What is Water's Role in a Carbon Neutral Future?

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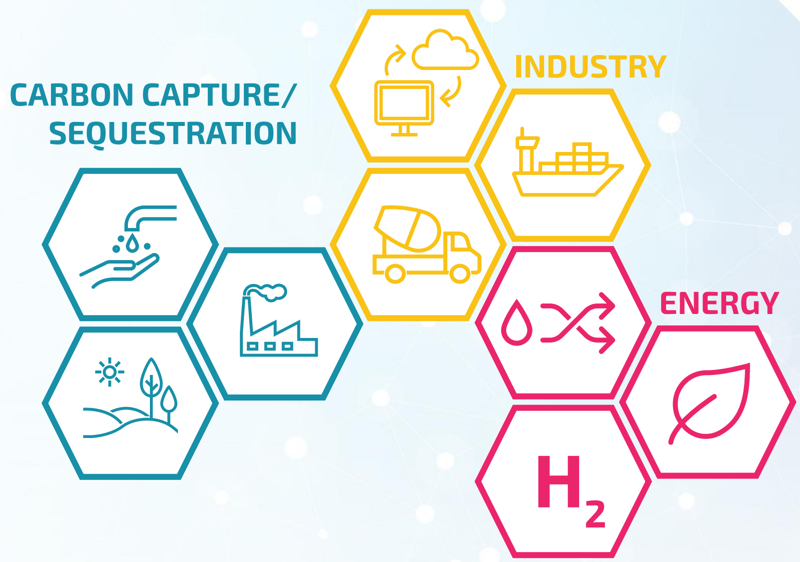

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Their insights highlighted key dynamics, priorities, and opportunities at the energy-water-carbon nexus.

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EXECUTIVE SUMMARY

There has been ever-growing interest and engagement regarding net-zero and carbon neutrality goals, with many nations committing to steep emissions reductions by mid-century. Although water plays critical roles in various sectors, there has been a distinct gap in discussions to date about the role of water in the transition to a carbon neutral future. To address this need, a webinar was convened in April 2022 to gain insights into how water can support or influence active strategies for addressing emissions activities across energy, industrial, and carbon sectors.

The webinar presentations and discussions highlighted various nuances of direct and indirect water use both within and across technology sectors (Figure ES-1). For example, hydrogen and concrete production, water for mining, and inland waterways transportation are all heavily influenced by the energy sources used (fossil fuels vs. renewable sources) as well as local resource availabilities. Algal biomass, on the other hand, can be produced across diverse geographies (terrestrial to sea) in a range of source water qualities, including wastewater and could also support pollution remediation through nutrient and metals recovery. Finally, water also influences carbon dynamics and cycling within natural systems across terrestrial, aquatic, and geologic systems. These dynamics underscore not only the critical role of water within the energy-water nexus, but also the extension into the energy-water-carbon nexus.

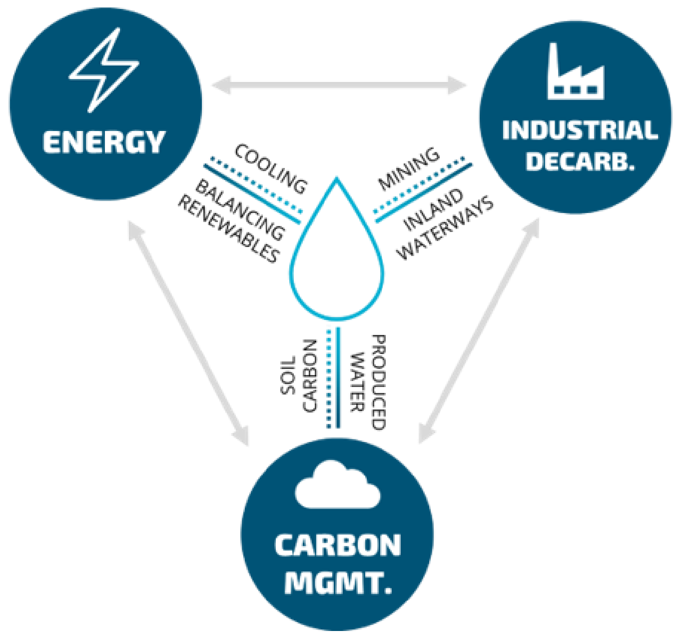

Figure ES-1. Water serves as both a direct (solid) and indirect (dashed) line for carbon neutral activities.

Numerous questions arose regarding the effective management of water across these activities, including scaling up of technologies (via pilot demonstrations), analytical assumptions, and institutional barriers across sectors. The discussions also highlighted a number of opportunities including the need for a systems approach and data to understand the embedded nature of water and associated dependencies across sectors. Given the deep uncertainty of future system states (across climate, technology maturity, and market conditions), a systems perspective is needed to fully understand the capabilities, requirements, and performance at the energy-water-carbon nexus. A data-driven approach could further disentangle current assumptions about system operations from possible future conditions to support creation of performance thresholds and inform investment priorities cognizant of different resource risks. Given that most of these technologies are in early stages of development, a data-driven systems approach would help ensure water resources are effectively being incorporated to successfully support the transition to a carbon neutral future while advancing critical priorities of resilience and justice.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CO_2	Carbon dioxide
DAC	Direct air capture
GHG	Greenhouse gas
H_2	Hydrogen
km^2	Square kilometers
R&D	Research & Development
US	United States
USGS	United States Geologic Survey

1. MOTIVATION

Climate change is well-recognized as a threat to national and global security [1]. One of the key methods to mitigate the impacts of climate change is through reducing greenhouse gas (GHG) emissions and removing legacy carbon from the atmosphere [2]. In particular, carbon neutrality – which refers to balancing activities that release carbon with equivalent activities that remove carbon – is increasingly becoming a priority for many and seen as an essential strategy to limit warming to less than 2°C above preindustrial levels [3].

A wide variety of mitigation strategies have been proposed to reduce carbon emissions, such as changing fuel and energy sources and developing technologies to capture and sequester carbon. Simultaneous with these opportunities, there are a number of risks that influence the successful transition into a carbon neutral future. One such risk is ensuring carbon mitigation efforts do not exacerbate water security risks, where projections indicate gaps between global water demand and supplies up to 40% by 2030 [4].

Water plays a critical role across many societal activities, such as energy development, industrial activities, and agriculture. Accordingly, a shift towards carbon neutrality will impact water use across all of these sectors, especially those that directly emit significant GHGs [5]. Concurrently, water resources are expected to be at the forefront of climate impacts, with extreme weather conditions influencing seasonal patterns, frequency of severe storms, and associated quality of available resources [6].

Although some discussions have started to focus on opportunities within the water sector itself [7], discussions about the role of water across carbon neutrality activities have been limited to date. This report draws attention to this issue by synthesizing key findings and nuances raised during the 9 presentations and subsequent discussions that occurred during the "What is Water's Role in a Carbon Neutral Future?" webinar series (hosted by Sandia National Laboratories from April 4-6, 2022). The following sections are organized into each of the 3 webinar themes (Energy, Industrial Decarbonization, and Carbon Management)[1], detailing key dynamics and nuances present within each sector. We conclude with a summary of needs and opportunities that can enable effective integration of water into transitions towards a secure, carbon neutral, and just climate future.

[1] The recorded presentations from the webinar series can be accessed online at: https://energy.sandia.gov/programs/energy-water/what-is-waters-role-in-a-carbon-neutral-future/

2. ENERGY

Energy-related emissions span multiple activities, including power, transportation, heating and cooling, and manufacturing. While renewable technologies (e.g., solar, wind, and hydropower) have demonstrated successful reduction of emissions from fuel switching, there are still issues related to the stochastic nature of these resources. Various opportunities exist for addressing these concerns, including hydrogen and algal biomass to re-envisioning the role of water and wastewater utility sectors as grid balancing efforts.

Hydrogen (H_2), which has been undergoing a quiet revolution over the last few decades, can provide a versatile solution to energy needs. Analogous to liquid-based fuels, hydrogen is a single product that can be transported easily to serve key resilience functions, such as energy storage and disaster recovery. Hydrogen production is projected to expand from ammonia and crude oil refinement (current uses) to support a sizable portion of final global energy demand; estimates of potential hydrogen adoption pathways range from 1-30% of domestic energy demand by 2050 [8]. The water requirements for hydrogen depend on the specific methods used to produce hydrogen. For example, steam methane forming uses half as much as water as electrolysis for feedstock since half of the water comes from steam. However, the total water usage is higher for electrolysis when indirect uses of water (e.g., for cooling) are taken into account. A back-of-the-envelope calculation indicates that water will not be a constraint in Arizona if water can be either: 1) repurposed from coal plants within the state or 2) sourced from desalinated water instead of freshwater. Although there is general consensus that the amount of water needed for hydrogen production will be much lower than fossil fuel-based energy production [9], increased demands and shifting climate patterns for water raise questions about the state of current infrastructures and costs for different water sources to support hydrogen production (Table 2-1). These questions will be important to answer in parallel to effort that are aiming to reduce costs of hydrogen production to $1/kilogram of clean H_2 in 1 decade [10].

Another technology being pursued to reduce energy-related emissions is cultivation of algae biomass, which can be used to support renewable production of various commodities, including feeds, fertilizers, polymers, and fuels. Unlike corn-based ethanol production, algae biomass can use non-arable land and non-freshwater resources, such as wastewater, agricultural or stormwater runoff, and saline water [11]. Furthermore, terrestrial algal systems can support both point source and direct air capture of carbon through free-floating and turf-based approaches respectively; algal biomass represents a major sink for carbon dioxide (CO_2) (1 ton of algae ~ 0.9 tons of fixed carbon). In fact, restoration of blue carbon ecosystems was identified by the National Academies as the largest near-term opportunity for minimizing atmospheric carbon accumulation. Although algal farming can be done across a wide geographic area, questions persist regarding operational efficiencies, environmental hardening, and economic feasibility (Table 2-1). Technoeconomic analyses indicate that scaling up algal cultivation for fuel production will be challenging. Incorporating the ecosystem service functions – such as algae's ability to address pollution and remediation through recovery of nutrients (from agricultural drainage) or metals (from waste remediation) – could significantly increase the market feasibility of this emerging resource. Increased attention to pilot demonstration and deployment sites could also help address productivity losses observed when transitioning algal systems from benchtop systems to the external environment.

Table 2-1. Outstanding Research Questions related to Energy (EN), Industrial Decarbonization (ID), and Carbon Management (CM) Identified During Webinar Series

Category	Research Question
EN	What issues do transfer or reallocation of water (from fossil fuel sources) to hydrogen production face, particularly in drought prone regions?
EN	Are there perception concerns associated with hydrogen energy?
EN	How can we streamline the algal harvesting and dewatering mechanisms to increase efficiency?
EN	How can we scale waste remediation capabilities of algae to advance equity and justice priorities?
EN	How could US analyses of hydropower operations incorporate insights from other nations' expertise (e.g., through benchmarks)?
ID	How do decarbonization efforts to reduce emissions and air pollution prioritize and address historical impacts on communities of color living near industrial areas?
CM	How can we optimize siting locations to balance access to energy, water supply for direct water consumption by DAC operations, and proximity to geologic reservoir?
CM	Could we characterize and identify which geological reservoirs are most feasible for long-term sequestration, geothermal energy, or a combination of both?
CM	How will changes in the frequency and intensity of precipitation impact viability and effectiveness of carbon farming as a means to sequester carbon?
CM	Can large-scale carbon farming coexist with global food production and demand?
CM	How can we reduce the uncertainty in climate-soil carbon feedback calculations within global climate models?
CM	What opportunities are there to incentivize adoption of carbon farming practices? Would these incentivization strategies differ across resource scarce areas?
EN, ID	What type of infrastructure is needed to support integration of desalination with hydrogen production?
EN, CM	What environmental hardening do algal farming methods need to buffer against evaporation losses and extreme weather?
EN, CM	How would different opportunities emerge for balancing timing when extending the water-energy nexus to include food priorities?
EN, ID, CM	How do assumptions in costs and prices impact market feasibility analyses of these technologies?
EN, ID, CM	How is uncertainty (price, availability) of assumptions captured in water calculations?
EN, ID, CM	What operational tools are needed to balance water quality priorities with energy efficiency opportunities?

In addition to new technology development, there are also a number of opportunities to leverage existing sectors to reduce carbon emissions within the energy sector. In particular, resources and activities managed by the water and wastewater utility sector have significant potential to support peak reduction, frequency responses, and balancing of reserves to the power grid. For example, the timing of pumping and treatment activities could be shifted to align with low energy demand periods. This alignment can also extend to the distribution system by using elevated storage tanks for hydraulic storage (short-term) or underground aquifers as water-energy banks (longer-term) buffers. While these activities are technically feasible, uptake has been limited due to coordination challenges. Practical barriers – including unclear price signals, limited automation equipment, workforce training, and operational designs that incorporate flexibility – have limited the integration of grid energy needs within the water and wastewater sectors (Table 2-1). Specialized software that incorporates the various priorities of water and wastewater utilities (e.g., public health) have been proposed to address some of these issues. Much more needs to be done, however, to address larger-scale institutional and economic barriers.

3. INDUSTRIAL DECARBONIZATION

Greater demands in materials and associated resources are expected in upcoming decades. To support these needs, construction, energy generation, and transportation sectors have focused on innovations within sustainable building materials, renewable energy and fuel sources, and low or no emission vehicles. Embedded within these solutions is a reliance on water for multiple needs.

Concrete is the most widely used construction material worldwide and the second most consumed material on the planet (after water, by mass). Producing concrete drives significant global GHG emissions and generation of air pollutants, such as CO_2, nitrous oxides, and particulate matter. For example, cement – a component of concrete serving as a hydraulic binder – alone accounts for ~7% of global carbon emissions, and has experienced a 10-fold increase in per capita consumption over the last 7 decades [12]. Concrete production is also associated with ~2% global water demand, since water is not only a constituent of the material (10-15% by weight), but is also consumed by processes, energy, and transportation at each stage of production. Processes such as dust suppression and cleaning concrete trucks as well as indirect uses of water (e.g., for energy generation) account for the largest fraction of water consumption [13]. Decarbonizing cement and concrete requires consideration of the entire value chain since concrete serves as a primary building material across multiple infrastructure systems. For example, switching from high-emitting fuels (commonly used by cement kilns among others) could drive down emissions by up to 50%. Rethinking building designs (e.g., appropriate mixture proportioning) could also enable use of concrete more efficiently, further reducing carbon emissions. Beyond these considerations, methods for enhancing carbonation or using alternative mineral constituents and cements to sequester CO_2 would mitigate some of the carbon emissions. Validation of novel materials and their properties will be key since infrastructure materials must adhere to strict reliability and durability requirements.

Another industrial resource that will be in high demand to support carbon transition activities involves mining and extraction of metals and minerals. Critical minerals and rare earth elements are essential to clean energy technologies and infrastructure ranging from electric vehicle batteries and fuel cells to photovoltaics and wind turbines. Metals such as cobalt, lithium, nickel, copper, manganese, and neodymium will be in intense demand to support a rapid green transition to net-zero emissions by 2050. Mining has a high return on water invested compared to other industries since value-added materials are produced per unit volume of water, which could justify continued water use. Industrial mineral extraction to produce metals from ore bodies has both direct and indirect uses of water, with notable regional impacts. Direct uses of water include dust suppression; physical and chemical mineral processing to extract materials; and water supply to camps for mines in remote, water scarce areas. Indirect uses include loss of water due to evaporation from reservoirs, water given up to the environment, and providing water to nearby communities as part of negotiations to operate the mine. Potential regional impacts relate to changes in water quantity and quality; for example, mining activities may cause impairment of streams and groundwater with acidity and heavy metals contamination. In some areas, water can be abundant, but functionally scarce due to poor quality. Though mining consumes a relatively small fraction of water compared to agriculture, demand varies based on the metal extracted and does not account for degradation in water quality downstream. However, long-term impacts to the natural environment require further study and assessment from a carbon neutrality perspective. Furthermore, indigenous communities have dealt with a disproportionate burden from the impacts of mining that future operations will need to remedy and mitigate (Table 2-1).

Last but not least, water can also serve as an important mechanism for transportation. The United States (US) inland waterway sector – which encompasses rivers that connect the Great Lakes and Canada as well as eastern and western parts of the country all the way down to ports – is an important means of freight transportation. Marine shipping is already one of the least carbon intensive modes of transport; global marine shipping accounts for ~3% of GHG emissions. Due to its relatively low carbon footprint, shipping across waterways may become more attractive over terrestrial means of moving goods. However, there are multiple sources of carbon emissions still present within the shipping sector. Decarbonizing the freight use of water as a mode of conveyance could involve a variety of pathways focused on fuels and vessel design. Most inland vessels in use were built in the 1970s and tend have long service lifetimes; the average fleet age is 36 years, with some still in operation after 100+ years. Retrofitting existing vessels rather than replacing them is a more likely approach to getting to carbon neutrality, especially since demand for new vessels is limited. Marine diesel, which is currently used to power vessels, could be replaced with alternate fuel and propulsion systems, such as biofuels, methanol, liquid natural gas, ammonia, and hydrogen. Multiple considerations determine the costs and benefits of switching fuels, including size, weight, and depth constraints; inland vessels need to navigate shallower rivers, tight bends, barge tows, and locks. Energy density is another crucial factor. For example, 2-2.5 times the amount of methanol would be needed to achieve the same results as marine diesel, requiring more frequent refueling and/or larger tank storage. Moreover, methanol is mostly produced by steam reforming natural gas, which is not without emissions. Instead, devising electrolysis methods or generating methanol from landfill gas would further decarbonization goals within the industry sector. Biofuels have also received serious attention because of their similar energy density to marine diesel and because their use is supported by existing infrastructure. However, most biofuels to date are soybean-based, which require careful management of total environmental lifecycle (Table 2-1).

4. CARBON MANAGEMENT

The webinar session on carbon management session focused on the nexus of energy-water and decarbonization. Session topics included a high-level overview of direct air capture (DAC) technologies, DAC combined with geothermal energy production, and soil-based carbon sequestration. These presentations and discussions highlighted the importance of understanding the natural ecosystems as well as the various synergies between carbon management, energy, and industrial decarbonization themes. For example, low purity-captured CO_2 could be used to enhance algal growth for bioenergy production while produced water generated from geologic storage could serve a source for critical minerals. More details are presented in the following subsection.

Carbon capture has historically been focused on abating point-source emissions from the power sector (e.g., capturing smokestack emissions), but recent research efforts have shifted attention to removing carbon from ambient air through direct air capture (DAC). DACs are viewed as valuable mechanisms to complement emission reductions since they can capture emissions from essential but hard-to-eliminate sources (e.g., emissions from agriculture). One way to conceptualize DAC is that it acts as a synthetic forest that can be deployed to pull CO_2 out of the atmosphere. Though for DAC to achieve net-removal of CO_2, it needs to be coupled with permanent storage (e.g., geologic sequestration). A benefit of ambient DAC over natural terrestrial approaches is that DACs could have a fraction of the land and water requirements of reforestation or afforestation [14]. For example, 0.4-1.7 square kilometers (km^2) of land area would be required to capture 1 million tons of CO_2/year for existing DACs technologies vs. 862 km^2 of land for reforestation [15]. The water requirement of DAC compared to reforestation is more nuanced because while vastly greater in volume, reforestation is supplied by green water (natural precipitation and soil moisture), while DAC uses blue water (abstractions sourced from surface water or groundwater). A significant challenge of large-scale DAC deployment, however, is the high energy intensity of the process. Depending on the source of energy, the water intensity footprint (including indirect water use) can be quite high. For example, if energy is supplied from a coal or gas power plant, there could be a substantial water footprint associated with energy production as well as an increase in the amount of carbon capture and storage needed to mitigate emissions from fossil fuel sources. Since current DAC technologies require inputs of both heat and electricity, siting DAC near geothermal plants could significantly reduce energy-related emissions. Deep saline aquifers in regions with high temperature gradients are the best candidates for supplying geothermally-sourced thermal and electrical energy to subsidize or in some cases fully meet the energy needs of DAC. The total resource requirements and embedded water footprint of DAC can be reduced if facilities are sited near the location of sequestration, which would reduce the need to convey CO_2 from the capture location to the sequestration location. Integration with renewable technologies (e.g., solar or wind) could also enable DAC technologies to operate with clean electricity with no direct water consumption.

Geologic storage is a critical enabler of net-removal of CO_2 from the atmosphere since it provides a long-term storage solution for the captured carbon. However, additional characterization is needed to evaluate feasibility of long-term sequestration capabilities (Table 2-1). Subsurface characterization efforts could also identify locations suitable for geothermally-driven DAC. However, the overall benefit of being sited near a suitable reservoir should be balanced against the consumptive water demand of capture technologies, which can be influenced by ambient temperature and humidity. For example, evaporative losses for DACs using liquid-based sorbents can be up to 1-7 tons of water per ton CO_2 captured [16]. Solid-based sorbents DACs also vary in their water consumption, but do have potential to be net-generators of water since water can be recovered through the process; one estimate indicates 0.8-2 tons of water could be recovered for every ton of CO_2 captured [17]. In addition to direct and indirect water requirements associated with capture technologies, geologic storage activities also need to consider management of produced water generated from geologic reservoirs used for CO_2 sequestration. Pumping CO_2 content into underground reservoirs displaces pore fluid in the reservoir (i.e., produced water), which is then pumped to the surface to manage reservoir pressure. Effective management of this produced water (through disposal or beneficial reuse) is critical to prevent adverse environmental impacts. For example, produced water could serve as a source for critical minerals or (after significant treatment) as an alternate source of water for irrigation. However, much more research is needed to efficiently and economically separate and recover solutes from these deep aquifer waters.

In addition to geologic carbon sequestration, there are also many opportunities to increase the terrestrial carbon sequestration capacity of soils. Soils represent an enormous pool of carbon, with the top two meters estimated to hold twice the amount in the atmosphere. Whether soil acts as a source or sink of carbon depends on climate and land use patterns. Historical cultivation practices have resulted in depletion/release of soil carbon. Carbon farming research seeks to evaluate and quantify practices that can counter these issues to enhance soil carbon storage while creating more resilient soils on cultivated lands. Examples of carbon farming approaches include crop rotation strategies, reduced or no tillage, improved grazing practices, bioenergy crops, and cover crops. In addition to sequestering atmospheric carbon, increasing soil carbon can create more resilient soils that can enhance food security through increased available nutrients, water retention capacity, and crop productivity. The complexity of natural soil ecosystems necessitates field studies of proposed approaches. Field data can then be combined with process-based models to evaluate the large-scale potential and associated water requirements of carbon farming strategies. An analysis in the US, for example, indicates that the 14 million hectares of cropland could be used to economically support bioenergy crops with dryland farming (i.e., no irrigation). This example illustrates the potential for sustainably combining carbon farming with bioenergy production. Additional carbon farming benefits of Miscanthus include its ability to place organic matter deeper into the soil profile and adoption of no-tillage practices, both of which increase soil organic matter. Numerous uncertainties exist, however, regarding soil carbon response to future climate including the impact of water surface hydrology and biological influences on this valuable resource. Additional research is needed to understand these coupled behaviors as well as identify larger food and social dynamics that affect the terrestrial soil carbon cycle (Table 2-1).

5. OPPORTUNITIES

Although the webinar series could not touch on all decarbonization strategies, the nine presentations and associated discussions highlighted the diversity of challenges and opportunities that exist around water in the areas of clean energy, industrial decarbonization, and carbon management. A key takeaway from the webinar is the many roles water plays in decarbonization efforts. Water can serve as a raw material (concrete, H_2, DAC), byproduct (mining, carbon sequestration, DAC), habitat (algae), transportation enabler (shipping), source/carrier of dissolved solutes (carbon sequestration, mining), receptor for pollution (mining), sustainable source of irrigation in the form of precipitation (carbon farming), and source of mechanical (pumped storage) or thermal (geothermal) energy (Figure 5-1). A unifying theme across the three sessions was the acknowledgement that we need to better understand and properly plan carbon neutral activities that recognize water as a limited resource, and to consider how shifts in water availability due to climate change could directly or indirectly affect decarbonization efforts. Such considerations are critical given that water demand has increased dramatically over the last century driven by population growth combined with rising affluence and living standards. It is important that the transition towards a carbon neutral future does not place undue or avoidable stress on water resources and threaten water security.

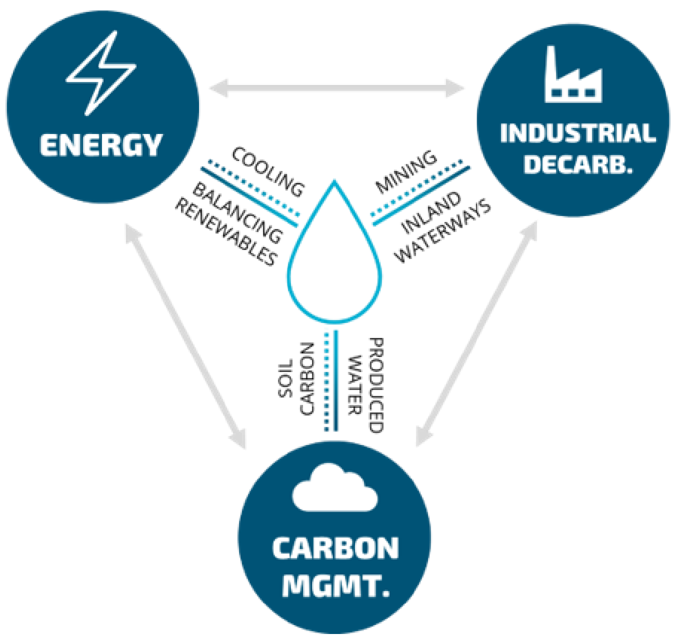

Figure 5-1. Direct (solid) and Indirect (dashed) Uses of Water for Carbon Neural Activities.

Given the diverse ways that water influences and interacts with decarbonization, the specific research needs vary depending on what approach is being considered. A few common themes did emerge regarding needs to help facilitate the planning development, and implementation of decarbonization approaches; these include regionality, data, and making robust decisions in the face of uncertainty. First, a topic of emphasis in each session was the need to consider decarbonization challenges and opportunities in the context of regional characteristics. Such regional considerations include understanding the existing (or lack of) water and energy infrastructure, availability of water resources by type (fresh, saline, waste, etc.), current and future energy/water demands, and how future climate may affect water availability to support a given decarbonization strategy. Another topic that came up was having better data available to support modeling and analysis efforts related to water supply for decarbonization approaches. These data needs include both observational data of water use across multiple spatial (cities, counties, states, and geographic regions) and temporal (annual, seasonal, daily) scales as well as access to downscaled climate data and models that can be used to inform studies looking at long-term performance and viability of decarbonization approaches. Unfortunately, the best nation-wide water data come from the US Geologic Survey (USGS) water census that is released every 5 years, with a two-to-three-year lag (e.g., the most recent water census is from 2015). Better observational records and access to local and regional climate modeling data will allow more accurate analysis and decision-making associated with water for carbon neutral strategies.

Given the deep uncertainty of future system states, a systems perspective is needed to fully understand the capabilities, requirements, and performance at the energy-water-carbon nexus. Concurrent with natural resource dynamics, technology maturity and market feasibility also impact our ability to achieve carbon neutrality. Disentangling current assumptions about system operations from possible future conditions would enable creation of performance thresholds that could inform specific R&D milestone goals for these technologies to enable them to have a greater chance of being effectively adopted and implemented. A data-driven systems approach would enable researchers and developers to inform investment priorities that consider multiple, complementary priorities – including resilience, sustainability, and justice. Because we still are in the planning stages of implementing these approaches, we have the opportunity to make sure that the transition to a carbon neutral future is sustainable, resilient, and environmentally just from a water perspective.

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