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Technology and Innovation

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tein20

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To cite this article: Cody Googin, Haihui Pu & Junhong Chen (05 Feb 2025): EXPLORING THE WATER-ENERGY-FOOD (WEF) NEXUS THROUGH AN INDUSTRY PERSPECTIVE ON NEW TECHNOLOGY, Technology and Innovation, DOI: 10.1080/19498241.2025.2454188

To link to this article: https://doi.org/10.1080/19498241.2025.2454188

TECHNOLOGY AND INNOVATION
https://doi.org/10.1080/19498241.2025.2454188

EXPLORING THE WATER-ENERGY-FOOD (WEF) NEXUS THROUGH AN INDUSTRY PERSPECTIVE ON NEW TECHNOLOGY

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ABSTRACT

This study explores the water-energy-food (WEF) nexus through an industry-focused lens highlighting how innovations in these spaces can go from lab to market. Based on data collected from 70+ customer discovery interviews and literature research, this paper presents interconnected issues, trends, opportunities, challenges, and industry analysis among these three areas. Also detailed are the ramifications of global climate change, the culture inside and outside the WEF, and regulations on innovation in these areas.

KEYWORDS

WEF nexus; industry perspective; AI; customer discovery

INTRODUCTION

Over the course of this research 71 customer discovery interviews were conducted with CEOs, scientists, founders, and members within the water, agriculture, and energy industries. The large majority of interviews were conducted within the water industry. The main topics that came up from these interviews were global warming, the disconnect between academia and industry, effect of regulations, and role of culture as it relates to innovation. Throughout, one critical theme that arose was the fractured nature between water, energy, and food, despite the intrinsic relationships between them.

Nobel Laureate Richard Smalley authored a list of the Top Ten Problems of Humanity with Energy, Water, and Food as the top three.[1] The first problem Smalley asserts is Energy. Energy demand is rapidly growing and innovation in fossil fuel extraction will continue to satiate this growth due to their abundance and low cost. This increasing use of fossil fuels will have consequences including decreasing lifespan and inducing climate change. A study by Ebenstrin, Fan, Greenstone, He, and Zhou (2016) “Revisiting the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China’s Huai River Policy” found that long-term exposure to an additional 10 ug/m^3 of long-run exposure to PM10 is associated with a decline in life expectancy of 0.64 years. Additionally, burning fossil fuels releases about 89% of CO2 emissions which rise into the Earth’s atmosphere trapping heat and increasing global temperature.[2]

The second problem asserted is Water. Water is critical for our current agriculture, industry, and domestic uses; however, The World Economic Forum projections show that at our current consumption rate, by 2030, the global water demand will be 40% over the global water supply.[3] This shortage is driven by high consumption of water in agriculture, climate change, food loss and waste, and our food value chain. An insufficient amount of water will not only affect the availability of drinking water, but also of agriculture.

The third problem Smalley focuses on is Food. Food security is a challenge both domestically and internationally. This challenge is driven by increasing population, changing tastes to more processed foods, climate change and water scarcity. The World Economic Forum projects that in 2050, the population will reach 9 billion. A population that today’s infrastructure cannot handle.[4]

These three big problems are intrinsically connected on a large scale through global warming and consequences of population growth. By zooming into local ecosystems, this paper will explore the day-to-day challenges that companies, individuals, and public entities face in engaging in this ecosystem. We will also pay a special attention to new innovations and how they are taken to market and ultimately implemented.

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WATER INDUSTRY

Industry breakdown

We can break down the water industry into For-Profit, Government, and Non-Profit to determine the ways research gets innovated and implemented in the industry. The For-Profit Industry and Utilities can be broken down into innovators and implementors. Innovators create new technology that is then implemented in the market.

There are three main types of innovators, each with a unique path to market and implementation. The first type is *Disruptive Forces* that come to market with revolutionary products and designs such as startups and VC Firms. The innovation process for these entities begins with a startup with an idea. Over the course of a year or potentially longer, a startup will do industry research. Once it is solidified that there is a market need and market-product fit for the technology, the team will go through the product development cycle. For the water and wastewater industry, this process can take up to 10+ years due to weather patterns that elongate the cycle compared to less weather-dependent industries.[5] Aqua Research is an example of a disruptive force. The company produces systems that generate disinfectant to sterilize health equipment, sanitize irrigation streams, and provide safe drinking water to low and middle-income countries. Founded in 2011, the company is still looking to accelerate their growth and raise money highlighting the slower company lifecycle compared to other industries such as software that can be developed and deployed in a shorter timescale. Once sufficient research and testing is done, or during the research process, the startup pitches to a VC Firm for funding. After passing EPA requirements and creating a finished product, the company will put their product on market, typically through a pilot program.

The second type is *Infrastructure Support*. This disruptor supports companies in designing highly efficient methods to streamline processes such as engineering and consulting firms. One example is IOSight, a data analytics company that focuses on data management and analytics tailored toward watersheds, wastewater, and energy. The company has a long history of working with utilities and supports them by injecting engineering and software solutions into their systems. This process starts with a customer with a problem coming to the firm in need of a solution. The company will typically hire the firm for advice and even engineering design. The firm will pitch their idea to the company and then, if accepted, will apply the design resulting in a changed, improved system.

The final type is *Continuous Innovators* such as technology companies, especially water monitoring and filtration systems that constantly work with implementers to maintain up-to-code water standards through technological devices. Innovators play a major role in shaping the water wastewater industry; however, it takes implementers to make the innovations into realities. One example is Tecta PDS (acquired by IDEXX), a company that produces a microbiological water quality testing system that was the first EPA approved testing system. This company strives to provide solutions for customers that must meet water standards. In this way, continuous innovation is driven by industry regulations as they push companies to develop novel solutions within tight boundary conditions. Regulations are regional and often updated, so keeping up is difficult for many utilities. Thus, technology companies such as Tectra PDS that provide general up to code products fill a large gap in the water innovation market.

Implementers are companies or facilities that use products developed in their every-day-processes. Examples of implementers are utility companies, end users, manufacturers, and agriculture. They are characterized by the fact that they continuously replace existing technology and use capital to invest in new technology from innovators (It is important to note that companies do participate in innovation, but not at the level defined by the innovators listed above often for scale issues). Implementers have two options engaging with new technology. The most common option is to keep replacing parts of their existing technology with slightly newer technology to meet EPA regulations. This is often the case for local or regional water suppliers that are affected by underpriced water. This leads to decreased innovation as the need for very new products is low but also leads to high switching costs providing an economic moat for products already in the market. The second option for implementors is to use capital to invest in new technology from innovators. For example, StormSensor is a company that utilizes sensors to collect data from storm water and sewer systems. A municipal water district or company may invest in this company to optimize their water drainage system. This option is less popular due to the high costs in an already capital-intensive industry. Most of the capital-intensive part of the water industry is within the implementation process (besides funding for R&D) for pumps, pipes, and other infrastructure.[6] Thus, most implementors stick with existing technology because they do not have the funds to invest in new technology. Many implementors would rather purchase add-ons than replace their entire system despite high recurring costs due to replacing parts.

Further, many utility companies are already underfunded due to the current water culture within the US which we will outline later.[7]

While For-Profit Industry and Utilities make up the tangible water industry, government entities such as the EPA regulate the entire water value chain and play a large role in the culture. Water is a highly regulated industry since it is known as a "public good." We will touch more on the ramifications of regulation later and will now focus on the implementation process in the water industry.

Now that we have outlined the industry structure for how changes and products are created and implemented into the market, we take a macro look at the four major issues mentioned by industry participants measured by the frequency these topics came up.

(1) Infrastructure: Old infrastructure on a national scale causes water impurities and high costs to maintain[8]
(2) Industry Conservatism: Due to regulations and overall culture, the water industry is slow to adopt and implement new technologies[9]
(3) Funding: Due to belief that water is not scarce, U.S. has too low costs of water leading to decreased revenue for companies to maintain infrastructure or work on projects; however, new Water Resources Development Act of 2020 may provide a cornerstone[10,11]
(4) Communication: Due to a decreasing quantity of skilled, knowledgeable labor in the workforce, many different sectors of water are not innovating or working in conjunction with other sectors slowing overall industry growth[12]

These issues are root causes of four tensions that affect innovation in water and wastewater.

The first tension is *New Technology versus Water Industry Conservatism*. The water industry has a history of using older technologies due to a long product development cycle and high regulations leading to a decreased interest in new technologies. For example, adding IoT for water quality monitoring can help save money on water treatment costs but present a high upfront cost for public water governance companies that implement the technology.[13] This tension is also catalyzed by an underpricing of water in the US that creates funding issues throughout the industry. The solution to this is providing cheaper solutions for already existing processes. This could come in the form of new molecular engineering applications such as biopolymers. Although this is currently an issue, it may be a motivator for new technology companies due to "stickiness" of products in the market.[14] Participants in customer discovery leaned toward the fact that new technology and innovation and water industry conservatism create a tension (Figure 1a).

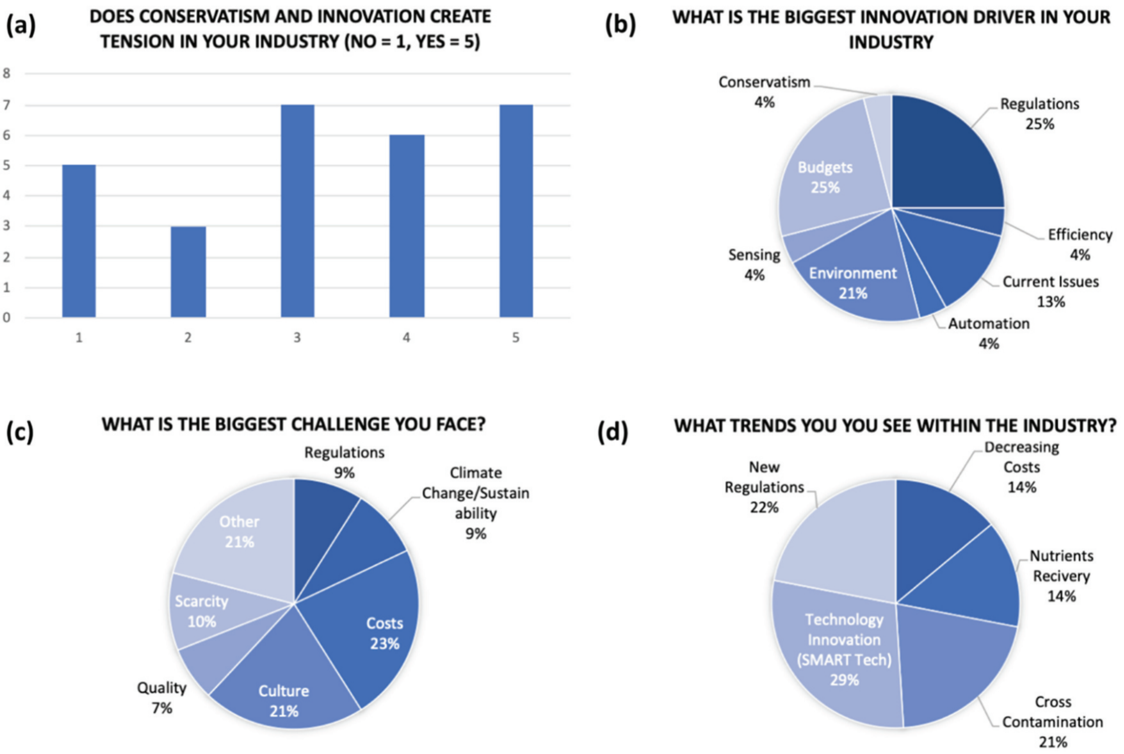

Figure 1. Participant responses to (a) new technology, (b) biggest innovation driver, (c) biggest challenge, and (d) industry trends.

The second tension is *Machine Optimization versus New Technology*. In adopting new practices, companies must decide whether to optimize current processes in terms of efficiency or cost or change their whole system by employing a new technology, for example, altering pump size to increase energy efficiency vs. adopting entire new system. This tension reflects how high capital costs and low funding leave many water processing plants to choose a system that may not be long-term sustainable due to budgets.[14] This tension is highlighted in Figure 2a where one of the more frequently talked about key words around water research was "Efficiency/Optimization."

The third tension is *Infrastructure versus Government Regulations*. Infrastructure is outdated causing quality problems and leaks, but government regulations make it hard to provide a cheap, improved solution disincentivizing innovation. One example brought up by an interviewee was that copper pipes put back chemicals into the water and are hard to fix. However, PVC piping is not allowed because of government mandates. This problem arises from a lack of communication between different parts of the water industry and must be solved through a cultural change. This problem is also a result of decreased education and awareness surrounding water availability within the US that drives commercial prices down not allowing public utilities to fix current infrastructure.[15] The lack of funding to fix poor infrastructure creating a tension with regulations creates a tension, but also pushes forward innovation to overcome these challenges as gathered from customer discovery participants (Figure 1b).

The fourth tension identified is *Water Availability/Scarcity versus Current Price of Water*. The belief that clean water is readily available is a myth within the US but is reflected in the low price of water. This low price leads to low capital within water entities decreasing innovation. There are three ways to decrease water scarcity: Increase supply by providing more points of source for clean water such as desalination, decrease loss by improving current infrastructure to decrease leaks and increase education so people decrease unnecessary water use, and finally, improve quality by decreasing contaminants.[16,17] The current price of water resulting in low funding was a common challenge brought up by participants. When asked what the biggest challenge they face was, 23% answered "Costs" (Figure 1c)

Research trends

There are two major approaches to water innovation: **end-to-end** or a **single point**. A full stack solution involves implementing a system that handles water from obtaining water to cleaning it for use and then collecting the wastewater. This vertical integration style allows for higher margins and takes advantage of many places where companies lose out on water value by not recycling water to be used in other area. The single point approach involves picking a single point in the water cycle such as wastewater and manufactured products for this area. The benefit is specialization and low switching costs for companies to adopt rather than a whole system. The drawback is smaller margins.

In general, there are two main areas of cutting edge research, materials-based and technological. The most common *materials-based trends* mentioned during customer discovery are biopolymers, membranes, and nano sensors. Biopolymer implementation was highlighted in the removal of certain particles from wastewater to decrease total costs with a key consideration of taking into account a way to monitor the biopolymers to determine lifetime.[18] Membranes were noted to be used for drinking water through reverse osmosis and more broadly purifying wastewater.[19,20] Finally, nano-sensors were used to monitor chemicals, microbes, and other analytes in drinking water.[21] Research is being done for nano-sensors to allow for specific enzymes to be targeted

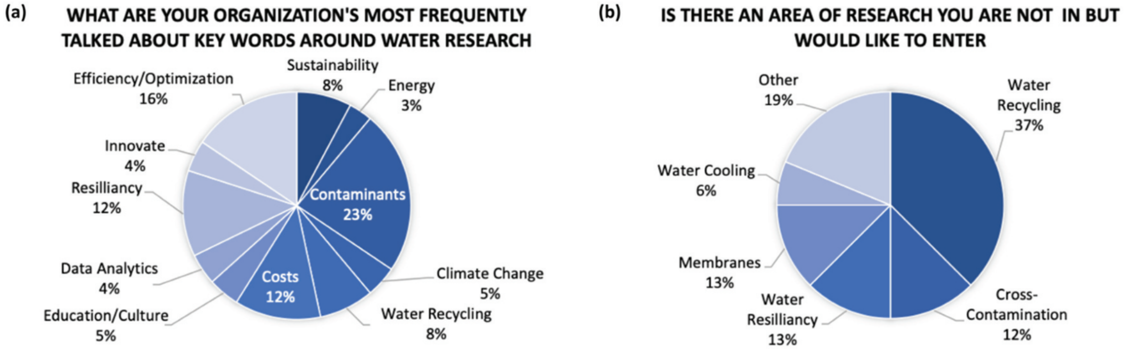

Figure 2. Participant responses to (a) keywords about water research and (b) new area with interest to enter.

and can be made out of stronger, lighter, more durable, and more reactive materials.

The most common *technological trends* were focused around Internet of Things (IoT), Analytics, and Artificial Intelligence (AI)/Machine Learning (ML). IoT research is mostly being implemented in drinking water and wastewater. The benefits of applications in drinking water is that it is a closed system allowing for easy IoT application. On the other hand, wastewater has constant inflow and outflow with different frequency creating more data points that must be consolidated and analyzed.[22,23] Analytics has also been gaining popularity due to applications and results of Big Data usage. This area of research has been mainly applied to water technologies to gain better insights and predictions for leakage and customer service.[24,25] Finally, AI/ML is a large area of research that is being implemented for better engineered equipment for increased durability and sensibility leading to better detection and prediction.[26–28] One benefit of the technological research is the high ability to quickly test, integrate, and adapt the products and employ them in conjunction with each other.

In addition to the macro materials and technology trends, the customer discovery highlighted specific trends and movements that are happening across the water and wastewater sector. These main trends are nutrients removal and collection, decreasing costs, desalination, water recycling, new regulations, and SMART Technology (Breakdown seen in Figure 1d) In order to identify the "market pull" for these technologies, we evaluate the end-user markets of the water industry. We also evaluated trends by asking "What are your organization's most frequently talked about key words around water research?" (Figure 2a)

Analysis of end-user markets

This section will be devoted to evaluating end-user markets based on market drivers, adoption rate, quality and quantity needs, government oversight and impact, and unifying factors. Due to the viability of AI/ML within the water industry, a focus will be given to applications within each of the end-user markets.

The water industry market can be segmented into four end users: buildings, agriculture, industry, and utilities. Buildings are defined as commercial buildings, home-owners, and residential areas characterized by being a high-value user. Agriculture are food growers and characterized by the largest global water user. Industry includes all water-intensive industries such as manufacturing, processing, extraction, and gas, which is the fastest adopter of new technology. Finally, utilities are defined as public and private wastewater facilities which is the largest market.

The discussion begins by highlighting the *market drivers* of each industry. The building end-user market is driven by the common demand for clean drinking water. This is especially important in "water scarce" areas such as California and the western, desert regions. Agriculture's market driver is the increasing consumption of produce and a critical need to deal with climate change consequences. Industry is driven by an increasing demand for manufactured goods and company's desire to improve productivity, efficiency, and cost margins. Finally, utilities are driven by consolidation as smaller, underfunded utilities companies fail to have enough funding and must deliver an undervalued resource to the public. These market drivers are essential in understanding how each end-user will behave as new technology is introduced to the market and influences the quality and quantity needs of each industry.

Each end-user market's quality and quantity needs can be ranked from highest to lowest. For quality needs, buildings is the highest followed by utilities, industry, and agriculture last. For quantity needs, agriculture has the highest needs followed by industry, then utilities, and finally, buildings.[29–31] Quality needs can typically be solved by better technologies to clean water often in the form of materials science and technologies similar to the *materials-based trends* mentioned earlier. Differently, quantity needs can be solved by AI/ML and technology for predictive leaking, finding optimized path for water flow, and need-basis maintenance. With different technologies solving the problems for each industry, the next topic this paper will focus on is the rate at which these new technologies can be introduced and implemented within the industry, also known as the adoption rate.

The *adoption rate* is important for the go-to-market strategy once the technology is developed. Ranking highest adoption rate to lowest, the end user markets can be ranked industry, buildings, agriculture and utilities. There are different benefits and detriments to having both a high adoption rate or low adoption rate that must be considered when determining the best end-user market to enter. For the end user markets with a higher adoption rate, the benefits are a quicker go-to-market timeline, ease in identifying and implementing current trends in technology, higher concentration of companies who are actively sourcing new technologies and have higher research and development budgets to invest and resources to support pilot projects. The largest detriment for high adoption rate is the very quick product lifecycle and shifting trends that may result in a technology becoming out of date at a relatively fast rate compared to the product development cycle that characterizes water technologies. Differently, the benefits of companies with low adoption rate are the long product life cycles. Thus, if a company is able to assert their technology into the industry and it is widely used, it will be a longer period of time until it gets replaced. However, the detriments to a low adoption rate are a conservative attitude toward new technology, long product development cycle due to risk-averse customer, and low investing budget. The adoption rate may vary depending on an entity's level of risk, but in general the adoption rate for each industry is determined by government oversight. This government oversight can fluctuate based on the need of the new technology.[32] Thus, to have a quicker go-to-market, it is best to create a technology that solves a crisis problem within the end-user market.

Government Oversight represents a high barrier to entry but economic moat once product passes regulations. It is important to note that government oversight fluctuates greatly depending on geography especially when comparing drier places such as California to areas with increased flooding risk such as Michigan, Illinois, and the East Coast. Each end user industry can also be ranked based on this analysis point with the highest being utilities. Since water is a public good, the industry overall is highly regulated by federal entities such as the Environmental Protection Agency (EPA). The second highest in this category is agriculture where the main source of regulation is from agriculture runoff including PFAS and nitrates. Agriculture is also regulated through the food produced, but this regulation is less regulated to water usage. Industry is the second lowest with government oversight different greatly based on the product produced. For example, water used to make consumable products such as beer must have a higher standard than to make textiles. Finally, buildings have the lowest government insight mainly due to the fact that their water is supplied by utilities that take on the brunt of the government oversight. This analysis point is extremely important, because due to the critical nature of water to our biological systems, any technology must be approved through the proper channels in order to be commercialized. In addition to the government oversight, many companies also require a pilot to have been conducted to ensure scalability and consistency of product before implementation.[33]

While each end user market has varying characteristics, Figure 2 highlights the unifying and differentiating factors. One clear factor that joins them all together is the desire for new technology. Due to the versatile nature of technologies such as IoT, AI/ML, and data science, these applications have created large trends of adoption within the water sector. Further, many industry players when asked the question, "Is there an area of research you are not in, but would like to enter?" largely answered "SMART Tech" seen in Figure 2b. Each one of these applications can be applied across the industry, but a quick analysis of the optimal areas for each technology is as follows.[34]

IoT is best used for water monitoring. Implementing sensors in waterways will allow for an increased understanding or targeting of certain areas of the water system. The most applicable end-user markets are industry, buildings, and utilities. AI/ML is best employed for predictive analysis. The best applications are looking at potential leaks, overflows, and diagnosing trends. The most applicable end-user markets for this technology are industry, agriculture, and utilities. Finally, data science can be employed to draw insight from data collected. This technology can contribute to finding the most efficient processes and gaining process insights which can be applied to great benefit across all end-user markets.[35]

AGRICULTURE MARKET RESEARCH

While conducting interviews, we find that the agriculture industry is heavily reliant on influencer chains such as consultant companies, cooperatives, companies, and word of mouth at conventions to source and ultimately implement new technology. Thus, this section will be focused on the agriculture value chain and influencers on it as the ability to get product to market can heavily rely on where it is inserted in this value chain.

Overview of agriculture value chain

Through customer discovery, we have identified key stages of the agriculture value chain. The first stage is the primary input where different types of seeds, fertilizer, and equipment are used to begin the growing process. This stage is followed by growth which includes the irrigation systems, monitoring devices, weather models, and satellite imaging, and any other process that farmers use to grow crops. The next stage is harvest where the farmers harvest the crops. The technology at this stage can be characterized by yield mapping and robotics. After these three stages, the food products enter the transport stage where food from farms moves to processing areas. This stage did not have any prevalent discussion about technological advancements in our customer discovery. The next step is processing where the food is prepared for consumption. This stage is extremely water intensive and can require water monitoring through AI/ML or IoT. The final stage is the sell stage where there is an emphasis on creating a culture of value in food to put more funds into the entire process. Overall, the value chain has the most activity in technological innovation in the primary input and growth stage where farmers work can be done to optimize harvest margins and quality of food growth. The processing and growth stage have the highest water consumption.[36]

We will now discuss the influencer value chain by highlighting four key players, consultants, farmers, cooperatives and similar companies, companies including public company R&D teams and private technology companies, and the role they play on influencing technology implementation.

Consultants

Consultants are an integral part of the entire value chain. A large component of the agriculture business is the consulting networks/services that are used by farmers and companies to source new technology. This network was mainly referenced in the **Primary Input** and **Growth** stages as consultant conversations were the main driver of innovation sourcing and implementation. In many ways, consultants act as a bridge between technology and farmers. During the latter parts of the value chain, consultants are often employed by processing factories and companies who want to sell the food, but this is not connected to water innovation. It is interesting to note that while consultants were often brought up during agriculture customer discovery interviews with respect to innovation, they were not mentioned during water industry interviews. This may be partly due to the tension of new technology vs. industry conservatism cause by regulations and underpricing as mentioned earlier. As many companies or public departments often do not have enough money to invest in newer technology, consultants are not vital. The role of consultants in the water industry is certainly a topic for further research.

Individual farmers

Farmers are involved in the first half of the value chain, from primary input to harvest. However, farmers invest most of their time in the **Growth** stage of the value chain where they seek innovators to ensure water control, crop monitoring, and quality life cycles for their crops.

Cooperatives and similar companies

Cooperatives and similar companies buy the crops produced by farmers and sell them to larger buyers or end-users. These companies often do not have major influence over farmers choice of technology used in the farming but can suggest and support their farmers. Contracts between farmers and these cooperatives can come in the form of "forward contracting" or contracting at time of harvest. Many cooperatives do research into agriculture sustainability geographical modeling, and regulations to keep farmers up-to-date. Cooperatives have some influence in the primary input and growth stage in terms of suggesting technology; however, they have most impact in the **Harvest** and **Transport** stage helping to get farmers product to processing areas.

Companies

Companies have a wide range of engagement with farmers depending on the size and involvement in their food growth. While some companies own their own farms and thus have influence over the first four steps of the value chain, primary input, growth, harvest, and transport, majority of companies only engage fully in the **Process** and **Sell** stage of their products. We can break up this category into company technology R&D teams which are mainly involved in the second half of the value chain (Transport, Process, and Sell stages). The goal of these companies is to optimize profit margins with the main source of revenue from the end-user such as customers buying produce at the grocery or eating a meal from the company. On the other hand, Private companies which develop innovation in the first half of the value chain supplying farmers or consultants with new technology for Primary Input, Growth, and Harvest. Private companies' goal is to ease challenges that farmers face and optimize food production.

The ways customer discovery participants bring their products to market are detailed in Figure 3. In addition to Conferences, representatives/consultants play a large role in ensuring technology reaches the marketplace. This is especially significant in agriculture as Ag Retail Magazines or Ag Retail Chains are trusted to help bring tech to market.

Innovation drivers

The top three innovation drivers mentioned during the agriculture interviews were COVID-19 Pandemic, Regulations, and Climate Change.

COVID-19 pandemic

COVID-19 exposed flaws in many food supply chain and the sustainability of our food system. The complex web of farmers, producers, shippers, and buyer is seen to need a new, more comprehensive system. This has led to many VCs funding startups/technology within the agri-food supply chains.[37]

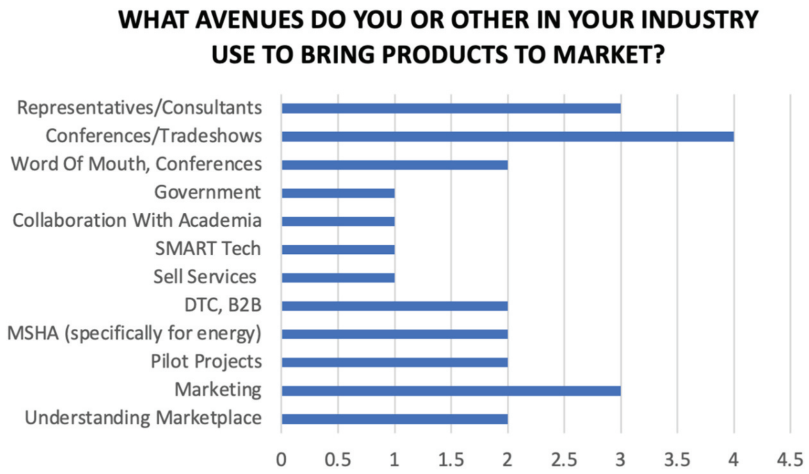

Figure 3. Ways to bring products to market.

Regulations

Regulations regarding water discharge, emissions, irrigation, etc. depending on geographical location push growers to rethink their systems. While regulations prevent challenges, they are often instigators for new, affordable systems to be adopted.[38]

Climate change

Climate change directly affects many growers through different levels of precipitation, soil moisture, temperature, sun exposure, storms, winds, etc. The increasingly unpredictability of the climate has pushed farmers to either 1.) Build more predictive models or 2.) Invest in technologies (ex. Hybridized crops) that can withstand the changes.[39]

Major agriculture concerns

There are five main concerns of agriculture participants: Climate change, geographical factors, economic constraints, regulations, and culture.

Climate change

The shifting climate has created poor environments to grow crops due to unpredictable and extreme weather patterns. This often comes in the form of floods, droughts, changes in crop and livestock viability, new pests and weed problems, and higher temperatures. Additionally, CO2 levels outside a crop's optimal level can result in lower yield.[40]

Geographical factors

Many areas are naturally subject to extreme types of weather (ex: drought in California or floods on the East Coast) making it difficult to find a "one size fits all" technological solution and creating a strain on crops. Crop production is concentrated mainly in the California and the Midwest; however, each has dramatically different climates leading to different technology needs and regulations. Additionally, these different climates and land availability lead to different types of crops.[41]

Economic constraints

Since farming is a capital-intensive market with razor-thin margins, having extra cash flow to buy new technologies or adjust to extenuating circumstances is difficult.[42]

Regulations

Due to standards for soil conservation, quality standards, food production, safety, water run-off, and a host of other reasons, there are many regulations put on agriculture. Many of these regulations are hard for farmers to keep up with and thus, they are left with little time to invest in new technologies besides those necessary.[43]

Culture

Unless buying organic, food is often sold at a relatively cheap cost despite the labor that is put into it, which is due to undervaluing of the food market. The culture also results in a lot of food being wasted. This creates issues for the sustainability of the industry and puts challenges on farmers as they must sell their product for a relatively cheap price.

ENERGY OVERVIEW

Energy and water

Energy and water are two highly connected industries. Water consumption drives energy use for transportation and purification and energy consumption drives water usage through cooling, transport, and extraction. This relationship requires high amounts of both water and energy, which creates a tension between resource uses and allocation. While a majority of our customer discovery was done within the water agriculture space, we will rely on a mixture of literature surrounding this topic and customer discovery we conducted in this area.

One current, widely used form of energy production is *fracking*. Fracking uses between 1.5 to 16 million gallons of water per well. Researchers at Duke University found that this could increase up to 50-fold in some regions by 2030.[44] This impacts the water cycle by producing contaminants such as radioactive elements and heavy metals and salts called "produced water." This produced water is often pumped into holding ponds which can leak into groundwater impacting wildlife and watersheds in neighborhood.[45] In addition to affecting the water cycle, fracking produces methane, a greenhouse gas that has severe impacts on the climate.

Due to the adverse effects of fracking, many renewable energies have been advocated for that use of water such as hydroelectric energy, thermoelectric energy, bioenergy. While these do not produce the greenhouse gases that fracking does, they still have an effect on the water cycle.

Hydroelectric energy impacts the surrounding areas by causing water stratification, supersaturation, changing water levels, and sedimentation. Stratification occurs in reservoirs when the flowrate is too slow causing surface water to warm while the colder water sinks to the bottom creating layers of water. This causes reduced oxygen levels on the bottom layer that can then travel to habitats downstream. Supersaturation occurs due to turbulence when water spills over a dam hitting the below pool trapping air in it. Due to the high levels of nitrogen in air (about 78%), the water retains high levels of nitrogen effecting aquatic life traveling between different concentrations of nitrogen due to the pressure change. The fluctuating water levels also disrupts habitat's normal conditions and cause erosion impacting the ecosystem and causing sedimentation. Sedimentation occurs when organic and inorganic materials usually suspended in water collect in the dam causing an unnatural dispersion of it throughout the river and causing depletion of oxygen supply in areas with high levels of material.[46]

Thermoelectric power generates energy from steam-driven turbine generators which are cooled by the circulation of water through the heat exchangers. By cooling the equipment, the water temperatures also rise. While the water is partly cooled before being dumped back into the water cycle, there are still ramifications in the quality and quantity of water returned to the cycle. The water leaving the power plants can contain heavy metals such as mercury that impact wildlife downstream. Additionally, the water returned is at a higher temperature than being taken out of the water cycle impacting water quality. Lower water quantity is also returned to the water cycle since some of the water taken into the plant evaporates during the cooling process.[47]

Bioenergy converts renewable biomass fuels into heat and electricity. While this process does decrease pollution and is a renewable resource, water is used heavily in this process. In addition to water used for agricultural growth, water is used to treat the biomass at certain steps of the energy production process. This creates a water competition for other necessary uses such as water consumption and food growth.

While energy production is moving toward a smaller carbon footprint, many of the solutions require high amounts of water or have consequences on the overall water cycle. Additionally, water purification requires high amounts of energy for transportation, cleaning, and monitoring purposes.

Energy and food

Energy and food also interact through the consumption of energy to produce and transport food, and more recently through the use of agricultural products to produce renewable fuel feedstocks.

An apparent connection between energy and food is the use of energy to produce agricultural products. By directly consuming fossil fuels or using products that require high amounts of energy to produce, such as fertilizer, agricultural production requires high amounts of energy. A study published by the U.S. Department of Agriculture (USDA) reported that over 2005–08, expenses from direct energy use averaged about 6.7% of total production expenses while fertilizer represented an additional 6.6%. Using a Food and Agricultural Policy Simulator, the same study found that the price of crops that have a high energy input share relative to the production cost, such as corn, are more affected by both low and high price changes in energy compared to crops with low-energy input relative to the production cost, such as soybeans.[48] This relationship reflects the intangible nature of the WEF nexus as the energy to agriculture interaction is rooted in the physical consumption of energy, but also has major economic impacts.

Food also has the potential to impact energy. One prime example is the production of biofuels, specifically biomass-based transport fuels. The most basic way to make a biofuel involves the fermentation of crops high in sugar or fat into ethanol that can be combined with gasoline to power cars. This process provides a clear way agriculture can also have an impact on food, but a review by Araujo et al. highlights the complexities of sustainable producing biofuel. The review utilizes historical international policy issues such as the "splash and dash" loophole and investment issues to show that commercializing biofuels is more costly than originally expected.[49]

This discussion on the connection between energy and food completes the last link in the dynamic WEF nexus. Throughout this paper, we have outlined how each resource is innately dependent on each other providing a complex issue of tradeoffs and allocation. We now move on to how these industries can be tied together in a more cohesive and productive manner with technology.

TYING IT ALL TOGETHER WITH TECHNOLOGY

While water, food, and energy are clearly connected due to resource tradeoffs, the applicable technologies across these industries are disparate, except a group of technologies including IoT, AI/ML, and data science known as self-monitoring analysis and reporting technology (SMART). This technology can be applied across all industries due to its agnostic nature and flexibility of applications. Additionally, when asked "if there is an area of research you are not in, but would like to enter," 36% of customer discovery participants answered SMART Tech highlighting the market pull for this application. The below chart reflects the high interest in SMART sensing systems (Figure 4).

To highlight the application of SMART technology within these industries we focus on two startup case studies: Agrichain and Pluto AI.

Agrichain

Agrichain aims to optimize and connect the agriculture supply chain and its stakeholders. The platform connects farmers, companies, logistics, and receival sites by using blockchain to enhance the end-to-end software. The platform is comprehensive including stock management, contracting, supply chain tracking, logistics automation, broker integration, truck receivals, traceability, and position reporting. Agrichain taps into the innovation driver, COVID-19 Pandemic, as the inefficiency and fractured nature of the agriculture supply chain was exposed. In addition it allows for decrease costs for both companies and farmers as food is not going to waste, and instead the delivery of food is streamlined.

Although this product is tailored to the agriculture industry, the platform style also has applications in water and energy. While agriculture is vertically fractured (fractured across different people within the supply chain), the water industry can be considered horizontally fractured as utilities often do not communicate with each other often. Energy is similar to water in that it is transported from site of energy production over a grid and to the end-user. In both water and energy, a platform system combined with tracking data collected can be used to optimize efficiency of travel and routing of resources to the best location. Additionally, due to the interconnectedness of all three industries, a platform could be used to connect all within a small geographical area. This would allow farmers to

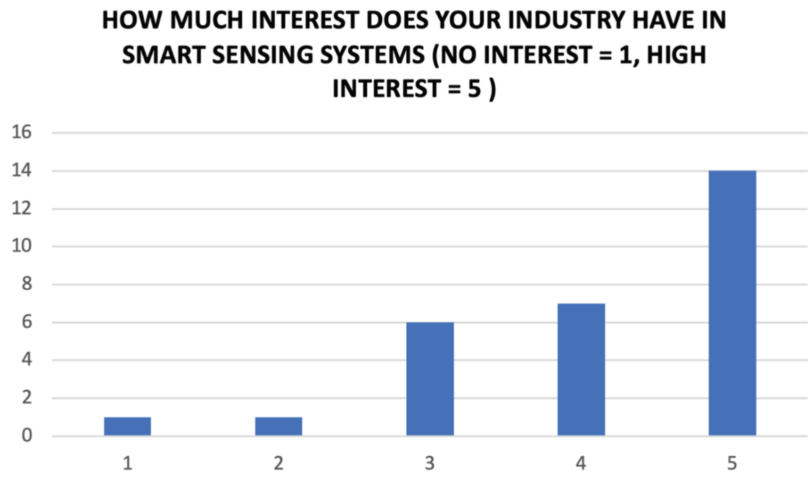

Figure 4. Interest in SMART sensing systems.

communicate data about crops and water runoff to nearby utilities, utilities to communicate water usage to energy companies, and energy companies to communicate energy usage to both. This case highlights the ability of SMART technology to transcend industry and be applied in both.

Pluto AI

Pluto AI is an analytics platform for smart water management that enables water treatment or processing facilities to prevent water waste, predict asset health, and minimize costs using AI. By taking data collected from the facilities, Pluto AI constructs the data in a meaningful, productive way. This startup targets the fact that water infrastructure has high capital costs and needs replacement. Additionally, by allowing increased, accurate information, to be accessed by employees, critical decision making can be made quickly.

This type of monitoring system provides insight into exactly where and how much water is flowing. Similar to Agrichain, it is generally industry agnostic as it could be applied to monitor irrigation and water runoff in agriculture or water movement and temperature levels in renewable energy systems.

Importance of creating cross-industry applications

While there has been a lot of innovation within each industry, it is also important to consider applications across industries due to the connections between them. One prominent example is agricultural water runoff. Due to an increase in population growth and increased food demand, agriculture as an industry has expanded. This results in an increase in the production of contaminants such as nitrates which can cause negative health impacts. These nitrates get carried away from the farms through water runoff and into water collection sites which degrades the water quality.[50] This contaminant creates a challenge for water facilities as it requires processes such as ion exchange, distillation, and reverse osmosis.[51] The amount of nitrate runoff is largely correlated to the amount of nitrates in the form of fertilizer and pesticides that are used on the crops.[52] Thus, finding a way to communicate the amount of nitrates used in a farm upstream from a water treatment facility could add more information points to the quality of water coming in. Similar to Pluto AI and Agrichain, this could come in the form of a platform or deep learning technology which would allow the facility to make more informed decisions and optimize behavior.

Agriculture runoff is a key example of how these three industries, water, energy, and food can become more connected simply by implementing key technology. Bringing these sectors together would not only support each individually but benefit each other because of their interconnectedness.

SOCIAL IMPACTS

In addition to the regional, environmental, and economic impacts of water as it connects to agriculture and energy, there are large social impacts regarding resource availability. As we have seen, water, energy, and food are intrinsically connected in the United States and abroad. This discussion will focus on water equity and stress. *Water equity* is a term that refers to the fair inclusion and occurs when all communities have access to clean, affordable water services. However, *water stress* occurs when individuals face difficulty accessing these services due to issues such as lack of funding and infrastructure. Water stress can be due to economic constraints, where people do not have enough money to obtain access to clean, safe water or geographical constraints, where the geography of the area does not have an adequate water supply for the demand. The water scarcity index can be defined as the ratio between total water demand and total water availability.

Domestic impact

Water stress is a large challenge within the US as overall funding for water services is low.[53] After 1971's Clean Water Act, the government allocated 30% of infrastructure funding to water. However, in 2020, the funding has decreased to less than 5% highlighting a critical funding gap.[54] At the same time, the infrastructure, some of which was put in place in the 1800s, is aging. This is resulting in not only maintenance, but a potential overhaul and replacement of the current water system.[55] This decrease in funding coinciding with a failing water system was prevalent in the customer discovery as a majority of people mentioned funding as one of the largest challenges they face. Additionally, a consequence of this funding results in local communities holding the bill for water maintenance, which in turn results in lower-income communities having economic challenges when trying to access high quality water. In addition to water maintenance, new regulations drive utilities to upgrade their machinery presenting another economic burden. This has resulted in and will continue to result in water inequity across the US.

A clear example of water inequity is Flint, Michigan's water crisis in 2015. After decades of financial decline, lead and other contaminants were found within the citizen's drinking water leading to brain damage among children. Within Flint, Michigan, 43% of the population lived in poverty. This event spurred many policy changes within the United States including partnerships between private, public, and nonprofit organization to raise awareness and communication about these issues to hopefully increase a sense of ownership in water quality.[56]

International impact

According to the United Nations World Water Development Report: Leaving No One Behind, although water has been deemed an internationally recognized human right, three out of ten people do not have access to safe drinking water globally.

Internationally, not participating in safe health practices adds to water contamination. For example, open defecation instead of in a designated, safe area is practiced in many communities causes additional challenges. This is often due to a lack of education around the matter and lack of sanitation infrastructure or water treatment facilities. In a study, 75% of drinking water samples from schools in Nepal were contaminated due to open defecation.[57] This practice creates a cycle of disease and poverty due to the medical issues arising from consuming contaminated water. Further, studies show that open defecation has a large impact on women and girls who express trauma in finding a suitable place to defecate and have to travel long distances to find private locations to manage menstrual necessities.[58]

Not only does a lack of education and resources to follow safe water drinking practices impact communities internationally, but the scarcity of drinking water can result in loss of economic opportunity. For example, women and girl are often designated with hauling water from the sources to homes. This time takes away from more productive work such as employment or schooling. A study emphasizes the value on time spent collecting water is approximately equivalent to the wage for unskilled labor and suggests that improved water services will benefit those in developing communities that participate in hauling water long distances.[59]

In both domestic and international cases, it is important to recognize the clear connection between water access and infrastructure and economic prosperity. In both cases, a vicious cycle is created where not having enough finances to participate or contribute to water services prevents access to clean water, which can then result in sickness or opportunity loss decreasing economic prosperity. As exhibited in this paper, water is deeply connected to energy and food and thus, the social impact of water also causes and are caused by the state of energy and food within these communities and also on a global scale.

CONCLUSION AND OUTLOOK

We have seen that the water, energy, and food industries are heavily connected, but differ slightly in the way products are taken from lab to market. While there are different key players and market drivers for each of them, they can be unified through the implementation of SMART Technology as it is relatively industry-agnostic. Additionally, through clever placement and applications, SMART Technology can create cross industry connections.

Looking forward, climate change will continue to strain resources and create unpredictable weather patterns heavily impacting water availability and crops, and traditional approaches will become an issue. Our customer discovery concluded that 18% of participants answered climate change or scarcity as the biggest challenge they face. Further, climate change will impact the regulations and costs of maintaining services, two key challenges that customer discovery participants faced across industries. As these challenges become more critical, it will be important to combat them by adopting new technology into each industry. This transfer of technology from the lab to market is important and must be a streamlined process.

By tracing how products get transferred from lab to market from an industry perspective, we have been able to gain insight into the tensions, drivers, and perception that surrounds the new technology. These attitudes are critical for scientists to understand as they will shape what technology will have product-market fit. With more open communication throughout the technology supply chain in the WEF industries and across them, more impact can be made from technologies as they can be designed with industry-application in mind (use-inspired) and then efficiently implemented at a manageable cost.

When asked "What is the best way to support your current research goals," 68% answered "Partnership." This inclination toward open communication with others highlights the potential presence of a collaborative community that will be essential in the productive development of new technology that leads to long-term sustainable processes across the WEF nexus.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

FUNDING

This work was financially supported by the University of Chicago faculty startup fund and Laboratory Directed Research and Development (LDRD) funding from Argonne National Laboratory, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

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