Water for Power Study

Final Report – February 2023

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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.

Contents

List of Figures

List of Tables

Executive Summary

Utah's fuel mix is changing. On a global basis, hydrogen is an emerging technology for electricity generation. On a statewide basis, unique Utah resources can be leveraged in support of emerging hydrogen technologies. Water consumption of electricity generation is a critical consideration for decision-making in Utah, and the Utah legislature commissioned this study for context on the effect of hydrogen production and power generation on the water cycle.

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 while coal gasification is 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. In the hydrogen life cycle, excess renewable energy is converted to hydrogen which is stored and used during peak demand to generate electricity. 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, including withdrawal and consumption, were compared for a variety of conventional, renewable and hydrogen energy generation processes. The first figure below shows the resulting water withdrawal of the electricity generation processes studied in this report.

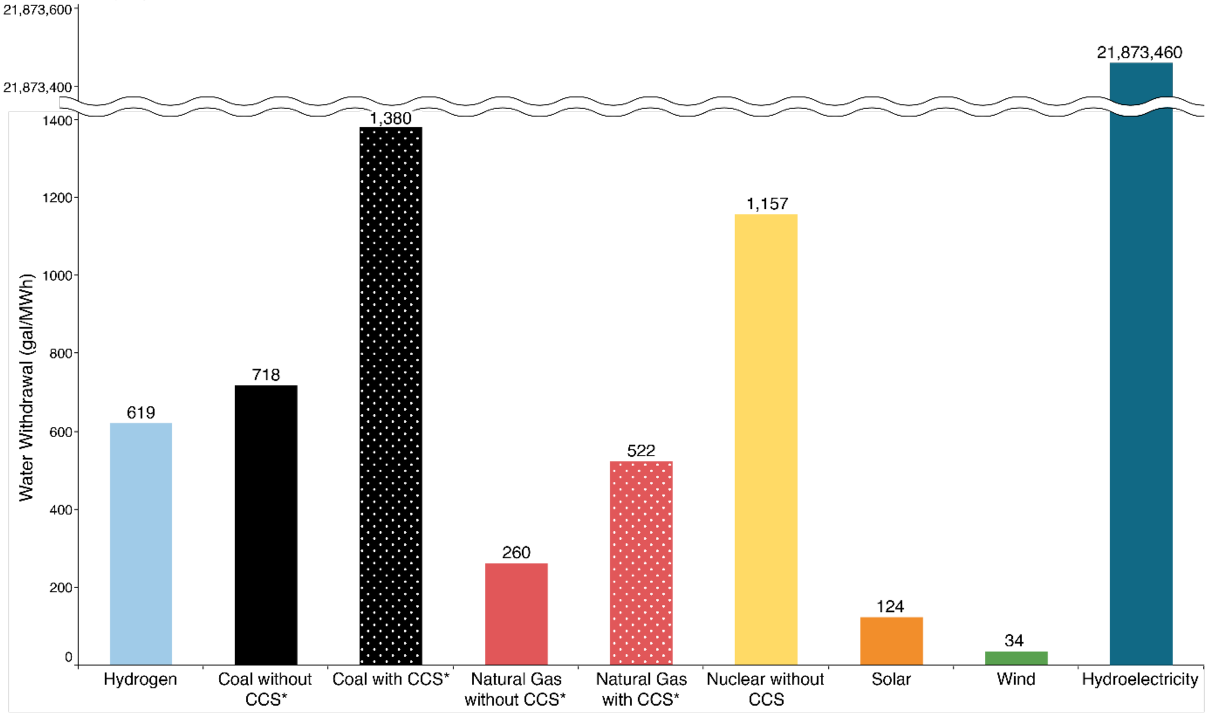

FIGURE: LIFE CYCLE WATER *WITHDRAWAL* FOR VARIOUS GENERATION OPTIONS (*CCS REPRESENTS CARBON CAPTURE AND SEQUESTRATION). HYDROGEN IN THE ABOVE DIAGRAM IS PRODUCED BY ELECTROLYSIS USING RENEWABLE ENERGY.

The next figure shows the resulting water consumption of the electricity generation processes studied in this report.

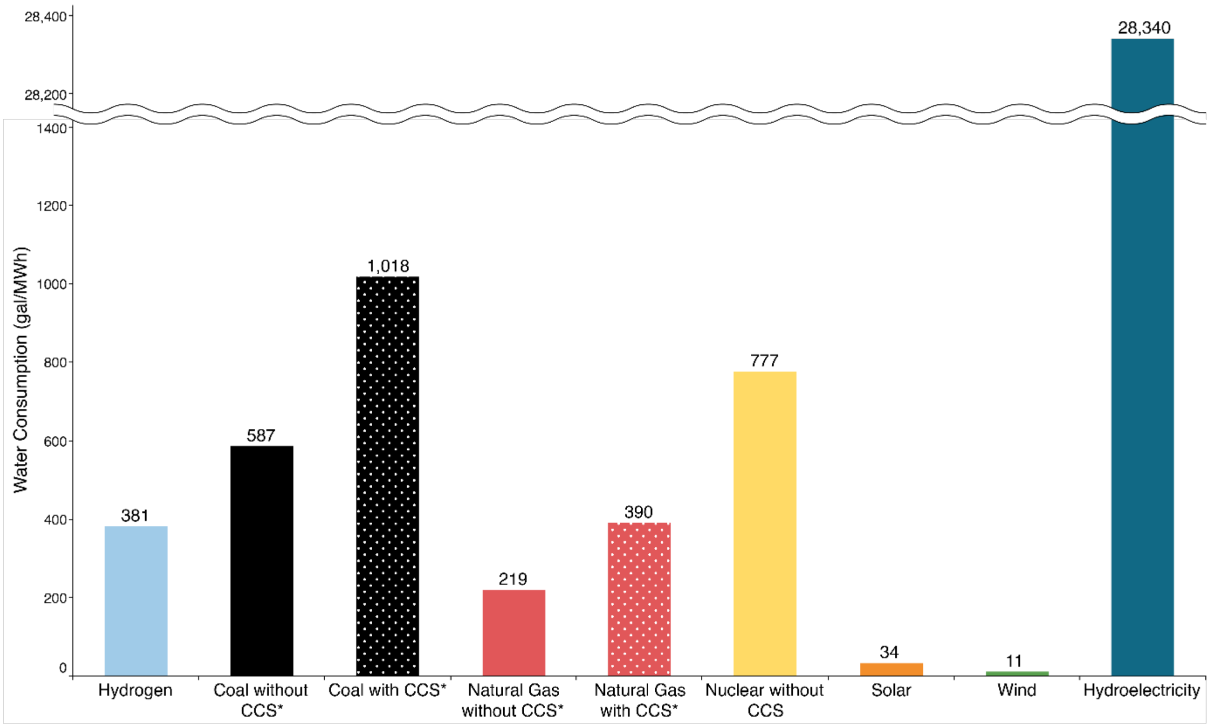

FIGURE: LIFE CYCLE WATER *CONSUMPTION* FOR VARIOUS GENERATION OPTIONS (*CCS REPRESENTS CARBON CAPTURE AND SEQUESTRATION). HYDROGEN IN THE ABOVE DIAGRAM IS PRODUCED BY ELECTROLYSIS USING RENEWABLE ENERGY.

Note that, in both figures above, Carbon Capture and Sequestration (CCS) is included for the coal and natural gas generation options shown. If hydrogen is generated using electrolysis, the power generated is produced without carbon dioxide – similar to nuclear and hydropower. 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. Like natural gas, hydrogen generation technologies represent a reduction in water consumption compared to Utah’s historical fuel mix. When considering the values of the above figures, water values associated with hydrogen generation technologies are commensurate with generation technologies that are a part of Utah’s current and future fuel mix.

Background and Introduction

During the 2022 Utah General Session, the Utah legislature passed H.B. 393, Water Reporting Amendments[1]. The bill requires the state engineer to commission a study to determine the quantitative impacts to the state's water cycle from producing hydrogen and burning hydrogen fuel for electricity generation. The bill includes provisions for the study to compare the quantitative impacts around hydrogen to other electricity generation technologies' impact on the water cycle. This report presents study results.

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.

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, Figure 1 conceptualizes the expansion of the hydrogen economy.

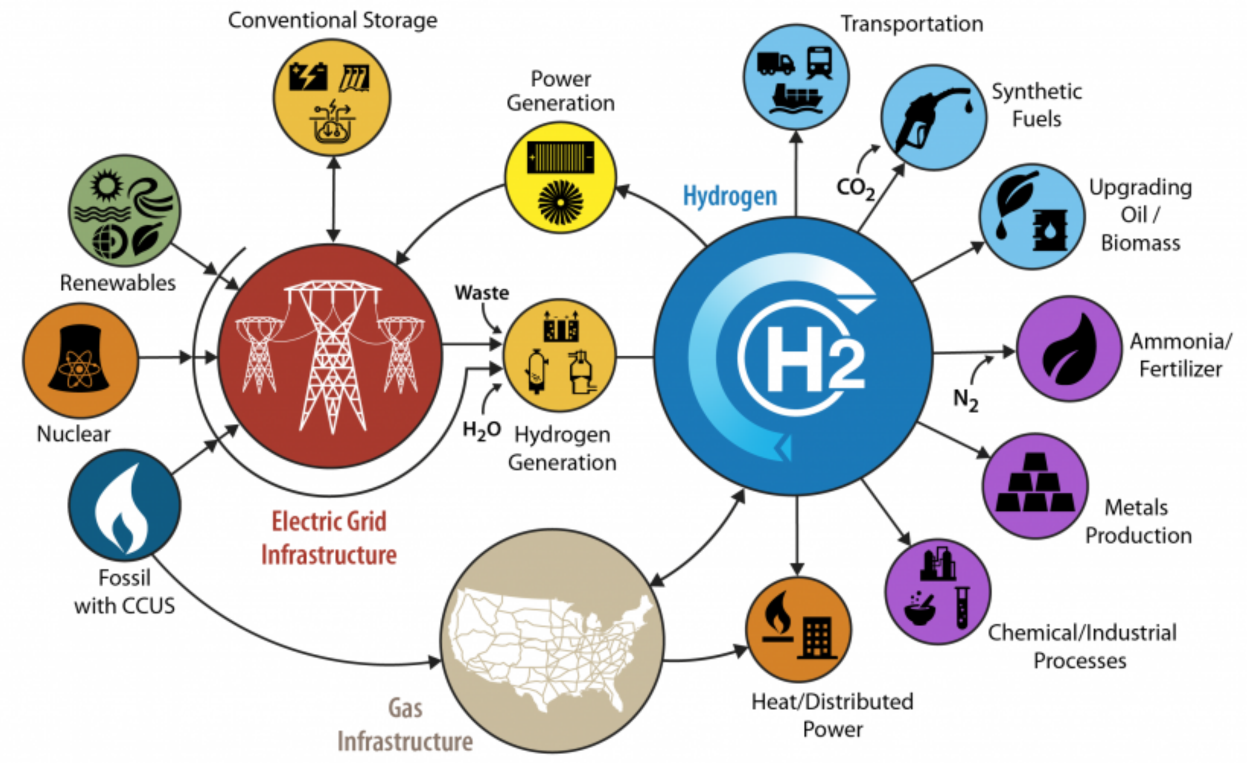

FIGURE 1: VARIOUS COMPONENTS OF THE HYDROGEN ECONOMY (FROM U.S. DEPARTMENT OF ENERGY, DOE)

Water is both used and produced in many hydrogen-related generation processes. This study first quantifies the amount of water usage for these hydrogen-related generation processes. This study also considers the use of water for power in the context of water use for other conventional and renewable fuels.

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[1] https://le.utah.gov/~2022/bills/static/HB0393.html

One final note of introduction is very important for context on the numerical results of this report. That is, when comparing water usage in various generation technologies, it is important to understand the language used to describe the water pathways. In this report specifically, the definition of water discharge was selected as the best fit to represent study intents (i.e., instead of water return) for all technologies except for renewable technologies (hydropower, solar and wind) were no discharge data is available. Moreover, the definitions for withdrawal and consumption follow those laid out by Grubert & Sanders (2018). The definition for discharge, however, is from the Energy Information Administration (EIA) and reflects measured Utah power plant data. Overall, then, the values of withdrawal and consumption come from a different sources than discharge values. Because of the use of different data sets, the values of withdrawal minus consumption are not equal to discharge. The definition of each term is detailed in Appendix A for clarity.

Hydrogen Electricity Generation

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. Note that 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.

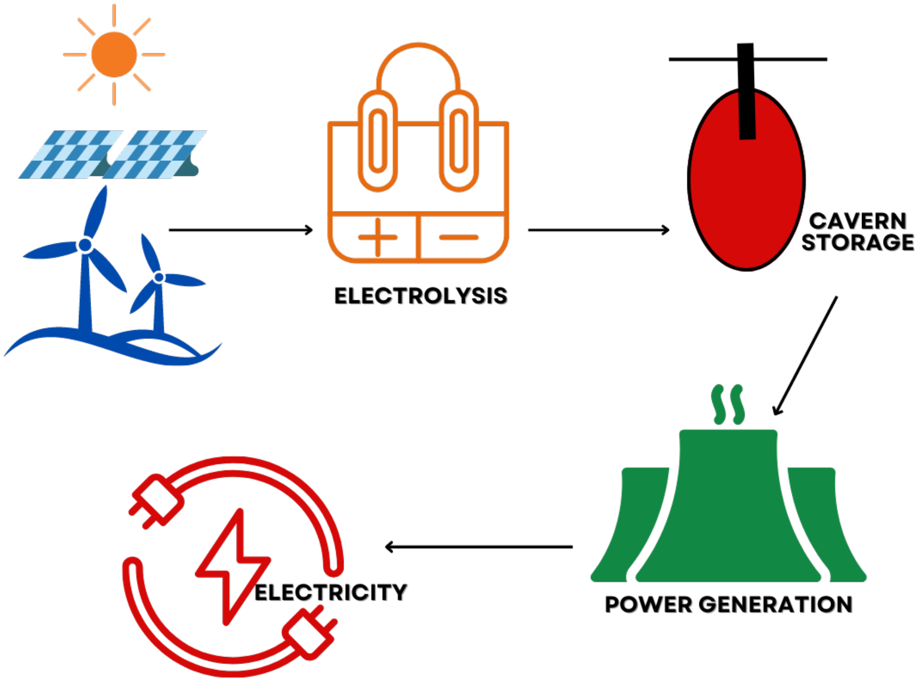

FIGURE 2: ELECTRICITY GENERATION USING HYDROGEN

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 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 and natural gas.

Production pathways from fossil fuels and possible other solid feedstocks are shown in Figure 3. Hydrogen produced may be used for transportation or generating electricity via fuel cells and hydrogen turbines. Hydrogen has also been produced in large quantities for industrial use. 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.

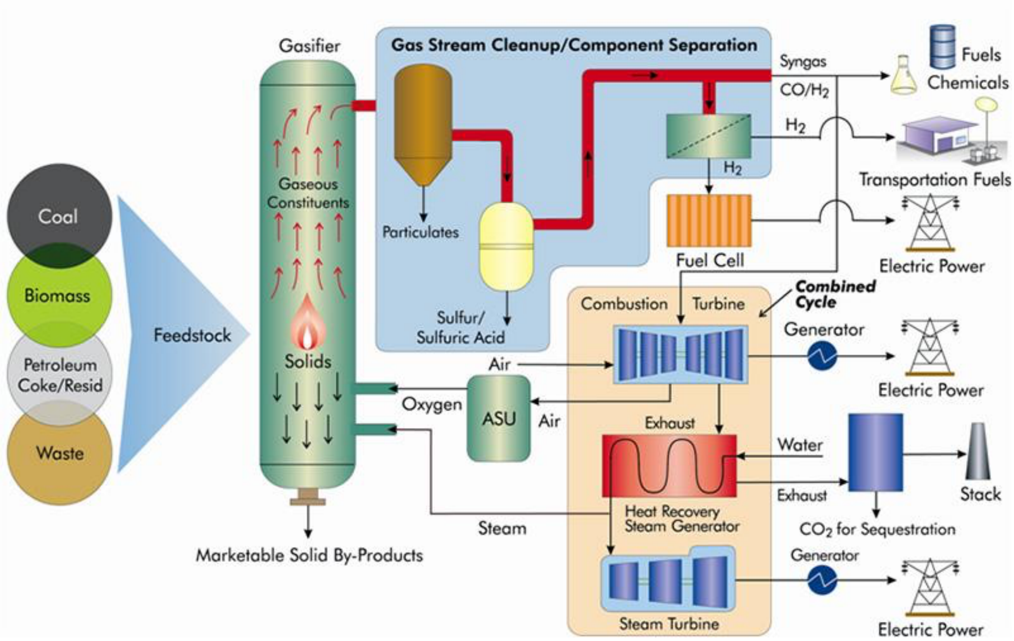

Figure 3: Hydrogen Production Pathways (From DOE Report DOE/NETL-2022/3241)

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. The process of steam reforming will also require water for steam production and system cooling.

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 SMR and there are only a few hundred commercial/semi-commercial/demonstration facilities worldwide. Complexity of a conceptual coal gasification plant is shown in Figure 4.

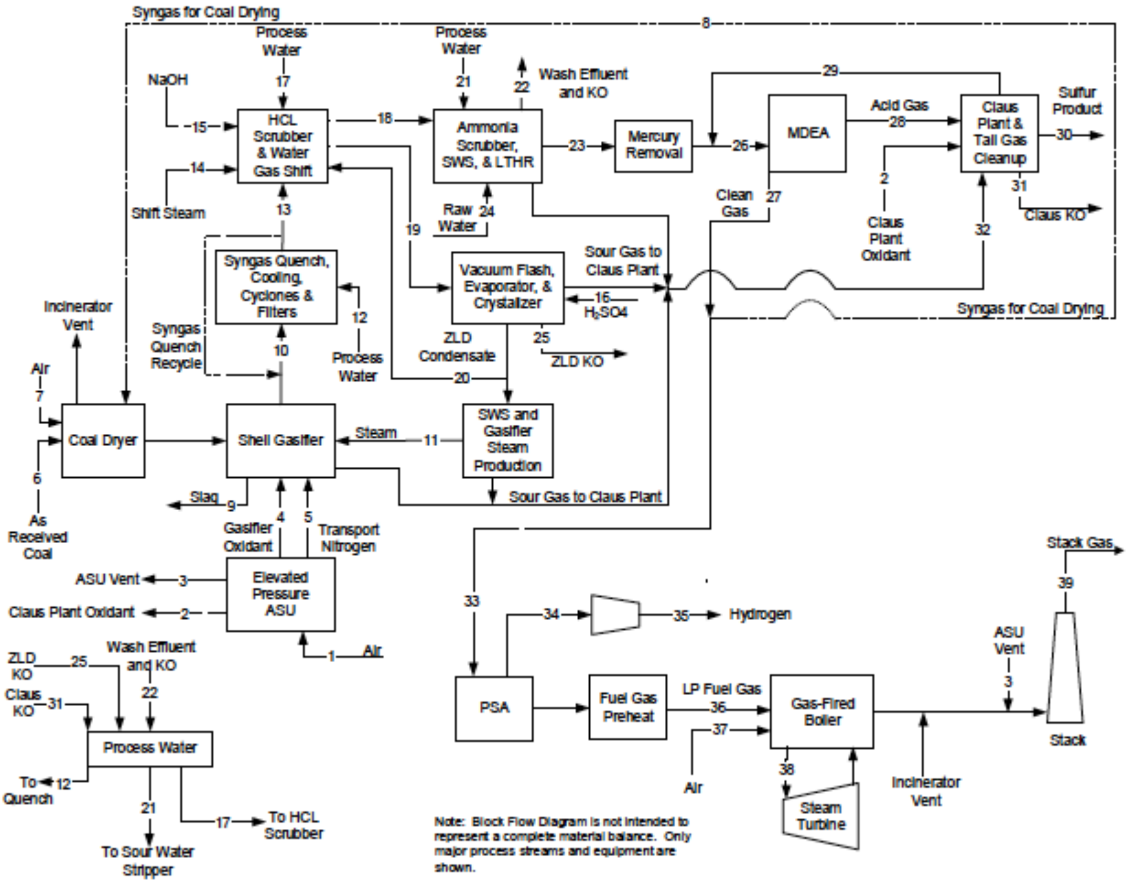

FIGURE 4: COAL GASIFICATION PROCESS FLOW DIAGRAM (DOE/NETL-2022/3241)

Electrolysis

In electrolysis, electrical energy is provided to the electrolyzer. Reactions are described by:

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

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

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

There are several types of electrolysis systems. A general schematic is shown in Figure 5.

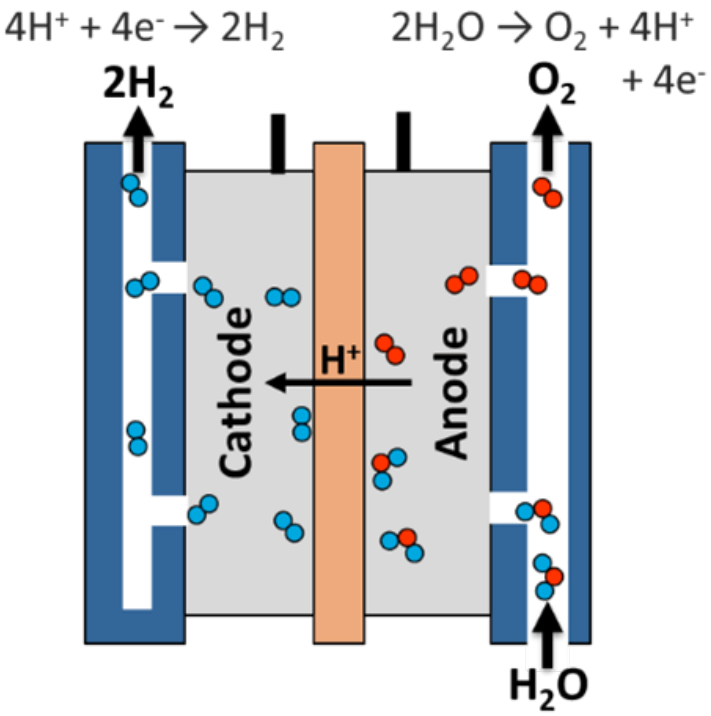

FIGURE 5: ELECTROLYSIS OF HYDROGEN (FROM DOE)

A proton exchange membrane electrolysis system is shown in Figure 6.

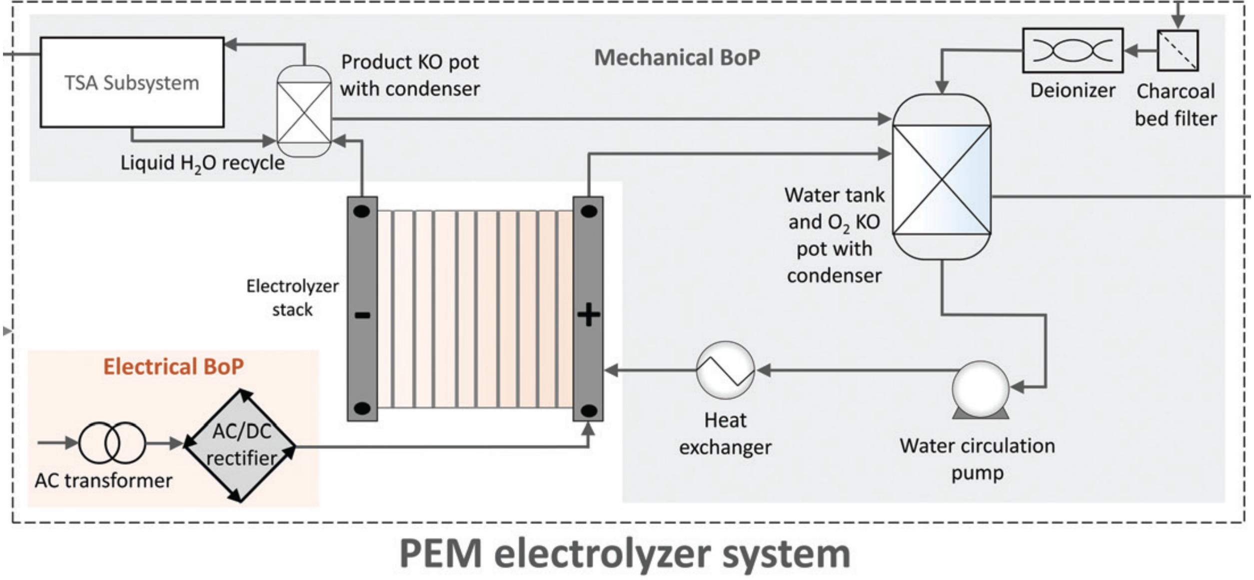

FIGURE 6: PROTON EXCHANGE MEMBRANE ELECTROLYSIS SYSTEM (FROM ENERGY ENVIRON. SCI., 2021)

Hydrogen Storage

A number of storage options and technologies are being developed. In most cases, long-term storage of hydrogen is desired. Large capacity of hydrogen storage allows for balancing excess periods of wind or solar electricity production and may even correct seasonal imbalances. 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. Salt cavern storage is considered to be the most viable option for long-term commercial-scale storage of hydrogen.

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 is currently practiced. Hydrogen is planned to be stored in salt domes created using a similar technology. Once salt caverns are created, they last over several decades.

Electricity from Hydrogen

In general, hydrogen is combined with oxygen to produce electricity, heat, and water vapor. The chemical formula is:

$$2H_2 + O_2 \rightarrow 2H_2O + electricity$$

The main advantage of electricity generated from hydrogen is that it produces only water vapor as a byproduct, making it a clean and environmentally friendly source of electricity. There are several ways to convert hydrogen to electricity, including fuel cells, combustion and nuclear fusion.

A fuel cell uses a chemical reaction between hydrogen and oxygen to produce electricity, heat, and water vapor. There are several types of fuel cells, including proton exchange membrane fuel cells, solid oxide fuel cells, and molten carbonate fuel cells.

Hydrogen can be burned in an internal combustion engine or turbine to generate electricity. Using a steam turbine, hydrogen combustion can be used to heat water, creating steam that drives a turbine to generate electricity. Hydrogen combustion can also power a gas turbine directly, similar to the way natural gas is used today. A combined cycle uses prime mover equipment (such as gas turbine and reciprocating engine) and a steam turbine to generate electricity. The heat generated by the prime mover is used to produce steam, which then powers a steam turbine. This allows for increased efficiency, as the heat that would normally be wasted in a traditional gas turbine can be recovered and used to generate additional electricity. Combined cycle power plants are considered one of the most efficient power generation technology. There are currently a limited number of hydrogen-based combined cycle power plants in operation, but research and development in this area are ongoing.

Nuclear fusion is the process of combining hydrogen atoms to form helium, releasing a large amount of energy in the process. Nuclear fusion is currently not a commercially viable technology.

Large-scale hydrogen power plants are just beginning to be built and not yet in operation. Subsequently, data on hydrogen power plants is limited at the time of this report. For now, the power plants can be reasonably considered to be similar in nature to natural gas power plants. Thermal conversion efficiencies of combined-cycle natural gas plants are about 60%. (Actual efficiencies of hydrogen plants are expected to be higher because of higher temperatures.)

Hydrogen Round-Trip Efficiency

Round-trip efficiency is the percentage of electricity put into storage that is later retrieved – or in the case of hydrogen, the percent of electricity that is used to make hydrogen versus that which is generated.[2] The round-trip efficiency of producing hydrogen and using it to generate electricity is lower than that of other energy storage solutions. According to one MIT study published in Nature Energy, electricity produced from hydrogen has a round-trip efficiency of 26 – 42%[3]. Other comparable long duration storage technologies, including pumped-storage hydropower and compressed air energy storage, have round-trip efficiencies of 70 – 85% and 42 – 67%, respectively. Flow batteries, a new technology, have a round-trip efficiency of 60 – 80%. Subsequently, in order to compete against other long duration storage technologies, the costs of hydrogen will need to fall significantly.

Hydrogen Life Cycle

The life cycle of hydrogen electricity generation is categorized into three stages: fuel cycle, operation and power plant. Summarizing the information from above, Figure 7 displays the hydrogen generation life cycle.

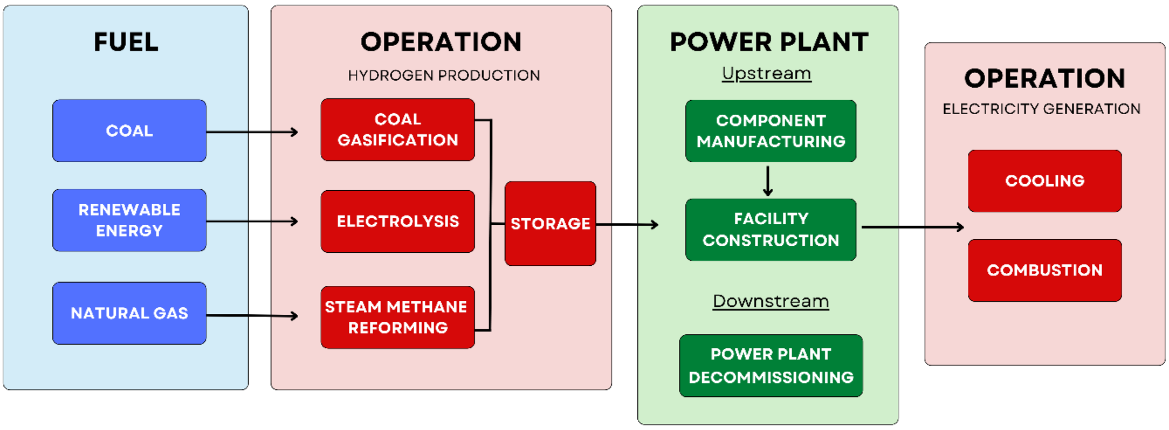

FIGURE 7: LIFE CYCLE FOR ELECTRICITY GENERATION FROM HYDROGEN

Hydrogen Water Use

Water withdrawal, consumption, discharge and return definitions are detailed in Appendix A. All of the water consumption intensities are normalized to gallons of water per megawatt hour of energy produced. A megawatt hour represents a unit of electricity generated and sent to the grid; it is a common standard in power generation.

Withdrawal numbers for hydrogen lifecycle are plotted in Figure 8. For this plot, renewable energy was chosen for the fuel part of the cycle and electrolysis for generating hydrogen. The power plant and the operation components of the hydrogen lifecycle will be identical for all the different fuel and hydrogen production operations.

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[2] https://www.eia.gov/todayinenergy/detail.php?id=46756#:~:text=Round%2Dtrip%20efficiency%20is%20the,lost%20in%20the%20storage%20process.

[3] Arjun Flora, Director of Energy Finance Studies for Europe at the Institute for Energy Economics and Financial Analysis (IEEFA) during IEEFA's virtual Energy Finance 2021 conference.

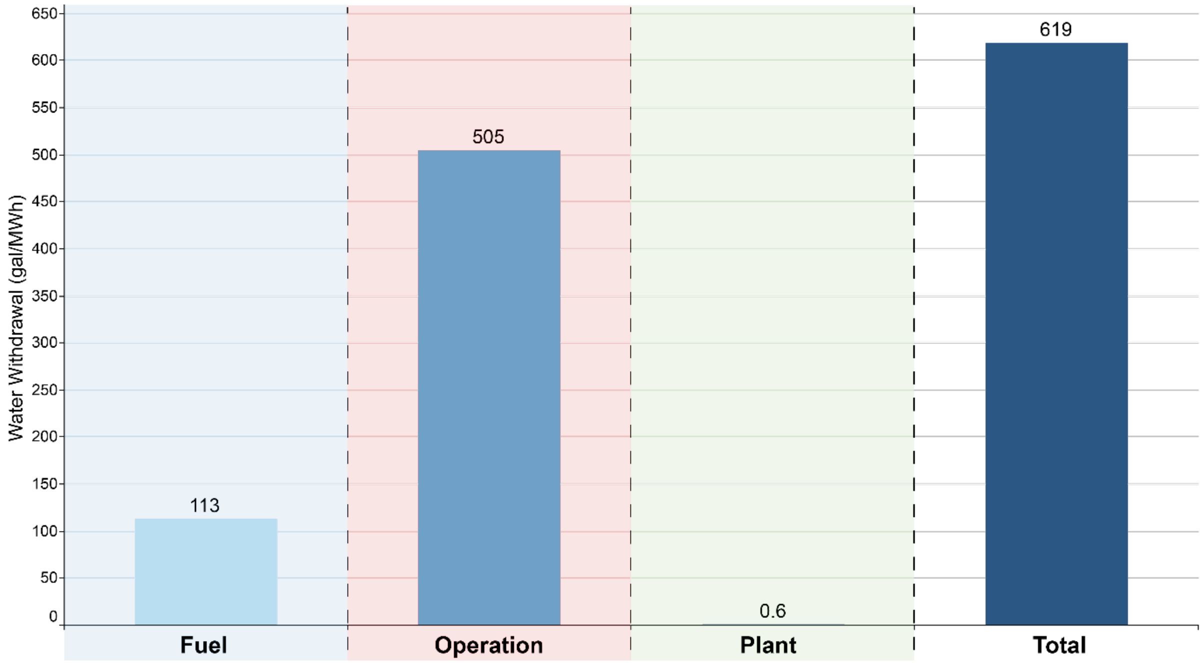

Figure 8: Water Withdrawal for Electricity Generation from Hydrogen

Hydrogen Water Consumption

Hydrogen Production Operation

Water consumption during the production of hydrogen varies depending on the process used. This report evaluates the water consumption for three types of hydrogen production: SMR, coal gasification, and electrolysis.

The theoretical stoichiometric minimum water consumed during SMR 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 SMR varies. A reliable number for SMR water consumption is 125 gal/MWh.

Water consumption for coal gasification is described in a detailed US Department of Energy's 2022 Report. For the gasification plant shown in Figure 4, the water consumption is found to be about 165 gal/MWh.

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, which purposefully exceeds the stoichiometric requirement of 71 gal/MWh.

Storage Operation

Using a set of reasonable assumptions, and the use of four salt caverns over a 50-year period, the water intensity was calculated at 15 gallons/MWh.

Generation Plant Operation

A hydrogen power plant's water consumption will depend on the cooling type employed. A description of four common cooling methods is included in Appendix B. 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. Figure 9 displays water consumption accordingly to life cycle stages related to electricity generation by hydrogen - as well as the total life cycle of generation from hydrogen. The life cycle stages for the Figure 9 reflects the components of hydrogen generated using renewable energy fuel and electrolysis production.

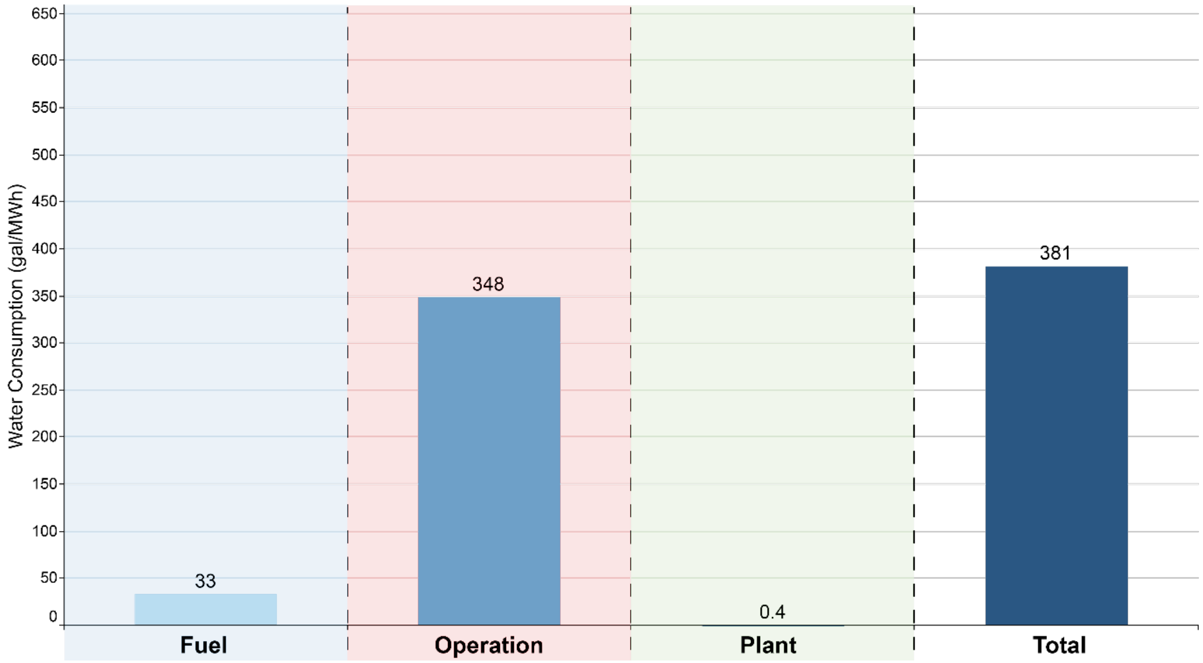

FIGURE 9: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM HYDROGEN (OPERATION INCLUDES ELECTROLYSIS, STORAGE AND COMBUSTION)

For clarity, Table 1 below is another type of breakout of the life cycle total, 381 gallons/MWh, shown in Figure 9. Table 1 summarizes the various values referenced in this section for hydrogen generated using renewable energy fuel and electrolysis production (not specifically organized accordingly to life cycle steps).

TABLE 1: BREAKDOWN OF WATER CONSUMPTION OVER THE HYDROGEN LIFE CYCLE

ELECTROLYSIS STAGE	WATER CONSUMPTION (GAL/MWH)
Renewable electricity generation (solar and wind average)	32.6
Electrolysis	123
Storage	15
Power plant construction	0.4, approximately
Power Generation	210
TOTAL	**381**

Hydrogen Water Discharge

Hydrogen power plants do not yet exist. However, their operation is expected to be similar to the operation of natural gas power plants. Discharge rates are available from median Energy Information Administration 2020 data for Utah natural gas combined cycle power plants using Cooling Method 1: Cooling Tower Recirculation. Hydrogen discharge rates are assumed to be identical to the natural gas discharge rates. Only operation life cycle stage data is available: 124 gal/MWh are discharged during plant operation of operating a hydrogen-based power plant.

Coal

Coal Basic Generation Description

As shown in Figure 10, 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. All Utah coal power plants are PC plants.

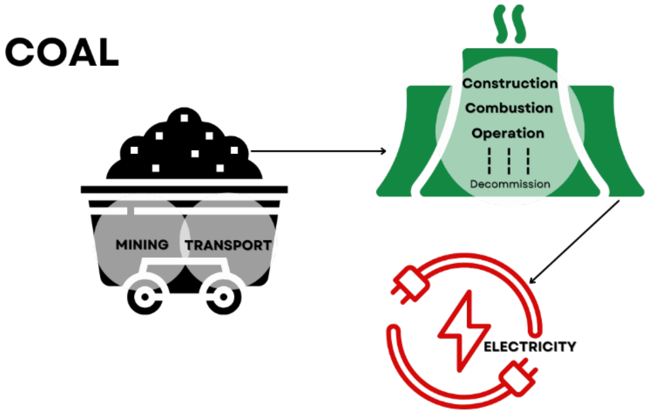

FIGURE 10: ELECTRICITY GENERATION USING COAL

Coal Life Cycle

The life cycle of electricity generation from coal is categorized into three stages: fuel, operation and power plant. Figure 11 displays the coal generation life cycle.

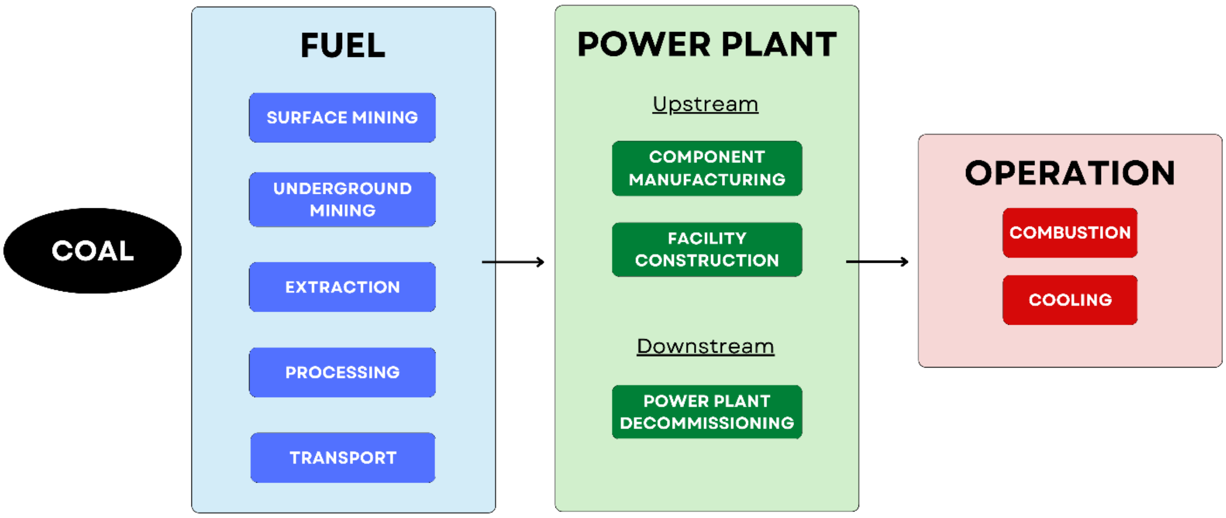

FIGURE 11: LIFE CYCLE FOR ELECTRICITY GENERATION FROM COAL

Coal Combustion Process

The process of using pulverized coal in a combustion power plant consists of burning coal to produce steam using a pulverized coil boiler. A steam turbine is then connected to a generator to produce electricity. Coal is a mixture of mineral matter and carbon-based matter which consists of carbon, hydrogen, nitrogen and sulfur. During combustion the elements that make up coal react with oxygen and form CO_2, SO_2, NO_x and H_2O.

There are different types of PC plants: subcritical and supercritical plants. All PC plants in Utah are subcritical PC plants which is the least efficient type of coal plant, as it uses lower steam pressure. The lower pressure steam transfers less energy from the boiler to the turbine, and subcritical plants need more steam flow and therefore, more cooling water, to generate the same amount of electricity as a supercritical plant.

Pulverized coal plants also have a scrubber, such as a wet flue gas desulfurization (FGD) unit to remove SO_2 from the flue gases produced by the combustion of pulverized coal. Wet FGD units require make-up water, and they commonly use limestone ($CaCO_3$) or slaked lime ($Ca(OH)_2$), which react with SO_2 to form a Ca-S compound (by-product called gypsum) when they come into contact with the warm flue gases. Even though most of the water is removed from the gypsum and recycled, some of it remains in the gypsum. In a PC plant, water is also lost in the flue gas as water vapor. Some of water in the flue gas is from the wet FGD unit; however, most is generated during combustion.

Coal Zero Carbon Emissions Solution

Coal electricity generation requires additional technology, such as carbon capture and sequestration (CCS), to operate without carbon emissions. The CCS process has three important components: capturing, transporting and storing the CO_2 produced in the combustion of pulverized coal, instead of being released to the atmosphere. CCS is a process that consists of three main components: capturing the CO_2 produced by the natural gas combustion, transporting the CO_2 to the storage site, and storing the CO_2 for a long period of time. The three common technologies for CO_2 capture are post-combustion capture, pre-combustion capture, and oxy-fuel capture. Post-combustion capture involves capturing the CO_2 from the gas turbine exhaust gases. This is then passed through a chemical solvent or absorbent that selectively binds to the CO_2, separating it from the other gases in the exhaust. One solvent commonly used is water, and this can contribute to additional water requirements. The separated CO_2 can then be separated from the solvent or absorbent and stored. The addition of this process is one of the major contributors to the increase in water requirements due to the increase in cooling requirements for the gas turbine. Pre-combustion CO_2 capture utilizes the ability to gasify the natural gas with oxygen or air and/or steam to produce synthesis gas (syngas) which is composed of CO and hydrogen. This is passed through a series of catalyst beds that will allow CO_2 to separate from the hydrogen-rich gas. In oxy-fuel capture, natural gas is combusted using pure oxygen instead of air to limit the exhaust gas to contain mainly CO_2 and water vapor. This can then be cleaned and separated.

Coal Water Comparisons

Coal power generation requires water to be withdrawn, consumed, and in some cases, discharged back to the environment (see Appendix A for water term definitions). The following sections compare how coal power generation uses water over each stage of the generation life cycle. As previously introduced, the water usage (in gallons) is normalized based on the electricity generated (in megawatt-hours).

Note that, as explained below, the cooling tower life cycle water value is used in the executive summary and conclusion to present a single value of water parameters without variation. The cooling tower life cycle water usage was chosen due to its high prevalence in Utah coal power plants.

Coal Water Withdrawal and Variability

Figure 12 displays water withdrawn for each life cycle stage related to electricity generation by coal combustion - as well as the total water withdrawn for the life cycle of coal power generation. (Note that the figure uses shading according to the life cycle stages introduced previously.) Withdrawal varies widely with the method of cooling used, and values for Cooling Methods 1-3 shown in Appendix B are presented from literature. Additional variation of withdrawal that is found in literature is included Appendix C.

As shown in Figure 12, a cooling tower only withdraws new water as water evaporates or is blown down to flush system (i.e., recycles most of the water withdrawn). Pond cooling withdraws a greater amount of water from a single point source and recirculates it to that same source. Once-through cooling withdraws the greatest amount of water to pass through a heat exchanger one time and then return or discharge from the plant.

Figure 12 also includes water withdrawal for the life cycle stages of generation from coal using carbon capture and sequestration (CCS) with cooling tower recirculation. As demonstrated, water withdrawal noticeably increases with the inclusion of CCS.

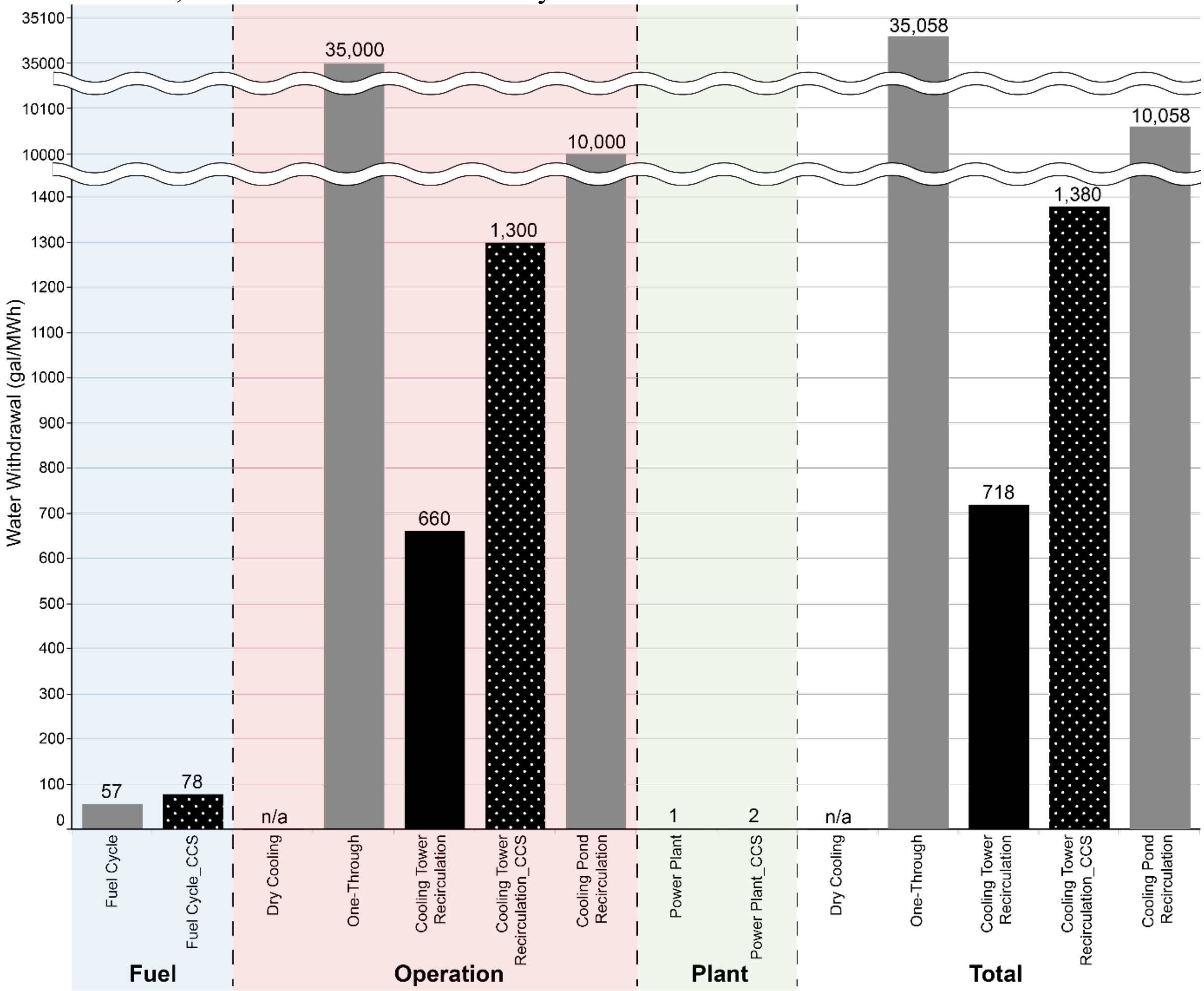

FIGURE 12: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM COAL

Coal Water Consumption

Figure 13 displays water consumption for each life cycle stage related to electricity generation by coal - as well as the total life cycle of generation from coal. 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 13 includes water consumption for the life cycle stages of generation from coal using carbon capture and sequestration (CCS) with cooling tower recirculation. As demonstrated, water consumption noticeably increases with the inclusion of CCS.

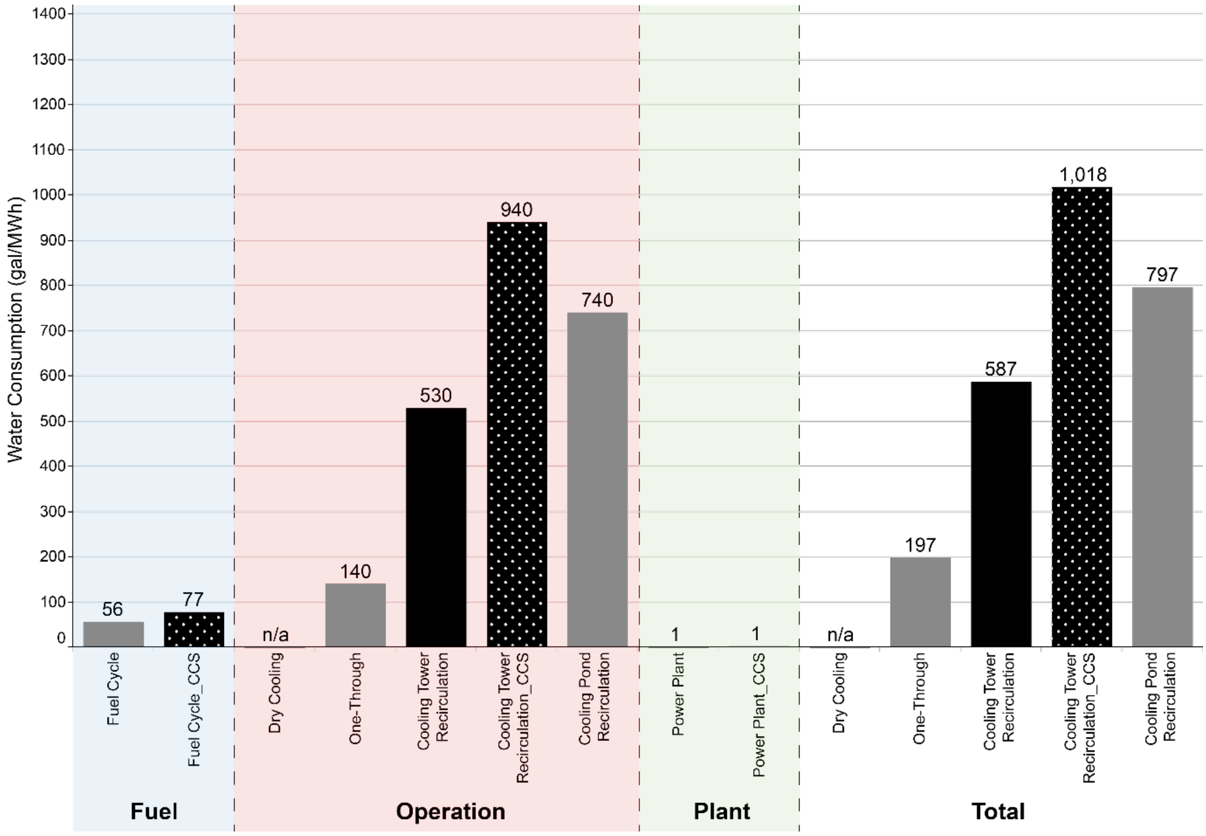

FIGURE 13: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM COAL

Coal Cooling Method and Consumption Variability

As previously mentioned, water is consumed at the power plant in cooling the steam. The water consumption is highly dependent on the cooling methods. As shown in Figure 13, a cooling tower consumes water as it evaporates or is blown down. Pond cooling consumes less water since it has a larger volume and will require less evaporation and blow down.

Coal Water Discharge

Discharge rates are calculated directly from median Energy Information Administration 2020 data for Utah subcritical coal power plants using Cooling Method 1: Cooling Tower Recirculation. As such, only operation life cycle stage data is available: 0 gal/MWh are discharged during plant operation. Note that it is assumed that most, if not all, Utah coal power plants utilize evaporative or treatment ponds for cooling tower water, and water returned to these ponds is not considered discharge.

Natural Gas

Natural Gas Basic Generation Description

Figure 14 diagrams the basic process of electricity generation from natural gas using a combined-cycle power plant. While combined cycle plants are not the most common in Utah, they are reflective of the more recent plants' technology as well as becoming standard for any new natural gas power plant.

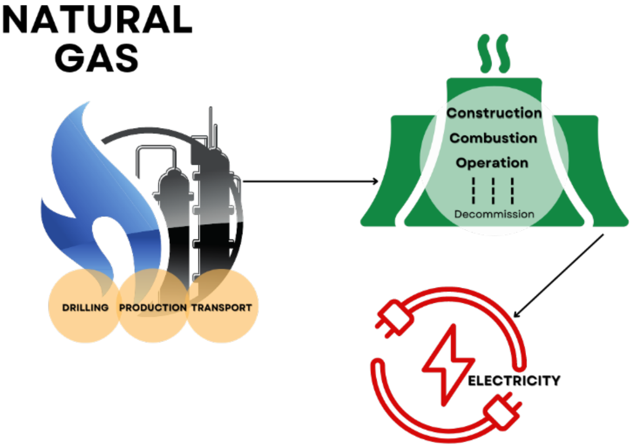

FIGURE 14: ELECTRICITY GENERATION USING NATURAL GAS

Natural Gas Life Cycle

The life cycle of electricity generation from natural gas is categorized into three stages: fuel, operation and power plant. Figure 15 displays the natural gas generation life cycle.

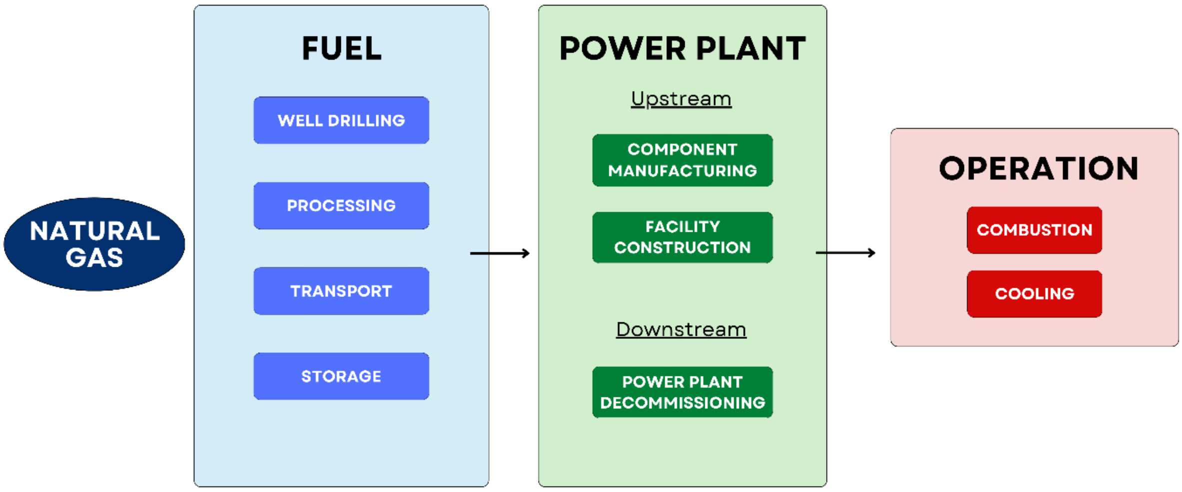

FIGURE 15: LIFE CYCLE FOR ELECTRICITY GENERATION USING NATURAL GAS

Natural Gas Combustion Process

Similar to the combined cycle described earlier for hydrogen, a natural gas combined cycle (NGCC) power plant is a type of power plant that uses natural gas as its fuel and a steam turbine to generate electricity. During the operational stage of a NGCC power plant, water is used in numerous places. One of the largest water users at power plants is cooling water. This water is used to cool the gas turbine during combustion to prevent the turbine from overheating. Water is recirculated in a heat recovery steam generator (HRSG) to transfer heat from the exhaust and form steam. This steam is then used to power the steam turbine and generate electricity. Cooling water is used to condense the steam to be recirculated in the HRSG. While both the cooling water and the water circulating in the HRSG will need makeup water as water is consumed, no water is consumed at the exhaust gas stack.

Natural Gas Zero Carbon Emissions

The combustion of fossil fuels such as natural gas produces harmful exhaust consisting of greenhouse gases (GHG) and other inert gases. The GHG produced in fossil fuel combustion is one of the most significant long-term environmental challenges facing the world. To decrease these emissions into the atmosphere, technologies have been developed to help capture some of the most harmful GHG. One technology used is carbon capture and sequestration (CCS). With the addition of CCS (defined in previous sections), there is a notable increase in water requirements for the process depending on the level of carbon capture. When compared to a power plant fueled by pulverized coal, it is noted that NGCC has a larger plant efficiency and smaller CO_2 emission intensity, which results in a lower increase of water requirements than that of PC.

Natural Gas Water Comparisons

Natural gas power generation requires water to be withdrawn, consumed, and in some cases, discharged back to the environment. The definition for each is included in Appendix A. The following sections compare how natural gas power generation uses water over each stage of the generation life cycle. Similar to hydrogen earlier in this report, the water usage (in gallons) is normalized based on the electricity generated (in megawatt-hours).

Natural Gas Withdrawal and Variability

Figure 16 displays water withdrawn for each life cycle stage related to electricity generation by natural gas combustion in a combined cycle - as well as the total water withdrawn for the life cycle of natural gas power generation. Withdrawal varies widely with the method of cooling used, and values for Cooling Methods 1-4 (as defined in Appendix B) are presented from literature. Additional variation in withdrawal found in literature is included Appendix C. As shown in Figure 16, open loop once-through cooling requires a much higher withdrawal rate as water is only passed through the system once. Pond recirculation operates similarly to the once-through method, so it requires only a slightly lower rate of withdrawal. A cooling tower recycles most of the water withdrawn and only withdraws new water as water evaporates or is blown down. Dry cooling withdraws almost no water. Note that the cooling tower life cycle water value is used in the executive summary and conclusion to present a single value of water withdrawal without variation. The cooling tower life cycle usage was chosen due to its prevalence in Utah natural gas power plants.

Figure 16 also displays water withdrawal for the life cycle stages of generation from natural gas using CCS with cooling tower recirculation. 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, water withdrawal increases by adding CCS.

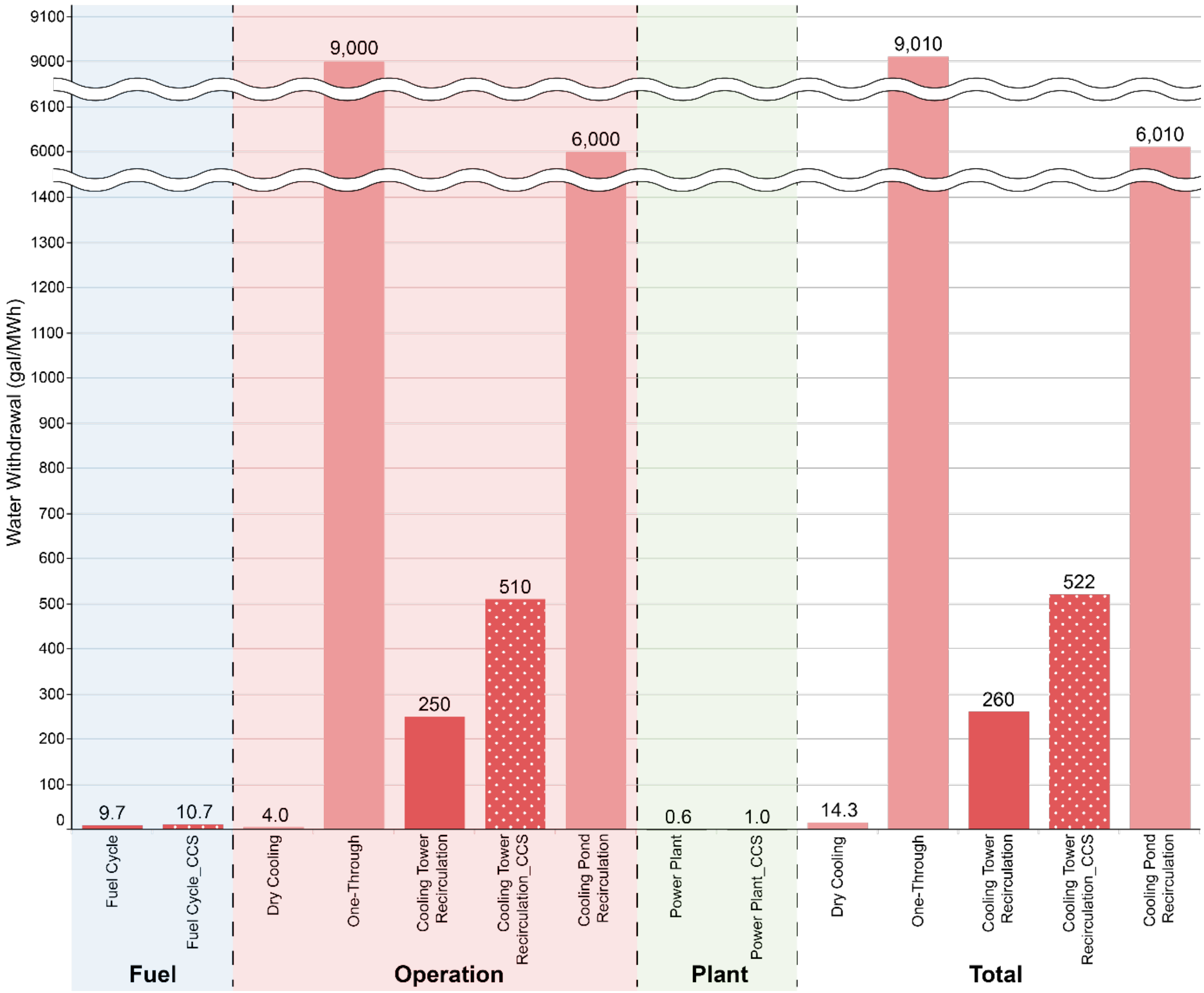

FIGURE 16: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM NATURAL GAS

Natural Gas Water Consumption

Figure 17 displays water consumption for each life cycle stage related to electricity generation by natural gas - as well as the total life cycle of generation from natural gas. For example, at the power plant, water is consumed in cooling the steam and maintaining the proper concentration of minerals within both steam and cooling water.

Figure 17 also displays water consumption for the life cycle stages of generation from natural gas using CCS with cooling tower recirculation. 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, water consumption increases by adding CCS.

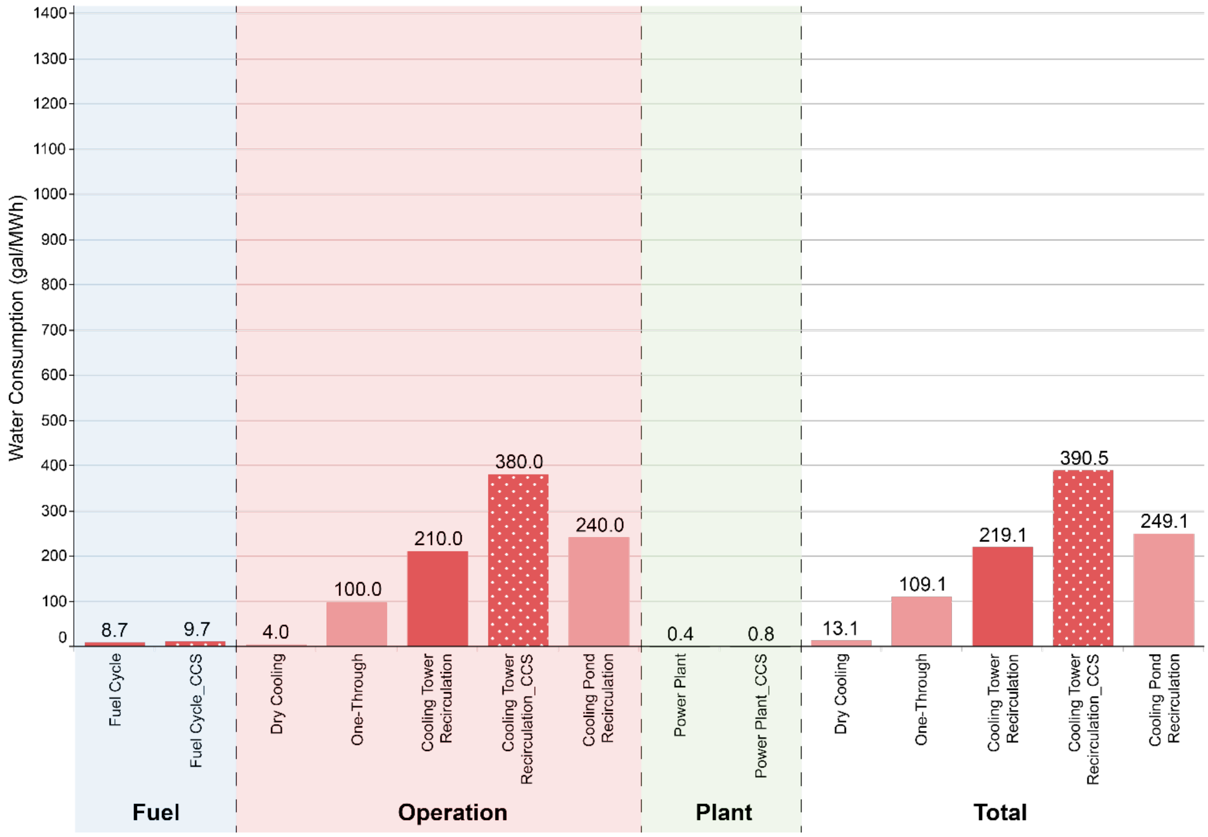

FIGURE 17: WATER CONSUMPTION FOR GENERATING ELECTRICITY FROM NATURAL GAS

Natural Gas Cooling Method and Consumption Variability

As shown in Figure 17, open loop cooling requires a lower consumption rate. A cooling tower consumes water as it evaporates or is blown down, and pond recirculation does the same. Dry cooling consumes almost no water. Note that the cooling tower life cycle water value is used in the executive summary and conclusion to present a single value of water consumption without variation. The cooling tower life cycle usage was chosen due to its prevalence in Utah natural gas power plants.

Natural Gas Water Discharge

Discharge rates are calculated directly from median Energy Information Administration 2020 data for Utah natural gas combined cycle power plants using Cooling Method 1: Cooling Tower Recirculation. As such, only operation life cycle stage data is available: 124 gal/MWh are discharged during plant operation.

Natural Gas and Hydrogen Mixtures

Current plans for the use of hydrogen include a phased approach, where mixtures of natural gas and hydrogen will be used in power plants. Not enough is known about these new-generation power plants. Since the water use pattern for the power plant portion of hydrogen and natural gas is identical, mixtures were treated as linear combinations. In other words, if 20% hydrogen and 80% natural gas was used to generate electricity, 20% of the water use (consumption or withdrawal) came from hydrogen and the reset from natural gas. Using this method, the withdrawal and consumption plots for hydrogen and natural gas mixtures are shown in Figure 18. As expected, the values for mixtures fall between the two end members – natural gas and hydrogen. It should be noted that the natural gas numbers used were without the CCS (Carbon Capture and Sequestration) component. Detailed breakdowns of water consumption and withdrawal for one of the scenarios (30% hydrogen and 70% natural gas) are shown in Figure 19 and Figure 20.

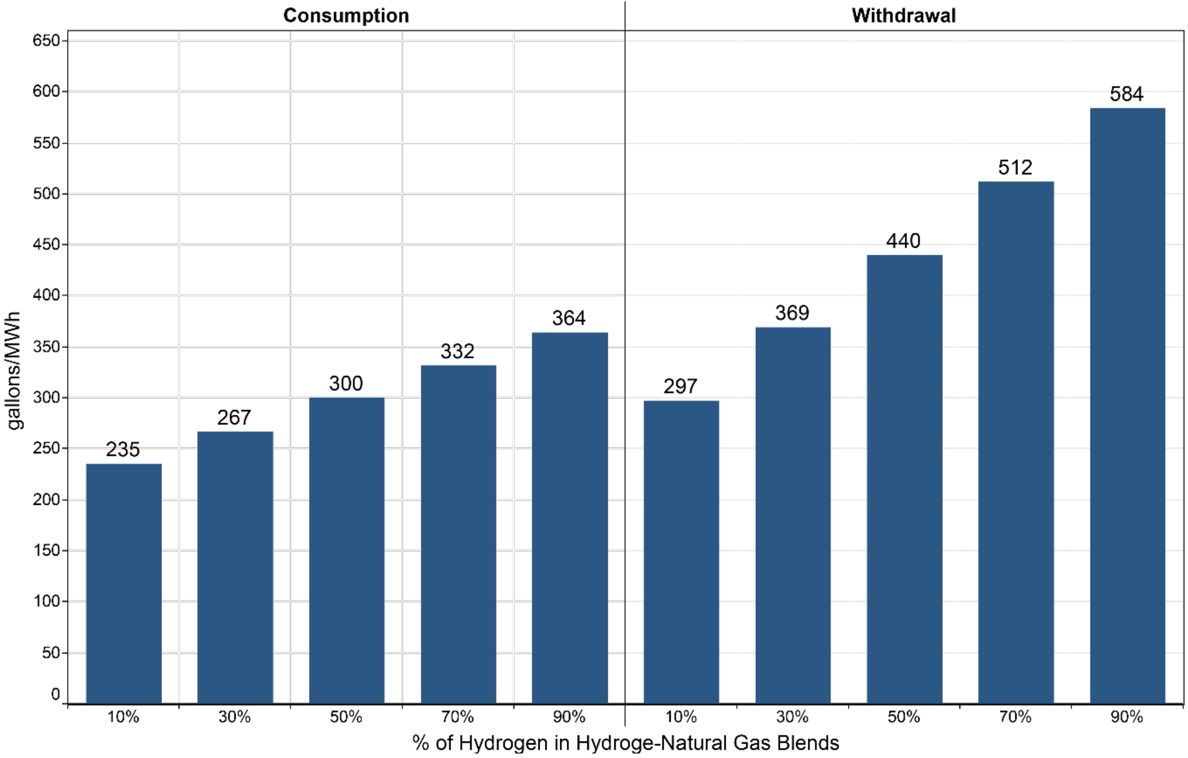

FIGURE 18: WATER CONSUMPTION AND WITHDRAWAL FOR MIXTURES OF HYDROGEN AND NATURAL GAS

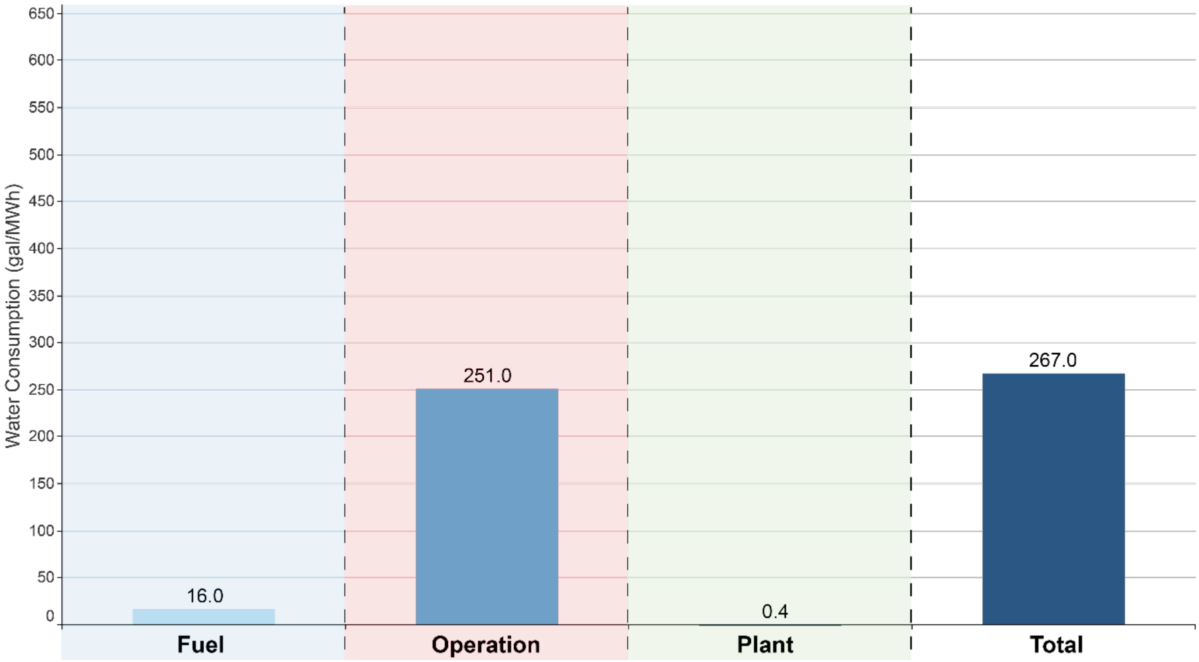

FIGURE 19: WATER CONSUMPTION FOR A MIXTURE OF 30% HYDROGEN AND 70% NATURAL GAS

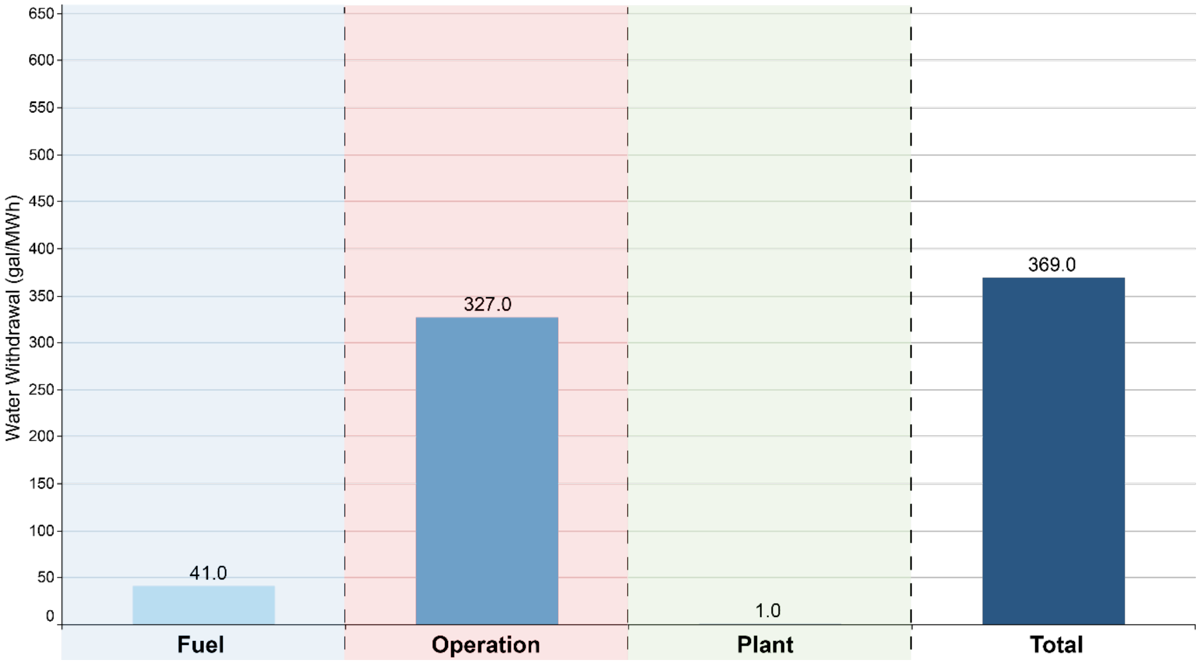

FIGURE 20: WATER WITHDRAWAL FOR A MIXTURE OF 30% HYDROGEN AND 70% NATURAL GAS

Nuclear

Nuclear Basic Generation Description

As shown in Figure 21, the life cycle of electricity generation from nuclear begins with mining and continues through to the point of generation, including steps for enrichment, fuel fabrication, power generation, plant construction/decommissioning, and treatment of spent fuel in the cycle. The process of nuclear fission consists of splitting uranium atoms to release energy and heat water to produce steam. A steam turbine is then connected to a generator to produce electricity. Spent uranium fuel must be safely stored and monitored, typically on-site. While there are no operating nuclear plants in Utah, there are ongoing projects with plans to install small modular reactors in or around Utah.

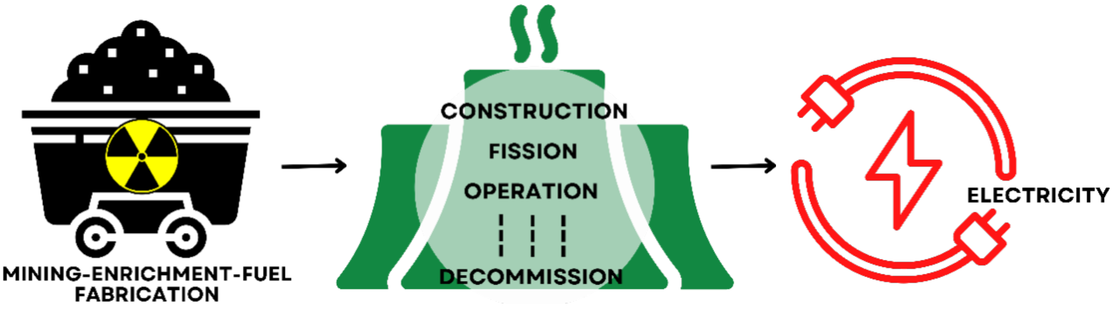

FIGURE 21: ELECTRICITY GENERATION USING NUCLEAR ENERGY

Nuclear Life Cycle

The life cycle of energy generation is categorized into three stages: fuel cycle, power plant, and operation. Figure 22 displays the nuclear generation life cycle.

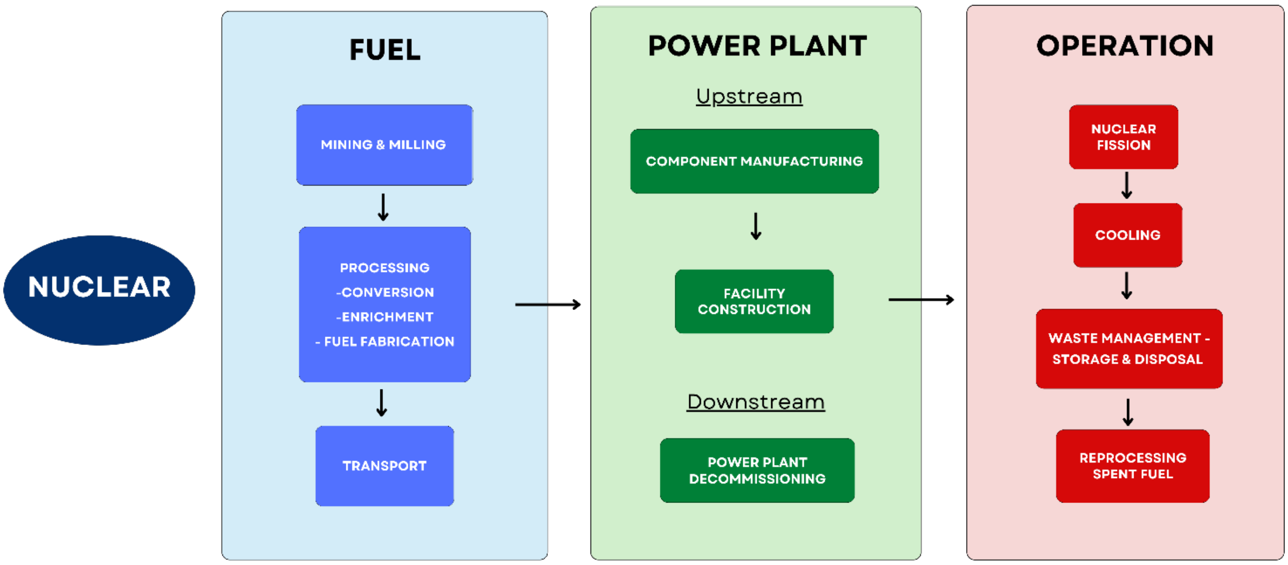

FIGURE 22: LIFE CYCLE FOR ELECTRICITY GENERATION FROM NUCLEAR

Nuclear Zero Carbon Emissions (and Combustion)

Nuclear energy generation requires no combustion and is a zero carbon emissions type of generation. However, construction of the nuclear power plant and mining of minerals needed for fusion will result in carbon emissions. Tabulating carbon footprint of all energy operations is beyond the scope of this report which is focused on water use.

Nuclear Water Comparisons

Nuclear power generation requires water to be withdrawn, consumed, and in some cases, discharged back to the environment. The definition for each is included in Appendix A. The following sections compare how nuclear power generation uses water over each stage of the generation life cycle.

Nuclear Water Withdrawal and Variability

Figure 23 displays water withdrawn for each life cycle stage related to electricity generation by nuclear fission - as well as the total water withdrawn for the life cycle of nuclear generation. Withdrawal varies widely with the method of cooling used, and values for Cooling Methods 1-3 (defined in Appendix B) are presented from literature. While dry cooling is not currently being used in any nuclear plant in the world, Appendix C includes additional numbers from upcoming Utah related small modular reactor projects which plan to utilize dry cooling.

As shown in Figure 23, open loop cooling requires a much higher withdrawal rate as water is only passed through the system once. A cooling tower recycles most of the water withdrawn and only withdraws new water as water evaporates or is blown down. Pond cooling withdraws water from a single point source and recirculates it to that same source. Note that the cooling tower life cycle water value is used in the executive summary and conclusion to present a single value of water withdrawal without variation. The cooling tower life cycle usage was chosen due to its predominant use in United States nuclear reactors.

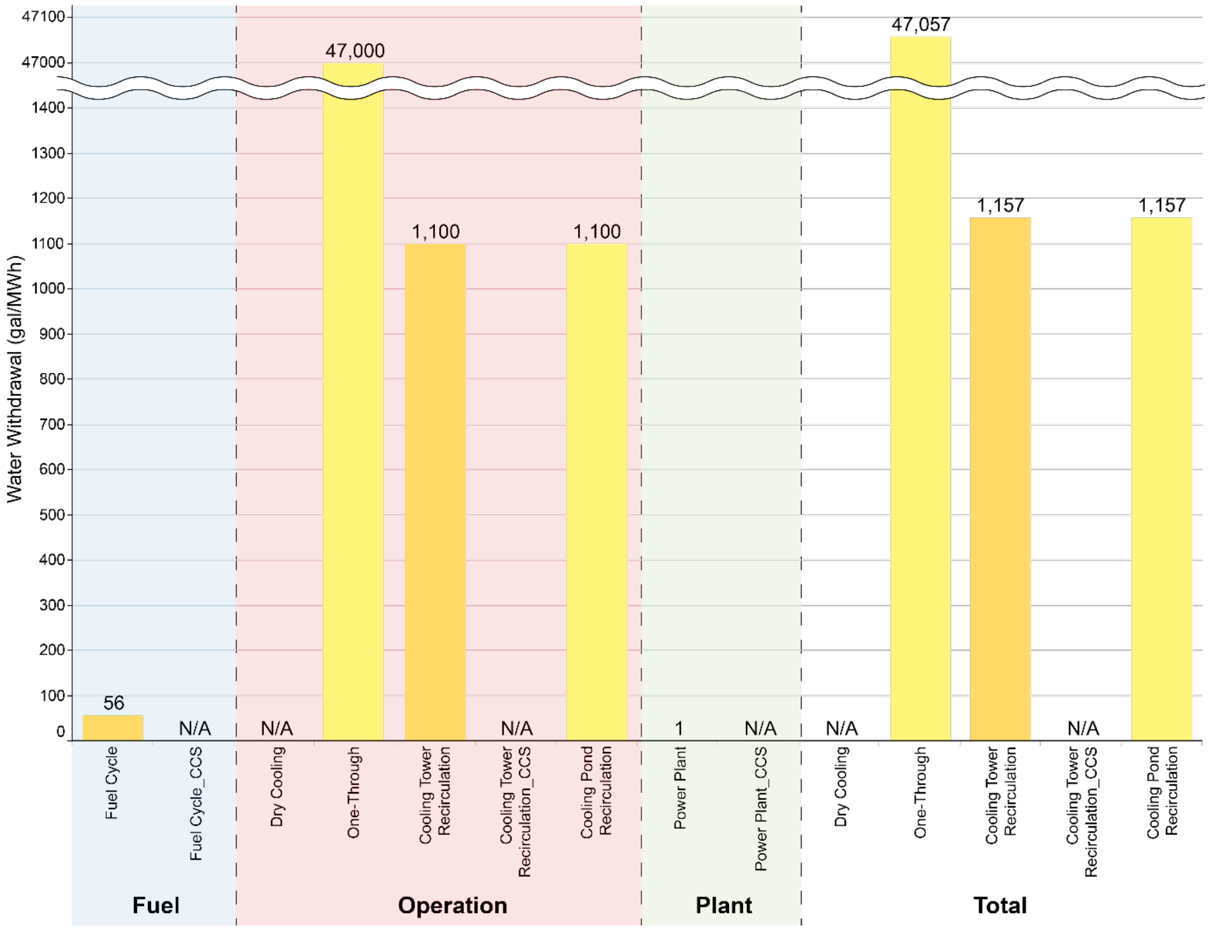

FIGURE 23: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM NUCLEAR

Nuclear Water Consumption

Figure 24 displays water consumption for each life cycle stage related to electricity generation by nuclear fission - as well as the total water consumption for the life cycle of nuclear generation. Consumption varies widely with the method of cooling used. As shown in Figure 24, open loop cooling consumes much less water. A cooling tower consumes the most water due to evaporation. Pond cooling also consumes more water due to evaporation but not as much as a cooling tower.

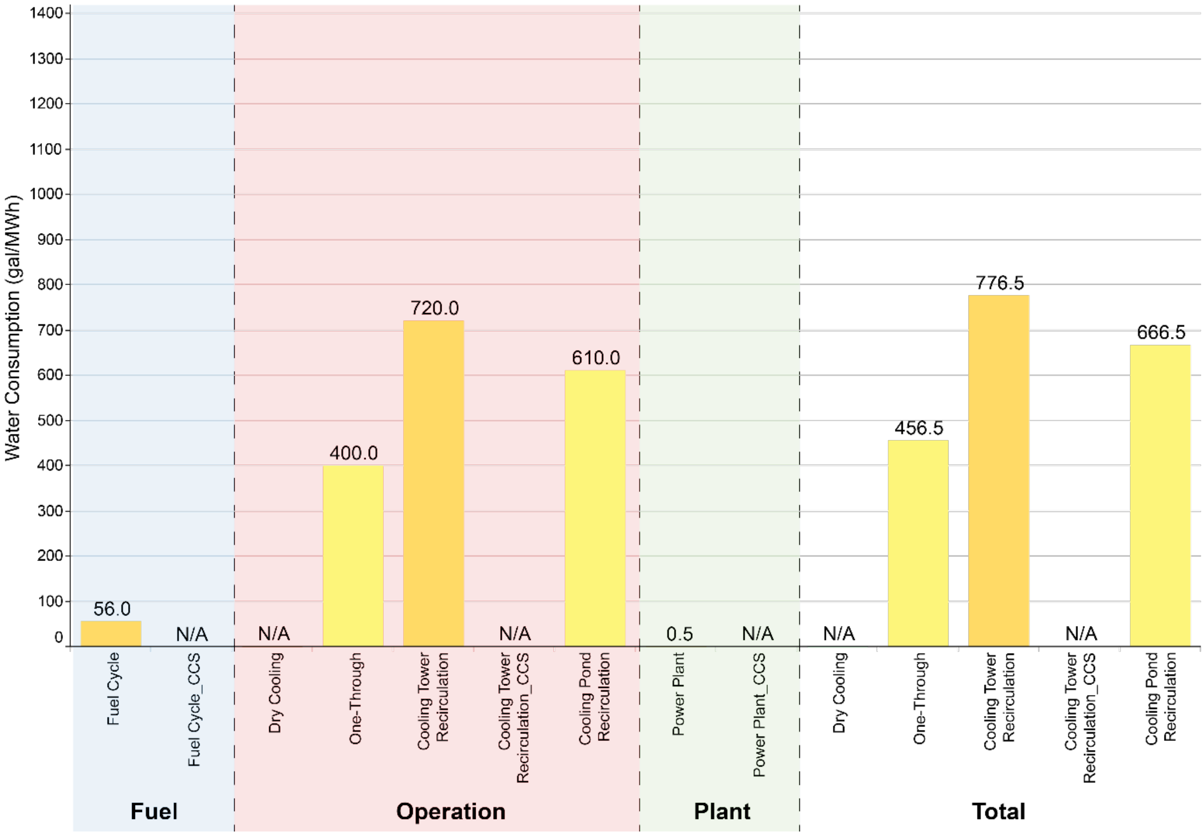

FIGURE 24: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM NUCLEAR

Nuclear Water Discharge

Discharge rates are calculated directly from the median of Energy Information Administration 2020 data for United States nuclear power plants using Cooling Method 1: Cooling Tower Recirculation. As such, only operation life cycle stage data is available: 178 gal/MWh are discharged during plant operation. Note that no nuclear power plants currently operate in Utah, so data for the entire United States was utilized.

Hydroelectric

Hydroelectric Basic Generation Description

Figure 25 diagrams the basic process of hydroelectricity generation. In a hydroelectric power plant, water is impounded by a dam in a reservoir to store potential energy. The water then flows through a turbine to harness the stored energy and produce electricity. While Utah generated 758,000 MWh of hydroelectric power in 2021[4], drought and dropping water levels in reservoirs have been decreasing Utah's capacity for hydroelectric power generation.

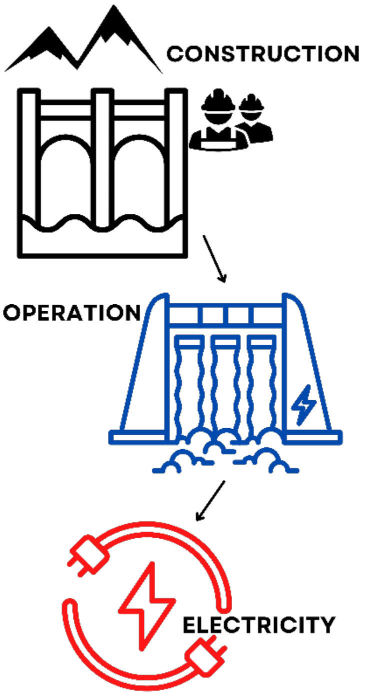

FIGURE 25: ELECTRICITY GENERATION USING HYDROPOWER

Hydroelectric Life Cycle

The life cycle of energy generation is categorized into two stages: power plant and operation. Figure 26 displays the hydroelectricity generation life cycle. Note that in hydroelectricity, water is the 'fuel'.

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[4] https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php

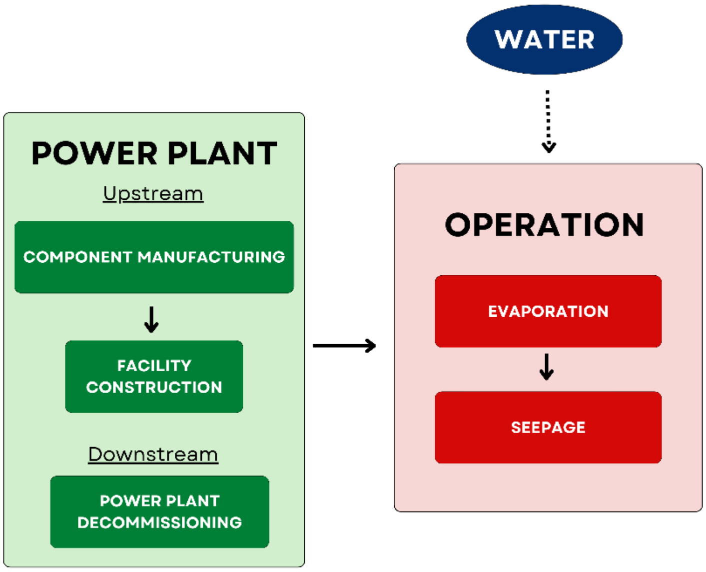

FIGURE 26: LIFE CYCLE FOR ELECTRICITY GENERATION USING HYDROPOWER

Hydroelectricity Zero Carbon Emissions (and Combustion)

Hydroelectricity requires no combustion and is a zero-carbon emissions generation type. However, several components of facility construction etc. will have a carbon footprint. Reporting on carbon emissions from various energy systems is beyond the scope of this report.

Hydroelectric Water Comparisons

Hydroelectric power generation requires water to be withdrawn, consumed, and, in some cases, discharged back to the environment. The definition for each is included in Appendix A. The following sections compare how hydroelectric power generation uses water over each stage of the generation life cycle. Similar to hydrogen earlier in this report, the water usage (in gallons) is normalized based on the electricity generated (in megawatt-hours).

Hydroelectric Water Withdrawal and Variability

Due to the nature of its generation, hydroelectricity withdraws most of any generation technology. Because of impacts water withdrawn may have on the surrounding and downstream environment, any water that flows through penstocks, or unnatural channels, to the turbines is considered withdrawn. Figure 27 displays water withdrawal for the life cycle generation from hydroelectricity in the Arizona centroid, which includes Utah. No water withdrawal values were available for construction and decommissioning of the power plant itself.

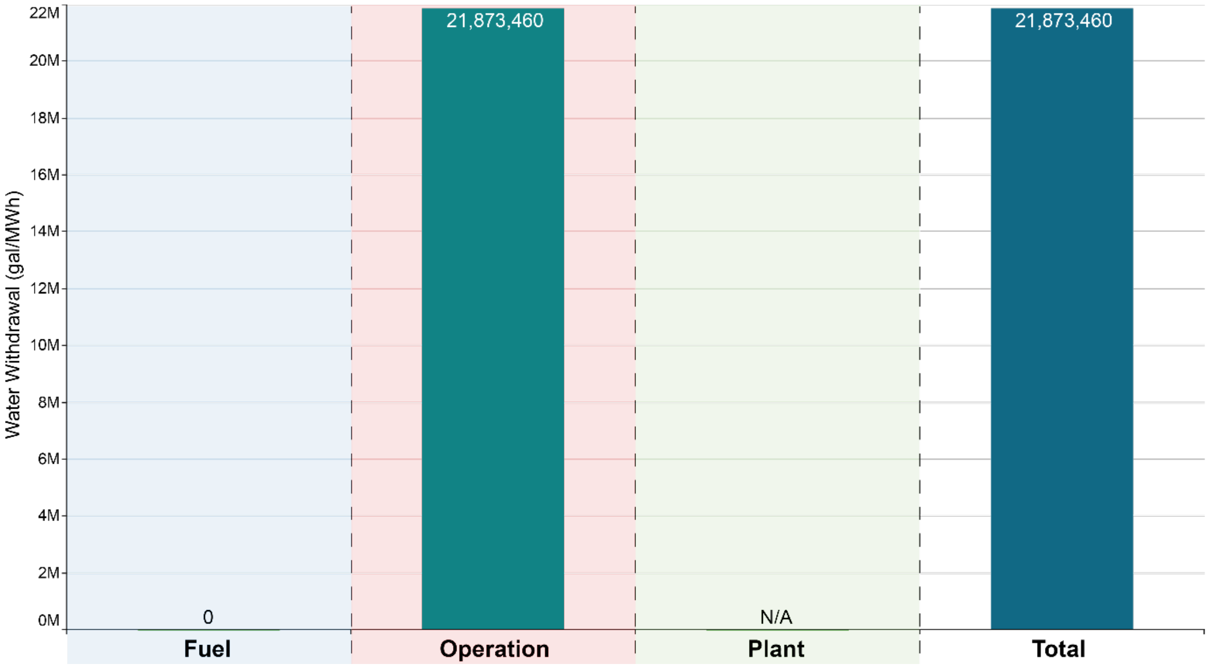

FIGURE 27: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM HYDROPOWER

Hydroelectric Water Consumption

Water consumption for hydroelectricity during plant operation comes from two sources: seepage and evaporation. Seepage is defined as water loss into the surrounding rocks and soil of the reservoir created by water impoundment. Evaporation is defined as net evaporation – the difference between the water evaporation rate before water impoundment and the water evaporation rate after water impoundment. Gross evaporation accounts for all water evaporation at the dam and reservoir after water impoundment. Due to the different environments around rivers, reservoirs can decrease gross evaporation in some locations. Gruber (2016) estimates net and gross evaporation by region. Figure 28 are results closest to Utah. Variation of water consumption found in literature is reported in Appendix C.

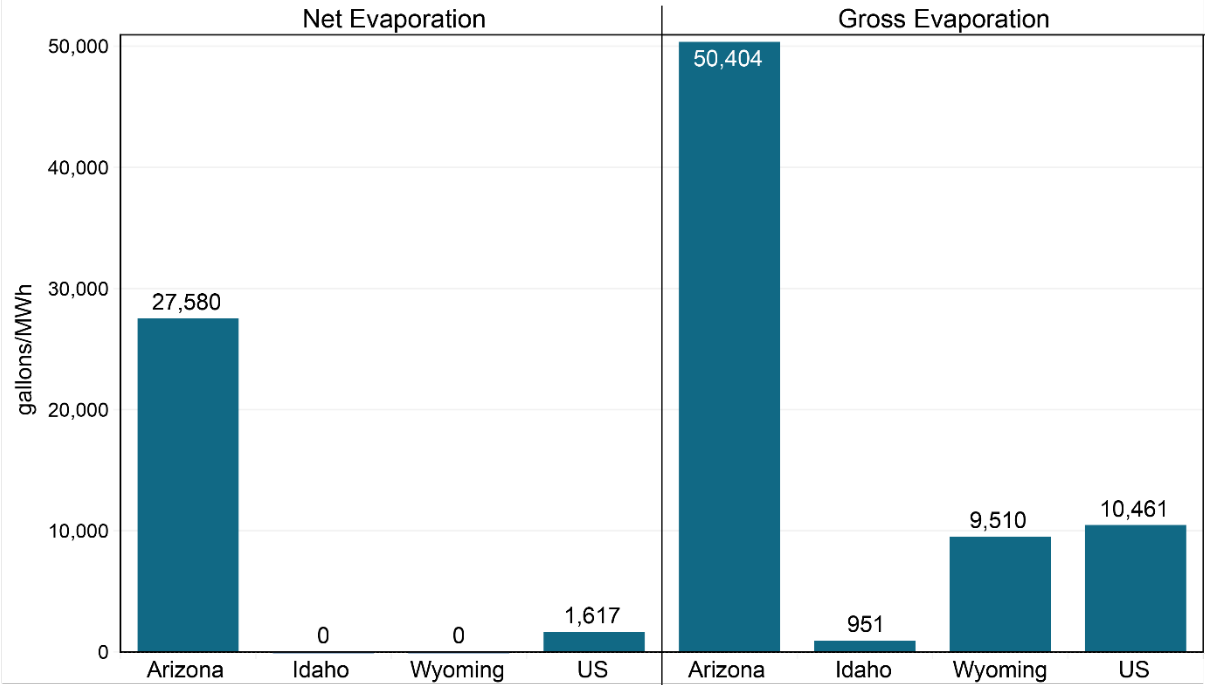

FIGURE 28: REGIONAL WATER EVAPORATION FROM HYDROELECTRIC RESERVOIRS

Figure 29 displays water consumption for the life cycle stage generation from hydroelectricity. The Arizona centroid is used to quantify operation water consumption, which includes both net evaporation and seepage. No water consumption values were available for construction and decommissioning of the power plant itself.

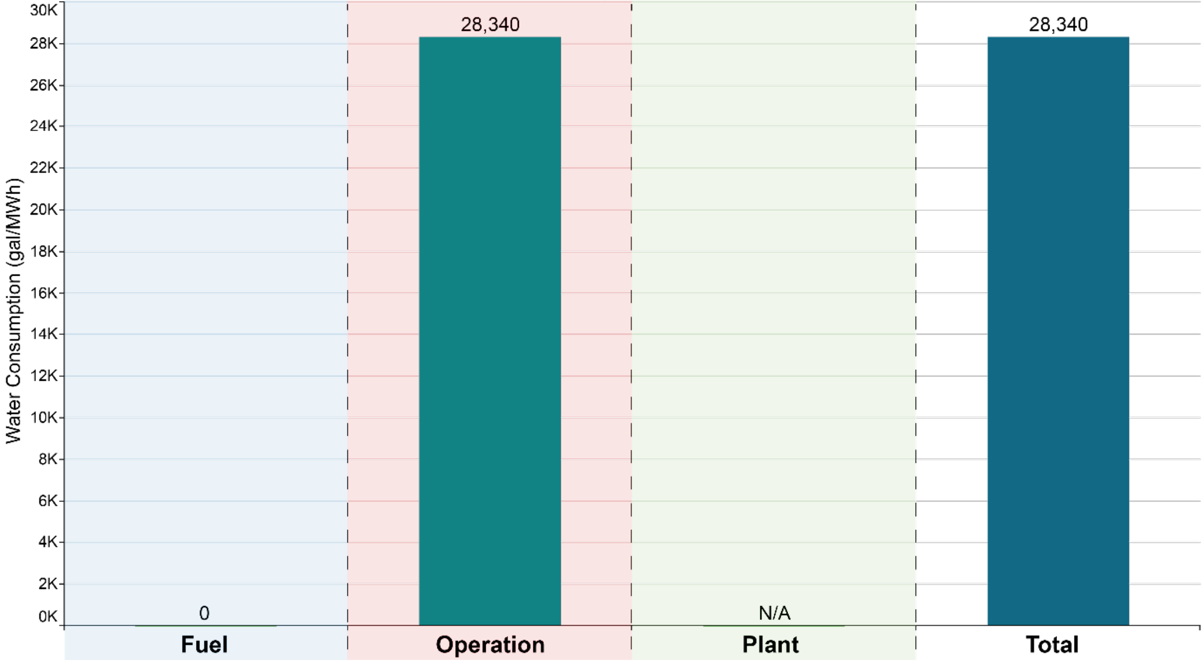

FIGURE 29: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM HYDROPOWER

Hydroelectric Water Return

Unlike traditional power plants, water discharged from hydroelectric plants is not typically measured. Therefore, water returned to the source is calculated as the difference between water withdrawn and water consumed. Using water withdrawn and consumed across U.S. facilities, 21,870,949 gal/MWh are returned.

Solar Electricity

Solar Electricity Basic Generation Description

Figure 30 diagrams the basic steps of electricity generation from solar energy. Solar electric, or photovoltaic, cells convert sunlight in direct current (DC) electricity. Utah ranked 11th in the country for solar generating capacity in 2021, with 1,843 MW of capacity and 360 MW more scheduled to come online in 2022.[5]

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[5] https://www.eia.gov/state/analysis.php?sid=UT#:~:text=Renewable%20energy,-In%202021%2C%20about&text=At%20the%20end%20of%202021,to%20come%20online%20in%202022.

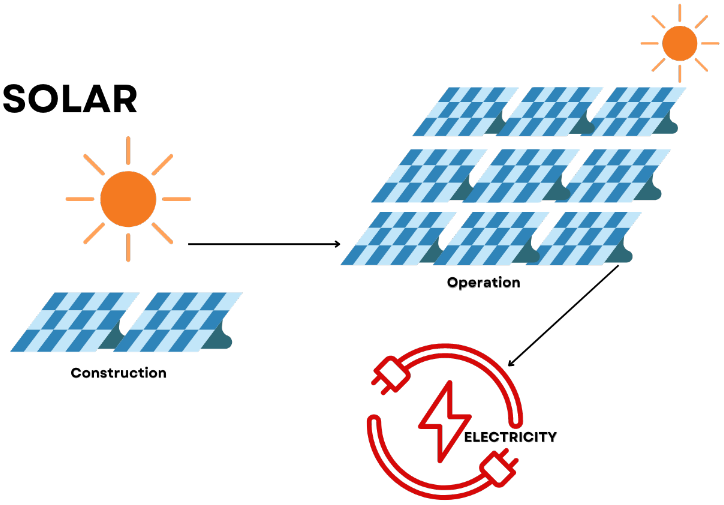

FIGURE 30: ELECTRICITY GENERATION USING SOLAR ENERGY

Solar Electricity Life Cycle

The life cycle of energy generation is categorized into two stages: power plant and operation. Figure 31 displays the solar generation life cycle. Note that in solar generation, the sun, or solar electricity, is the 'fuel'.

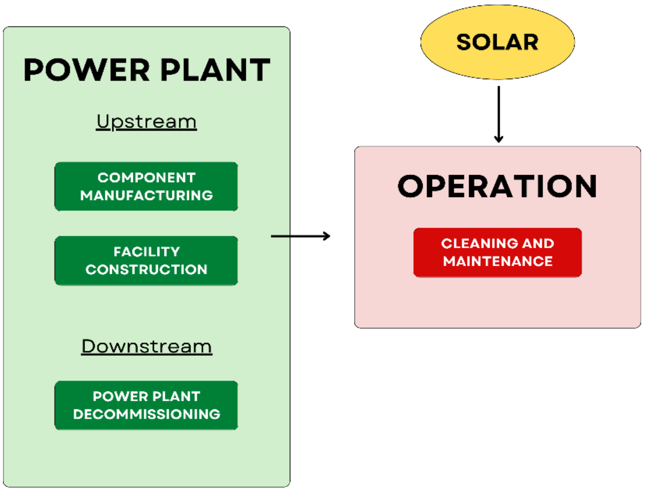

FIGURE 31: LIFE CYCLE FOR ELECTRICITY GENERATION FROM SOLAR

Solar Electricity Zero Carbon Emissions (and Combustion)

Solar electricity requires no combustion and is a zero-carbon emissions generation type. Lifecycle carbon dioxide emissions from plant construction, etc. are not zero – however, estimating those is beyond the scope of this report.

Solar Electricity Water Comparisons

Solar power generation requires water to be withdrawn, consumed, and in some cases, returned to the environment. The definition for each is included in Appendix A. The following sections compare how solar power generation uses water over each stage of the generation life cycle. Similar to hydrogen earlier in this report, the water usage (in gallons) is normalized based on the electricity generated (in megawatt-hours).

Solar Electricity Withdrawal and Variability

Figure 32 displays water withdrawn for each life cycle stage related to solar electricity generation - as well as the total water withdrawn for the life cycle of solar generation. For the operation stage, withdrawal is for panel washing. Note that there is no major variation in operation process, and the life cycle values used in the executive summary and conclusion to present a single value of water withdrawal are for flat panel photovoltaic systems. These systems were chosen because 38 of 39 systems in Utah at the time of this publication are flat panel photovoltaic. Variation in literature values are presented in Appendix C.

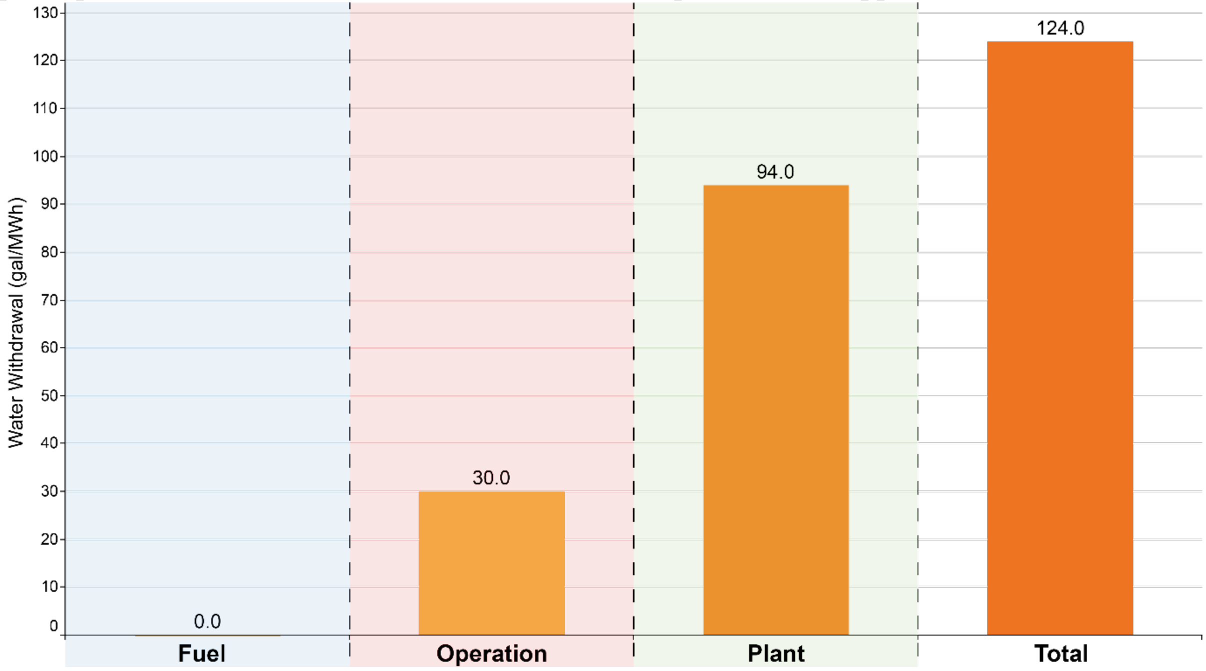

FIGURE 32: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM SOLAR

Solar Electricity Water Consumption

Figure 33 displays water consumption for the life cycle stages of generation from solar. For example, water is consumed in the production and field maintenance of photovoltaic cells.

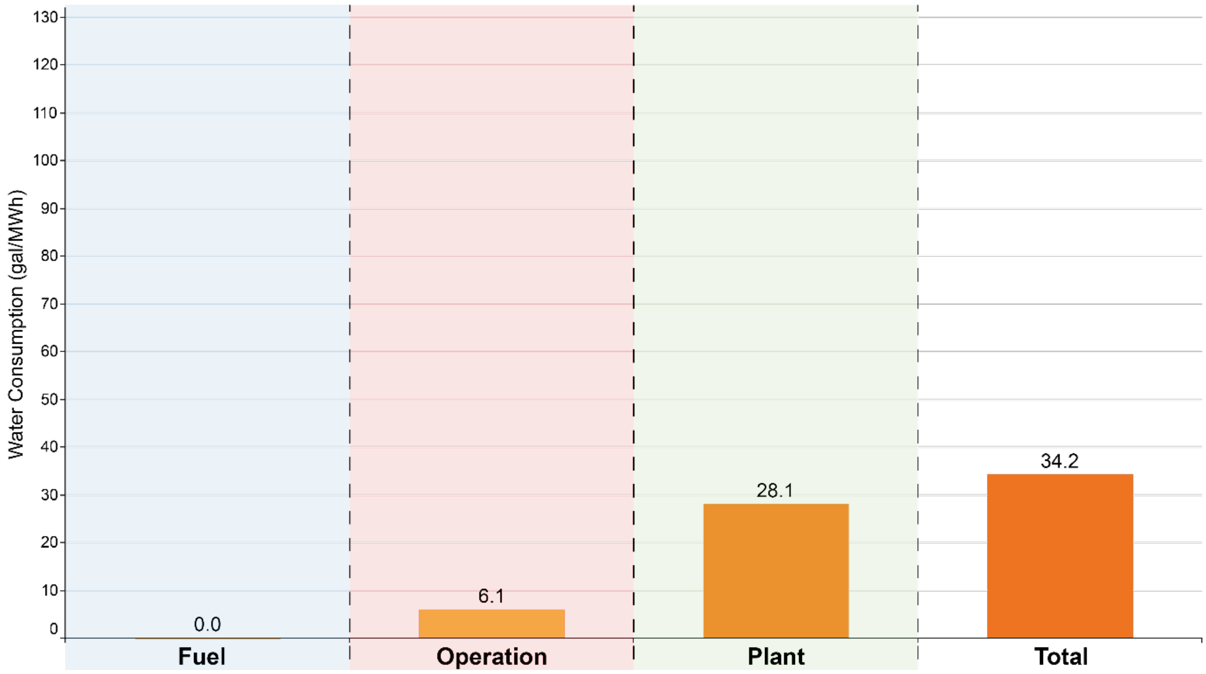

FIGURE 33: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM SOLAR

Solar Electricity Consumption Variability

While water consumption varies between the type of solar system utilized, large variation during operation is not widely reported, and single values for flat panel photovoltaic life cycle steps are presented in Figure 33. Additional variation found in literature is reported in Appendix C.

Solar Electricity Water Return

Because the nature of solar photovoltaic generation plants is different than that of a traditional power plant, water discharged is not typically measured. Therefore, return values are calculated as the difference between water withdrawn and water consumed, or 90 gal/MWh.

Wind Energy

Wind Energy Basic Generation Description

Figure 34 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. Utah has five wind farms with approximately 400 MW of generating capacity at the time of this publication. 6

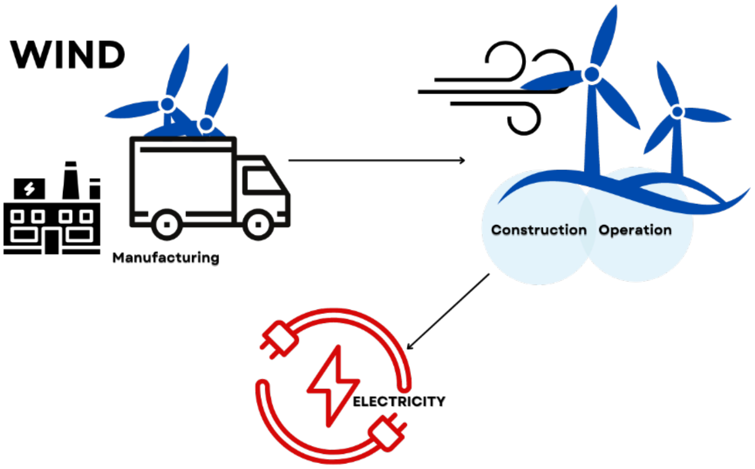

FIGURE 34: ELECTRICITY GENERATION USING WIND ENERGY

Wind Life Cycle

The life cycle of energy generation is categorized into two stages: power plant and operation. Figure 35 displays the wind generation life cycle. Note that in wind generation, wind is the 'fuel'.

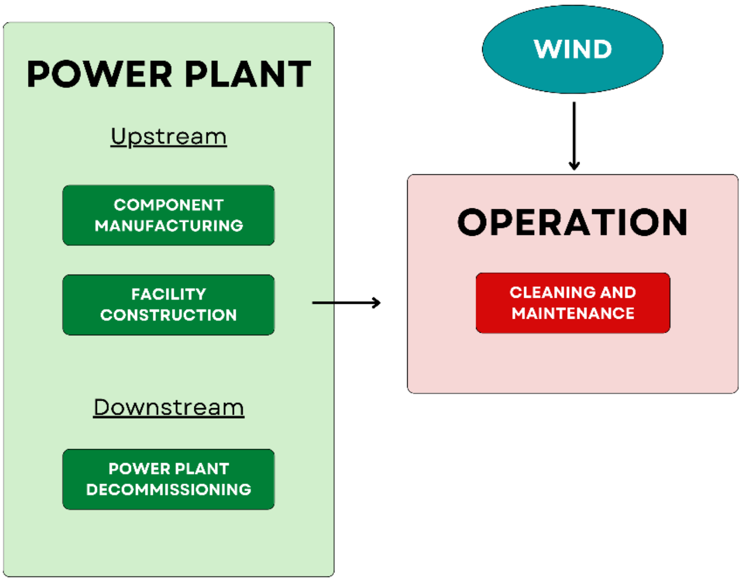

FIGURE 35: LIFE CYCLE FOR ELECTRICITY GENERATION FROM WIND

Wind Zero Carbon Emissions (and Combustion)

Wind electricity generation requires no combustion and is a zero-carbon emissions generation type during operation. Lifecycle carbon emission estimates have not been made in the report.

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[6] https://www.eia.gov/state/analysis.php?sid=UT#:~:text=Renewable%20energy,-In%202021%2C%20about&text=At%20the%20end%20of%202021,to%20come%20online%20in%202022.

Wind Water Comparisons

Wind power generation requires water to be withdrawn, consumed, and in some cases, returned to the environment. The definition for each is included in Appendix A. The following sections compare how wind power generation uses water over each stage of the generation life cycle. Similar to hydrogen earlier in this report, the water usage (in gallons) is normalized based on the electricity generated (in megawatt-hours).

Wind Water Withdrawal and Variability

Figure 36 displays water withdrawn for each life cycle stage related to wind electricity generation - as well as the total water withdrawn for the life cycle of wind generation. Note that the onshore life cycle values are used in the executive summary and conclusion to present a single value of water consumption without variation. Onshore wind plants were chosen because any system in Utah will be onshore.

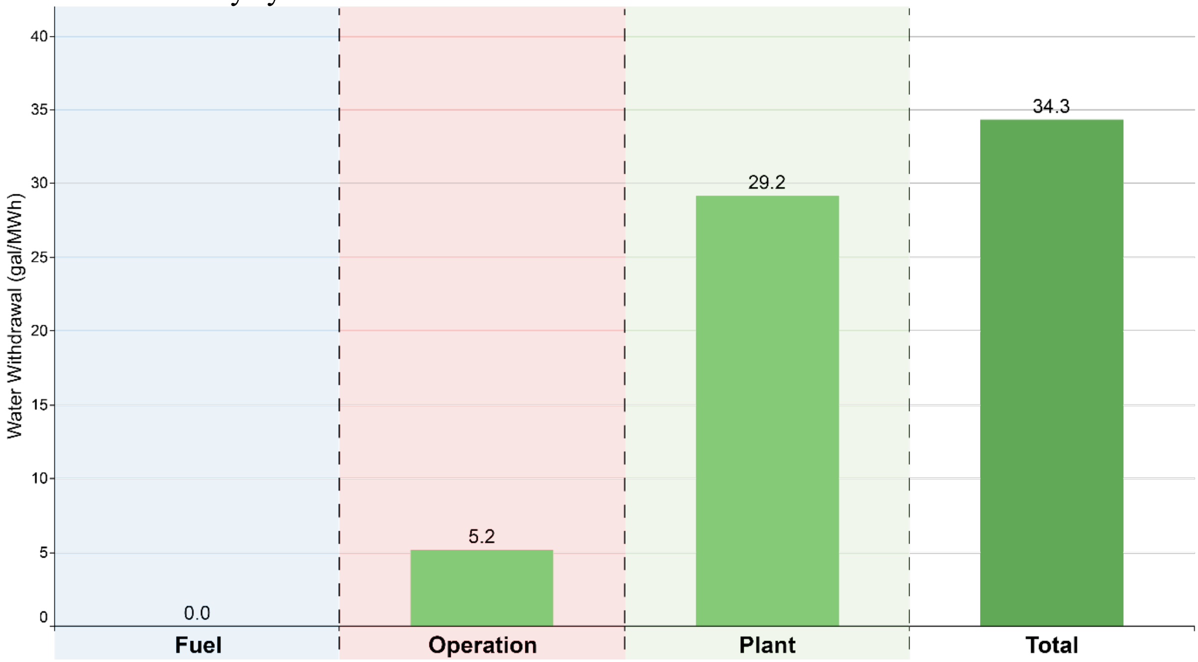

FIGURE 36: WATER WITHDRAWAL FOR ELECTRICITY GENERATION FROM WIND

Wind Water Consumption

Figure 37 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 37: WATER CONSUMPTION FOR ELECTRICITY GENERATION FROM WIND

Wind Consumption Variability

While water consumption varies between the location of the wind generation plant (either onshore or offshore), large variation in onshore plants is not widely reported. Single values for each life cycle step of an onshore plant are presented in Figure 37, and additional variation found in literature is reported in Appendix C.

Wind Water Return

Because the nature of wind generation plants is different than that of a traditional power plant, water discharged is not typically measured (similar to water discharge for solar generation plants). Therefore, return values are calculated as the difference between water withdrawn and water consumed, or about 23 gal/MWh.

Summary and Next Steps

The following figures summarize key data presented in this report. Water requirements for the three hydrogen production processes are compared in Figure 38.

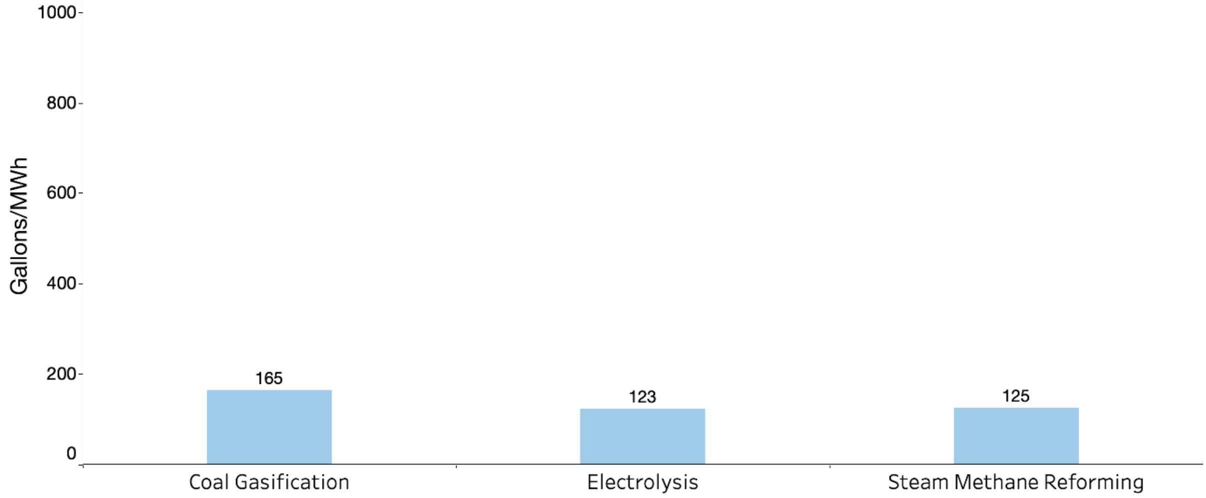

FIGURE 38: WATER CONSUMPTION FOR VARIOUS METHODS OF HYDROGEN PRODUCTION

Figure 39 shows the water withdrawal of the electricity generation processes considered in this report.

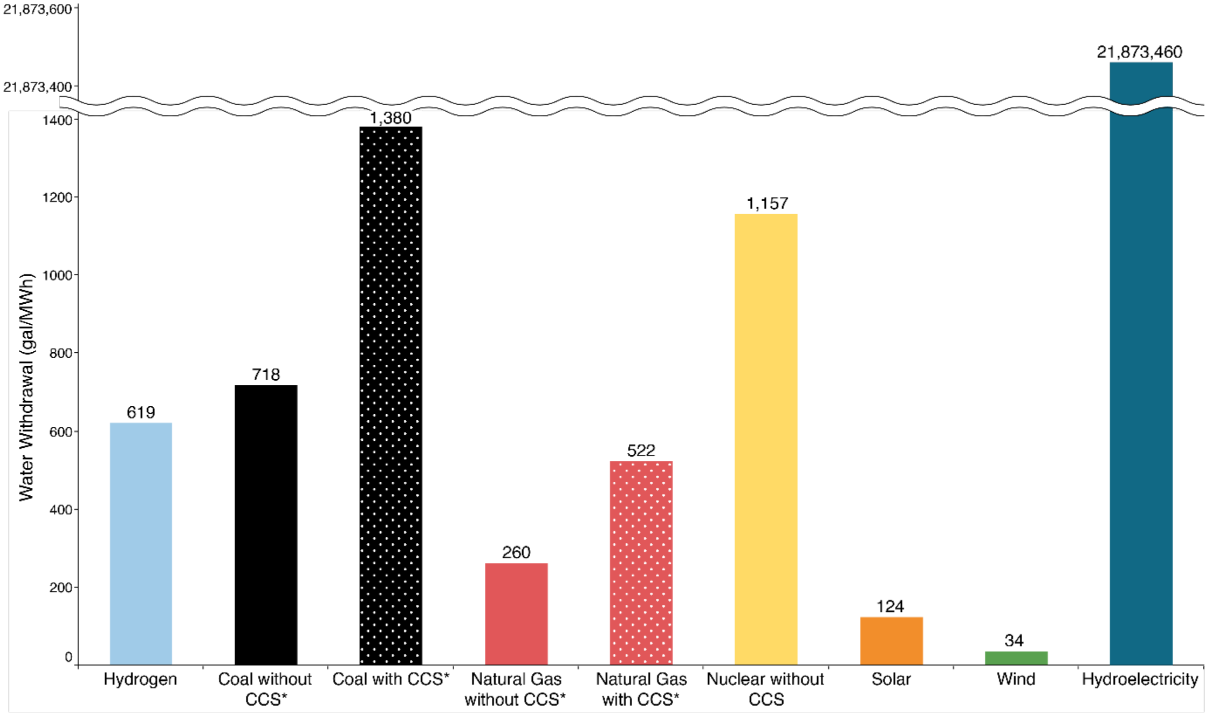

FIGURE 39: LIFE CYCLE WATER *WITHDRAWAL* FOR VARIOUS GENERATION OPTIONS (*CCS REPRESENTS CARBON CAPTURE AND SEQUESTRATION). HYDROGEN IN THE ABOVE DIAGRAM IS PRODUCED BY ELECTROLYSIS USING RENEWABLE ENERGY.

Figure 39 compares water consumed in (only) the operation life cycle stage for various electricity generation processes considered in this report.

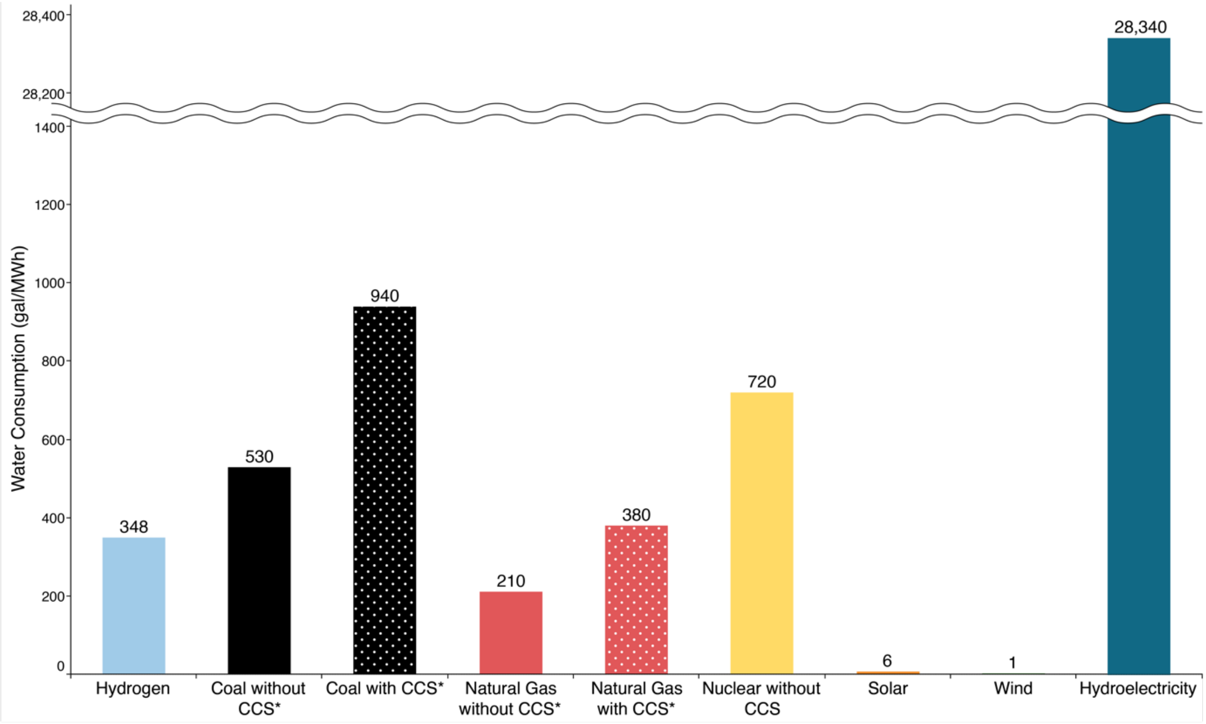

FIGURE 39: WATER CONSUMED IN POWER PLANT OPERATIONS (ONLY) FOR VARIOUS GENERATION OPTIONS

Figure 40 below shows the water consumption of the electricity generation processes considered in this report.

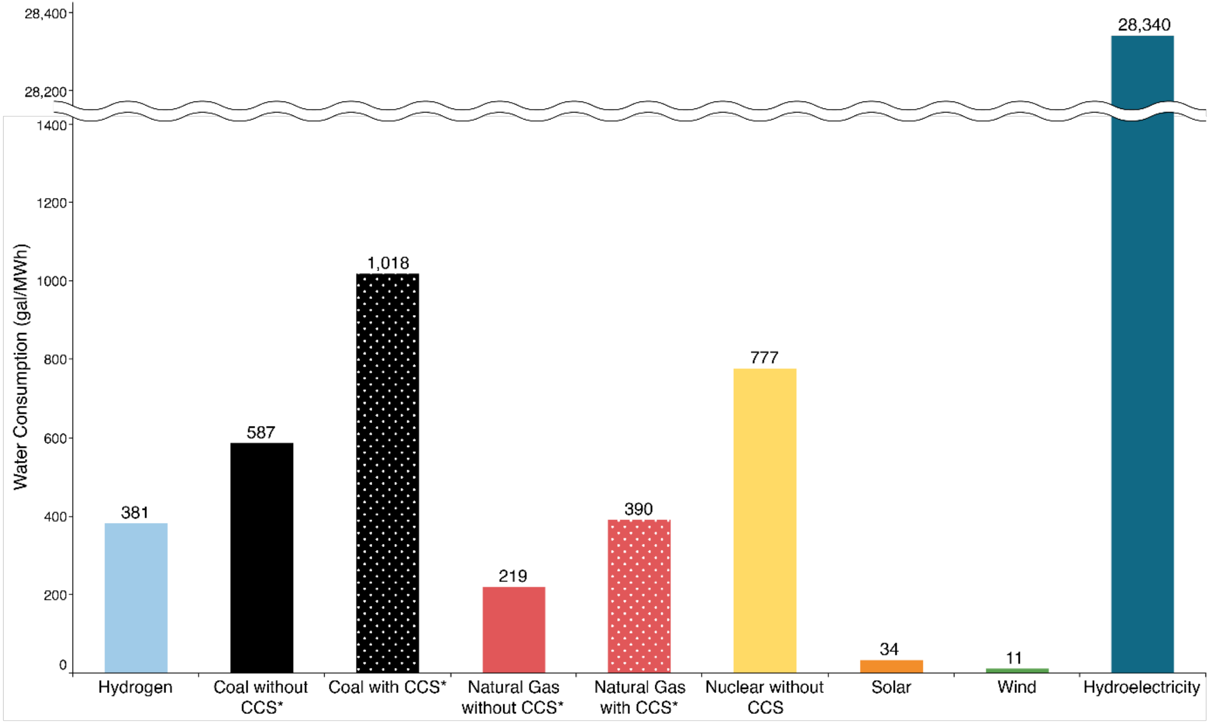

FIGURE 40: LIFE CYCLE WATER *CONSUMPTION* FOR VARIOUS GENERATION OPTIONS (*CCS REPRESENTS CARBON CAPTURE AND SEQUESTRATION). HYDROGEN IN THE ABOVE DIAGRAM IS PRODUCED BY ELECTROLYSIS USING RENEWABLE ENERGY.

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. Water consumption of hydrogen generation technologies is commensurate with generation technologies that are a part Utah’s current and future fuel mix.

Finally, future study is recommended to holistically consider hydrogen generation aspects that will impact decision-making for Utah’s future fuel mix. The impact of on air emissions and overall economics are of particular importance for any future studies.

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.

Megawatt hour: Unit of measurement that represents the amount of electricity generated and sent to the grid over a given time.

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 not found as a natural resource. Primary fuels are used to generate secondary fuels.

Appendix A: Water Comparison Terms

In comparing water usage in various generation technologies, it is important to understand the language used to describe the water pathways. In this report, definitions for withdrawal and consumption follow those laid out by Grubert & Sanders (2018). The definition for discharge, however, is from the Energy Information Administration (EIA) and reflects measured Utah power plant data. The EIA data set was specifically selected to provide an accurate understanding of water being discharged from Utah power plants with cooling tower recirculation.

Collectively, then, the values of withdrawal and consumption come from a different source than discharge values. Because of the use of different data sets, the values of withdrawal minus consumption are not equal to discharge. Each term is defined as follows for clarity.

Withdrawal

Water withdrawal is the removal of water from its originating source, whether or not it is returned.

Consumption

Water consumed is the removal of water from its originating source without directly returning it. *Water consumed may include evaporation*, incorporation, and delivery to a non-originating body (including groundwater that is discharged at the surface).

Discharge

Discharged water is the delivery of water to a natural body of water or multi-use reservoir (not a cooling pond) in liquid form, whether or not it is delivered to the water's originating source. For example, a power plant may withdraw water from a stream but discharge it to a nearby farmer's field. *Discharged water does not include evaporation or water recirculated in a treatment or evaporation pond*.

Return

Water returned is the delivery of water to its proximate originating source. For example, a hydroelectric plant may withdraw water from a reservoir and return the water to the river just below the reservoir. *Returned water does not include evaporation or water discharged to a body outside of the originating source*.

Appendix B: Electricity Generation Cooling Methods

Many generation technologies utilize steam turbines to generate electricity, and these turbines require large amounts of cooling. Because the method of cooling utilized in a power plant has a large impact on the water it withdraws and consumes, four common methods of cooling are defined in this section. Most generation technologies considered in this report will utilize one or more of the following cooling methods. Variability in specific water withdrawal and consumption for each generation technology will be presented in individual technology sections.

Cooling Method 1 – Cooling Tower Recirculation

Cooling using cooling tower recirculation involves a system which withdraws water and recirculates it for cooling, rather than discharging it. Water is recirculated through a cooling tower, which utilizes evaporation and phase change principles to cool the water. The cooling tower may use fans to force air over the water, or it may use a natural draft with the shape of the cooling tower drawing air over the water. Water is consumed through evaporation and drift, which is replaced by 'makeup' water, or additional withdrawn water. To maintain an appropriate concentration of minerals and contaminants in the water, a limited amount of water may also be discharged as 'blowdown'. Refer to Figure B1 for a diagram of Cooling Method 1. Note that some plants may use a treatment or evaporation pond for makeup water; withdrawn water then would supply the pond and discharge would come from the pond rather than directly from the plant.

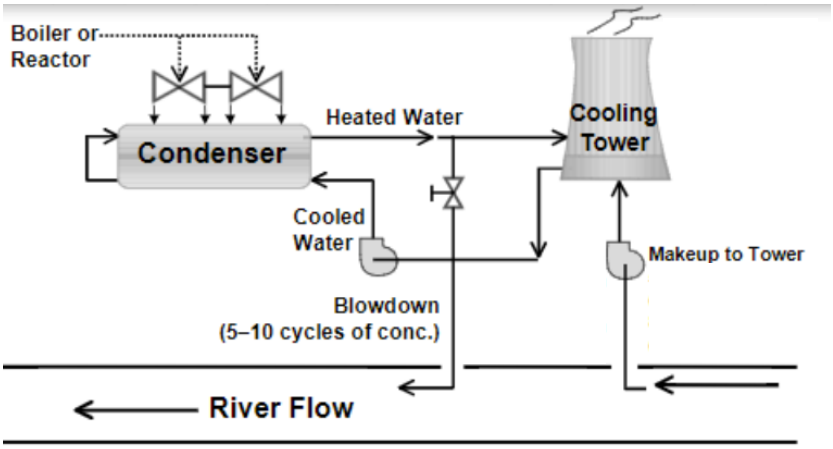

Figure B1: Cooling Method 1 Process Flow Diagram - Cooling Tower Recirculation[7]

Due to the high quantities of makeup and blowdown water consumed in the cooling tower process, Cooling Method 1 has low water withdrawal but high water consumption. This is the most commonly used method by Utah power plants due to limited water sources and its low withdrawal requirements.

Cooling Method 2 – Pond Recirculation

Cooling using pond recirculation involves a system which withdraws water from a small volume source and discharges it back to the same source. Typically, water is pulled from a pond, circulated through a heat exchanger, and discharged back to the pond at a higher temperature. Some water is consumed through evaporation at the pond due to higher return water temperatures. Depending on the size and location of the pond, makeup water may need to be added to account for the evaporation. Blowdown to another source is also still required in order to keep the concentration of minerals and contaminants in the pond to an appropriate level. Refer to Figure B2 for a diagram of Cooling Method 2.

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[7] Myhre (2002), Figure 3-3

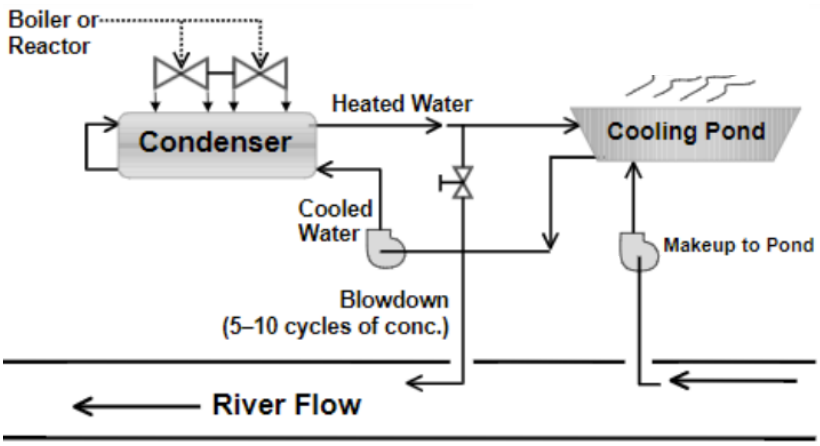

Figure B2: Cooling Method 2 Process Flow Diagram - Pond Recirculation[8]

Cooling Method 2 has high water withdrawal but lower water consumption. This method has some limited use in Utah power plants.

Cooling Method 3 – Open Loop - Once-Through Cooling

Cooling using an open loop involves a system which withdraws water from a large volume source (such as a river or reservoir) and then discharges it back to that source or another nearby source. Typically, water is pulled from a river, pumped through a heat exchanger, and discharged at a higher temperature. Some water is consumed through evaporation at the river or reservoir due to higher return water temperature. No makeup water or blowdown is required due to the high volume of water at the source. Refer to Figure B3 for a diagram of Cooling Method 3.

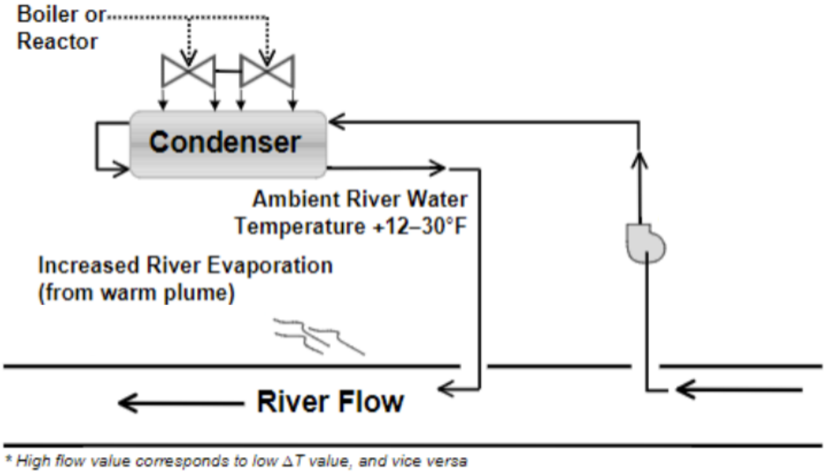

Figure B3: Cooling Method 3 Process Flow Diagram – Open Loop, Once-Through Cooling[9]

Cooling Method 3 has the highest water withdrawal but lowest water consumption of the wet cooling methods. While this cooling method is common in the eastern United States, it is not used in any Utah power plants.

Cooling Method 4 – Dry Cooling

Dry cooling does not involve water withdrawal or consumption. Instead, it relies on ambient air as the primary coolant medium to transfer heat through a surface away from the cooling fluid. Typically, fans pull ambient air over a heat exchanger in order to provide cooling. Because dry cooling relies heavily on ambient air temperature and humidity, its efficiency may

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[8] Myhre (2002), Figure 3-4

[9] Myhre (2002), Figure 3-1

fluctuate greatly throughout the year. Capital costs for a dry cooling system can be up to ten times more than a once-through cooling system, and they typically consume a larger amount of electricity to operate than any other system due to the number of fans required. Refer to Figure B4 for a diagram of Cooling Method 4.

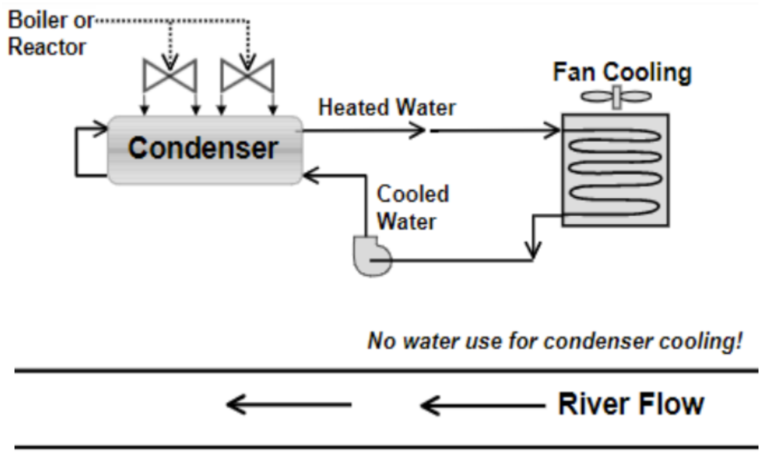

FIGURE B4: METHOD 3 DIAGRAM – ONCE- COOLING PROCESS FLOW OPEN LOOP, THROUGH COOLING [10]

Dry cooling requires no water withdrawal or consumption but has limited use throughout the United States due to its high operating costs and variability in efficiency. Utah power plants have some limited use of dry cooling.

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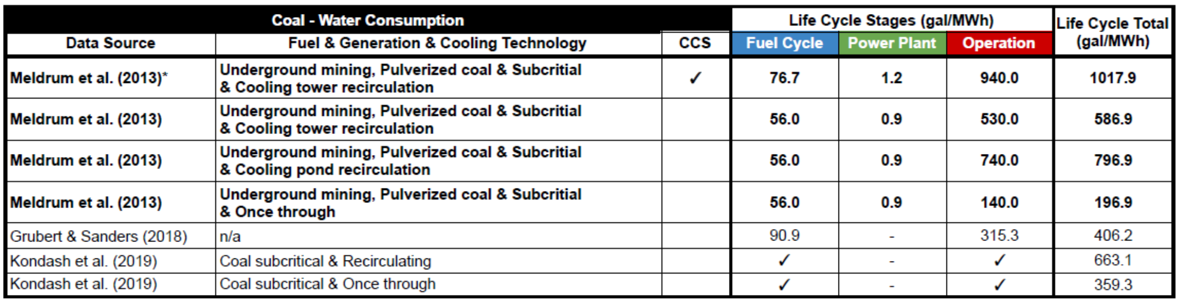
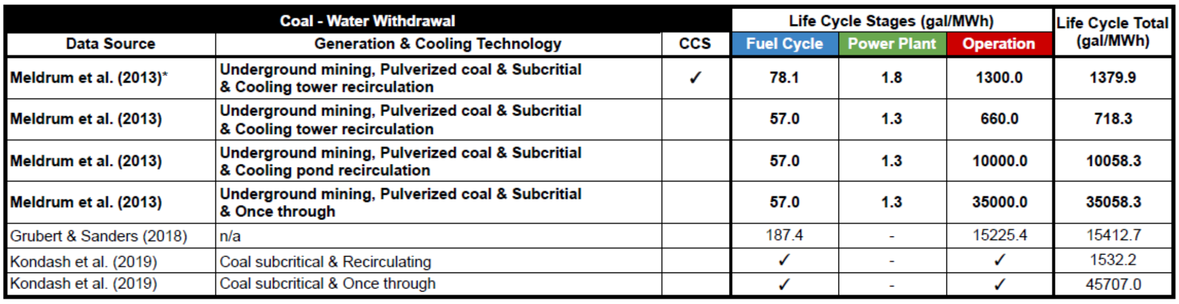
[10] Myhre (2002), Figure 3-6

Appendix C: Water Comparison Variation in Literature



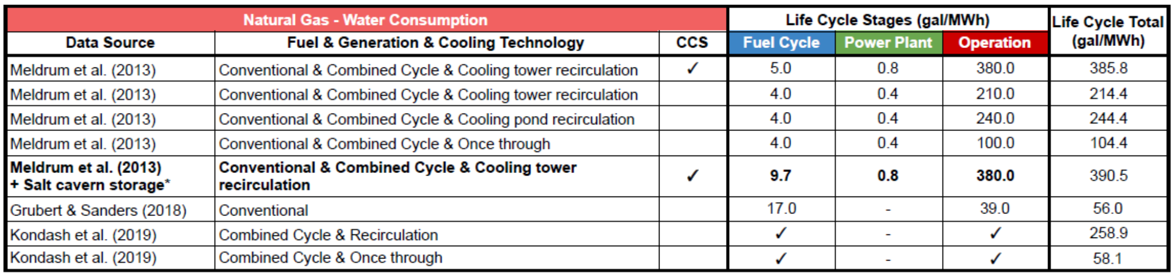
Coal - Water Consumption			**Life Cycle Stages (gal/MWh)**			**Life Cycle Total (gal/MWh)**
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)*	**Underground mining, Pulverized coal & Subcritial & Cooling tower recirculation**	✓	**76.7**	**1.2**	**940.0**	**1017.9**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Cooling tower recirculation**		**56.0**	**0.9**	**530.0**	**586.9**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Cooling pond recirculation**		**56.0**	**0.9**	**740.0**	**796.9**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Once through**		**56.0**	**0.9**	**140.0**	**196.9**
Grubert & Sanders (2018)	n/a		90.9	-	315.3	406.2
Kondash et al. (2019)	Coal subcritical & Recirculating		✓	-	✓	663.1
Kondash et al. (2019)	Coal subcritical & Once through		✓	-	✓	359.3

*included in the executive summary figure



Coal - Water Withdrawal			**Life Cycle Stages (gal/MWh)**			**Life Cycle Total (gal/MWh)**
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)*	**Underground mining, Pulverized coal & Subcritial & Cooling tower recirculation**	✓	**78.1**	**1.8**	**1300.0**	**1379.9**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Cooling tower recirculation**		**57.0**	**1.3**	**660.0**	**718.3**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Cooling pond recirculation**		**57.0**	**1.3**	**10000.0**	**10058.3**
Meldrum et al. (2013)	**Underground mining, Pulverized coal & Subcritial & Once through**		**57.0**	**1.3**	**35000.0**	**35058.3**
Grubert & Sanders (2018)	n/a		187.4	-	15225.4	15412.7
Kondash et al. (2019)	Coal subcritical & Recirculating		✓	-	✓	1532.2
Kondash et al. (2019)	Coal subcritical & Once through		✓	-	✓	45707.0

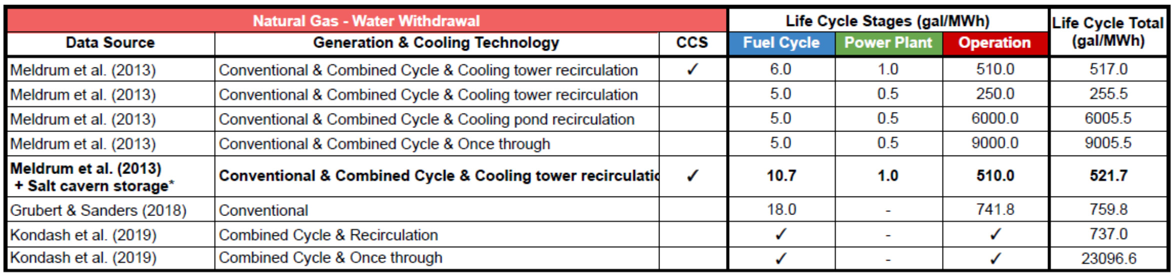
*included in the executive summary figure



Natural Gas - Water Consumption			**Life Cycle Stages (gal/MWh)**			**Life Cycle Total (gal/MWh)**
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling tower recirculation	✓	5.0	0.8	380.0	385.8
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling tower recirculation		4.0	0.4	210.0	214.4
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling pond recirculation		4.0	0.4	240.0	244.4
Meldrum et al. (2013)	Conventional & Combined Cycle & Once through		4.0	0.4	100.0	104.4
Meldrum et al. (2013) + Salt cavern storage*	**Conventional & Combined Cycle & Cooling tower recirculation**	✓	**9.7**	**0.8**	**380.0**	390.5
Grubert & Sanders (2018)	Conventional		17.0	-	39.0	56.0
Kondash et al. (2019)	Combined Cycle & Recirculation		✓	-	✓	258.9
Kondash et al. (2019)	Combined Cycle & Once through		✓	-	✓	58.1

Salt cavern storage from Grubert & Sanders (2018)

*included in the executive summary figure



Natural Gas - Water Withdrawal			**Life Cycle Stages (gal/MWh)**			**Life Cycle Total (gal/MWh)**
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling tower recirculation	✓	6.0	1.0	510.0	517.0
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling tower recirculation		5.0	0.5	250.0	255.5
Meldrum et al. (2013)	Conventional & Combined Cycle & Cooling pond recirculation		5.0	0.5	6000.0	6005.5
Meldrum et al. (2013)	Conventional & Combined Cycle & Once through		5.0	0.5	9000.0	9005.5
Meldrum et al. (2013) + Salt cavern storage*	**Conventional & Combined Cycle & Cooling tower recirculatio**	✓	**10.7**	**1.0**	**510.0**	**521.7**
Grubert & Sanders (2018)	Conventional		18.0	-	741.8	759.8
Kondash et al. (2019)	Combined Cycle & Recirculation		✓	-	✓	737.0
Kondash et al. (2019)	Combined Cycle & Once through		✓	-	✓	23096.6

Salt cavern storage from Grubert & Sanders (2018)

*included in the executive summary figure

Nuclear - Water Consumption			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)*	**Centrifugal enrichment & Cooling tower recirculation**		**56.0**	**0.5**	**720.0**	**776.5**
Meldrum et al. (2013)	Centrifugal enrichment & Cooling pond recirculation		56.0	0.5	610.0	666.5
Meldrum et al. (2013)	Centrifugal enrichment & Open loop cooling		56.0	0.5	400.0	456.5
Grubert & Sanders (2018)	n/a		3.7	-	573.8	577.5
Peer & Sanders (2016)	Cooling tower recirculation (induced draft)		-	-	758.0	758.0
Peer & Sanders (2016)	Cooling tower recirculation (natural draft)		-	-	672.0	672.0
NuScale (2022)**	Small Modular Reactor & Water cooling		-	-	740.0	740.0
NuScale (2022)**	Small Modular Reactor & Dry cooling		-	-	1.1	1.1

**in licensing

*included in the executive summary figure

Nuclear - Water Withdrawal			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)*	**Centrifugal enrichment & Cooling tower recirculation**		**56.0**	**0.5**	**1100.0**	**1156.5**
Meldrum et al. (2013)	Centrifugal enrichment & Cooling pond recirculation		56.0	0.5	1100.0	1156.5
Meldrum et al. (2013)	Centrifugal enrichment & Open loop cooling		56.0	0.5	47000.0	47056.5
Grubert & Sanders (2018)	n/a		4.0	-	24729.7	24733.7
Peer & Sanders (2016)	Cooling tower recirculation (induced draft)		-	-	1150.0	1150.0
Peer & Sanders (2016)	Cooling tower recirculation (natural draft)		-	-	1304.0	1304.0

*included in the executive summary figure

Hydroelectricity - Water Consumption			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Grubert & Sanders (2018)	Operation (Evaporation + Seepage)		-	-	2511	2511
Grubert (2016)	Evaporation Only (Centroid = Arizona)		-	-	27580	27580
Grubert (2016) + Grubert & Sanders (2018)*	**Evaporation (Centroid = Arizona) + Seepage**		**-**	**-**	**28340**	**28340**
Lampert et al. (2015)	Evaporation Only		-	-	10550	10550
Lee et al. (2018)	Evaporation Only (Western Electricity Coordinating Council)		-	-	3329	3329
Lee et al. (2018)	Evaporation Only (Southwest Power Pool, Regional Entity)		-	-	21979	21979

*included in the executive summary figure

Hydroelectricity - Water Withdrawal			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Grubert & Sanders (2018)*	**Operation (Evaporation + Seepage)**		**-**	**-**	**21873460**	**21873460**

*included in the executive summary figure

Solar - Water Consumption			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Photovoltaics (C-Si), Concentrated PV		-	81.0	30.0	111.0
Meldrum et al. (2013)	Photovoltaics (C-Si), Flat panel		-	81.0	6.0	87.0
Grubert & Sanders (2018)	Photovoltaics		-	-	1.8	1.8
Macknick et al. (2014)*	**Photovoltaics (C-Si)**		**-**	**28.1**	**6.1**	**34.2**
Frisvold & Marquez (2013)	Photovoltaics		-	-	1–310	1–310

*included in the executive summary figure

Solar - Water Withdrawal			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Photovoltaics (C-Si), Concentrated PV		-	94.0	30.0	124.0
Meldrum et al. (2013)	Photovoltaics (C-Si), Flat panel		-	94.0	6.0	100.0
Grubert & Sanders (2018)	Photovoltaics		-	-	1.8	1.8
Macknick et al. (2014)*	**Photovoltaics (C-Si)**		**-**	**94.0**	**30.0**	**124.0**

*included in the executive summary figure

Wind - Water Consumption			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Fuel & Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Wind: Onshore		-	1.0	1.0	2.0
Grubert & Sanders (2018)	n/a		-	-	3.0	3.0
Yang & Chen (2016)*	**Wind: Onshore**		**-**	**10.1**	**1.2**	**11.4**

*included in the executive summary figure

Wind - Water Withdrawal			Life Cycle Stages (gal/MWh)			Life Cycle Total (gal/MWh)
Data Source	**Generation & Cooling Technology**	**CCS**	**Fuel Cycle**	**Power Plant**	**Operation**	
Meldrum et al. (2013)	Wind: Onshore		-	26.0	1.0	27.0
Grubert & Sanders (2018)	n/a		-	-	3.0	3.0
Yang & Chen (2016)*			**-**	**29.2**	**5.2**	**34.3**

*included in the executive summary figure

Appendix D: References of Report

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