays water consumption for each of life cycle stage related to electricity generation by coal - as well as the total life cycle of generation from coal. Water consumption is again defined as water not returned to the source of the water following use/application. Similar to hydrogen earlier in this report, the water consumption (in gallons) is normalized based on the electricity generated (in megawatt-hours). For example, at the power plant, water is consumed in cooling the steam. Water is also consumed to control emissions, for dust control purposes and to treat solid waste generated in the process.

Figure 14 displays water consumption for the life cycle stages of generation from coal using carbon capture and sequestration (CCS). From a climate perspective, coal electricity generation with CCS is more equivalent to hydrogen generation (compared to coal generation without CCS). As demonstrated when comparing Figures 13 and 14, water consumption noticeably increases with the inclusion of CCS.

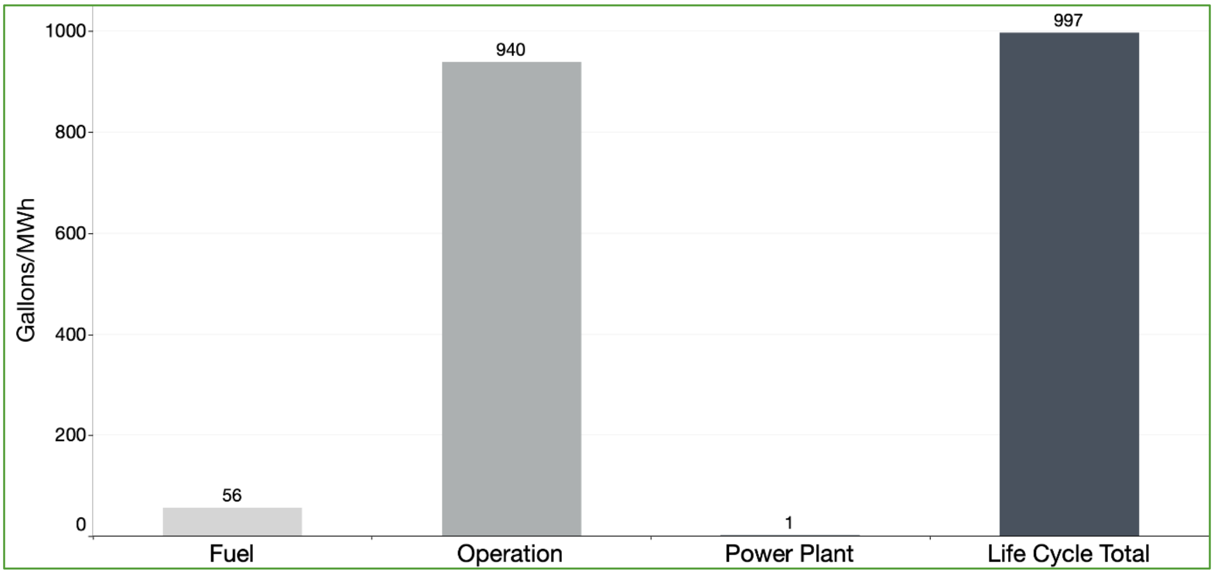

FIGURE 14: COAL GENERATION WITH CCS WATER CONSUMPTION

Natural Gas

Basic Generation Description

Figure 15 diagrams the basic process of electricity generation from natural gas using a combined-cycle. In a natural gas combined-cycle power plant, a gas turbine and a steam turbine produce electricity. The gas turbine generates electricity and the waste heat (from the gas turbine) is used to drive a steam turbine (that also generates electricity).

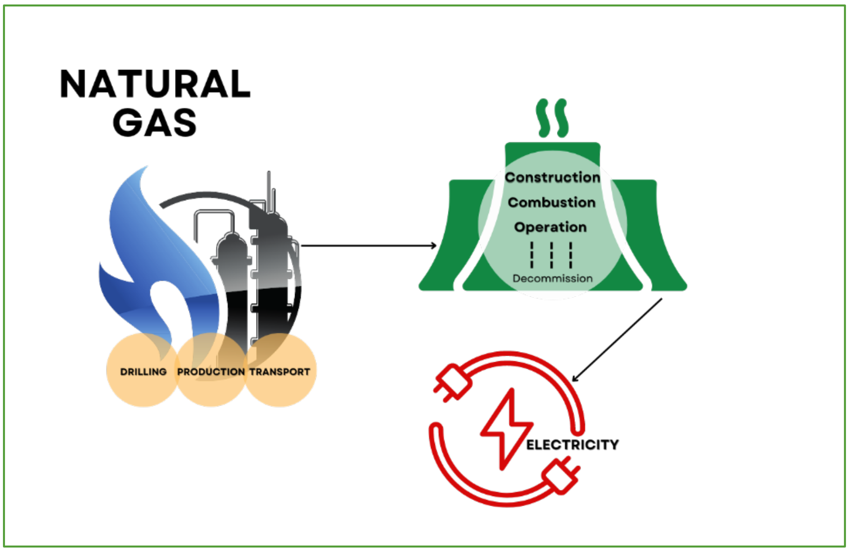

FIGURE 15: NATURAL GAS GENERATION PROCESS

Water Consumption

Figure 16 displays the natural gas generation life cycle.

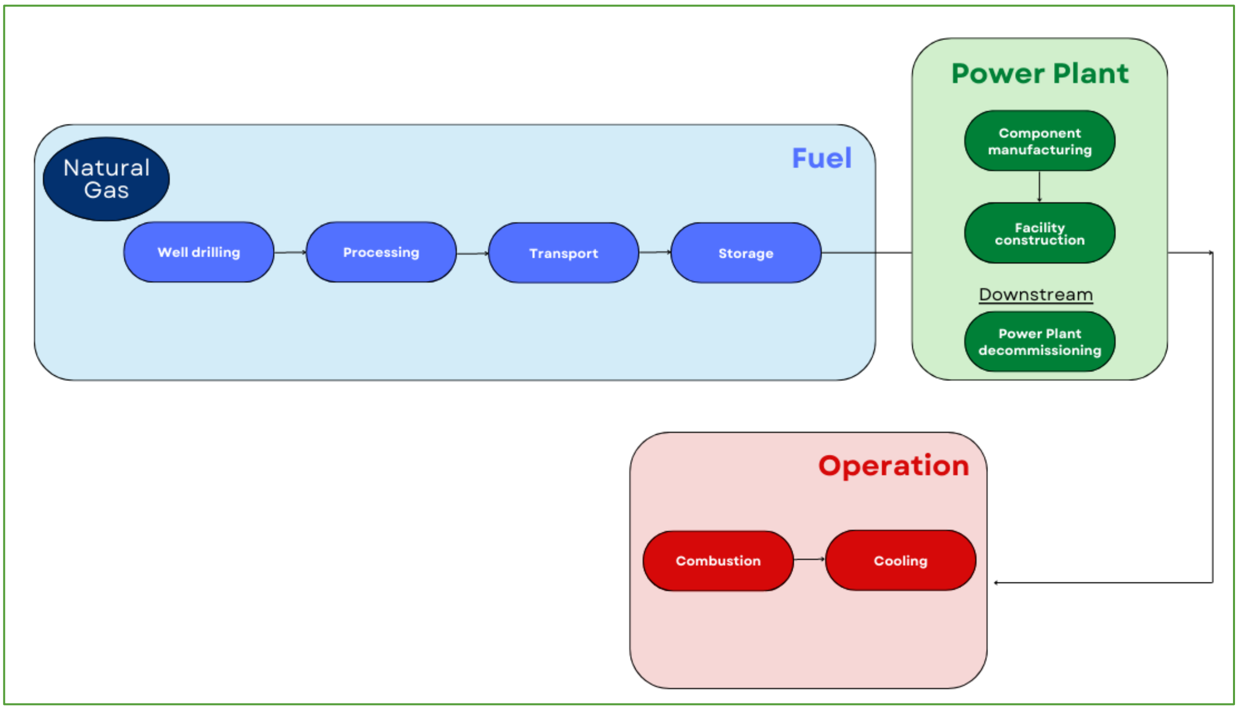

FIGURE 16: LIFE CYCLE FOR GENERATION FROM NATURAL GAS

Figure 17 displays water consumption for the life cycle stage generation from natural gas. For example, water is used to extract natural gas from an underground source. Water is also used in combusting natural gas into electricity.

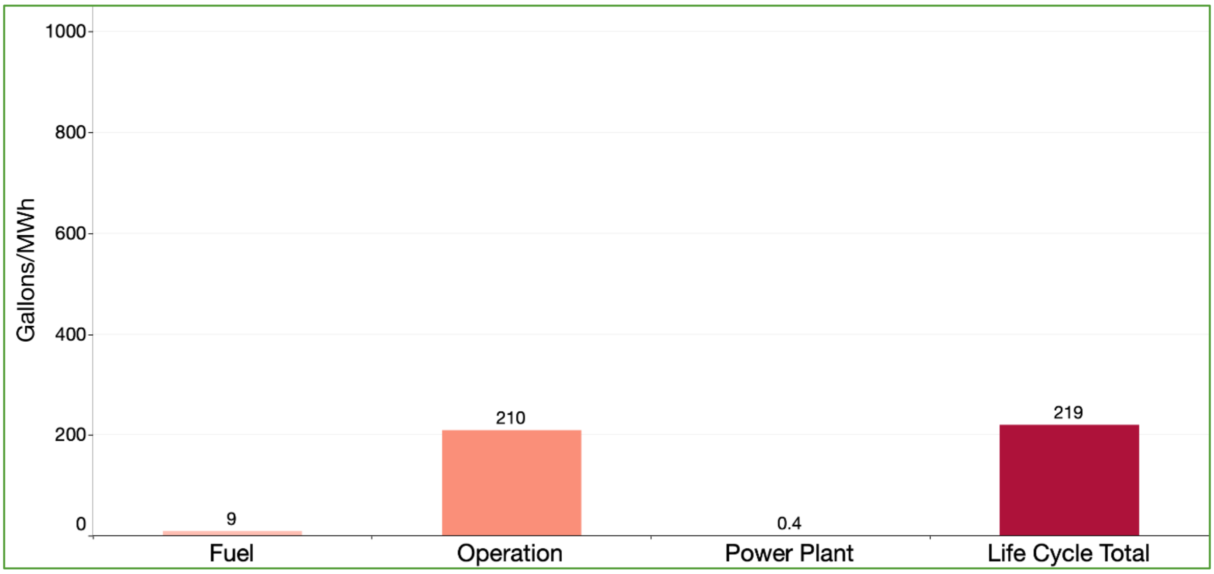

FIGURE 17: NATURAL GAS WATER CONSUMPTION

Figure 18 displays water consumption for the life cycle stages of generation from natural using CCS. Like coal, natural gas generation with CCS is more equivalent to hydrogen generation (compared to natural gas generation without CCS) from a climate perspective. As demonstrated when comparing Figures 17 and 18, water consumption increases by adding CCS.

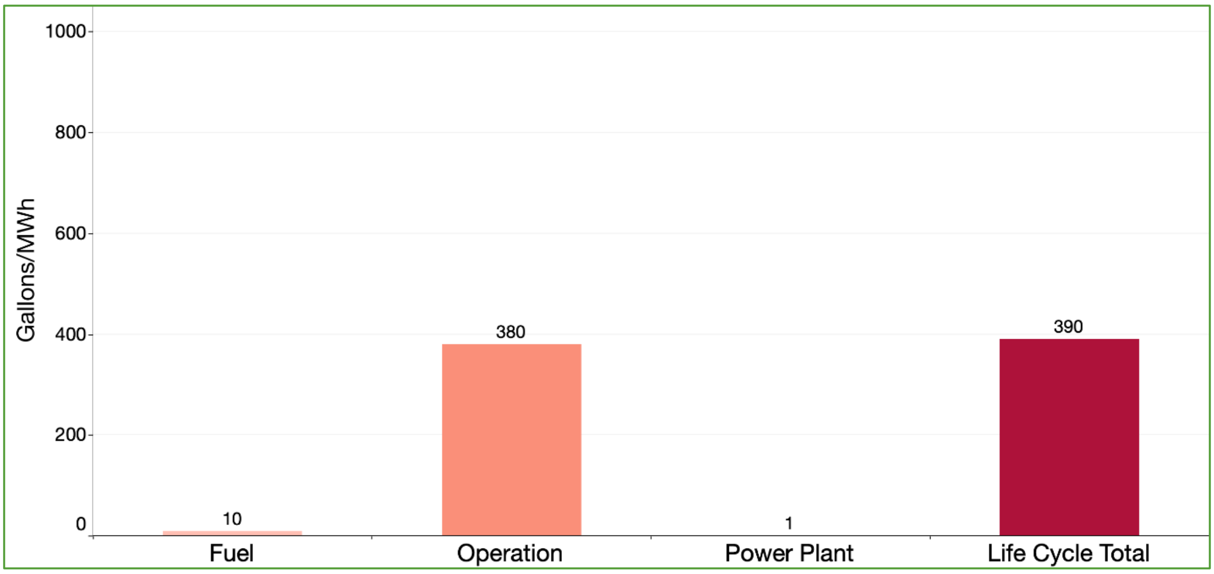

FIGURE 18: NATURAL GAS WITH CCS WATER CONSUMPTION

Renewable Electricity Generation and Water Use

Solar Energy

Basic Generation Description

Figure 19 diagrams the basic steps of electricity generation from solar energy. Solar electric, or photovoltaic, cells convert sunlight in direct current (DC) electricity.

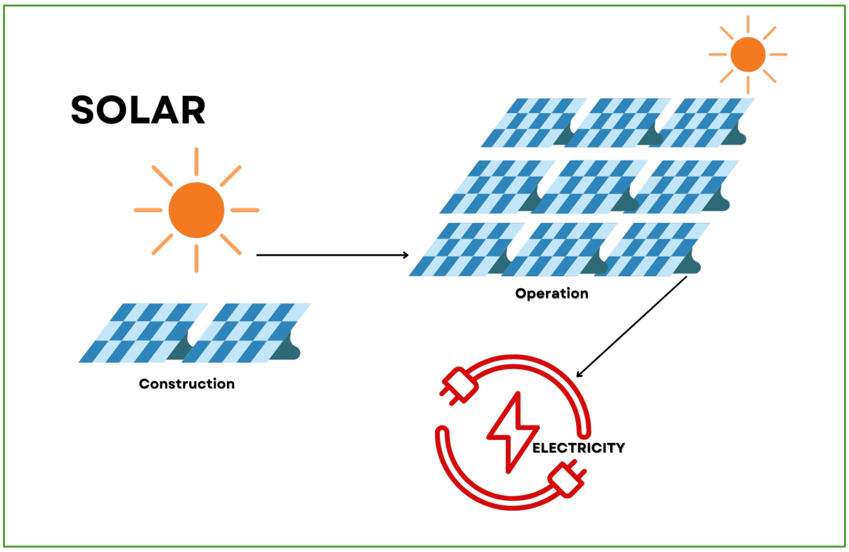

FIGURE 19: SOLAR ENERGY GENERATION PROCESS

Water Consumption

Figure 20 displays the solar energy generation life cycle. Note that fuel cycle stage is not applicable for this generation type.

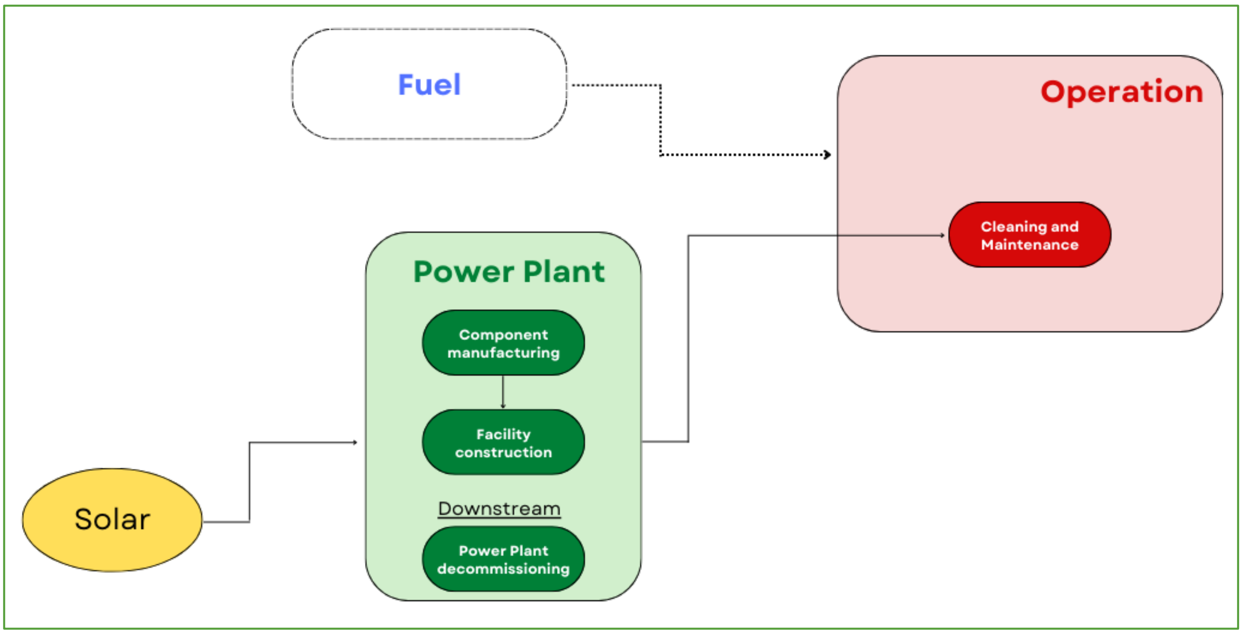

FIGURE 20: LIFE CYCLE FOR SOLAR ENERGY GENERATION

Figure 21 displays water consumption for the life cycle stage of generation from solar. For example, water is consumed in the production and field maintenance of photovoltaic cells.

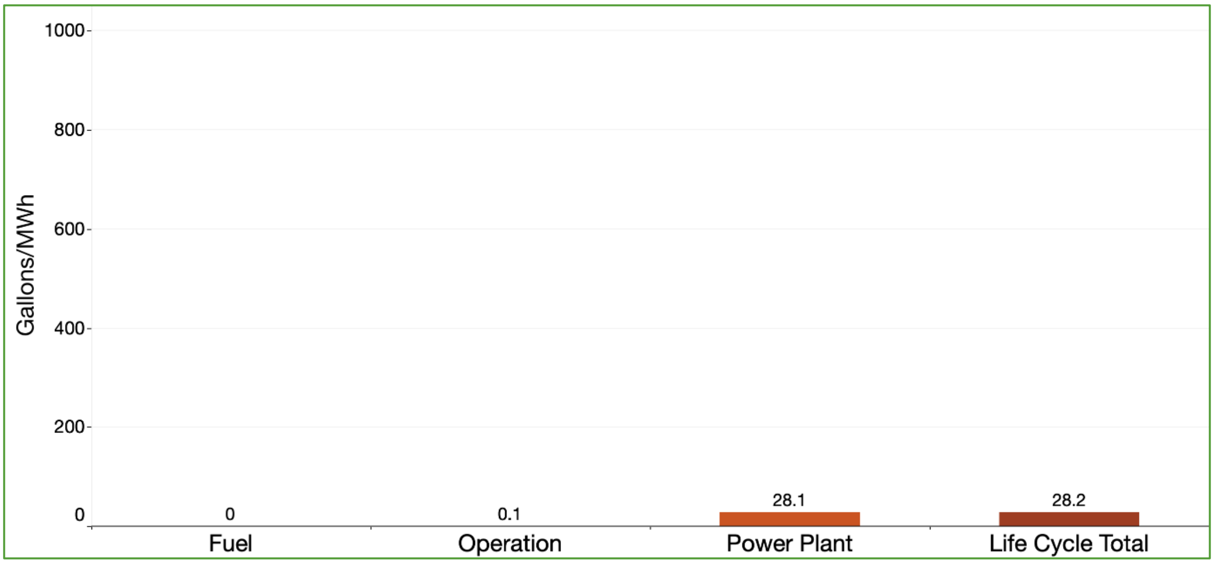

FIGURE 21: SOLAR ENERGY GENERATION WATER CONSUMPTION

Wind Energy

Basic Generation Description

Figure 22 diagrams the basic steps of electricity generation from wind energy. At the plant, wind turns the blades of a wind turbine around a rotor - which drives a generator to create electricity.

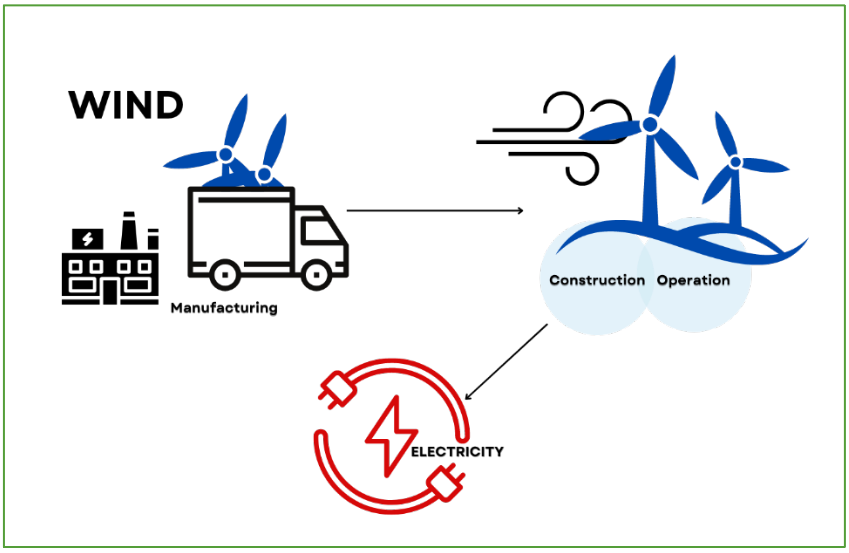

FIGURE 22: WIND ENERGY GENERATION PROCESS

Water Consumption

Figure 23 displays the wind energy generation life cycle. Like solar, the fuel cycle stage is not applicable for this generation type's life cycle.

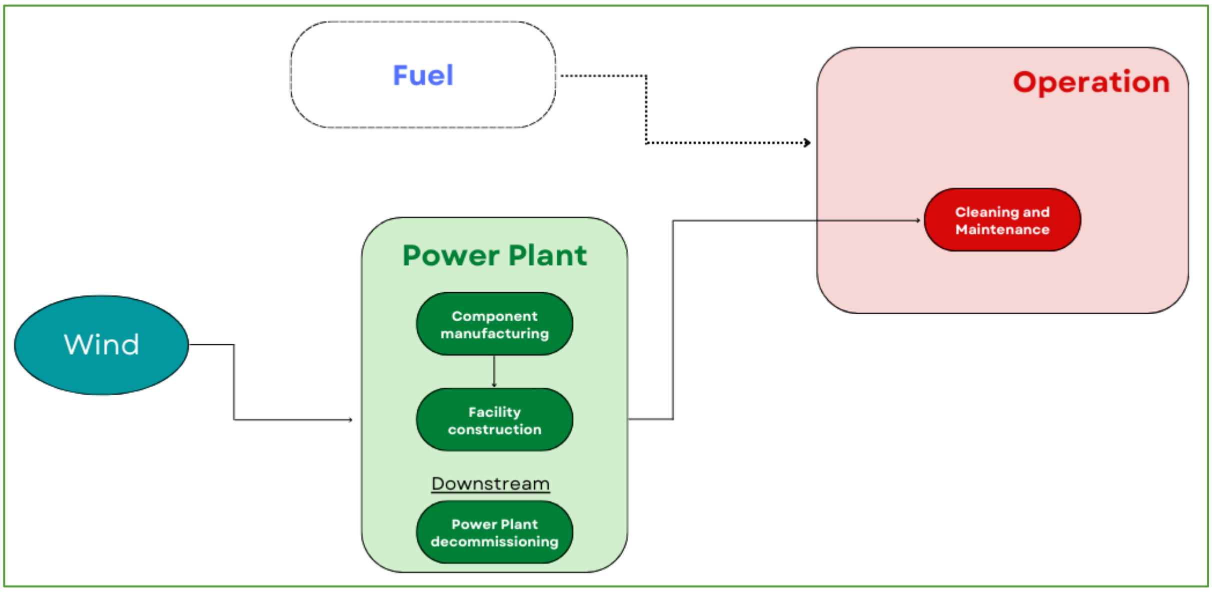

FIGURE 23: LIFE CYCLE FOR WIND ENERGY GENERATION

Figure 24 displays water consumption for the life cycle stage of generation from wind. For example, water is consumed in the production and field maintenance of wind turbine blades.

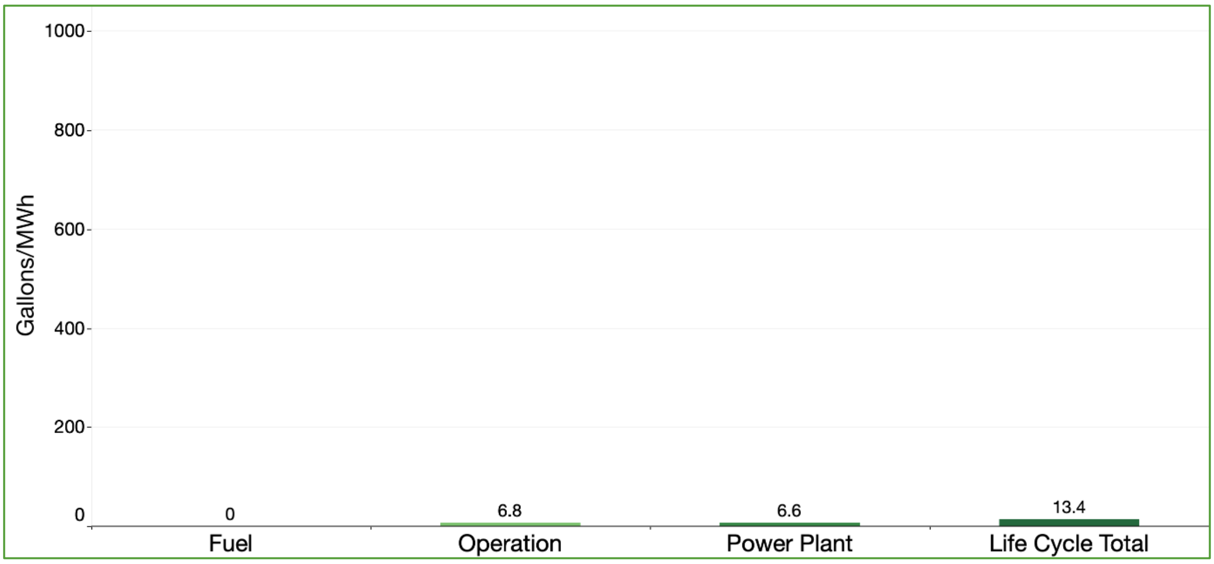

FIGURE 24: WIND ENERGY GENERATION WATER CONSUMPTION

Operation Life Cycle Stage Water Consumption

Summarizing related data previously presented, Figure 25 compares water consumed in the operation life cycle stage for various electricity generation processes.

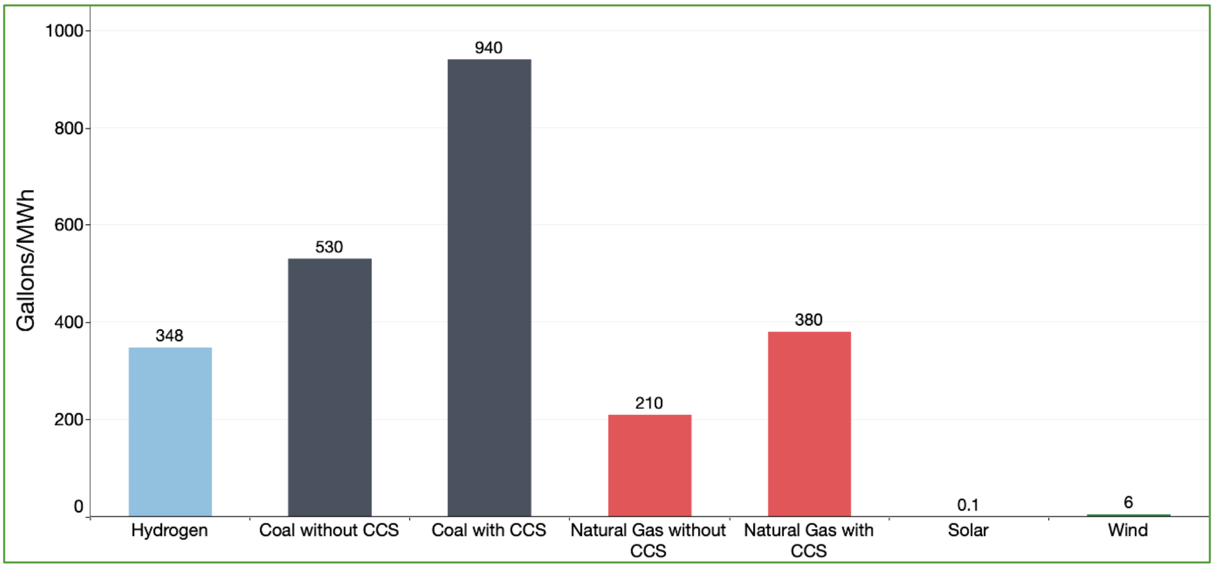

FIGURE 25: WATER CONSUMED IN POWER PLANT OPERATIONS

Summary and Next Steps

Summarizing the data previously presented, Figure 26 shows the resulting water consumption of the electricity generation processes. (*As noted previously, CCS in the figure represents carbon capture and sequestration.)

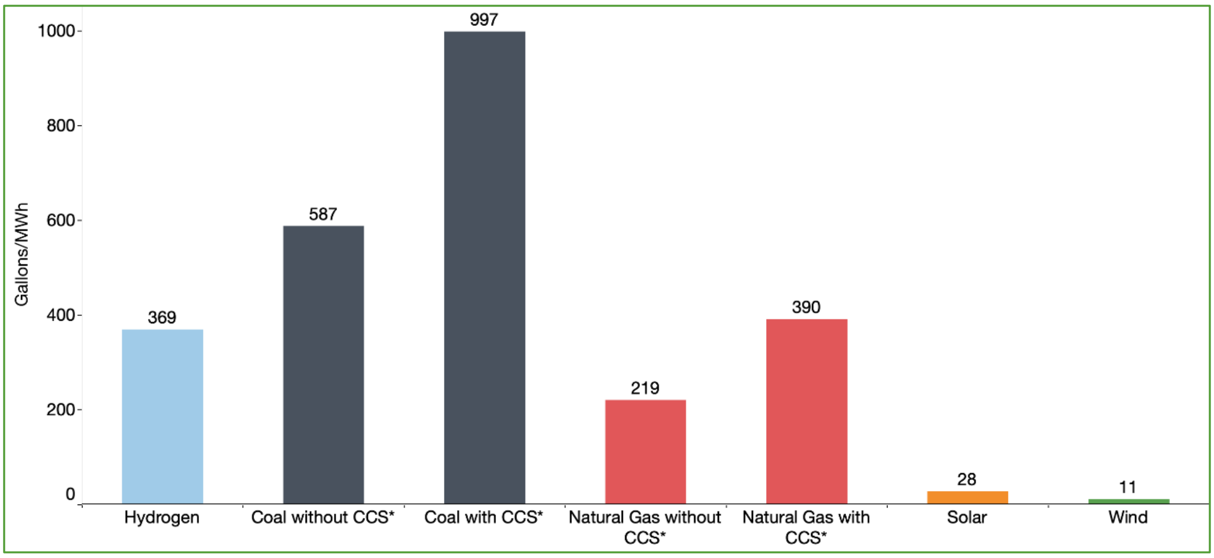

FIGURE 26: LIFE CYCLE WATER CONSUMPTION FOR VARIOUS ENERGY GENERATION OPTIONS

As previously noted, the fuel mix in Utah for generating electricity is changing. One part of this change is the reduction of water consumption related to electricity generation processes. Like natural gas, hydrogen generation technologies represent a reduction in water consumption compared to the fuel mix historically used in Utah. When considering the values of the above figure, the water consumption of hydrogen generation technologies are very much in line with generation technologies that are a part Utah's current and future fuel mix.

Water consumption numbers provided in this report are technology dependent (the type of cooling used in the process, etc.). There is also regional and process variability. This Interim Report will be finalized by providing more detailed information on water consumption when using different technologies. Non-consumptive water use will be provided where applicable. Variability in water use observed will also be documented. A comprehensive list of references and resources will be provided.

Finally, future study is recommended to holistically consider hydrogen generation aspects that will impact decision-making for Utah's future fuel mix. Of particular importance is the consideration of nuclear energy, impact of processes on air emissions and overall process economics.

Definitions

CCS: Carbon capture and sequestration, or CCS, is a set of technologies that capture, transport and inject the carbon generated from various processes (e.g., power plants) into underground storage.

Life cycle: The life cycle of energy generation is categorized into three stages: ***fuel cycle***, ***operation*** and ***power plant***. The ***fuel cycle*** category involves any related production and processing. ***Operation*** involves steps related to energy conversion and post-conversion. ***Power plant*** involves any activities related to the plant beyond those related to energy conversion/post-conversion, including plant construction, plant decommissioning and production of related materials.

Water consumption: As opposed to ***water withdrawal***, water that is consumed is not returned to the source of the water following use/application.

SMR: Steam-methane reforming, or SMR, is a hydrogen production process and consumption. For example, almost all of the hydrogen currently used in industrial processes is generated using methane steam reforming (SMR) process

Green, blue and grey hydrogen: Hydrogen is often referenced according to the fuel source used in production. For example, the production of ***green hydrogen*** uses renewable energy as its fuel source. The fuel source for ***blue hydrogen*** is most commonly defined to be natural gas with CCS. ***Grey hydrogen*** uses fossil fuels.

Primary fuel: Fuels found as a natural resource. These fuels are fully collected and processed prior to use (i.e., conversion into energy).

Secondary fuel: Fuels <u>not</u> found as a natural resource. Primary fuels are used to generate secondary fuels.