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Decarbonization of Water Sectors in the US and Germany

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Executive Summary

Water sector infrastructure accounts for 2% of global greenhouse gas emissions, comparable to the combined emissions of the shipping and aviation industries. To meet the UN's 1.5°C climate target, emissions must be reduced by 42% by 2030 compared to 2019 levels. This report analyzes the current state of the water sector in Germany and the United States, exploring opportunities to accelerate decarbonization through digitalization.

Using a comprehensive approach that combined desk research with 37 expert interviews across policy, engineering, and architecture, the report captures interdisciplinary insights into how digital tools can drive sustainable water management. Field visits to water treatment facilities and stakeholder consultations enriched the analysis, providing a strong basis for identifying key trends and solutions.

The research shows that digital twin technology is being increasingly adopted to optimize water system operations, enabling predictive maintenance and reducing water losses. Machine learning models are playing an important role in forecasting water demand and identifying potential system vulnerabilities, boosting resilience and efficiency. One key finding was the difference in regulatory environments: Germany benefits from cohesive EU policies that encourage cross-border collaboration, while the US operates under more state-driven policies, creating both challenges and opportunities. Public-private partnerships were highlighted as essential for driving technological progress and balancing financial and technical responsibilities.

While digital technologies hold great potential for decarbonizing the water sector and enhancing climate resilience, challenges such as funding limitations, data privacy concerns, and workforce skill gaps need to be addressed. The report recommends:

- Expanding digital infrastructure for real-time data collection and AI-driven analytics.
- Aligning policies to support digital and sustainability initiatives at all levels of government.
- Investing in workforce training programs to build necessary technical expertise.
- Leveraging public-private partnerships and targeted funding to support the adoption of innovative solutions.

In conclusion, while digital technologies offer significant opportunities, substantial challenges remain. Overcoming these barriers is crucial to fully realize the benefits. By investing in digital infrastructure, aligning policies, developing workforce skills, and fostering public-private partnerships, Germany and the United States can reinforce their roles as leaders in sustainable water management and make meaningful contributions to global climate goals.

Note: *This report is an output of the 2024 fellowship and was completed in October 2024. As such, it reflects the policy landscape and priorities at that time and may not account for subsequent developments.*

Table of Contents

1. Shaping the Future of Water

Water systems encompass climate resilience, energy efficiency, and public infrastructure operations. When examined from a broad perspective, the water sector is responsible for 10% of global CO_2 emissions; this calculation accounts for emissions related to water consumption, storage, distribution, wastewater treatment, as well as topics such as the lack of wastewater treatment and land use.[1] More directly, the water and wastewater sector in Germany produced 5.5 million tons of CO_2 equivalent in 2023, representing 0.82% of the country's total emissions.[2] In the United States, water systems operations contribute approximately 45 million tons of greenhouse gasses annually, accounting for 2% of the country's energy consumption according to the Environmental Protection Agency (EPA). 30-40% of energy used by municipal governments is attributed to water plants, and up to 40% of operating costs of drinking water systems are attributed to energy costs.[3] Therefore, reducing energy consumption would both decrease the amount of greenhouse gasses emitted by water systems and reduce the costs required to operate.

This research report aims to investigate sustainable methods of water handling in the United States and Germany, with a particular focus on how digital transformation can advance comprehensive sustainability goals. Beyond decarbonization, the report explores how innovative approaches to water management can simultaneously address climate adaptation, operational efficiency, and social equity. The report is structured around four interconnected research questions, moving from broad strategic frameworks to specific technological solutions:

01	**What are the key energy-efficient technologies and practices currently used in water treatment and production facilities in the US and Germany?**	*Section 4 examines technologies and their applications, highlighting opportunities for knowledge exchange between the two countries.*
02	**How does digitalization (AI, IoT sensors, and predictive analytics) contribute to enhancing climate resilience in water sectors in regions prone to droughts and heavy rainfall, such as North Germany and the southwest US?**	*Section 5 explores emerging digital solutions that are reshaping decarbonization and resilience efforts.*
03	**What are the techniques and approaches employed to improve water efficiency and conservation in the water sector in Germany and the US?**	*Section 6 analyzes how technical practices intersect with social equity and community resilience.*
04	**What are the policy frameworks, technological innovations, and best practices driving decarbonization efforts in Germany and the US?**	*Section 7 examines broader approaches that enable transformative change toward decarbonization, illustrated through case studies.*

Figure 1. Research Questions. Source: Authors

[1] CDP. (2020). *Global Water Report 2020*. CDP. https://cdn.cdp.net/cdp-production/cms/reports/documents/000/005/577/original/CDP_Water_analysis_report_2020.pdf?1617987510
[2] Association of Drinking Water from Reservoirs (ATT), German Association of Energy and Water Industries (BDEW), German Alliance of Water Management Associations (DBVW), German Technical and Scientific Association for Gas and Water (DVGW), German Association for Water, Wastewater and Waste (DWA), & German Association of Local Utilities (VKU) (Eds.). (2015, June 25). *Profile of the German Water Sector 2015.* Wirtschafts- u. Verlagsges. Gas u. Wasser. https://www.bdew.de/media/documents/20150625_Profile-German-Water-Sector-2015.pdf
[3] Environmental Protection Agency. (2024, June 14). *Energy Efficiency for Water Utilities*. EPA. https://www.epa.gov/sustainable-water-infrastructure/energy-efficiency-water-utilities

2. Defining Key Terms in Context

To give context to the investigation of current trends in the water sector, understanding the relevance of decarbonization and digitalization with respect to the industry is a necessary foundation.

2.1. Decarbonization

Decarbonization refers to the reduction of carbon emissions, but the term can be more broadly interpreted as the reduction of greenhouse gas emissions. It manifests through the efficient use of energy, the reduction of fossil fuel energy consumption, and the increased uptake of renewable energy. Globally, efforts to decarbonize are intensifying in response to accelerating effects from climate change.[4] The water sector is affected by climate change through impacts on water sources, greater severity of extreme weather events, and increased frequency of extreme weather events.[5]

Within the water sector, there has been success in strategic energy usage and reducing relative water consumption, thus lowering associated carbon emissions. Methods to reduce consumption include water-saving technologies and processes, minimizing water losses, water reuse, and demand-based water tariffs. Other approaches include the reduction of fossil resources in the construction and operation of water management facilities; such approaches reduce both emissions of greenhouse gas and reliance on externally-produced energy resources. Utilizing digital tools holds the ability to further reduce carbon emissions in more transformative ways.

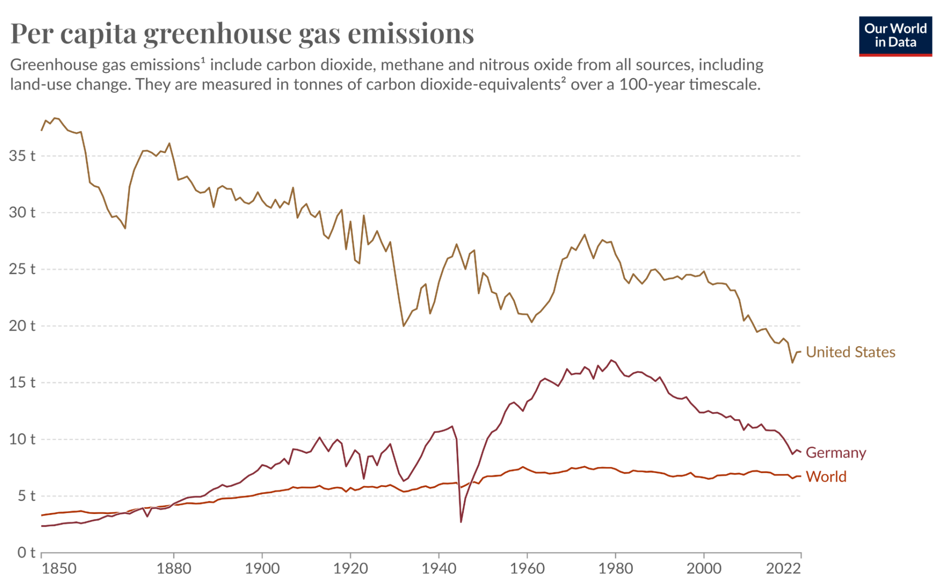

Figure 2. Per capita GHG emissions, CC BY. Source: Our World in Data[6]

[4] Meza, A. (2022). *Decarbonization cannot wait*. United Nations Framework Convention on Climate Change. https://unfccc.int/news/decarbonization-cannot-wait

[5] Xylem Inc. (2022). *Net Zero: The Race We All Win*. Xylem Water Solutions & Water Technology. https://www.xylem.com/en-us/campaigns/net-zero/

[6] Ritchie, H., Rosado, P., & Roser, M. (2023). *CO_2 and greenhouse gas emissions*. Our World in Data. https://ourworldindata.org/co2-and-greenhouse-gas-emissions

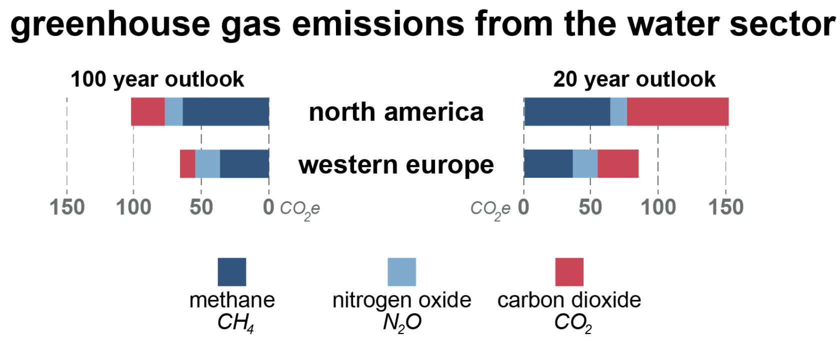

Figure 3. GHG emissions of the water sector by region. Adapted from: Global Water Intelligence[7]

2.2. Digitalization

Digitalization refers to the impacts of digital information about physical objects on social life. Regarding water, the term describes the "increasing implementation of digital water tools, such as sensors or interactive apps, into the daily relations between water and society."[8] Digitalization goes beyond the technical process and tools themselves to encompass the impacts on water sector employees, consumers, and existing political systems.

In the context of the following report, digitalization is explored as a strategy of utilizing digital tools to advance goals of decarbonization. Digital solutions are presented in light of pressing challenges in the water sector and with consideration of the industry stakeholders described in Chapter 3: Investigating Key Trends in the Water Sector.

2.3. Climate Change Impacts

Climate change impacts vary by geography but generally result in rising air and water temperatures, disrupted water cycles, and more intense storms, affecting water supplies vital to life. The United States Environmental Protection Authority (EPA) has identified key effects on water resources: reduced supplies, impaired quality, and stressed infrastructure. In areas of the western United States, such as California, decreased snowpack due to warmer winters and altered precipitation patterns threatens water availability.[9] Water scarce regions, such as eastern Germany, are facing mounting pressures as the groundwater levels have decreased steadily due to both increased consumption and limited groundwater recharge.[10] Additionally, water infrastructure faces risks from extreme weather events, such as hurricanes and floods, that can inundate systems with excess water or cause physical damage through severe winds.[11]

[7] Lutkin, T. (2022). *Taking stock of water's GHG emissions profile – and where the industry needs to go next*. Global Water Intelligence. https://www.globalwaterintel.com/articles/taking-stock-of-water-s-ghg-emissions-profile-and-where-the-industry-needs-to-go-next
[8] Walter, C. (2023). Digital Technologies for the future of the Water Sector? examining the discourse on Digital Water. *Geoforum*, *148*(103918), 1–10. https://doi.org/10.1016/j.geoforum.2023.103918
[9] Environmental Protection Agency. (2024). *Climate Change Impacts on Freshwater Resources*. EPA. https://www.epa.gov/climateimpacts/climate-change-impacts-freshwater-resources
[10] Cullmann, A., Sundermann, G., Wägner, N., von Hirschhausen, C., & Kemfert, C. (2022). Water resources in Germany: Increasingly polluted and regionally overused. DIW Weekly Report, 49/50, 307–315. https://doi.org/https://doi.org/10.18723/diw_dwr:2022-49-1
[11] Ibid., 9.

2.4. Climate Resilience

Climate resilience is the capacity of systems to anticipate, prepare for, and adapt to climate-related disruptions while maintaining essential functions. Resilience involves diminishing vulnerability in the short-term while enhancing the capacity for transformation in response to future risks. It is an ongoing process of risk assessment and adaptation. In light of the increasing severity and unpredictability of climate impacts, such assessments are of paramount importance for resilience planning. Planning efforts must consider both the direct impacts of climate change, such as heatwaves, droughts, floods, and rising sea levels, and the indirect consequences, such as food insecurity, economic instability, and displacement.[12]

Attaining climate resilience can require transformational change. Examples include a shift from fossil fuel-based pumping systems to renewable energy sources, the redesign of water infrastructure to better cope with flooding and drought cycles, and the adaptation of storage practices to accommodate altered precipitation patterns. The process of building climate resilience requires reinforcing adaptive capacity. Adaptive capacity is the ability of systems to adapt to climate variability and extremes while simultaneously mitigating potential damages. In the water sector, adaptive capacity can manifest through holistic drought management approaches, considering impacts of water policies on citizens, and increasing access and interaction between governments and stakeholders. Enhancing capacity demands investments in education, infrastructure, governance, and technology, which facilitate adjustments in response to changing climatic conditions.[13]

Water resources management is particularly critical, given the sector's vulnerability to climate impacts like altered precipitation and extreme weather. Building resilience in water systems requires integrating sustainable practices with digital tools, such as real-time monitoring and data-driven forecasting, to enable adaptive responses and ensure long-term water security.[14]

[12] Denton, F., T.J.Wilbanks, A.C. Abeysinghe, I. Burton, Q. Gao, M.C. Lemos, T. Masui, K.L. O'Brien, and K.Warner, 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.
[13] Ibid., 12.
[14] Schipper, E. L. F., Revi, A., Preston, B. L., Carr, E. R., Eriksen, S. H., Fernandez-Carril, L. R., Glavovic, B., Hilmi, N. J. M., Ley, D., Mukerji, R., Muylaert de Araujo, M. S., Perez, R., Rose, S. K., & Singh, P. K. (2022). Climate resilient development pathways. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 2655–2807). Cambridge University Press.

3. Investigating Key Trends in the Water Sector

The research conducted for the following report has chiefly been organized around interviews with experts in the United States and Germany, as well as written reports from a range of sources from stakeholders in the water industry. Interviews were carried out in-person and online with stakeholders across the water sector, ranging from those working at water treatment plants to social scientists at research institutions. Interviewees were identified through their geographical location, industry, and role relating to topics of water, digitalization, sustainability, and resilience.

During a two-week trip to the United States, in-person semi-structured interviews were held primarily with research institutions and universities. A notable site visit included a water treatment plant in California's Bay Area. Following the trip, additional online interviews were conducted with American experts to fill gaps and include broader perspectives. Similar interviews were carried out in Germany to ensure contextual balance. Experts were identified through professional networks, conferences, companies, and recommendations.

Semi-structured interviews allowed flexibility, combining pre-determined questions with open discussions. Stakeholders from outside the United States and Germany were included when relevant expertise was available. Desk research, including industry reports, white papers, peer-reviewed studies, and government documents, supported interview preparation and filled knowledge gaps.

Based on findings from interviews and written research, core topics were identified based on overlaps and frequency of discussion. Core topics were then aligned with the four research questions that drive the report in order to understand connections and overall relevancy. The following report identifies the key trends found during the desk research process.

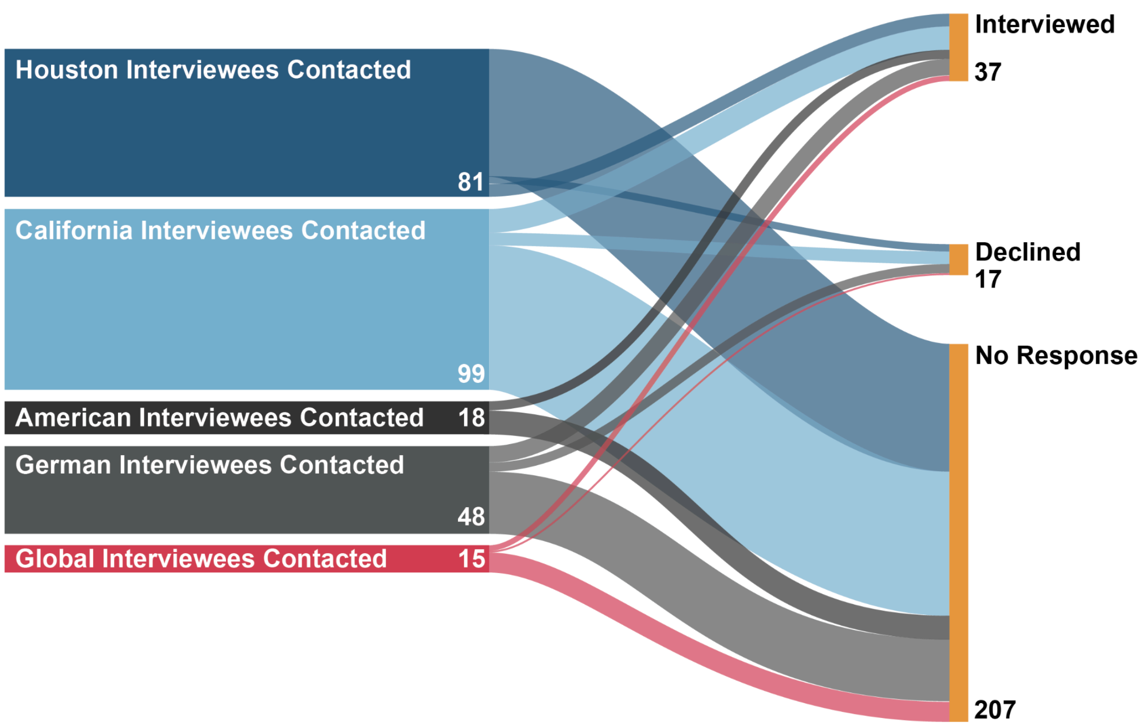

Figure 4. Interview outreach overview. Source: Chloe Kiernicki

4. Water Sector System and Stakeholders

Understanding digitalization and decarbonization in the water sector requires assessing the interconnected stakeholders in the United States and Germany. Effective climate protection in water supply depends on involving stakeholders such as municipalities, governments, environmental organizations, businesses, and consumers. Collaboration with local communities allows for tailored, sustainable solutions. Water utilities should engage in political initiatives, contribute to regulatory development, and help shape policies supporting a low-carbon economy.

Germany and the United States implement water efficiency and conservation measures at national and local levels, including strategies, funding programs, and infrastructure adaptation efforts. Chapter 9 provides recommendations for targeted stakeholders and pathways within these contexts.

4.1. Relevant Regulations

There are no global regulatory bodies regarding water sources or drinking water production. In the United States, the Environmental Protection Agency (EPA) oversees water regulations, with individual states managing issues beyond EPA mandates. In contrast, Germany adheres to European Union (EU) regulations, focusing on a river basin-based approach rather than state-level governance.[15]

4.1.1. United States

The Safe Water Drinking Act (SDWA), enacted in 1974, grants the EPA authority to establish National Primary Drinking Water Regulations (NPDWR) for drinking water quality and reportings.[16] The NPDWR are updated periodically as contaminants emerge in quantities and frequencies.[17] The 1996 amendment expanded the EPA's role to include source water protection, operator training, and public communication.[18] States can assume regulatory enforcement ("primacy") if they meet or exceed EPA standards. Currently, 49 states have this authority, leaving Wyoming, Washington D.C., and most tribal lands under direct EPA oversight.[19]

America's Water Infrastructure Act (AWIA) of 2018 introduced major changes, such as enhancing access to monitoring data, mandating emergency response plans, and supporting asset management development. In 2022, a Compliance Monitoring Strategic Plan addressed data accuracy, submission challenges, and public accessibility.[20]

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[15] European Commission. (2023). *Water framework directive*. Environment. https://environment.ec.europa.eu/topics/water/water-framework-directive_en

[16] Environmental Protection Agency. (2024). *Overview of the Safe Drinking Water Act*. EPA. https://www.epa.gov/sdwa/overview-safe-drinking-water-act

[17] Environmental Protection Agency. (2024). *National Primary Drinking Water Regulations*. EPA. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

[18] Environmental Protection Agency. (2024). *Overview of the Safe Drinking Water Act*. EPA. https://www.epa.gov/sdwa/overview-safe-drinking-water-act

[19] Environmental Protection Agency. (2023). *Primacy Enforcement Responsibility for Public Water Systems*. EPA. https://www.epa.gov/dwreginfo/primacy-enforcement-responsibility-public-water-systems

[20] Environmental Protection Agency. (2024). *America's Water Infrastructure Act of 2018 (AWIA)*. EPA. https://www.epa.gov/ground-water-and-drinking-water/americas-water-infrastructure-act-2018-awia

4.1.2. Germany

Germany, as an EU member, adheres to the Water Framework Directive (WFD), which promotes integrated water management, river basin monitoring, and cross-border coordination.[21] The Groundwater Directive (GWD) and Environmental Quality Standards Directive (EQSD) enhance protection for groundwater and surface water.[22]

The EU Drinking Water Directive (DWD) updates quality standards, reduces pollutant limits, and prioritizes access for marginalized groups[23], with a preventative approach emphasizing risk assessment and early action.[24] Germany integrated the DWD into its Drinking Water Ordinance (TrinkwV), managed by the Federal Ministry of Health[25] and the Federal Environmental Agency[26], requiring initial and six-year risk assessments, focusing on climate impacts and infrastructure.[27] The WFD was incorporated into the Federal Water Act (WHG), Germany's water regulation since 1957, adopting a holistic approach with river basin management and pollution controls.[28] The WHG allows states to adapt their laws in line with EU directives.[29]

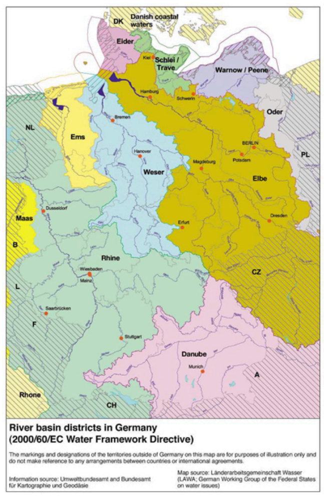

Figure 5. Map of the river basins in Germany. Source: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection[30]

[21] European Parliament, Council of the European Union. (2014). *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. EUR-Lex. http://data.europa.eu/eli/dir/2000/60/2014-11-20

[22] Ibid., 15.

[23] European Commission. (2022). *Drinking water.* Environment. https://environment.ec.europa.eu/topics/water/drinking-water_en

[24] European Parliament, Council of the European Union. (2020). *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast)*. EUR-Lex. http://data.europa.eu/eli/dir/2020/2184/oj

[25] European Parliament, Council of the European Union. (2020). *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast)*. EUR-Lex. http://data.europa.eu/eli/dir/2020/2184/oj

[26] Federal Ministry of Health. (2024). *Drinking Water*. Federal Ministry of Health. https://www.bundesgesundheitsministerium.de/en/topics/drinking-water

[27] Federal Ministry of Justice. (2023). *Drinking Water Ordinance of 20 June 2023.* Federal Law Gazette 2023 I No. 159. https://www.gesetze-im-internet.de/englisch_trinkwv/englisch_trinkwv.html#p0085

[28] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2010). *Implementation of European Water Framework Directive in Germany*. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. https://www.bmuv.de/WS1915-1

[29] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2010). *Implementation of European Water Framework Directive in Germany*. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. https://www.bmuv.de/WS1915-1

[30] Ibid., 28.

Water bodies in Germany are managed by states, but cross-border management is facilitated by amendments to the Federal Water Act (WHG), which allows states to collaborate on shared waters through river basin communities.[31]

The federal government oversees water protection, with states adding provisions within their administrative procedures acts. Water management is executed by states, with a three-level authority structure: supreme authority (federal ministry, typically the Ministry for the Environment), intermediate authority (regional and state offices), and lower authorities (county and municipal jurisdictions).[32]

In 2023, the federal government released the National Water Strategy in response to droughts, focusing on optimizing data flows, climate adaptation, sustainability, and strategic funding for research and infrastructure investments.[33] Key issues also include protecting water cycles and enhancing system resilience against climate change impacts.[34] Local authorities manage water supply and wastewater disposal, with most services publicly managed. Privatization exists in some cases for water supply, but wastewater management remains a public service.[35]

4.2. Government Funding

The majority of water systems in Germany and the United States are publicly owned. Domestic and industrial customers pay rates for the water they consume, but funding required for major transformations come from outside sources, such as the federal, regional, or state governments.[36]

4.2.1. United States

Federal funding for public water systems is primarily through the EPA's Drinking Water State Revolving Fund (DWSRF). Congress allocates funds annually, and states match 20% of the grants. States may set aside up to 31% for programs like administration, technical assistance, and management. Since 1996, DWSRF has provided over $21 billion in federal funding, generating $41.1 billion in investments by 2019.[37]

In 2018, the Bipartisan Infrastructure Law pledged $50 billion to the EPA to improve water infrastructure; this funding is funneled through the DWSRF and the Clean Water State Revolving Fund (CWSRF).[38] National agencies, including National Aeronautics and Space Administration (NASA), and Federal Emergency Management Agency

[31] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2010). *Implementation of European Water Framework Directive in Germany*. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. https://www.bmuv.de/WS1915-1
[32] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2016). *Water protection policy in Germany*. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. https://www.bmuv.de/WS633-1
[33] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2023). *Background information on the National Water Strategy*. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. https://www.bmuv.de/WS5871-1
[34] Schiller, A. (2023, March 21). *National Water Strategy*. Umweltbundesamt. https://www.umweltbundesamt.de/en/topics/water/water-resource-management/nationale-wasserstrategie
[35] Ibid., 29.
[36] Profile of the German Water Sector, (2020) Retrieved September 11, 2024 https://www.dvgw.de/medien/dvgw/leistungen/publikationen/branchenbild_2020_engl.pdf
[37] Environmental Protection Agency. (2023). *How the Drinking Water State Revolving Fund Works*. EPA. https://www.epa.gov/dwsrf/how-drinking-water-state-revolving-fund-works
[38] Ibid., 37.

(FEMA), provide funding for specific projects relating to shared interests between agencies and water topics.[39] The Water Infrastructure Finance and Innovation Act of 2014 (WIFIA) provides funding for significant infrastructure projects. As of 2023, WIFIA has provided $1.1 billion of investments to reduce greenhouse gas emissions and $11.5 billion of investments to increase system resilience and climate-related events.[40]

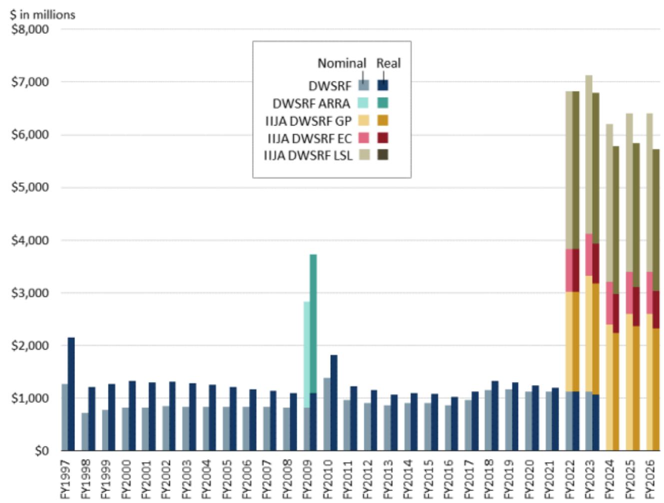

Figure 6. Appropriations for the Drinking Water State Revolving Fund. Source: Congressional Research Service[41]

Other significant federal funding sources include the USDA Rural Development Water Program, and Department of Commerce Economic Development Administration for economically declining areas.[42] The American Rescue Plan Act allocated about $20 billion for water infrastructure during pandemic recovery.[43] As seen in Figure 6 above, the American Recovery and Reinvestment Act (ARRA) in 2009 led to a funding spike, addressing the 2008 recession, while the Infrastructure Investment and Jobs Act (IIJA), starting in 2022, boosts funding through the Bipartisan Infrastructure Law.[44] While the Inflation Reduction Act (IRA) is not specifically focused on water infrastructure, water systems have been able to use the funding for renewable energy installations onsite.[45]

4.2.2. Germany

Under the EU-Germany Partnership Agreement (2021-2027), Germany will receive €27.072 billion in funding from several EU funds including the European Regional Development Fund (ERDF), European Social Fund (ESF+), and

[39] Environmental Protection Agency. (2024). *Climate Adaptation Funding for Water Sector Utilities*. EPA. https://www.epa.gov/crwu/climate-adaptation-funding-water-sector-utilities
[40] Environmental Protection Agency. (2024). *Water Infrastructure Finance and Innovation Act (WIFIA)*. EPA. https://www.epa.gov/wifia
[41] Congressional Research Service. (2024). *Changes to the Drinking Water State Revolving Fund (DWSRF) Program*. Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R47935
[42] Environmental Protection Agency. (2024). *Effective Funding Frameworks for Water Infrastructure*. EPA. https://www.epa.gov/waterfinancecenter/effective-funding-frameworks-water-infrastructure
[43] Connolly, S., & Oberthur, A. (2024). *How pandemic recovery funds are helping states upgrade critical water infrastructure*. The Pew Charitable Trusts. https://www.pewtrusts.org/en/research-and-analysis/articles/2024/06/03/how-pandemic-recovery-funds-are-helping-states-upgrade-critical-water-infrastructure
[44] Ibid., 41.
[45] Interview with Kavita Heyn, City of Portland Water Bureau, August 2024.

the Just Transition Fund (JTF). These funds target five political objectives, with three key to decarbonization and digitalization: a smarter Europe, a greener, low-carbon Europe, and a more connected Europe.[46]

The smart Europe goal focuses on innovation, digitalization, and sustainable energy, while a greener, low-carbon Europe targets renewable energy, climate adaptation, and disaster resilience. A more connected Europe addresses mobility and IT infrastructure, particularly in the context of green transitions.[47] Funding for the National Water Strategy comes from the Federal Ministry for the Environment (BMUV), supported by the Federal Action Plan on Nature-based Solutions for Climate and Biodiversity.[48]

4.3. Public Institutions

4.3.1. United States

At the federal level, the EPA is the central regulatory agency, with the US Geological Survey (USGS) providing real-time water resource data for all 50 states, available on the National Water Dashboard.[49] This data is fundamental to the work of those working in the water sector.[50] The WaterSense program, also led by the EPA, promotes water efficiency through certification for products and services that meet specific standards, encouraging smarter consumer choices.[51]

The National Science Foundation (NSF), another federal agency, allocates funding for water-related research, including digitalization and data tools. In 2024, NSF granted $9.8 million to 15 projects under "Managing Water for a Changing Planet" and "Climate Resilience and Water Resources," with nearly half focusing on digitalization.[52] At the state level, water policies are governed by State Water Plans within the Departments of Natural/Water Resources.[53] Locally, over 148,000 public water systems provide water to 90% of the United States population, managed by entities ranging from cities and counties to private businesses.[54]

4.3.2. Germany

The Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection is the primary ministry overseeing water supply[55], with other ministries like the Federal Ministry of Health, Federal

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[46] European Commission. (2022). Partnership Agreement with Germany – 2021-2027. https://commission.europa.eu/document/download/f50ae4b0-e46c-41a3-a29b-168dc904fa86_de?prefLang=en
[47] Ibid., 46.
[48] Schiller, A. (2023). *National Water Strategy*. Umweltbundesamt. https://www.umweltbundesamt.de/en/topics/water/water-resource-management/nationale-wasserstrategie
[49] United States Geological Survey. (n.d.). *National Water Dashboard*. USGS. https://dashboard.waterdata.usgs.gov/app/nwd/en/
[50] Interview with Michael Schramm, 2024
[51] Environmental Protection Agency. (2024) *Using Water Efficiently*. EPA. https://www.epa.gov/watersense/using-water-efficiently
[52] National Science Foundation. (2024). *NSF invests $9.8M to advance equitable water solutions*. NSF. https://new.nsf.gov/news/nsf-invests-9-8m-advance-equitable-water-solutions
[53] Texas Water Development Board. (n.d.). *State Water Plan*. Texas Water Development Board. https://www.twdb.texas.gov/waterplanning/swp/index.asp
[54] Environmental Protection Agency. (2023). *Information about Public Water Systems*. Drinking Water Requirements for States and Public Water Systems. https://www.epa.gov/dwreginfo/information-about-public-water-systems
[55] Schiller, A. (2023). *National Water Strategy*. Umweltbundesamt. https://www.umweltbundesamt.de/en/topics/water/water-resource-management/nationale-wasserstrategie

Ministry of Justice, and Federal Ministry for Economic Affairs and Climate Action collaborating on water regulation, digitalization, and climate change.[56]

Water regulation in Germany follows an ecosystem-based approach, with states and river basin areas managing implementation. Municipal utilities, known as Stadtwerke, provide water supply and wastewater treatment. Unlike the United States, which has around 148,000 public water systems, Germany has approximately 900 Stadtwerke.[57]

4.4. Private Market

The private sector accelerates innovation in water technologies, often without the funding restrictions of the public sector. Unlike conservative water utilities, private companies can test and develop new solutions, such as digital tools to improve efficiency, which is particularly beneficial for smaller utilities lacking in-house resources.Due to their ability to raise funding, such businesses take on the risk of developing and testing relevant sensors and ensuring their proper placement and function.[58] Engineering consulting firms also play a key role, providing expertise in organizing, ensuring interoperability, and setting up system architecture for water utility data, which is essential for utilities to make use of collected information.[59]

4.4.1. United States

In recent years, large companies have started implementing water strategies as part of their corporate environmental commitments. For example, in the tech sector, Microsoft, AWS, Google and Meta have all pledged to become water positive by 2030.[60] With a large global impact, Microsoft's commitment requires targeted actions and strategy that include utilizing their own technology to monitor and manage water data, urban water efficiency, testing efforts with AI and water risk, and promoting water resilience action from other companies.[61]

Large companies hold significant power across industries, and their dominance has reduced opportunities for smaller startups.[62] Still, startups play an important role in advancing industries through disrupting established patterns: they have the ability to be agile, especially in the tech sector involving software solutions.[63]

Public-private partnerships provide a vital link in the American water sector, as companies can raise capital much faster and easier compared to traditional public utilities. Between 1985-2009, private investment in water infrastructure totaled $187 million.[64] While privatization in the 1970s allowed for quick capital influx, it was

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[56] BMWK. (n.d.). *Taking control of the Digital Transformation*. German Federal Ministry for Economic Affairs and Climate Action. https://www.bmwk.de/Redaktion/EN/Dossier/digitisation.html
[57] Wagner, O., Berlo, K., Herr, C., & Companie, M. (2021). Success factors for the foundation of Municipal Utilities in Germany. *Energies*, *14*(4), 981. https://doi.org/10.3390/en14040981
[58] Karmous-Edwards, G., Tomić, S., Savic, D., & Fleming, P. (2023). *AI & Water Management: What Utilities Need To Know Now*. Qatium. https://drive.google.com/file/d/1Ov37EU0iIf1EntnXnTzgDx6mD9TLpCiV/view?usp=sharing
[59] Interview with Prashank Mishra, Seirify Data Services, July 2024
[60] Interview with Paul Fleming, Water Value, August 2024
[61] Nakagawa, M. (2024). *The journey to water positive*. Microsoft On the Issues. https://blogs.microsoft.com/on-the-issues/2023/03/22/water-positive-climate-resilience-open-call/
[62] Yeh, Chen. (2023) "Why Are Startups Important for the Economy?" *Federal Reserve Bank of Richmond Economic Brief*, No. 23-06.
[63] Ibid., 60.
[64] Debaere, P., & Kapral, A. (2021). The potential of the private sector in combating water scarcity: The Economics. *Water Security*, *13*(1000901), 1–11. https://doi.org/10.1016/j.wasec.2021.100090

critiqued for inadequate maintenance of systems over time.[65] Ideally, this recent emphasis on public-private partnerships can capture both the capital of companies with the social responsibility of local governments.

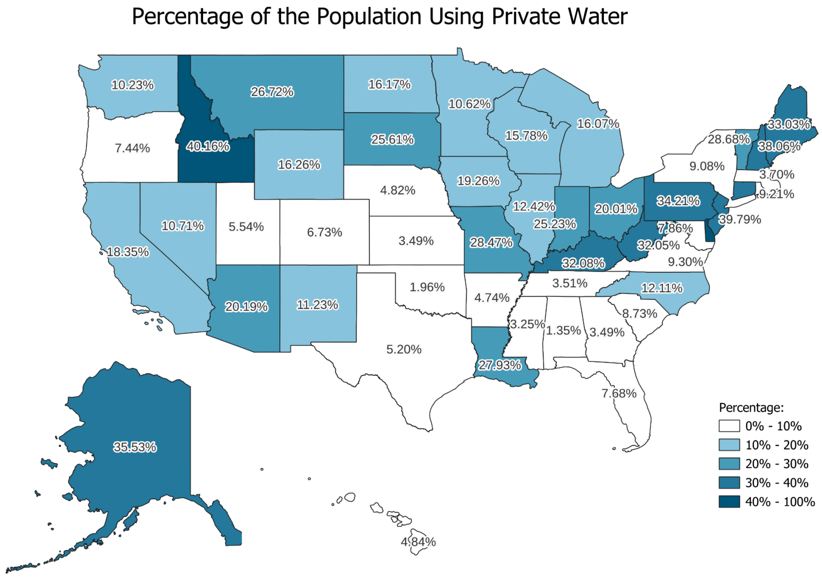

Figure 7. Population percentage that uses private water supply systems. Created with data from: EPA SDWIS[66].

4.4.2. Germany

In Germany, water services are publicly owned but often managed by private companies through public-private partnerships, ensuring national standards. The National Water Strategy emphasizes private-sector roles in sustainability, water protection, efficient use, risk assessment, and climate adaptation, fostering a resilient water future.[67]

4.5. Research & Academia

Higher education institutions (HEIs) and publicly funded research bodies drive innovation in the water sector by publishing research and collaborating with water service providers, regulators, and private companies. They also transfer key knowledge to the current and future workforce.[68]

At the United Nations 2023 Water Conference, experts emphasized the importance of collaboration between academia and governments to implement the Sustainable Development Goals, especially in decarbonization.[69] Universities in Europe and North America collaborate with various sectors to reduce greenhouse gas

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[65] Furlong, K. (2010). *Neoliberal Water Management: Trends, Limitations, Reformulations*. *Environment and Society*, 1(1). doi:10.3167/ares.2010.010103

[66] Environmental Protection Agency. (n.d.). *SDWIS Federal Reports Search*. EPA. https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/200

[67] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. (2023). *National water strategy - cabinet decision of 15 March 2023*. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Binnengewaesser/nationale_wasserstrategie_2023_en_bf.pdf

[68] Bikfalvi, A., Marques, P., Pérez-Cabaní, M.-L., Juandó Bosch, J., & Rodriguez-Roda, I. (2018). Bridging academia and water-related business through competence development: Evidence from a pan-European project. *Journal of Cleaner Production*, *171*. https://doi.org/10.1016/j.jclepro.2016.12.135

[69] United Nations. (2023). *Experts discuss role of academia and partnerships on water action*. United Nations. https://www.un.org/en/academic-impact/experts-discuss-role-academia-and-partnerships-water-action

emissions.[70] Academics also contribute to business and government sectors, working with councils, technology companies, and public-private partnerships to support evidence-based public policy.[71]

4.6. Citizen Action

Water infrastructure's largely invisible nature often results in limited public engagement with water management issues, except during service disruptions.[72] However, citizen science and digital tools are changing this, enabling greater public involvement in water stewardship.

Citizen science involves public participation in water monitoring, from data collection to research management.[73] Community-based water monitoring has emerged as a method for people to join together to steward their local bodies of water and increase public awareness of the value of water.[74] Efforts described as "extreme citizen science"[75] and "democratization of research"[76] further involve the role of the citizen as a driver of research management and planning, in addition to implementation. Ideally, data gathered by citizen science efforts would not be necessary, but often public institutions responsible for assessing water resources lack the funding or capacity to collect widespread data.[77] Digital tools, especially smartphones with their widespread availability and built-in sensors, facilitate data collection and feedback[78], helping create early warning systems for water quality.[79]

Challenges include data sharing and interoperability.[80] At the level of the group actions, IoT-based water quality measurement sensors could integrate well with citizen science efforts as citizen science acts as the human labor required to check sensor calibration and battery status that may be cost prohibitive for public institutions. From the deployed sensors, water quality could be measured and then forecasted through the use of machine learning to predict future trends.[81] Digitalization complements citizen science to better understand and disseminate research findings with the aim of improving water policy and management.

[70] United Nations. (2023). *Experts discuss role of academia and partnerships on water action*. United Nations. https://www.un.org/en/academic-impact/experts-discuss-role-academia-and-partnerships-water-action
[71] Dworkin, J. (2024). *Working with academics: A Primer for U.S. Government agencies*. Federation of American Scientists. https://fas.org/publication/working-with-academics-primer/
[72] Brown, K. P. (2017). Water, water everywhere (or, seeing is believing): The visibility of water supply and the public will for conservation. *Nature and Culture*, *12*(3), 219–245. https://doi.org/10.3167/nc.2017.120302
[73] Carroll, J. M., Beck, J., Boyer, E. W., Dhanorkar, S., & Gupta, S. (2019). Empowering Community Water Data Stakeholders. *Interacting with Computers*, *31*(5), 492–506. https://doi.org/10.1093/iwcomp/iwz032
[74] Millar, E., Melles, S., & Rinner, C. (2023). Screens, streams, and flows: Implications of digital platforms for aquatic citizen science. *Geoforum*, *146*(103864). https://doi.org/10.1016/j.geoforum.2023.103864
[75] Ibid., 73.
[76] Ibid., 74.
[77] Ibid., 73.
[78] Pattinson, N. B., Taylor, J., Dickens, C. W., & Graham, P. M. (2023). *Digital Innovation in Citizen Science to Enhance Water Quality Monitoring in Developing Countries*. https://doi.org/10.5337/2024.201
[79] von Gönner, J., Gröning, J., Grescho, V., Neuer, L., Gottfried, B., Hänsch, V. G., Molsberger-Lange, E., Wilharm, E., Liess, M., & Bonn, A. (2024). Citizen science shows that small agricultural streams in Germany are in a poor ecological status. *Science of The Total Environment*, *922*, 171183. https://doi.org/10.1016/j.scitotenv.2024.171183
[80] Ibid., 74.
[81] Amador-Castro, F., González-López, M. E., Lopez-Gonzalez, G., Garcia-Gonzalez, A., Díaz-Torres, O., Carbajal-Espinosa, O., & Gradilla-Hernández, M. S. (2024). Internet of things and citizen science as alternative water quality monitoring approaches and the importance of effective water quality communication. *Journal of Environmental Management*, *352*, 119959. https://doi.org/10.1016/j.jenvman.2023.119959

4.6.1. United States

In 2018, Proceedings from the United States National Academy of Sciences (PNAS) presented a study on citizen groups and water quality management. The empirical assessment found that public participation in the water sector aligns with improved water supply.[82] Further, increased interest from the public about water quality data has stimulated the development of open data platforms and data visualization tools from government agencies.[83]

4.6.2. Germany

In Germany, ⅔ of the river network are described as small streams, and many fall outside of the guidelines of the WFD. Therefore, there is a lack of monitoring efforts and data on such streams. Citizen science is heralded as a mode of collecting data, fostering stewardship for local bodies of water, and activating local populations to conserve water sources. As in the United States, German citizen science efforts in the water sector are described as a complement to government-based monitoring. Country-wide, citizen science could help assist in creating a high-resolution monitoring network to protect drinking water sources and identify pollution events quickly.[84]

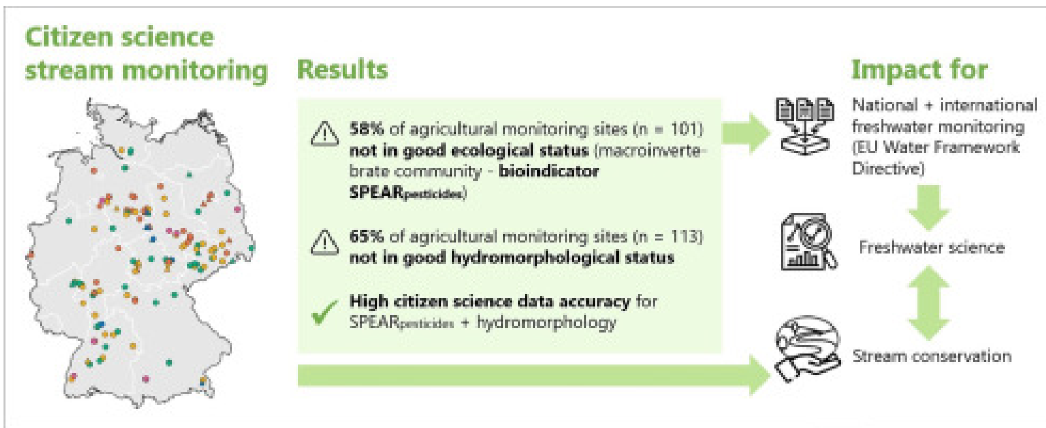

Figure 8. Citizen Science stream monitoring. CC. Source: von Gönner et al.[85]

[82] Grant, L., & Langpap, C. (2018). Private provision of public goods by environmental groups. *Proceedings of the National Academy of Sciences*, *116*(12), 5334–5340. https://doi.org/10.1073/pnas.1805336115
[83] Ibid., 73.
[84] Ibid., 79.
[85] Ibid., 79.

4.7. Stakeholder Map

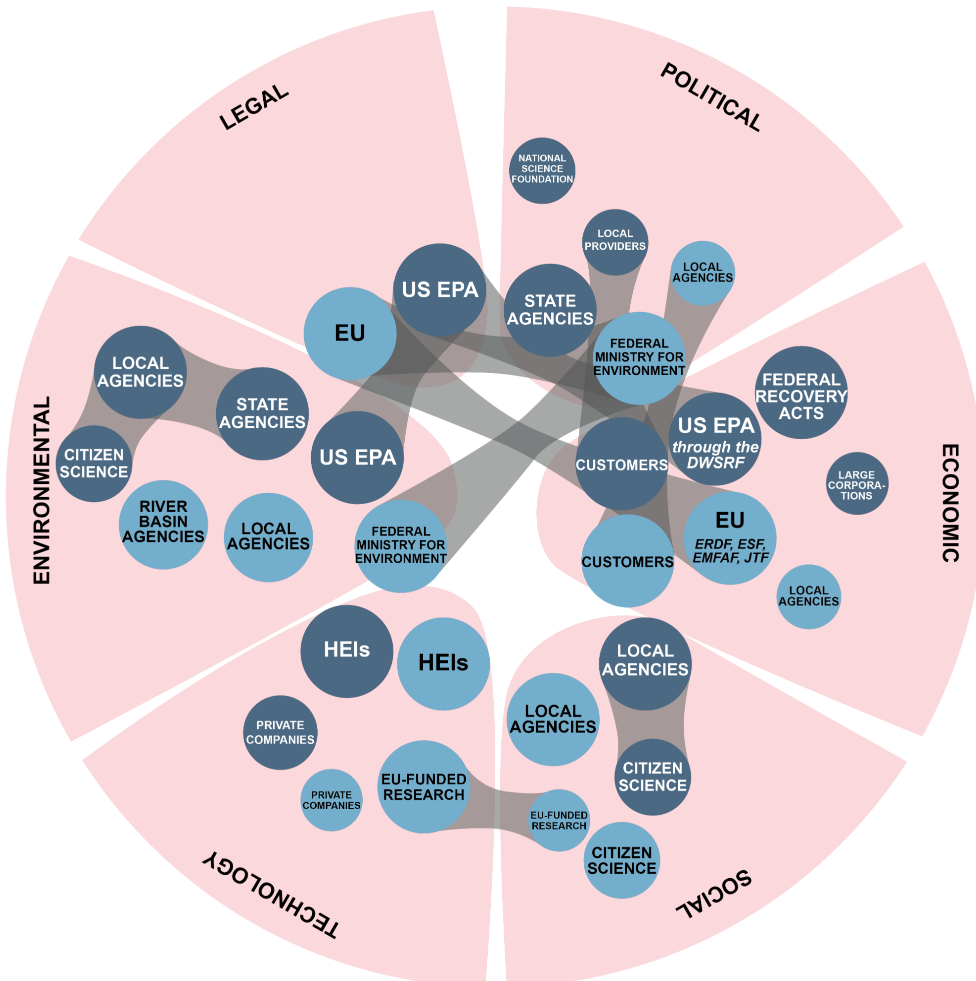

Figure 9. Stakeholder map for water sectors in Germany (light blue) and the United States (navy). Source: Chloe Kiernicki

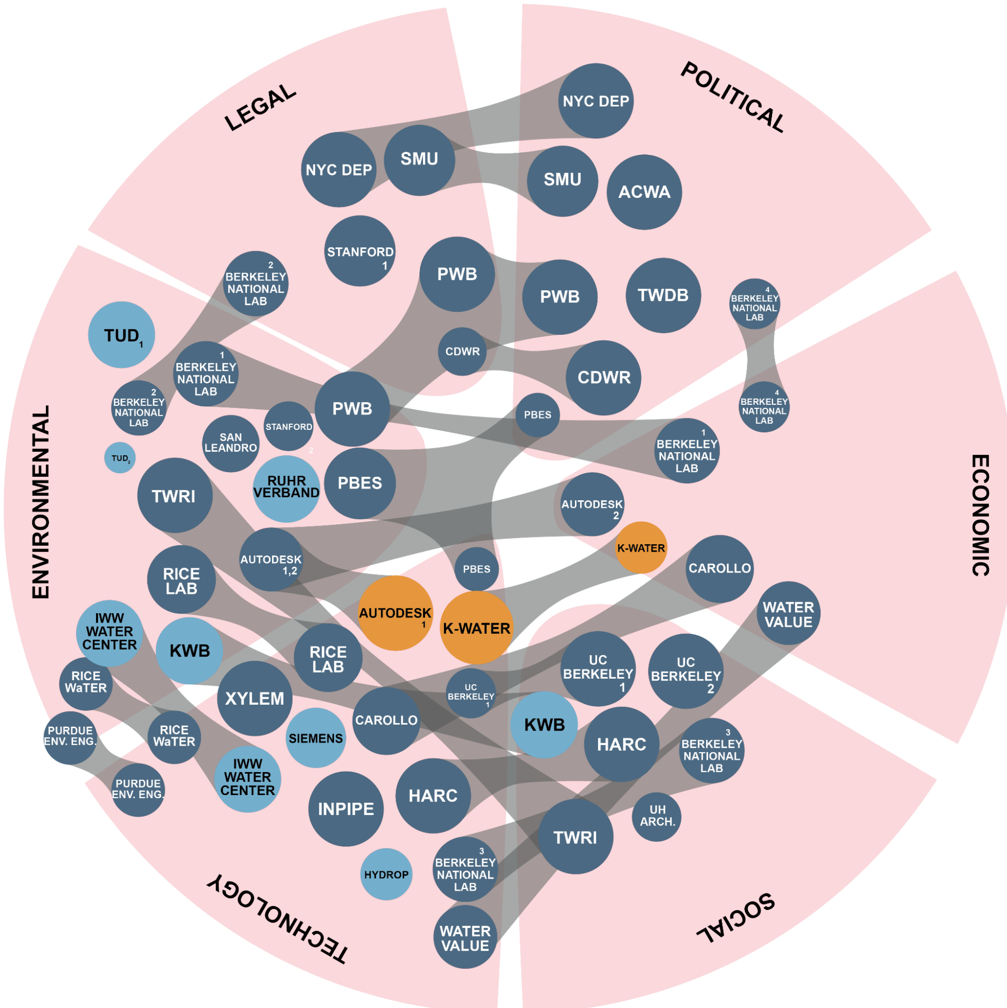

Figure 10. Stakeholder map of experts interviewed. Source: Chloe Kiernicki

5. Challenges Facing the Water Sector

Water supply in Germany and the United States faces several challenges. A PESTEL analysis is carried out to assess political, economic, social, technological, environmental, and legal factors influencing digitalization and decarbonization efforts.[86]

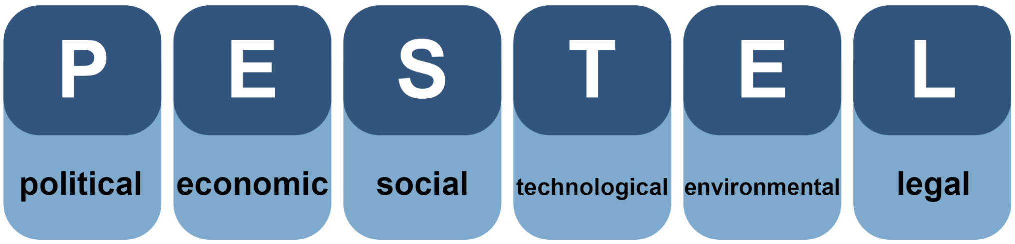

Figure 11. PESTEL analysis elements. Source: Authors

5.1. Political & Legal

Water resource protection through legal regulations is of central importance in both countries. In Germany, EU regulations play a key role in regulating water quality and water protection, while national regulations play a similar role in the United States. However, both face challenges in implementing these regulations due to insufficient resources and capacity to update infrastructure while complying with environmental standards.[87]

In Germany, regulation drives progress, but many citizens support increasing state debt to fund climate change and infrastructure efforts.[88] In the United States., regulations are often seen as restrictive, though infrastructure-related regulation has historically been positively viewed, despite being a low priority among voters.[89] Water systems in the United States are federalized, with states setting policies aligned with EPA standards. This results in varying priorities, with some states focusing on climate change, while others frame challenges in terms of population growth.[90]

5.2. Economic

Both countries face economic challenges in maintaining reliable water services, primarily due to a lack of capital for necessary infrastructure investments. For instance, in the United States an estimated $1 trillion is needed over 25 years to modernize water infrastructure.[91] Additionally, energy costs significantly burden water operations, as the entire water process, from extraction to distribution, is highly energy-intensive.

An aging workforce and a shortage of skilled workers hinders the future of the sector. In Germany, it is projected that by 2030, more than 30% of the workforce will retire, severely impacting the availability of qualified personnel

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[86] Xylem. (2021). *Smart water in water and wastewater management: Intelligent concepts for future-proof water management* (p. 4).
[87] National Geographic Education. (n.d.). How climate change impacts water access. National Geographic Society. https://education.nationalgeographic.org/resource/how-climate-change-impacts-water-access/
[88] Wehrmann, B. (2024). Most Germans favour greater investments in climate, infrastructure over keeping debt limit – survey. Clean Energy Wire. https://www.cleanenergywire.org/news/most-germans-favour-greater-investments-climate-infrastructure-over-keeping-debt-limit-surve
[89] Newport, F. (2021). *American public opinion and infrastructure legislation*. Gallup. https://news.gallup.com/opinion/polling-matters/351815/american-public-opinion-infrastructure-legislation.aspx
[90] Interview with anonymous researcher, July 2024
[91] American Society of Civil Engineers. (2021). *2021 Report card for America's infrastructure*. https://www.infrastructurereportcard.org

needed to operate and maintain the water infrastructure.[92] In the United States, workforce challenges arise from both retiring employees and insufficient new talent entering the field, exacerbated by a lack of interest from younger professionals and limited career awareness.[93]

5.3. Social

Digitalization can exacerbate existing social issues surrounding the accessibility of digital tools. The European Parliament has identified age, income, geography, education, health, ethnicity, and employment as factors impacting vulnerability toward digital transformation.[94] 80% of young adults aged 16 to 24 and 87% of students report having at least basic digital skills in Europe, compared to only 33% of adults aged 55 to 74. In rural areas, 48% of people report at least basic digital skills, while urban areas report 62% of the population possessing digital skills, according to a report on digitalization from the Council of Europe.[95] Further, those with the education and ability to affect the algorithms used and data gathered comprise a “small, relatively homogenous, community of experts” which varies from the “inherent diversity” of the communities served by public water infrastructure. This knowledge concentration can lead to accidental bias in data analysis and algorithm construction.[96]

As estimated by the US Water Alliance, more than two million Americans live without running water and basic indoor plumbing, and many more without sanitation. This disproportionately affects underserved communities such as communities of color, low income people in rural areas, immigrants, and tribal communities. Race and poverty is identified as the strongest obstacle to water access. African Americans and Latinx households are 2 times more likely to lack complete plumbing than white households while Native American households are 19 times more likely.[97] Historical discriminatory practices on funding allocation and water infrastructure have paved the current reality for these communities. Examples of discriminatory practices include: the California Bay-Delta region where communities with high levels of poverty, limited education, and low English proficiency are disproportionately exposed to toxic surface water.[98] Similarly, in Red Mesa, Arizona, home to the Navajo Nation, approximately 30% of residents lack access to running water and rely on groundwater contaminated by abandoned uranium mines. The Navajo Nation has faced longstanding violations of their water rights, further compounding these environmental injustices. Today, the cost of expanding water access now falls heavily on state and local governments through revenues on water rates, which is often not financially feasible for vulnerable communities. [99]

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[92] Bundesverband der Energie- und Wasserwirtschaft (BDEW). (n.d.). Fachkräftesicherung: Dossier. https://www.bdew.de/energie/dossier-fachkraeftesicherung/

[93] American Water Works Association (AWWA). (2024). *2024 State of the water industry: Executive summary*. https://www.awwa.org/wp-content/uploads/2024-SOTWI-Executive-Summary.pdf

[94] Mazzoni, L., Botta, M., Carlini, R., Filistrucchi, L., Menendez Gonzalez, N., & Parcu, P. L. (2024, March). Implications of the Digital Transformation on Different Social Groups. In *European Parliament* (PE 760.277). Policy Department for Citizens' Rights and Constitutional Affairs. https://www.europarl.europa.eu/RegData/etudes/STUD/2024/760277/IPOL_STU(2024)760277_EN.pdf

[95] Tavits, G., & Sargsyan, A. (2022). THE IMPACT OF DIGITALISATION AND IT DEVELOPMENTS ON SOCIAL RIGHTS AND SOCIAL COHESION. In *Council of Europe* (CCS(2022)4). European Committee for Social Cohesion. https://rm.coe.int/ccs-2022-4-draft-report-digitalisation-en/1680a91c5d

[96] Hoolohan, C., Amankwaa, G., Browne, A. L., Clear, A., Holstead, K., Machen, R., Michalec, O., & Ward, S. (2021). Resocializing digital water transformations: Outlining social science perspectives on the digital water journey. Wiley Interdisciplinary Reviews Water, 8(3). https://doi.org/10.1002/wat2.1512

[97] US Water Alliance (2023) Closing-the-Water-Access-Gap-in-the-United-States_DIGITAL.pdf

[98] Liévanos, Raoul S. (2016) Socio Spatial Dimensions of Water Injustice: The Distribution of Surface Water Toxic Releases in California'sBay-Delta
lievanos-2016-sociospatial-dimensions-of-water-injustice-the-distribution-of-surface-water-toxic-releases-in-california.pdf

[99] US Water Alliance (2023) Closing-the-Water-Access-Gap-in-the-United-States_DIGITAL.pdf

Issues rooted in bias, power, and control are being addressed at the community level in places such as Portland, Oregon, where the local government has appropriated funds to grant to communities bearing the consequences of historical injustices. Specifically, Portland's Community Watershed Stewardship Program aims to benefit both the natural and social environment of marginalized communities.[100] Other states are addressing water affordability at a greater scale such as California's Safe and Affordable Drinking Water Fund which will provide water infrastructure funding to vulnerable communities. Public understanding of water scarcity and resource management also remains low in both countries[101], making educational initiatives essential to foster a culture of conservation and responsible water usage.[102]

5.4. Technological

The water sector is also grappling with various technological challenges. Cybersecurity threats pose significant risks to water supply systems as they increasingly rely on digital tools for monitoring and management. Ensuring the security of these systems against cyberattacks is critical to protecting public health and maintaining operational integrity in both countries.[103] The modernization of water systems is further complicated by outdated infrastructure and insufficient funding, limiting water utilities' capacity in both the United States and Germany to implement new technologies that could enhance service delivery and operational efficiency.

5.5. Environmental

As a result of climate change, both countries are increasingly experiencing extreme weather events such as droughts, floods and water shortages.[104] In the United States, droughts primarily mainly affect the West, where regions such as California often have to contend with water shortages and rising energy costs for the water supply. However, water supply challenges extend beyond just drought-affected areas. Regions in the South, such as Texas and Florida, are increasingly vulnerable to flooding and severe storm events. These weather-related incidents disrupt water supply systems, complicating water management efforts and making it more difficult to ensure reliable access to clean water. In Germany, northeastern states such as Saxony-Anhalt (East-Germany) and Brandenburg (North-East of Germany) are also feeling the effects of the dry conditions.[105]

[100] Ibid., 45.
[101] Ibid., 9.
[102] Deutsches Institut für Wirtschaftsforschung. (2022). The impact of climate change on freshwater resources (DIW Discussion Paper No. 22-49). https://www.diw.de/documents/publikationen/73/diw_01.c.862060.de/dwr-22-49-1.pdf
[103] National Institute of Standards and Technology (NIST). (2023). *Securing water and wastewater utilities: Project description*. https://www.nccoe.nist.gov/sites/default/files/2023-06/securing-water-and-wastewater-utilities-project-description-final.pdf
[104] Jones, J. A. A. (2014). Water sustainability: a global perspective. Routledge.
[105] Deutscher Wetterdienst (DWD). (2022). Jahresbilanz 2022: Deutschlandwetter [Press release]. https://www.dwd.de/DE/presse/pressemitteilungen/DE/2022/20221230_deutschlandwetter_jahr2022_news.html

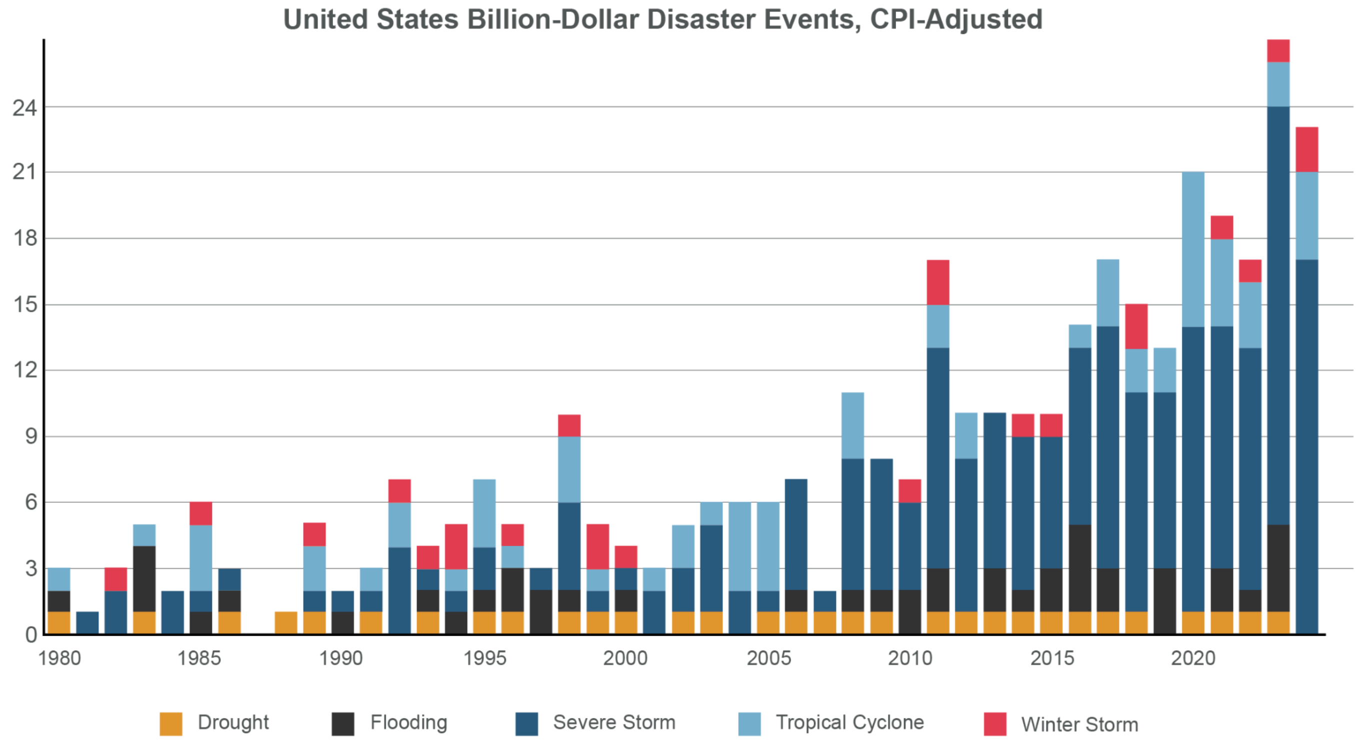

Figure 12. United States Billion-Dollar Disaster Events 1980-2024 (CPI-Adjusted). Adapted from: NOAA National Centers for Environmental Information[106]

Extreme weather events such as flooding also cause damage to the water infrastructure, which is expensive to repair. Rising energy costs, which are required for the extraction, treatment and distribution of water, are placing a financial burden on water suppliers and make an energy-efficient and climate-friendly water supply urgently necessary.[107]

[106] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

[107] Karlsruher Institut für Technologie. (2022). Groundwater level threatens to fall in Germany due to climate change. KIT. https://www.kit.edu/kit/english/pi_2022_018_groundwater-level-threatens-to-fall-in-germany-due-to-climate-change.php

6. Assessment of Energy Efficiency Technologies

6.1. Overview of Current Technologies

Drinking and wastewater systems consist of various components that can be grouped into physical, cyber, and regulatory elements.

- Physical elements include the water source (groundwater, surface water, or both), conveyance systems (pipes or canals), treatment plants, and storage facilities. These elements ensure proper water flow, treatment, and distribution, with monitoring systems tracking water quality and pressure. [108]
- Cyber elements involve automation and control through systems like Supervisory Control and Data Acquisition (SCADA), which link monitoring and control systems to a central display for optimization and automation. Additionally, electronic systems manage non-operational tasks such as billing and administration, while cybersecurity measures protect these systems.[109]
- Regulatory policies increasingly focus on water conservation, treatment, and reuse. Some countries and states are looking at policies that will tightly monitor, track and ban harmful contaminants like PFAs. The European Commission laid out a strategy to phase out most uses of PFAS compounds by 2030.[99] In addition to stricter regulations on water discharge and contaminant removal. Water reuse policies in San Francisco require on-site water treatment and reuse for non potable applications such as toilet flushing, clothes washing, and irrigation.[110]

6.1.1. Drinking Water Treatment Technology

Water treatment involves several steps: raw water extraction, screening, coagulation, flocculation, sedimentation, advanced treatment, filtration, and disinfection.[111] Energy usage varies based on the water source, facility age, treatment type, and system size. Drinking water facilities treat surface and groundwater to meet potable standards based on resource availability and quality in each location. Surface water generally requires more intensive treatment due to higher pollutant levels from human, agricultural, and industrial activities.[112]

The process begins with coagulation, followed by flocculation, sedimentation, filtration, and disinfection. Coagulation uses chemicals like salts to bind particles, while flocculation forms larger flocs. In sedimentation, these flocs settle, and filtration removes particles and contaminants. Finally, disinfection ensures residual disinfectant levels are safe but sufficient to protect water through distribution systems.[113]

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[108] United States Department of Homeland Security. (2015). Water and Wastewater Systems Sector-Specific Plan. https://www.cisa.gov/sites/default/files/publications/nipp-ssp-water-2015-508.pdf
[109] Ibid., 101
[110] San Francisco Water Power Sewer. Services of the San Francisco Public Utilities Comission https://www.sfpuc.gov/construction-contracts/design-guidelines-standards/onsite-water-reuse
[111] U.S. Centers for Disease and Control Prevention. (2024). How Water Treatment Works. https://www.cdc.gov/drinking-water/about/how-water-treatment-works.html
[112] Environmental Protection Agency. (2016) Energy Use Assessments at Water and Wastewater Systems Guide https://www.epa.gov/sites/default/files/2016-01/documents/energy-use-assessments-at-water-and-wastewater-systems-guide.pdf
[113] Ibid., 104.

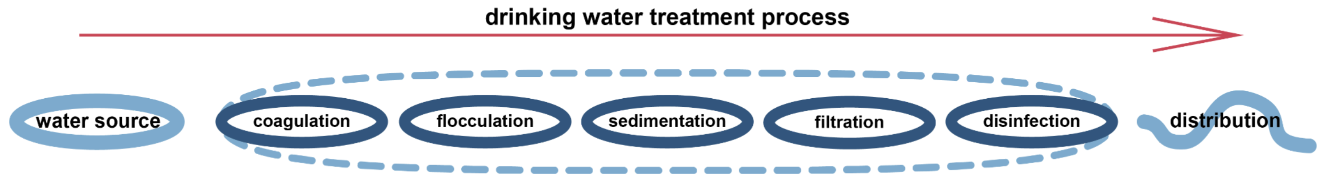

Figure 13. Drinking Water Treatment System. Adapted from: U.S. Centers for Disease Control and Prevention[114]

According to the EPA, drinking water and wastewater services consume 3% to 4% of national electricity, costing about $4 billion annually.[115] Energy costs represent 25% to 30% of utility operation and maintenance expenses and are the largest controllable cost. Reducing energy consumption in water systems is essential for cost savings and decarbonization.[116] In drinking water treatment, most energy is used for pumping raw and treated water, with energy consumption varying based on factors like equipment age, raw water source, and topography.[117] For instance, in systems using surface water, pumping can account for 85% of electricity usage.[118]

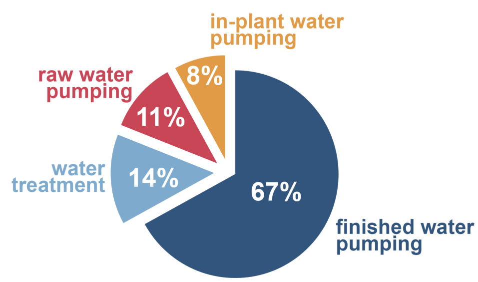

Figure 14. Electricity Use in a Typical Public Surface Water System. Adapted from: Hamilton et al.[119]

6.1.2. Wastewater Treatment Technology

Wastewater treatment requirements vary by local environmental conditions and government standards, primarily through stream and effluent standards. Stream standards limit specific pollutants in natural bodies of water, while effluent standards regulate the quality of treated wastewater discharged from treatment plants, focusing on factors like biochemical oxygen demand (BOD), suspended solids, acidity, and coliforms. BOD reflects the oxygen needed by microorganisms to break down organic matter in sewage—the more organic material, the higher the BOD.[120]

Wastewater treatment has three levels: primary, secondary, and tertiary. Primary treatment removes around 60% of suspended solids and 35% of BOD. Secondary treatment increases removal rates to over 85% for both.

[114] Ibid., 104.
[115] Environmental Protection Agency. Water and Energy Efficiency at Utilities and in the Home Make the Drops-to-Watts Connection. https://19january2021snapshot.epa.gov/sustainable-water-infrastructure/water-and-energy-efficiency-utilities-and-home_.html#:~:text=EPA%20estimates%203%20to%204,and%20wastewater%20services%20each%20year
[116] Environmental Protection Agency. (2024) Energy Efficiency for Water Utilities. https://www.epa.gov/sustainable-water-infrastructure/energy-efficiency-water-utilities
[117] Grzegorzek, M et al., (2023). Review of water treatment methods with a focus on energy consumption, International Communications in Heat and Mass Transfer, Volume 143, 2023, 106674, ISSN 0735-1933, https://doi.org/10.1016/j.icheatmasstransfer.2023.106674.
[118] Hamilton, G et al., (2009). Driving Energy Efficiency in the U.S. Water & Wastewater Industry by Focusing on Operating and Maintenance Cost Reductions. https://www.aceee.org/files/proceedings/2009/data/papers/6_83.pdf
[119] Ibid., 111.
[120] Ambulkar, A. and Nathanson, Jerry A. (2024). Wastewater Treatment. Encyclopedia Britannica. https://www.britannica.com/technology/wastewater-treatment/Sources-of-water-pollution

Tertiary treatment removes more than 99% of impurities, producing effluent of near-drinking-water quality. Tertiary treatment, often doubling the cost of secondary, is only used in special cases, such as when treatment standards require the removal of plant nutrients from the sewage. The final step before discharge is disinfection, which eliminates any remaining pathogens in the treated effluent.[121]

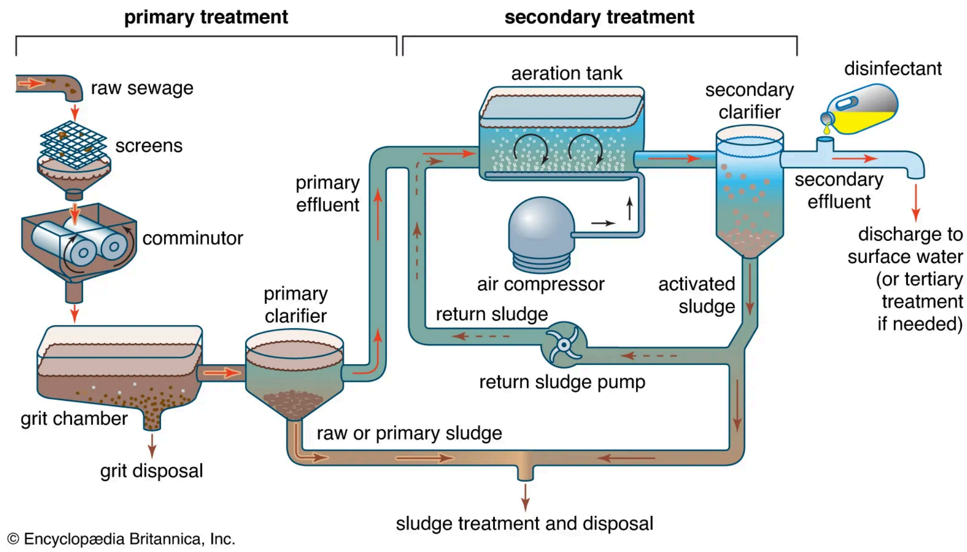

Figure 15. Wastewater Treatment System Processes. Source: Encyclopedia Britannica[122]

In wastewater treatment, energy-intensive processes like mechanical aerators, blowers, and diffusers are crucial for keeping solids suspended and supplying oxygen.[123] Aeration accounts for 50-60% of total electricity use, while sludge treatment uses 25-30% and pumping requires 15-20%. Optimizing aeration, sludge processing, and pumping can significantly reduce energy consumption in secondary treatment facilities.[124]

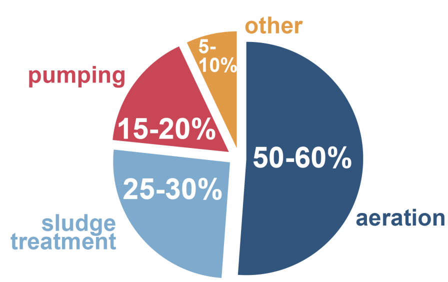

Figure 16. Total Electricity Use in a Typical Wastewater Treatment Plant with an Activated Sludge System. Adapted from: Hamilton et al.[125]

Local governments can cut costs by improving the efficiency of pumps and aeration equipment. A 10% reduction in energy use in the United States water system could save $400 million and reduce energy consumption by 5

[121] Ibid., 113.
[122] Ibid., 113.
[123] Environmental Protection Agency. (2013) Energy Efficiency in Water and Wastewater Facilities A Guide to Developing and Implementing Greenhouse Gas Reduction Programs. https://www.epa.gov/sites/default/files/2017-06/documents/wastewater-guide.pdf
[124] Ibid., 111.
[125] Ibid., 111.

billion kWh annually. Further savings can be achieved by shifting energy use to off-peak hours or using combined heat and power (CHP) systems to generate electricity and heat from biogas in wastewater plants.[126]

6.2. Water Utility Infrastructure

Water infrastructure consists of both artificial and natural systems ensuring water supply, treatment, and conservation. These include traditional gray infrastructure such as pipes, pumps, and centralized treatment facilities, as well as green infrastructure like rain gardens and on-site systems, such as septic tanks. Natural resources, including rivers, lakes, and aquifers, are also essential components. Generally water infrastructure refers to the entire network of drinking water, wastewater, stormwater, and green systems in a region.[127]

Over 75% of the United States population is served by centralized wastewater collection and treatment systems. Approximately 16,000 municipal wastewater treatment facilities are in operation nationwide.[128] Approximately 87% of the population relies on drinking water provided by a public utility. As urbanization drives development, decentralized systems that treat wastewater on-site, serve 18% of households and are becoming more common in newer developments.[129] Historically, the 1970s saw significant federal investment allocating over $60 billion to public wastewater treatment projects.[130]

In Germany, water management evolved differently in the East and West following World War II. The Federal Republic of Germany in the West maintained a decentralized structure, reinforced by constitutional protections for local governance. In contrast, the German Democratic Republic in the East adopted a centralized model with state-owned utilities managing water resources. After reunification, the centralized utilities in the East were decentralized, with management transferred to municipalities.[131] Today, more than 6,000 decentralized water companies manage Germany's water supply[132], which includes about 540,000 kilometers of drinking water pipelines and 590,000 kilometers of public sewage systems. The German water and wastewater industry invests approximately EUR 4 billion annually[133], with much of it directed toward renovating the pipe network.[134]

Across the United States and Western Europe, water infrastructure is aging and requires significant upgrades or replacements. Water utilities face challenges that were not anticipated when water infrastructure was built. In the US, there are still 6 to 10 million lead service lines in cities and towns across the country, many of which are in communities of color and low-income neighborhoods. Lead-related health crises like in Flint, Michigan, have

[126] Ibid., 113.
[127] Kane, J., & Tomer A. (2018). Renewing the Water Workforce: Improving water infrastructure and creating a pipeline of opportunity. https://www.brookings.edu/wp-content/uploads/2018/06/Brookings-Metro-Renewing-the-Water-Workforce-June-2018.pdf
[128] Ibid., 66.
[129] Environmental Protection Agency. Report to Congress On The Prevalence Throughout the U.S. of Low- and Moderate-Income Households Without Access to a Treatment Works and The Use by States of Assistance under Section 603(c)(12) of the Federal Water Pollution Control Act (2021). https://www3.epa.gov/npdes/pubs/primer.pdf
[130] Ibid., 116.
[131] Hecht, C. (2015). German municipalities take back control of water. https://www.tni.org/files/download/ourpublicwaterfuture-05_chapter_three.pdf
[132] Winterberg Group. (2023). German Emergency Water Supply Market. https://winterberg.group/de/german-emergency-water-supply-market-interesting-niche-for-private-equity/
[133] Birkert, J et al. (2018). German Water Partnership. Skill Development in the Water Sector Guidelines. https://germanwaterpartnership.de/wp-content/uploads/2018/11/06314020-Brosch%C3%BCre-Guidelines-Skill-Development-V4___Ansicht.pdf
[134] Underground Infrastructure. (2024). International report: Germany accelerates plans for energy development. https://undergroundinfrastructure.com/magazine/2024/august-2024-vol-79-no-8/features/international-report-germany-accelerates-plans-for-energy-development

increased public attention and a call to remove and replace lead service lines. However, fully removing lead service lines is a complex expensive process, costing between $5,000 and $7,500 per service line.[135]

Another stressor to United States water infrastructure is population growth which further strains water resources. Although per capita residential water demand decreased over the last two decades, many utilities still need to develop new water supplies or construct new storage facilities manage future demand. Many of the fastest growing communities are in water-scarce regions like the Southwest, elevating the need to identify and develop new supplies, which can be improved through managing demand through conservation, water recycling, and addressing non-revenue water loss (leaks).[136] Investing in water infrastructure is critical to protecting public health, economic growth, and sustainability. As of October 2024, the Bipartisan Infrastructure Law now commits over $50 billion through the EPA to improve drinking water, wastewater, and stormwater infrastructure marking the federal government's largest-ever investment in water in American history.[137]

6.2.1. Workforce Development

The United States water sector faces significant challenges in attracting and retaining skilled workers, especially younger and more diverse talent. With many utilities experiencing retirement waves, staffing vacancies can reach up to 50%. The sector's lack of public visibility and a decline in career and technical education (CTE) have further reduced interest in water-related careers.[138]

Water treatment operators increasingly rely on digital tools, yet training on these tools remains limited.[139] The workforce itself is aging, with 53% holding a high school diploma or less, and 24% projected to retire by 2025. Only 10.2% of water workers are under 24, compared to 12.5% nationally.[140]

Projections from the Bureau of Labor Statistics indicate that, while water employment is expected to grow 9.9% from 2016 to 2026, the sector will face significant workforce gaps due to retirements. Addressing this gap requires proactive workforce planning and collaboration between utilities, community partners, and policymakers.[141] EPA is addressing these challenges through initiatives like the Innovative Water Workforce Development Grant Program, which, in July 2024, allocated over $20 million to 13 organizations to expand career opportunities and raise awareness about water sector jobs.[142]

[135] Environmental Protection Agency. (2024). Water Infrastructure Investments. https://www.epa.gov/infrastructure/water-infrastructure-investments
[136] American Society of Civil Engineers. (2021). The Economic Benefits of Investing in Water Infrastructure How a Failure to Act Would Affect the US Economic Recovery. https://infrastructurereportcard.org/wp-content/uploads/2021/03/Failure-to-Act-Water-Wastewater-2020-Final.pdf
[137] Ibid., 128.
[138] Ibid., 126.
[139] Davis, C. (2022). Digital Competency in the Water Industry. Skills Required for Mission-Critical Jobs https://www.baywork.org/wp-content/uploads/2020/07/Digital-Competency-in-the-Water-Industry-Report-2022.pdf
[140] Ibid., 126.
[141] Ibid., 126.
[142] Environmental Protection Agency. (2024). Innovative Water Infrastructure Workforce Development Program. https://www.epa.gov/sustainable-water-infrastructure/innovative-water-infrastructure-workforce-development-program

6.3. Technology and Data Management

Historically, U.S. water systems managed assets using paper records, later transitioning to Geographic Information Systems (GIS), spreadsheets, or other digital methods. Due to the absence of standardized federal regulations, data collection methods vary widely across communities,[143] leading to data silos—isolated datasets that hinder cross-departmental access, real-time decision-making, and large-scale forecasting. These silos often result in duplicate entries and errors from manual input. Moreover, managing large volumes of data without proper systems exacerbates inefficiencies.[144]

Data integration addresses these challenges by centralizing information across departments, enabling a holistic view of water systems that supports resource optimization, process streamlining, and informed decision-making. Key steps in this process include:

- Data Profiling: Analyzing data structure, quality, and completeness to identify inconsistencies.
- Data Cleaning: Correcting errors, removing duplicates, and standardizing values.
- Data Transformation: Normalizing data formats for compatibility.
- Data Enrichment: Adding context through merging data or applying business rules.
- Data Validation: Ensuring accuracy and completeness for operational use.

These steps create a reliable data foundation, turning fragmented data into a strategic asset for comprehensive water management.[145]

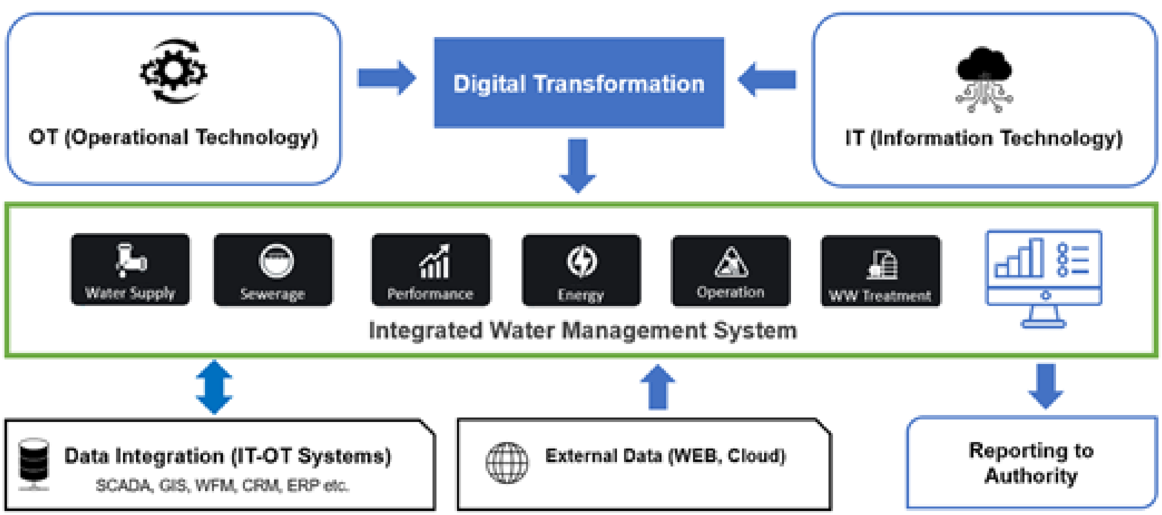

Figure 17. Integrated Water Management System. Open Access. Source: Bettin, A.[146].

[143] Government Technology. (2021). How Effective Data Management Impacts Water Infrastructure.
[144] Bettin, A. (2023). Digital transformation for the water industry: how a data-driven business intelligence platform can improve operations. Water Practice and Technology; 18 (7): 1599–1607. doi: https://doi.org/10.2166/wpt.2023.091
[145] Ibid., 137.
[146] Ibid., 137.

New regulations, such as the Lead and Copper Rule Revisions (LCRR), effective October 2024, mandate maintaining comprehensive lead service line inventories. This has pushed utilities to modernize data management systems for regulatory compliance and transparency.

Examples of successful modernization include:

- Kentucky's Sanitation District No. 1 (SD1): Upgraded to an enterprise content management system, automating workflows and reducing manual errors, resulting in significant time and cost savings.[147]
- Nashville Metro Water Services: Adopted automated water meters linked to a real-time analytics platform, reducing costs by $181,000 monthly and improving technician safety and efficiency.[148]

While some operators resist new technology fearing job disruption, demonstrating tangible benefits fosters smoother adoption and builds confidence. Utilities embracing efficient data management are better equipped to meet compliance requirements, respond to consumer inquiries, and secure federal funding for critical projects.[149]

6.3.1. Data Extraction and Value

Initiatives in the United States such as the Department of the Interior's Open Water Data Initiative, California's Open and Transparent Water Data Act of 2016, the California Water Data Consortium, and the Water Data Exchange Program exemplify the growing investment in expanding open water datasets and online platforms. These efforts enhance transparency, accountability, and public participation, benefiting the water industry by enabling data-driven decisions and fostering collaboration, especially for smaller utilities.[150]

Open data promotes transparency and builds trust with water service providers by giving customers and stakeholders insight into water usage, quality, and management. These initiatives empower communities and industry partners to engage in sustainable water management.[151] A notable example is Germany's Pegel-Online platform, which offers real-time water level data for over 7,300 kilometers of rivers and canals. This open-data tool aids decision-making and supports community-driven environmental responses.[152]

Challenges to open data can be categorized into four main areas: costs, risks, lack of motivating factors, and end-user barriers. Costs include capacity-related expenses for collecting, managing, and publishing data, as well as governance-related costs for developing policies to ensure data accuracy and compliance. For example, Germany's PortalU cost €750,000, while the US data.gov portal required $10 million annually. Risks arise from tensions between demands for transparency and the need for organizational control, deterring data providers due to concerns over public scrutiny, misinterpretation, and privacy issues related to personal identifiable information. Lack of motivating factors involves a limited understanding of the value of open data and insufficient incentives for researchers and organizations to publish their data. End-user barriers include

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147 Ibid., 136.

148 Xylem. (2024). Rise Above the Data Deluge. https://prod.xylem.com/siteassets/brand/xylem-vue/articles/data-deluge/xyl_vue_pga_wp_final.pdf

149 The Aspen Institute. (2017). Internet of Water: Sharing and Integrating Water Data for Sustainability. https://www.aspeninstitute.org/wp-content/uploads/2017/05/Internet-of-Water-Report-May-2017.pdf

150 Sugg, Z. (2022). Social barriers to open (water) data. Wiley Interdisciplinary Reviews: Water, 9(1), e1564. https://doi.org/10.1002/wat2.1564

151 Water Online. (2024). How Open Data Is Unlocking Innovation For The Water Industry. https://www.wateronline.com/doc/how-open-data-is-unlocking-innovation-for-the-water-industry-0001

152 Ooijen, C. et al., (2023). Data Europa EU Rethinking the impact of open data: Towards a European impact assessment for open data. https://data.europa.eu/sites/default/files/report/Rethinking%20impact%20of%20open%20data.pdf

difficulties in accessing data, low discoverability, and concerns about the quality of available datasets, making it challenging for users to find and utilize open data effectively.[153]

6.3.2. Cybersecurity

The integration of ICS and SCADA systems in the water and wastewater sector has introduced new vulnerabilities. These systems are essential for delivering safe drinking water and managing wastewater but are now potential targets for cybercriminals.[154]

In Germany, the water sector's growing reliance on digitalization poses significant challenges, including cyberattacks and physical threats such as floods. As part of the country's critical infrastructure, any disruptions can impact public safety and economic stability. To address these risks, the German Association for Gas and Water (DVGW) and the German Water Association (DWA) developed the Sector-Specific IT Security Standard for water and wastewater utilities. Recognized in 2017 by the German Federal Office for Information Security, this standard aligns with technological advancements and provides protective measures under Section 8a of the German IT Security Act.[155]

In the United States, there is widespread acknowledgment of the need for robust cybersecurity in the water sector. Despite this, many utilities hesitate to disclose cyberattacks, fearing damage to public trust and further attacks.[156] [157] The Department of Homeland Security (DHS) reported an increase in attacks on water utilities from 15 in 2014 to 25 in 2015, accounting for 8.5% of all cyber incidents.[158]

Cyber attacks can be prevented through improved cybersecurity practices. Key challenges include integrating traditional control systems with modern IT securely. While 79% of U.S. community water systems use SCADA, only 21% are optimized for remote management, highlighting potential vulnerabilities. Modern SCADA systems offer improved connectivity, but without a clear cybersecurity strategy, these advancements can expose critical weaknesses.[159]

The proliferation of Internet of Things (IoT) devices, such as smart water meters and remote monitoring tools, introduces additional risks. These devices, often lacking robust security, can serve as entry points for cyberattacks that compromise entire networks. Moreover, remote work setups present another layer of vulnerability, emphasizing the need for strict safeguards against breaches through personal devices.[160]

In the United States, the 2018 Water Infrastructure Act mandates utilities serving over 3,300 people to conduct a risk and resilience assessment, renewed every five years. The ISO 27001 standard provides a framework for an

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[153] Ibid., 146.
[154] Johnson, E. (2023). Water and Wastewater Sector Perspectives. Domestic Preparedness. https://www.domprep.com/articles/water-and-wastewater-sector-perspectives
[155] Ibid., 56.
[156] Cybersecurity and Infrastructure Security Agency. Water and Wastewater Systems. https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors/water-and-wastewater-sector
[157] Global Water Research Coalition. (2023). The Digital Water Utility of the Future. https://globalwaterresearchcoalition.net/wp-content/uploads/2023/05/Digital-Water-Utility-of-the-Future-Final.pdf
[158] Clark, M. et al., (2016). U.S. Department of Energy. Idaho National Laboratories. PROTECTING DRINKING WATER UTILITIES FROM CYBER THREATS. https://www.osti.gov/pages/servlets/purl/1372266
[159] Ibid., 153.
[160] Ibid., 153.

Information Security Management System (ISMS), covering technology, people, and processes to ensure comprehensive protection.[161]

7. Strategies

7.1. Energy Efficiency and the Reduction of Emissions

Water treatment and distribution are energy-intensive processes, contributing to about 2% of global greenhouse gas emissions, equivalent to the entire global shipping industry.[162] Efforts to decarbonize the water sector focus on energy efficiency, savings, and emission reduction. The German government's strategy prioritizes "Efficiency first," aiming for substantial and sustained energy consumption reductions across all sectors, including water supply, by promoting renewable energy and process optimization.[163]

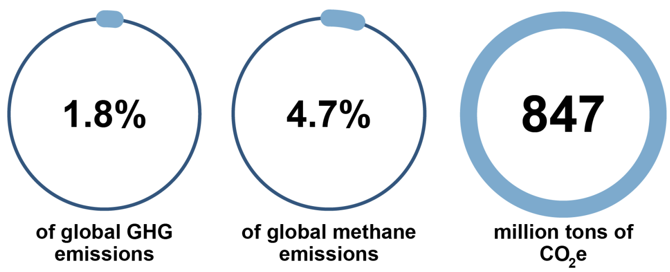

Figure 18. Water Infrastructure GHG Emissions. Created from: Global Water Intelligence[164]

As discussed in more detail in Chapter 5: Challenges Facing the Water Sector, water supply systems face many challenges. Energy efficiency can address challenges in the water sector by shifting resources from high energy bills to modernizing infrastructure, improving treatment technologies, and engaging the public. Water utilities can reduce emissions and save money by monitoring energy use and reducing water losses. By understanding the energy consumption of a drinking water system and taking advantage of energy efficiency opportunities, water systems can save money and energy.[165]

The energy costs of operating water systems, particularly pumps that transport water long distances or to higher elevations, are significant. Optimizing energy use is crucial for the long-term economic viability of these systems, reducing reliance on fossil fuels and lowering greenhouse gas emissions.[166]

[161] Ibid., 153.
[162] Decker, P. (2022). *How the water sector can lead the way to net-zero*. World Economic Forum. https://www.weforum.org/agenda/2022/03/water-sector-net-zero-decarbonization/
[163] Bundesministerium für Wirtschaft und Klimaschutz. (2019). *Energieeffizienzstrategie 2050*. https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/energieeffiezienzstrategie-2050.html
[164] *Mapping Water's Carbon Footprint*. Global Water Intelligence. (2023). https://kh.aquaenergyexpo.com/wp-content/uploads/2023/01/Mapping-Waters-Carbon-Footprint-Our-Net-Zero-Future-Hinges-on-Wastewater.pdf
[165] Interview with Klaer, K., August 2024, Ruhrverband
[166] Office of Water. (2013). *Strategies for saving energy at Public Water Systems*. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-04/documents/epa816f13004.pdf

The strategy also promotes the use of renewable energy in the water industry to replace fossil fuels.[167] However, implementation will vary depending on resources like staff expertise and funding, as well as priorities such as reducing water losses, cutting energy bills, or lowering carbon footprints. Achieving decarbonization requires continuous and consistent efforts toward sustainability.

7.1.1. Greenhouse Gas Accounting

The Greenhouse Gas (GHG) Protocol[168], established in 1998, serves as a global standard for measuring and managing greenhouse gas emissions. It provides a framework for identifying inefficiencies and energy-saving opportunities, helping organizations create detailed energy baselines.[169]

The protocol divides emissions into three categories, as shown in the diagram below.

- **Scope 1:** Direct Emissions from owned or controlled sources.
- **Scope 2:** Indirect Emissions from the generation of purchased electricity.
- **Scope 3:** Upstream and Downstream Value Chain Emissions.

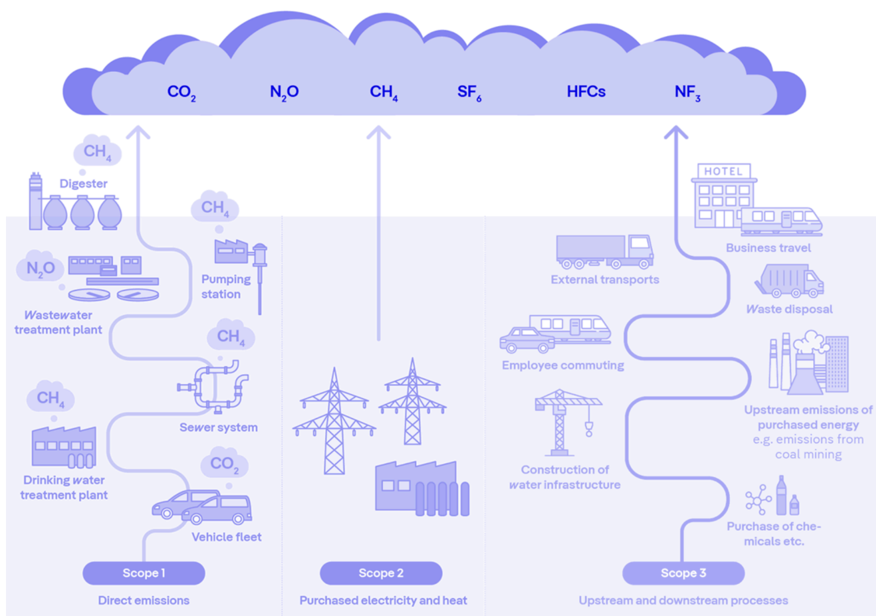

Figure 19. Three Scopes of the Greenhouse Gas Protocol for the water sector. Source: Kompetenzzentrum Wasser Berlin[170]

This classification helps water suppliers gain a comprehensive understanding of emission sources across the supply chain. By analyzing these areas, utilities can reduce emissions by adopting energy-efficient technologies,

167 Bundesministerium für Wirtschaft und Klimaschutz. (2019). *Energieeffizienzstrategie 2050*. https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/energieeffiezienzstrategie-2050.html
168 Greenhouse Gas Protocol. (2004). *A corporate accounting and reporting standard* (Revised Edition). World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI). https://ghgprotocol.org/corporate-standard
169 Kompetenzzentrum Wasser Berlin. (n.d.). *Scope3M: Scope 3 model for assessing the carbon footprint of water utilities*. Kompetenzzentrum Wasser Berlin. https://kompetenz-wasser.de/en/forschung/projekte/scope3m
170 Ibid., 163.

utilizing clean energy, and addressing emissions throughout the value chain, significantly lowering the carbon footprint of water supply over time.[171]

7.1.1.1. Direct Emissions: Scope 1

Scope 1 emissions are directly controlled by the water supplier, including emissions from combustion, mobile sources, and treatment processes. Reducing emissions can be achieved by integrating battery electric vehicles (EVs) into the fleet, which produce no CO_2 emissions when powered by self-generated electricity, lowering reliance on external energy sources. If a full switch to EVs is not feasible, improving vehicle efficiency through regular maintenance, optimized driving, and replacing inefficient vehicles can reduce emissions and operating costs.[172] Converting to renewable energy, such as solar or wind, can further lower Scope 1 emissions (see Chapter 7.1. Energy Efficiency and the Reduction of Emissions).

7.1.1.2. Indirect Emissions: Scope 2

Indirect emissions, Scope 2, result from purchased energy, such as electricity or heat, which are generated by upstream suppliers using fossil fuels.[173] To reduce these emissions, water utilities can purchase green energy or generate it independently, such as through solar or wind power (discussed in Chapter 7.1.2. Implementation of Renewable Energy). Optimizing system operations and reducing water losses (see Chapter 7.1.4.2 Water Losses) are effective measures to reduce energy consumption and extend system life.

7.1.1.3. Upstream or Downstream Emissions: Scope 3

Upstream and downstream activities, Scope 3, must also be considered when calculating the greenhouse gas footprint of water utilities. Scope 3 includes purchased goods, services, capital goods, waste and transport.[174] Scope 3 emissions often make up the largest part of an organization's carbon footprint but are more difficult to measure and influence. Similar to Scope 2, these emissions are not directly caused by the company, and they are challenging to affect as they are beyond direct control. However, water suppliers can take steps to reduce these emissions by selecting sustainable suppliers that use environmentally friendly materials and production methods and optimizing their own value chain. Using recycled materials, promoting the circular economy and improving waste management are also approaches to reducing Scope 3 emissions and improving the overall environmental footprint.

Several water utilities, including Berliner Wasserbetriebe, Gelsenwasser, and Hamburg Wasser, have produced a guide for Scope 3 accounting in the water industry.[175] This guide outlines how to track emissions from purchased goods and services (Scope 3.1), capital goods (Scope 3.2), and waste (Scope 3.5), integrating these processes into systems like SAP. By implementing these practices, water utilities can identify emissions sources and reduce them across the value chain.[176] Effective climate management also plays a key role in addressing

[171] Krause, G., & Salcher, M. (n.d.). Klimaneutralität in Verteilnetzen. KPMG. https://kpmg.com/de/de/home/themen/2022/01/klimaneutralitaet-in-verteilnetzen.html#:~:text=Eine%20erfolgreiche%20Energiewende%20beruht%20auf,Treibhausgasemissionen%20bilanzieren%20und%20reduzieren%20kann
[172] DVGW. (2024). *Treibhausgase in der Wasserversorgung – Bilanzierung, Management und Maßnahmen* (DVGW W 1006). Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH.
[173] Ibid., 163.
[174] Ibid., 164.
[175] Bolling, B., Saric, E., Beyer, E., Freitag, S., Jäntschi, A., & Lenz, J. (2024). *Bilanzierung von Scope 3-Emissionen*. Hanse Wasser. https://www.hansewasser.de/service/downloads/2024-07-04_scope3-bilanzierung_v1.pdf
[176] Ibid., 166.

Scope 3 emissions (see Chapter 7.2. Climate Management), raising awareness, and encouraging sustainable decisions throughout the supply chain.

7.1.2. Implementation of Renewable Energy

Additionally, incorporating renewable energies alongside emission-free technologies, such as battery-powered electric vehicles, will play a crucial role in long-term decarbonization efforts.[177] In addition, the use of renewable energy for self-sufficiency can improve the resilience of water infrastructure.[178] In times of energy shortages or rising prices, water utilities with their own energy sources are better equipped to maintain operations.[179]

In addition, the transition to renewable energy and electric vehicles offers water utilities the opportunity to take advantage of government subsidies and incentives for climate-friendly technologies. These strategic investments not only help to optimize operations, but also to meet long-term climate targets. The result is an environmentally and economically sustainable utility that makes a measurable contribution to the global energy transition. This enables environmentally friendly energy generation and reduces the need for purchased energy, directly contributing to a reduction in Scope 2 emissions.

7.1.3. Energy-Efficient Pump Systems

Pumping systems are energy-intensive, especially in moving water against gravity, and account for about 80% of the energy consumption in Germany's water sector, which used 8.35 TWh in 2020 (enough to power 2.4 million households annually).[180] (source). Pumps alone account for around 80% of the sector's energy consumption[181], making pump optimization a key strategy for reducing energy use and carbon emissions.[182]

To improve efficiency, water utilities can install modern, high-efficiency pumps and motors[183], replace outdated models, and ensure proper sizing based on hydraulic power requirements.[184] Traditional pumps often operate at a constant speed, but variable-speed systems adjust to actual demand, reducing energy waste, especially with load fluctuations.[185] Advanced control systems, incorporating real-time sensors and data analytics, can further optimize pump operations. By using data from pressure, flow, and vibration sensors, these systems can adjust operations to minimize energy losses. For instance, Chen et al. (2022) highlight how such systems can employ machine learning to predict pump conditions and initiate preventive maintenance, preventing unexpected failures.[186]

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[177] International Renewable Energy Agency. (2015). Water, energy, food nexus: Solutions for a sustainable world. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Water_Energy_Food_Nexus_2015.pdf

[178] Interview with Kreienborg, K., September 2024, DVGW

[179] Asian Development Bank. (2023). *Decarbonizing the water sector: A roadmap for action. https://www.adb.org/sites/default/files/institutional-document/874256/adotr2023bp-decarbonizing-water-sector.pdf*

[180] Statistisches Bundesamt. (2023). *Stromverbrauch der privaten Haushalte nach Haushaltsgrößenklassen*. Statistisches Bundesamt. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/private-haushalte/Tabellen/stromverbrauch-haushalte.html

[181] Bundesministerium für Wirtschaft und Klimaschutz. (2023). *Wasserversorgung vom Grunde auf energieeffizient*. Industrie Energieforschung. https://www.industrie-energieforschung.de/projekte/de/enerwag_energieeffiziente_wasserversorgung_wassergewinnung

[182] Interview with Gies, W., September 2024, DVGW

[183] Ibid., 161.

[184] DVGW. (2023). *Pumpensysteme in der Trinkwasserversorgung* (DVGW W 610). Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH.

[185] Plath, M., Wichmann, K., & Ludwig, G. (2010). *Handbuch Energieeffizienz/Energieeinsparung in der Wasserversorgung (DVGW-Information Wasser Nr. 77)*. DVGW Deutscher Verein des Gas- und Wasserfaches e.V.

[186] Chen, L., Wei, L., Wang, Y., Wang, J., & Li, W. (2022). *Monitoring and predictive maintenance of centrifugal pumps based on smart sensors*. Sensors, 22(6), 2106. https://doi.org/10.3390/s22062106

Regular condition monitoring and maintenance of pumps is also important. Efficiency losses occur gradually when pumps are not optimally maintained. Clogged filters, corroded parts or misaligned motors can all increase energy consumption.[187] Proactive maintenance strategies, such as the use of predictive maintenance using digital twins and machine learning (see chapter 7.3. Digitalization), allow such problems to be identified and rectified at an early stage.

7.1.4. Water Efficiency

Water efficiency reduces energy consumption by minimizing the amount of water needed for production, treatment, and distribution. This can be achieved through supply-side measures (e.g., leak detection and repair) and demand-side measures (e.g., public awareness programs).[188]

7.1.4.1. Leak Detection

In Germany, water loss from leaks is around 8%, while in the U.S., it averages 14-18%, equating to nearly 6 billion gallons daily.[189] Efficient leak monitoring and infrastructure modernization are key to reducing water loss.

In Germany, automated leak detection systems using sensors and GIS-based analysis, like Enigma3m, allow for quick identification and repair of leaks.[190] In cities such as Basel, this system enables repairs within 24 hours, saving water and labor.[191]

In the United States, the Bipartisan Infrastructure Law (BIL) aims to modernize the country's aging water infrastructure. Much of the water network dates from the 1970s and 1980s, and up to 18% of treated drinking water is lost through leaks. The BIL includes investments of more than $55 billion to replace old lead pipes and reduce water losses. It also invests in innovative leak detection technologies that use artificial intelligence and robotics to detect even the smallest leaks early.[192] Watchtower Robotics is developing a soft robotic system that moves through water pipes and detects minute pressure differences that indicate leaks. This technology has the potential to detect leaks before they cause pipes to burst, preventing massive water loss.[193]

These modern approaches to leak monitoring and infrastructure renewal show how both Germany and the United States are trying to meet the challenges of aging water systems through technological innovation and targeted investment.

7.1.4.2. Water Losses

Water losses caused by leaks, inefficient infrastructure, or inadequate maintenance lead to a loss of water and also to increased energy consumption for pumping and treating water. Every liter of water that is lost means that

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[187] CRI Group. (n.d.). *The ultimate guide to pump maintenance: Ensuring optimal performance and efficiency*. CRI Group. https://www.crigroups.com/blog-lists/the-ultimate-guide-to-pump-maintenance-ensuring-optimal-performance-and-efficiency/

[188] U.S. Environmental Protection Agency. (2013). Drinking water infrastructure needs survey and assessment: Fifth report to Congress (EPA 816-F-13-004). https://www.epa.gov/sites/default/files/2015-04/documents/epa816f13004.pdf

[189] McKinsey & Company. (2022). The US Bipartisan Infrastructure Law: Reinvesting in water. https://www.mckinsey.com/industries/public-sector/our-insights/the-us-bipartisan-infrastructure-law-reinvesting-in-water

[190] Fentker, C. (2023). *Automated leak detection*. Esders GmbH. https://www.esders.com/2020/05/automated-leak-detection/

[191] Hurst, N. (2019). *These technologies could put an end to leaky water mains*. Smithsonian Magazine. https://www.smithsonianmag.com/innovation/these-technologies-could-put-end-leaky-water-mains-180971177/

[192] Ibid., 186.

[193] Ibid., 188.

additional energy has to be used to replace the missing water and treat it for use. Reasons for water loss include leaks in fittings, pipes and burst pipes.

In the European Union, leaks contribute to about 24% of water consumption, resulting in increased energy usage and greenhouse gas emissions.[194] For instance, in Germany, the average percentage of non-revenue water (NRW), which encompasses water losses, is about 6%.[195] The main reasons for water loss include leaks in fittings, pipes, and burst pipes, which not only waste water but also lead to unnecessary energy expenditures for pumping and treatment. Therefore, addressing these issues through regular maintenance, investment in infrastructure, and the implementation of advanced leak detection technologies is crucial for enhancing both water and energy efficiency in water distribution systems.[196]

Water suppliers can take a variety of measures to effectively reduce water losses. Modern leak detection technologies, which use sensors and digital monitoring systems to analyze the condition of water pipes in real time, can help identify potential leaks at an early stage and avoid major losses.

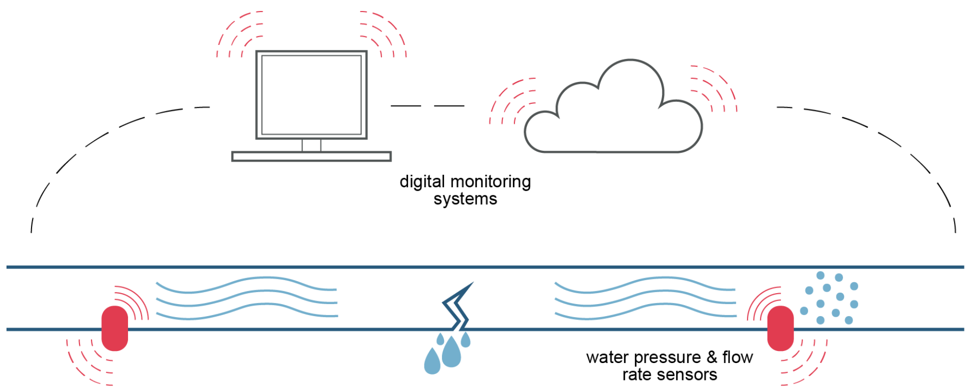

Figure 20. Schematic of a water leak detection system. Open Access. Created from: Ociepa-Kubicka, et al.[197]

In addition, regular maintenance and renewal of old pipes can help minimize the risk of leaks. Many water utilities already carry out comprehensive inspection programs to assess the condition of their infrastructure and plan targeted renovation or renewal measures. The integration of digital technologies into these processes has significantly enhanced the efficiency and effectiveness of maintenance strategies. For instance, GIS and remote sensing technologies allow utilities to map their entire water distribution network accurately, helping to identify vulnerable areas where leaks are more likely to occur based on historical data and real-time monitoring.[198]

Furthermore, data analytics and predictive modeling tools can analyze trends in water usage and system performance, enabling utilities to prioritize maintenance activities.[199] By leveraging Internet of Things (IoT) sensors placed within the network, utilities can continuously monitor factors such as pressure and flow rates,

[194] Ociepa-Kubicka, A., Deska, I., & Ociepa, E. (2024). Issues in Implementation of EU Regulations in Terms of Evaluation of Water Losses: Towards Energy Efficiency Optimization in Water Supply Systems. *Energies*, 17(3), 633. https://doi.org/10.3390/en17030633
[195] Ociepa-Kubicka, A., Deska, I., & Ociepa, E. (2023). Water losses. In *Water Losses: A Critical Review* (pp. 123-145). Springer. https://doi.org/10.1007/978-981-19-8677-2_5
[196] Ibid., 191.
[197] Ibid., 191.
[198] Senzia, A., et al. (2019). Application of remote sensing and GIS for water distribution networks. *Water, 11*(6), 1272. https://www.researchgate.net/publication/362126518_Water_Distribution_Network_A_Remote_Sensing_and_GIS_Approach
[199] Kapelan, Z., et al. (2016). Decision support for water distribution systems: Challenges and opportunities. *Water Science and Technology: Water Supply, 16*(2), 303-312. http://dx.doi.org/10.2166/wst.2009.538

providing immediate alerts when anomalies are detected. This proactive approach not only facilitates timely repairs but also allows for better resource allocation and planning for future infrastructure investments.[200] Overall, digitalization empowers water utilities to make informed decisions, reducing downtime and ensuring the sustainability of the water supply system.

7.2. Climate Management

Reducing greenhouse gas emissions through energy efficiency and renewable energy is vital for companies to contribute to climate protection. However, accounting alone is not enough to effectively counteract climate change. Comprehensive climate management is required in order to avoid and reduce emissions and thus ensure efficient and effective management of processes and targets within the company.[201] Climate management involves strategic and systematic engagement with all activities affecting the climate, including the reduction of CO_2, methane, and nitrous oxide emissions, which helps companies identify risks and opportunities arising from climate change, enhancing long-term sustainability.[202]

Energy efficiency practices, integrated into day-to-day management and long-term planning, significantly contribute to sustainability.[203] By monitoring and analyzing energy efficiency, water systems gain insights into infrastructure conditions, enabling early action to improve efficiency, reduce system load, and lower maintenance costs over time.[204]

An essential componentof climate management is the creation of a greenhouse gas inventory, as outlined in Chapter 7.1.1. This inventory categorizes emissions into three scopes: direct emissions (Scope 1), indirect emissions from purchased energy (Scope 2), and other indirect emissions from the value chain (Scope 3). Understanding these categories helps identify major emission sources and reduction opportunities.

Water utilities also assess climate change risks, such as altered precipitation patterns, extreme weather events, and rising temperatures. This risk assessment enables the development of adaptation strategies to enhance the resilience of the water supply, including building facilities to withstand extreme weather and improving water storage for better flood and drought management. Furthermore, the implementation of climate protection measures should be aligned with the company's sustainability goals. Key actions include optimizing energy consumption, switching to renewable energy sources, and reducing emissions from the supply chain.[205]

7.2.1. Smart Metering

Effective climate management requires comprehensive data management and monitoring. The use of sensors and digital technologies enables real-time monitoring of water flow, quality, and consumption, while the analysis of long-term data helps identify trends and predict future developments.

[200] García, S., et al. (2019). Smart water management: An overview of the IoT in water systems. *Water Resources Management, 33*(12), 3935-3952. https://www.mdpi.com/1424-8220/22/16/6225
[201] Ibid., 168.
[202] KliMaWirtschaft. (2024). *Klimamanagement in Unternehmen: Leitfaden für eine nachhaltige betriebliche Ausrichtung*. Bundesministerium für Wirtschaft und Klimaschutz (BMWK).
[203] U.S. Environmental Protection Agency. (n.d.). Energy efficiency for water utilities. https://www.epa.gov/sustainable-water-infrastructure/energy-efficiency-water-utilities
[204] Rogers, P., & Hall, A. W. (2003). Effective water governance. Global Water Partnership. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/07-effective-water-governance-2003-english.pdf
[205] Ibid., 199.

Smart metering is an increasingly important digital solution in water supply. Smart water meters record real-time consumption, providing valuable data for early detection of water losses, such as leaks. This not only reduces wasted water but also saves energy used for pumping, treating, and distributing water. The collected data allows the water supply system to adjust dynamically to actual demand, reducing unnecessary operations.

A key advantage of smart metering is the automatic and regular data collection, providing accurate monitoring of water usage. Consumers and providers can access real-time data, promoting transparency. Consumers can optimize their behavior, and providers can address issues early. With smart meters and apps, users can make informed decisions about their consumption based on a clear overview.[206] Smart metering also enables detailed analysis of consumption patterns, helping water suppliers optimize systems, identify weaknesses, and reduce consumption.[207] Remote reading of data through digital technologies replaces manual readings, saving time, costs, and minimizing errors.[208]

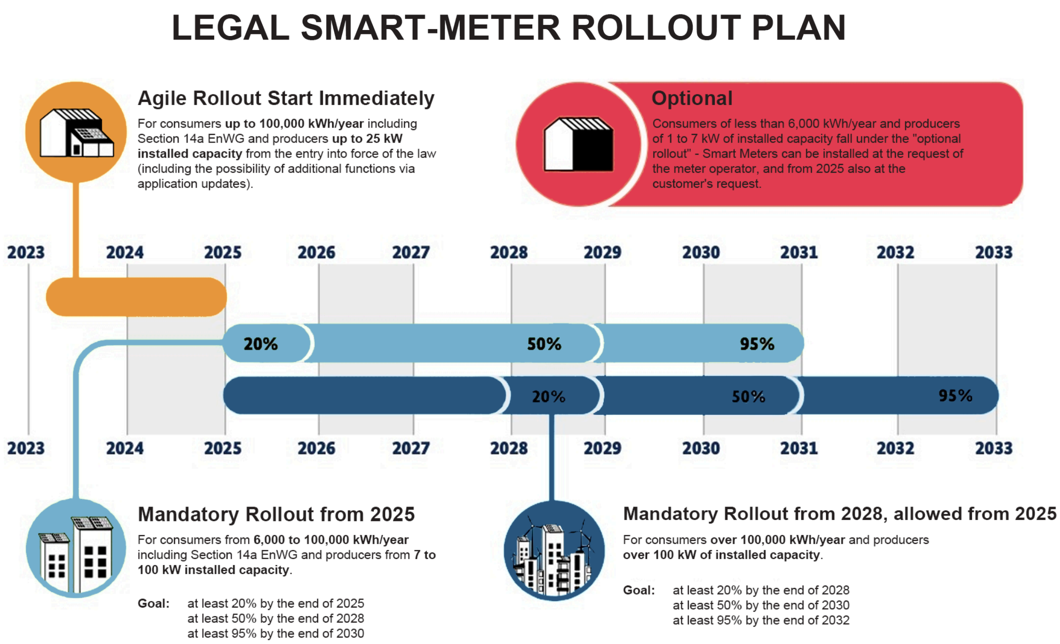

Figure 21. BMWK Smart Meter Rollout Plan. Translated from: BMWK[209]

The smart meter rollout, as described in the BMWK's roadmap shown in Figure 21 above, primarily targets the electricity sector, aiming to introduce smart meters to all electricity consumers to enhance efficiency and support the energy transition. The large-scale rollout is set to begin in 2024, modernizing the energy infrastructure and providing consumers with greater transparency on electricity consumption.[210]

[206] E.ON Group. (n.d.). *So Sorgen Smart Meter für Nachhaltigeren Wasserverbrauch.* E.On. https://www.eon.com/de/innovation/zukunft-der-energie/intelligente-netze/so-sorgen-smart-meter-fuer-nachhaltigeren-wasserverbrauch.html
[207] Interview with Luthy, Dr. R., June 2024, Stanford University
[208] Bundesministerium für Wirtschaft und Klimaschutz. (n.d.). *Smart meter: Intelligente Messsysteme für die energiewende*. BMWK. https://www.bmwk.de/Redaktion/DE/Textsammlungen/Energie/smart-meter.html
[209] Ibid., 204.
[210] Ibid., 205.

While this initiative focuses on the electricity sector, similar efforts are underway in the water sector with the introduction of smart water meters. These meters digitally record water consumption in real-time, improving efficiency, monitoring, and reducing water losses. Although not yet legally regulated like in the energy sector, smart metering is gaining traction globally. In the United States, cities like Austin are implementing smart water meters as part of long-term water conservation efforts, such as the My ATX Water project, which aims to replace 250,000 meters by 2025. In the United States, cities like Austin are implementing smart water meters as part of long-term water conservation efforts, such as the My ATX Water project, which aims to replace 250,000 meters by 2025.[211] The project is part of the City of Austin's long-term water conservation plan, Water Forward.[212]

7.2.2. Further Measures

In addition to energy efficiency and emission reduction measures described in Chapter 7.1., climate management can be enhanced through tailored strategies that fit each organization's needs. Implementing renewable energy storage systems ensures a reliable supply, while rainwater utilization can reduce consumption and conserve resources.[213] Companies should also assess material selection, focusing on low-carbon options to minimize emissions across the value chain.[214]

Investing in infrastructure, such as upgrading water pipes and installing waste recovery systems, improves efficiency and reduces waste, benefiting both ecology and economy.[215] Employee training and public awareness programs foster a culture of sustainability, engaging staff in climate management efforts.[216] Employee engagement and the establishment of sustainability teams within organizations are key to ensuring the long-term success of climate management initiatives. The specifics of these initiatives and available options will be discussed in Chapter 7.4. Awareness Raising.

Another key to successful climate management lies in the integration of digital solutions, which allow for more precise monitoring and control of processes. Digital solutions, like smart meters and data analytics, allow for more precise monitoring and control of processes. These technologies enable real-time data collection, optimizing operations and reducing emissions. Effective climate management combines adaptation to climate change impacts with proactive emission reductions, ensuring sustainable water supply and supporting global climate protection.[217]

7.3. Digitalization

Adaptation to the risks of climate change can be greatly facilitated by the use of digital tools. These tools allow for a more efficient design of workflows, improve the accuracy of predictions and facilitate targeted responses to emerging problems. As a result, not only will workflows be optimized, but the challenges in the water sector (see Chapter 5: Challenges in the Water Sector) will be better addressed. The targeted use of digital technologies also

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[211] City of Austin. (n.d.). *My ATX Water*. AustinTexas.gov. https://www.austintexas.gov/department/my-atx-water

[212] Devenyns, J. (2020). *Austin water begins piloting Smart water meters*. Austin Monitor. https://www.austintexas.gov/department/my-atx-water

[213] Stanford University. (2024). How water systems can accelerate renewable energy adoption. Stanford News. https://news.stanford.edu/stories/2024/09/how-water-systems-can-accelerate-renewable-energy-adoption

[214] Ibid., 199.

[215] Hellström, D., Jeppsson, U., & Kärrman, E. (2000). A framework for systems analysis of sustainable urban water management. Environmental Impact Assessment Review, 20(4), 311–321. https://doi.org/10.1016/S0195-9255(00)00043-3

[216] Gourbesville, P. (2016). Innovations in Water Management: Systems Efficiency and Energy Applications in the Water Sector. *Procedia Engineering*, 154, 11–18.

[217] Ibid., 168.

helps to save energy and emissions in specific areas. These tools help to identify problems early and implement targeted improvement and maintenance measures to increase process efficiency. The technologies mentioned above are described and analyzed in more detail below.

7.3.1. Digital Twin

Digital twin technology has become a pivotal innovation in the digital transformation journey, particularly relevant to sectors like water management that are increasingly focused on achieving climate resilience. A digital twin is a virtual representation of a physical system, continuously updated through data exchange between the physical and digital domains. In the water sector, a digital twin can represent infrastructure such as pipelines, treatment facilities, or entire water networks, all of which are monitored and managed through their digital counterparts.

In the context of climate resilience, digital twin technology enables water utilities to better adapt to extreme weather events, manage water resources more precisely, and predict system vulnerabilities. By simulating scenarios like floods or droughts, digital twins empower operators to make informed decisions that mitigate the impacts of climate change. Moreover, these virtual models offer predictive insights, helping to forecast potential system failures or resource shortages before they occur, thereby strengthening the resilience of critical water infrastructure.

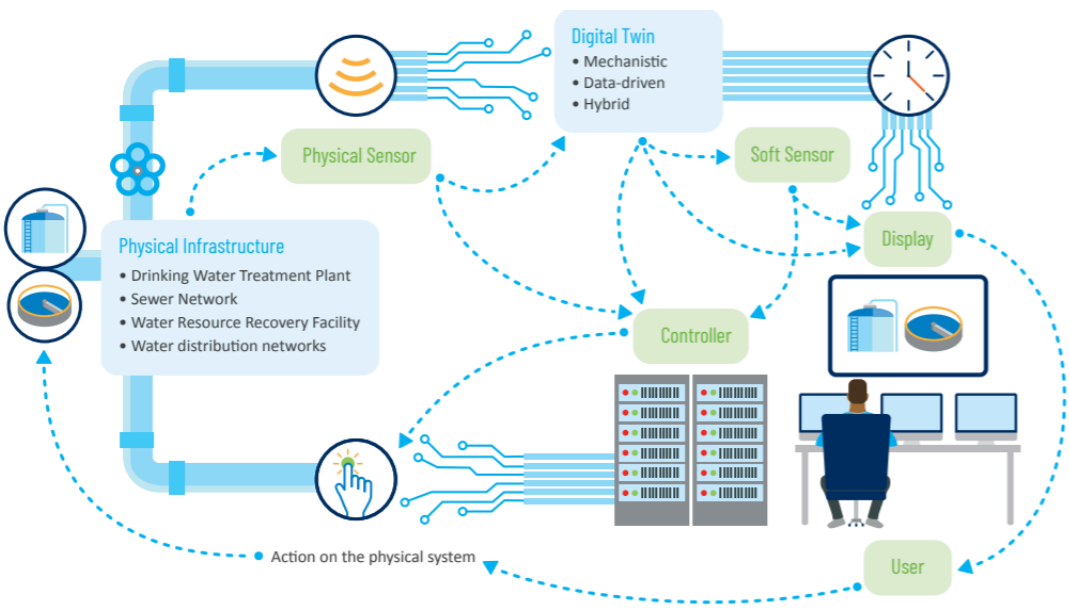

Figure 22. Schematic of a digital twin model in the water sector. Source: © IWA 2020[218]

Digital twin technology provides real-time monitoring, predictive maintenance, and long-term planning in water management, addressing climate change challenges[219] Digital twins represent the convergence of several key technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and cloud computing. The integration of these technologies allows for the collection and analysis of data from sensors

[218] *Digital Water: Operational Digital Twins in the Urban Water Sector*. International Water Association. (2021). https://iwa-network.org/publications/operational-digital-twins-in-the-urban-water-sector-case-studies/
[219] VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. Decision support systems, 145, 113524.

embedded in water infrastructure.[220] This real-time connection enables water managers to swiftly identify and address issues like leaks, pressure imbalances, or contamination, enhancing operational efficiency. For example, Portsmouth Water leverages predictive maintenance by analyzing real-time and historical data, reducing emergency repairs and ensuring reliable service.[221]

Digital twins support scenario planning, such as simulating population growth or extreme weather impacts, enabling informed decisions on system upgrades and investments to maintain resilience. However, challenges include limited data access[222], lack of standardization across utilities[223], high implementation costs, and the need for expertise in data science and hydraulic modeling[224].

The capacity to simulate different strategies and conditions is especially beneficial in the context of river and dam management, where the potential for flood management can be enhanced. Digital twins can be utilized to simulate water flow, predict flood risks, and optimize the operation of dams with the objective of achieving an equilibrium between water storage and release. The integration of real-time data on precipitation, river levels, and environmental conditions enables digital twins to facilitate proactive water resource management, reducing the risk of flooding during extreme weather events and ensuring an adequate water supply during droughts..[225]

In wastewater and drinking water treatment facilities, digital twins can facilitate the modulation of plants, thereby reducing the energy consumption associated with the transportation of water over extended distances. Furthermore, these virtual models facilitate the monitoring of water quality, enable the prediction of potential equipment malfunctions, and facilitate the optimization of treatment processes. By simulating the behavior of different treatment methods and adjusting operations in real time based on incoming water quality data, digital twins can enhance efficiency and effectiveness..[226]

For water utilities, digital twins provide a comprehensive representation of the entire water distribution network, enabling real-time monitoring of water flow, pressure, and quality across the system. Such models facilitate the early detection of leaks and inefficiencies, thereby reducing water loss and minimizing disruptions to service.[227] Furthermore, digital twins can simulate the impact of diverse operational strategies, infrastructure enhancements, and emergency responses, thereby facilitating more prudent decision-making and long-term planning.[228] This is especially advantageous in the context of climate resilience, where digital twins can assist utilities in preparing for and mitigating the impacts of extreme weather events, such as storms and droughts, on water supply and infrastructure. Large-scale initiatives like Destination Earth explore global applications of digital twins for managing natural resources.[229]

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[220] Ibid., 215.

[221] Portsmouth Water UK. (n.d.). https://www.portsmouthwater.co.uk/wp-content/uploads/2022/08/PW-Vision-Brochure-Interactive.v2.pdf&ved=2ahUKEwi3oN29zaKJAxWw5wIHHVLPIAgQFnoECBQQAQ&usg=AOvVaw3XO-NTnVhroMKjuzC6m_s9

[222] Conejos Fuertes, P., Martínez Alzamora, F., Hervás Carot, M., & Alonso Campos, J. C. (2020). Building and exploiting a Digital Twin for the management of drinking water distribution networks. Urban Water Journal, 17(8), 704–713.

[223] Ibid., 59.

[224] Maksoud, N., & Mohamed, M. M. (2023). Digital twins applications in the water sector. In AIP Conference Proceedings (Vol. 2928, No. 1). AIP Publishing.

[225] Interview with Kim, J., July 2024, K-Water

[226] Interview with May, H., July 2024, Siemens

[227] Karmous-Edwards, G., Conejos, P., Mahinthakumar, K., Braman, S., Vicat-Blanc, P., & Barba, J. (2019). Foundations for building a digital twin for water utilities. Smart Water Report–Navigating the smart water journey: From Leadership To Results, Water Online, SWAN, 9-20.

[228] Interview with Fiske, P., June 2024, Berkeley National Lab

[229] DestinE. (2024). European Union. https://destination-earth.eu/

7.3.2. Machine Learning

Machine learning (ML), a subset of artificial intelligence, enables systems to learn from data, identify patterns, and predict outcomes without explicit programming.[230] In water management, ML is used for predicting water demand, optimizing distribution, detecting anomalies, and forecasting environmental events, making it valuable in dynamic conditions.[231]

ML operates through three primary types: supervised learning (using labeled data for tasks like forecasting demand), unsupervised learning (identifying patterns in unlabeled data, such as detecting irregular water use), and reinforcement learning (optimizing dynamic systems through feedback, useful for real-time water distribution).

The effectiveness of ML depends on data quality and appropriate algorithm selection. Water utilities leverage sensor data, historical records, and climate models to train accurate ML models that enhance predictive insights and decision-making.[232] For example, ML improves weather forecasts by refining traditional models like numerical weather prediction (NWP). Using tools like XGBoost, ML enhances hydrological quantitative precipitation forecasts (HQPFs), providing localized flood risk assessments and improving infrastructure protection In a sector that is increasingly focused on resilience and decarbonization, using ML to improve extreme weather forecasting is a critical step forward in preparing for the unpredictable effects of climate change.[233] In the context of climate resilience, ML improves flood forecasting by continuously learning from large datasets, such as historical flood events, meteorological patterns, and environmental conditions, to predict flood risks with greater accuracy.[234] As climate change increases the variability of extreme rainfall and flood events, ML-based models adapt to these changes, enabling water managers to anticipate and mitigate the impacts of both short-term flash floods and long-term seasonal flood risks.

One of the key contributions of ML to climate resilience is its ability to enhance flood forecast accuracy, particularly in regions with rapidly changing weather. By leveraging real-time data, ML models can identify emerging flood risks and issue early warnings, helping to mitigate damage and protect communities. Additionally, hybrid ML approaches reduce uncertainty in flood forecasts, enabling water utilities to make more informed decisions on infrastructure investments, ensuring flood defenses are strengthened and water systems remain resilient against increasing flood risks. ML is also applied to detect water events, such as pipe leaks, critical to maintaining the efficiency and sustainability of water distribution systems. Integrated with smart water meters (SWMs), ML analyzes real-time data on flow, pressure, and consumption to identify anomalies such as leaks, breaks, or irregular usage, enabling prompt action and reducing energy consumption and carbon emissions.[235]

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[230] Rebala, G., Ravi, A., Churiwala, S., Rebala, G., Ravi, A., & Churiwala, S. (2019). Machine learning definition and basics. An introduction to machine learning, 1-17. https://doi.org/10.1007/978-3-030-15729-6

[231] Sarmas, E., Spiliotis, E., Marinakis, V., Tzanes, G., Kaldellis, J. K., & Doukas, H. (2022). ML-based energy management of water pumping systems for the application of peak shaving in small-scale islands. *Sustainable Cities and Society*, *82*(103873), 1–16. https://doi.org/10.1016/j.scs.2022.103873

[232] Ibid., 227.

[233] Ko, C. M., Jeong, Y. Y., Lee, Y. M., & Kim, B. S. (2020). The development of a quantitative precipitation forecast correction technique based on machine learning for hydrological applications. Atmosphere, 11(1), 111.

[234] Hadi, F. A., Mohd Sidek, L., Ahmed Salih, G. H., Basri, H., Sammen, S. Sh., Mohd Dom, N., Muhamad Ali, Z., & Najah Ahmed, A. (2024). Machine learning techniques for flood forecasting. *Journal of Hydroinformatics*, *26*(4), 779–799. https://doi.org/10.2166/hydro.2024.208

[235] Ibid., 230.

Clustering techniques are among the most widely used ML approaches for water event detection. These methods group similar data points together, allowing the model to identify outliers that deviate from typical usage patterns. For example, an unexpected spike in water consumption during off-peak hours could signal a leak or malfunction. Other techniques, such as hybrid methods that combine multiple algorithms, are also used to improve detection accuracy.

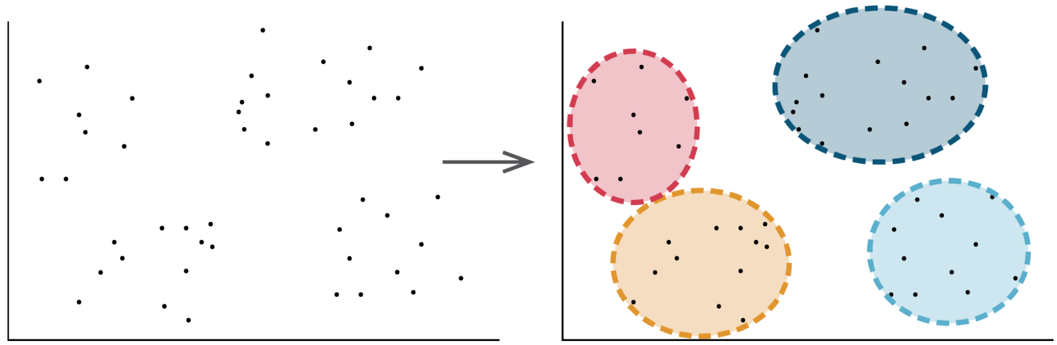

Figure 23. Schematic diagram of data clustering techniques employed in Machine Learning. Created from: Rebala et al.[236]

A key benefit of using ML for detecting water events is the ability to provide real-time alerts. When a leak or anomaly is detected, the system immediately notifies utility operators or consumers, enabling prompt repairs and reducing water loss. This proactive approach helps prevent major damage and minimizes service interruptions, leading to significant cost savings. ML-based detection systems are especially effective in identifying hidden leaks that may persist without surface signs. These small, continuous leaks can cause substantial water loss, but ML algorithms can flag even minor anomalies for investigation.[237]

The broader application of ML in the water sector extends to predictive maintenance. This proactive approach aims to anticipate and prevent future failures before they occur, significantly improving long-term system resilience and sustainability.[238] Unlike event detection, which focuses on responding to anomalies in real time, predictive maintenance uses historical data and advanced algorithms to predict the likelihood of future failures, allowing for more strategic, planned interventions.

Predictive maintenance uses data from SWMs, as well as historical records of pipe failures, environmental conditions, and system performance metrics. ML algorithms analyze these data sets to identify patterns and trends that indicate when components, such as pipes or pumps, are likely to fail. By predicting the time to failure, utilities can schedule maintenance activities in advance, reducing the need for emergency repairs and minimizing unplanned downtime.[239]

This data-driven approach not only reduces the incidence of unexpected leaks, but also optimizes the allocation of resources. Maintenance teams can prioritize their efforts on high-risk assets, extending the overall life of the infrastructure and reducing operating costs. This approach also plays a critical role in the sector's

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[236] Ibid., 226.
[237] Rahim, M. S., Nguyen, K. A., Stewart, R. A., Giurco, D., & Blumenstein, M. (2020). Machine learning and data analytic techniques in digital water metering: A review. Water, 12(1), 294.
[238] Kulik, J. (2024). *How to implement predictive maintenance using machine learning?*. NeuroSYS. https://neurosys.com/blog/predictive-maintenance-using-machine-learning
[239] Ibid., 234.

decarbonization efforts, as fewer emergency interventions and more efficient maintenance schedules reduce the energy consumption associated with reactive repairs.

The predictive capabilities of ML in water networks are further enhanced through cross-validation and model tuning. Unlike traditional methods that rely on fixed maintenance schedules, ML-based systems continuously learn and adjust based on new data inputs, improving the accuracy of predictions over time. This adaptability ensures that models remain relevant and effective as system conditions evolve.[240]

The implementation of ML in the water sector presents several challenges that require careful consideration. One of the primary issues is the quality and availability of data. Incomplete or biased data can lead to distorted outcomes, especially in regions with inconsistent data collection practices, which can result in unreliable predictions and unequal access to water resources. Ensuring fairness and equity in ML-driven decision-making processes is crucial, particularly when managing essential resources like water.

Another challenge is the lack of transparency and interpretability in ML models. These models are often described as "black boxes," which makes it difficult for human stakeholders to understand their internal workings unless those stakeholders take a significant role in programming the software.[241] In the context of the water sector, where decision-making involves multiple stakeholders, the inability to explain how ML models arrive at specific conclusions can impede trust and adoption. Transparent and interpretable models are essential to foster trust, accountability, and informed decision-making across all levels of management.

Furthermore, scalability also poses a significant obstacle. While ML models may perform well in localized contexts, scaling these solutions to larger or more complex water networks across diverse geographical regions can be technically demanding. The heterogeneity of water infrastructure, climate conditions, and socio-economic factors complicates the deployment of universal ML solutions. Additionally, integrating ML with existing water utility systems often requires substantial investments in new technologies, infrastructure upgrades, and personnel training.[242]

7.3.3. Digital Data Instrumentation

Digital instruments are essential for data collection in both wastewater management and drinking water systems, enabling real-time monitoring, predictive maintenance, and system optimization. IoT sensors play a pivotal role by continuously collecting data on parameters such as water flow, pressure, and quality, transmitting it to cloud-based platforms for analysis.[243] For instance, Smart Water Meters (SWM) utilize the Hall Effect principle to measure water flow and provide real-time data visualization through mobile apps, empowering users to monitor consumption and set limits to reduce waste. Cloud-based data storage facilitates predictive actions, enabling seasonal water usage analysis to optimize distribution and improve efficiency.[244]

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[240] Velasco, A. R., Muñuzuri, J., Onieva, L., & Palero, M. R. (2021). Trends and applications of machine learning in water supply networks management. Journal of Industrial Engineering and Management, 14(1), 45-54.
[241] Interview with Christine Selker, City of Portland Bureau of Environmental Services, July 2024
[242] Upcoretech. (2024l). Navigating the Evolving Landscape: Top 10 Machine Learning Challenges in 2024. https://www.upcoretech.com/insights/machine-learning-challenges/
[243] Webbylab. (n.d.). Smart water management using IoT: Benefits & solutions. https://webbylab.com/blog/smart-water-management-using-iot-benefits-solutions/
[244] Rajurkar, C., Prabaharan, S. R. S., & Muthulakshmi, S. (2017). IoT based water management. In 2017 International Conference on Nextgen Electronic Technologies: Silicon to Software (ICNETS2) (pp. 255-259). IEEE.

Data collection begins with the deployment of sensors monitoring key parameters like flow rates, pressure, and water quality (e.g., pH and turbidity). These sensors transmit data using communication technologies such as GSM, Wi-Fi, LoRa, and satellite communication, depending on network scale and environmental needs. Urban areas often rely on GSM and Wi-Fi, while remote regions may use LoRa or satellite systems for long-range transmission. Each technology has limitations: GSM and Wi-Fi require infrastructure and power, whereas LoRa and satellites have lower bandwidth.

Sensor reliability is another challenge, as environmental conditions can degrade sensors, causing data inaccuracies. Regular calibration is needed, especially in harsh environments. Additionally, IoT systems often lack advanced processing capabilities, leading to an overwhelming influx of unprocessed data, complicating real-time analysis and actionable insights.

Moreover, power consumption presents a significant challenge in two ways. First, systems deployed in remote locations face difficulties due to limited access to power. Second, the reliance of IoT sensors on wireless communication technologies creates maintenance challenges[245], as frequent battery recharging or replacement increases operational costs. Although low-power alternatives have been explored, their limited range and data transmission rates remain significant limitations for certain applications.[246]

Subsequently, data must be securely stored for long-term analysis and compliance. Cloud-based storage solutions are widely used due to their scalability, but they have environmental implications. Data centers consume significant energy, contributing to carbon emissions. Mitigating this impact requires energy-efficient hardware, compression algorithms, and optimized storage strategies.[247]

Finally, long-distance data transmission poses challenges. Technologies like GSM, Wi-Fi, and ZigBee have range limitations, requiring higher power consumption or additional infrastructure. Satellite communication, though effective, is costly, and delays in transmission can hinder timely interventions, especially during critical events such as water contamination.[248]

7.3.4. Data and Methods for Long-term Resilience

Data is a critical tool for building climate resilience in the water sector, enabling informed decision-making to protect infrastructure and ecosystems. By leveraging real-time monitoring, satellite imagery, historical climate data, and advanced analytics, utilities can identify vulnerabilities, optimize resource allocation, and implement predictive maintenance strategies. Integrated data from multiple sources also enhances climate change modeling, supporting long-term planning and adaptive measures to mitigate risks and ensure sustainable water management.[249]

[245] Interview with Zhi Zhou, Purdue University, June 2024

[246] Zulkifli, C. Z., Garfan, S., Talal, M., Alamoodi, A. H., Alamleh, A., Ahmaro, I. Y., ... & Chiang, H. H. (2022). IoT-based water monitoring systems: a systematic review. Water, 14(22), 3621.

[247] Mark, J., & Bommu, R. (2024). Tackling Environmental Concerns: Mitigating the Carbon Footprint of Data Transmission in Cloud Computing. Unique Endeavor in Business & Social Sciences, 3(1), 99-112.

[248] Ibid., 242.

[249] Reynolds, S., Glazer, Y. R., Oikonomou, K., Homer, J. S., & Webber, M. (2024). A Review of Resilience and Long-Term Planning in Power and Water Systems in the United States.

7.3.5. Reducing Uncertainty with Digital Solutions

As part of a broader strategy of leveraging data for long-term resilience, digital solutions afford utilities the capacity to predict, manage, and mitigate risks in a more effective manner. The integration of digital tools enables utilities to gain a more comprehensive and up-to-date understanding of their systems, thereby facilitating a more rapid response to changes and disruptions, which are becoming increasingly frequent due to climate change.

IoT sensors are of great consequence in this process. Such devices facilitate the continuous monitoring of water systems, thereby generating data on critical factors such as water flow, pressure, and quality. The data is made available to utilities without delay, thus reducing the uncertainty that arises from unanticipated system failures or environmental changes. This capability is crucial for ensuring the long-term resilience of water infrastructure, as it allows for timely maintenance and a rapid response to disruptions.

Furthermore, digital solutions facilitate enhanced collaboration between sectors, notably between the interdependent water and power sectors. For example, water utilities may utilize digital tools to facilitate coordination with power utilities, thereby ensuring the continued operational status of critical water infrastructure during power outages. Such collaboration is made possible by the sharing of data, which allows both sectors to anticipate and respond to disruptions that might affect the other. This integrated approach to managing interdependencies is of paramount importance for the development of long-term resilience across essential infrastructure systems.

In addition to enhancing operational efficacy and reducing uncertainty, digital solutions assist in reducing the costs associated with system failures and emergency responses. By optimizing system performance and implementing predictive maintenance, utilities can circumvent costly repairs and minimize service interruptions. This not only ensures a more resilient water system but also contributes to long-term financial sustainability.

In conclusion, the reduction of uncertainty through digital solutions represents a fundamental component of the construction of long-term resilience in the water sector. The provision of real-time data, the facilitation of predictive analytics, and the encouragement of cross-sector collaboration equip utilities with the capacity to more effectively address future challenges and ensure the continued reliability and sustainability of water systems.[250]

7.3.6. Proactive Adaptation to a Changing Climate and Demographics

As climate and demographic changes intensify, the phenomenon of rural-to-urban migration is placing an increasing strain on urban water systems, thereby underscoring the necessity for proactive planning. Adaptation strategies must account for the growth of populations and ensure that urban infrastructure can support future demand without exacerbating existing inequalities. In rural areas, where agriculture is heavily dependent on water availability, proactive measures must prioritize the securing of water resources and the management of the impacts of climate variability. By focusing on long-term sustainability and addressing socio-economic barriers, the water sector can enhance its ability to navigate the uncertainties posed by both climate change and demographic shifts.[251]

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[250] Ibid., 245.
[251] Ibid., 14.

7.3.7. Increased Water Security

The term "water security" is used to describe the sustainable management of water resources, with the objective of ensuring sufficient and reliable access to safe water for humans and ecosystems. In light of the growing unpredictability of the global climate, the attainment of water security has emerged as a pivotal global concern. The current situation of water resources is characterized by unprecedented pressure, which is caused by a number of factors, including rapid urbanization, population growth and socioeconomic changes. These factors are themselves exacerbated by the effects of climate change. A significant aspect of water security is the resolution of imbalances in water availability, whether resulting from scarcity, excess, or pollution. In addition to its role in sustaining life, water is critical to economic development, ecosystem health, and resilience against water-related disasters such as floods and droughts.[252]

The concept of water security is not limited to the mere physical availability of water; it also encompasses its quality and equitable distribution. Physical scarcity refers to the insufficient availability of water to meet demand, whereas economic scarcity pertains to the lack of infrastructure or financial resources to access available water resources. The effects of climate change serve to compound these challenges, with disruption to rainfall patterns, intensification of droughts, and increased competition for dwindling water resources. To address these issues, it is imperative that sustainable water management strategies be implemented, combining approaches such as enhanced water conservation, technological innovation, and policy reforms.[253]

The impact of climate change on water security is particularly pronounced in regions that are already prone to water scarcity, such as semi-arid regions in North America. For example, in regions such as California, altered rainfall patterns and frequent droughts have resulted in increased competition for water, which has in turn affected livelihoods and exacerbated tensions over water rights. This scenario elucidates the broader relationship between climate change, water insecurity, and social stability, with drought-induced water shortages serving as a catalyst for conflict and undermining local economies. Consequently, enhancing water governance is pivotal to enhancing resilience and addressing the social and economic consequences of water insecurity.[254]

7.4. Awareness Raising

Water is essential for life, and ensuring safe drinking water is critical for public health. Protecting source water is vital, especially with climate change causing unpredictable weather patterns, from droughts to flooding. Public awareness of water sources and the importance of reliable water management is increasingly important.[255] Awareness-raising programs aim to create lasting impacts by educating the public on the effects of climate change and promoting responsible resource use for long-term environmental protection.

In both Germany and the United States, public campaigns are highlighting water conservation. For instance, California's Save Our Water campaign educates residents on water conservation, offering tips for reducing usage and addressing drought issues. The campaign uses educational resources, social media, and community

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[252] Mishra, B. K., Kumar, P., Saraswat, C., Chakraborty, S., & Gautam, A. (2021). Water security in a changing environment: Concept, challenges and solutions. Water, 13(4), 490.
[253] Dinko, D. H., & Bahati, I. (2023). A review of the impact of climate change on water security and livelihoods in semiarid Africa: Cases from Kenya, Malawi, and Ghana. Journal of Climate Resilience and Justice, 1(1), 107–118. https://direct.mit.edu/crcj/article/doi/10.1162/crcj_a_00002/117386/A-Review-of-the-Impact-of-Climate-Change-on-Water
[254] Van Beek, E., & Arriens, W. L. (2014). Water security: Putting the concept into practice (p. 55). Stockholm: Global Water Partnership.
[255] Interview with Tuck, C., June 2024, Association of California Water Agencies

outreach to encourage actions like fixing leaks and reducing outdoor water consumption.[256] In Germany, the "Smart Water" project in Darmstadt fosters community involvement to improve water management. It aims to optimize water use, incorporate digital technologies, and demonstrate how sustainable management can sustain quality of life amid water scarcity, enhancing the city's resilience to climate change.[257]

Figure 24. Smart City values in Darmstadt. Adapted from: Smart Water Darmstadt[258]

Campaigns like these aim to raise awareness of water scarcity and encourage sustainable use of water resources. Through educational initiatives, consumers can learn how their behaviors impact water consumption and CO_2 emissions. This collective effort benefits both water suppliers and society by promoting sustainable resource management.

Raising awareness and encouraging water-saving practices, such as water reuse, are as crucial as technical and infrastructure improvements. A holistic understanding of the challenges, combined with public involvement, is essential for sustainable solutions to water issues. Water education plays a key role in addressing global challenges like water scarcity and climate change, emphasizing the importance of responsible water management.

7.4.1. Educational Initiatives

An effective way to raise awareness is through comprehensive educational initiatives. Schools, local governments, and community organizations can implement programs that educate about the importance of clean drinking water, global water challenges, and the impact of individual water consumption. Information campaigns on social media, workshops, and interactive events help spread knowledge and make the topic more accessible.

Examples of successful educational initiatives include the "Project WET" (Water Education for Teachers) program in the United States and the Wasserschule project in Germany. Launched in the 1980s, Project WET aims to teach students and teachers about the significance of water, global water issues, and responsible water management. The program offers teaching materials, interactive workshops, and activities for different age

[256] Save our Water. (n.d.). State of California. https://saveourwater.com
[257] Smart Water Darmstadt. (n.d.). City of Darmstadt. https://smartwater.darmstadt.de
[258] *Strategie*. Smart Water Darmstadt. (2023). https://smartwater.darmstadt.de/strategie/

groups and educational levels. Schools and communities in the US use Project WET to raise awareness about water scarcity, clean water sources, and the impact of water consumption, incorporating it into science curricula. Additionally, it trains teachers to engage students with the topic in a comprehensive and interactive manner.[259]

7.4.2. Promotion of Sustainable Consumption

The water footprint measures all water used to produce goods and services for human consumption, including municipal, agricultural, and industrial usage. Agriculture is the largest consumer, accounting for 70% of freshwater withdrawals globally, while 20% goes to industry and 10% to residential use.[260]

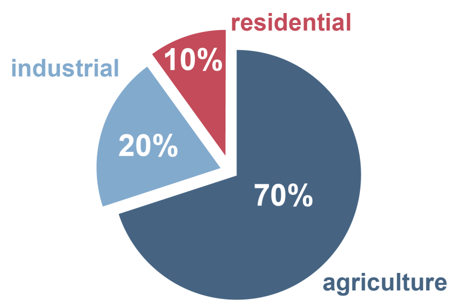

Figure 25. Division of freshwater consumers. Created from: Current Directions in Water Scarcity Research.[261]

Agricultural water conservation can be greatly enhanced through several key strategies, such as minimizing water losses in conveyance and application networks by utilizing technologies like GIS and telemetry, and improving irrigation systems with methods like drip and sprinkler irrigation. Additionally, adopting efficient practices such as regulated deficit irrigation, along with policies that implement proper pricing, volumetric metering, and drought surcharges, can further encourage conservation efforts.[262]

In industry, reducing water footprints involves adopting water-efficient technologies, optimizing processes to allow for recycling and reuse, sourcing sustainable alternatives such as rainwater harvesting, and fostering partnerships with local communities to mitigate shared water risks. Policy and regulatory measures, including water pricing mechanisms, water use laws, and infrastructure upgrades, play a vital role in enforcing and guiding sustainable practices.[263]

On an individual level, water reduction can be achieved by installing water-saving appliances, cultivating responsible indoor and outdoor water habits, reducing food waste, and making dietary choices that consume less water. Public education and awareness campaigns strengthen conservation by highlighting the impact of water footprints and encouraging sustainable choices. Collectively, these efforts across agricultural, industrial, and personal levels, supported by policy and education, are essential for a sustainable water future.[264]

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[259] Project WET Foundation. (n.d.). About us. https://www.projectwet.org/about-us
[260] Malla, F. et al., (2024). Current Directions in Water Scarcity Research Chapter 13 - Strategies for the reduction of water footprints. https://doi.org/10.1016/B978-0-443-23631-0.00013-3.
[261] Ibid., 256.
[262] Konstantinos Chartzoulakis, Maria Bertaki. (2015). Agriculture and Agricultural Science Procedia. Sustainable Water Management in Agriculture under Climate Change https://doi.org/10.1016/j.aaspro.2015.03.011
[263] Ibid., 256.
[264] Ibid., 256.

An example of a successful information campaign aimed at reducing everyday water use is the WaterSense programme of the Environmental Protection Agency in the United States. This programme not only provides certification for water-efficient products, but also offers comprehensive education campaigns that encourage consumers to implement simple water-saving measures in their daily lives. Actions promoted by WaterSense include fixing leaky faucets, installing water-efficient showerheads and toilets, and reducing shower time. According to the EPA, a single leaky faucet can waste up to 11,000 liters of water a year if left unfixed. The EPA is educating people on how these simple steps can significantly reduce household water use. Another important aspect is the promotion of tap water instead of disposable plastic bottles. Many cities and towns in the US and Europe are actively promoting the use of tap water as an environmentally friendly and safe alternative.[265]

[265] U.S. Environmental Protection Agency. (n.d.). WaterSense. https://www.epa.gov/watersense

8. Comparative Analysis of Decarbonization Strategies

8.1. Best Practices: Portland Water Bureau, Oregon

Portland, Oregon, faces increasing climate challenges, including rising temperatures, drier summers, and more frequent heatwaves and wildfires. These changes impact water availability, with reduced summer water levels, higher water temperatures, and increased winter flows, all projected to worsen over time.[266]

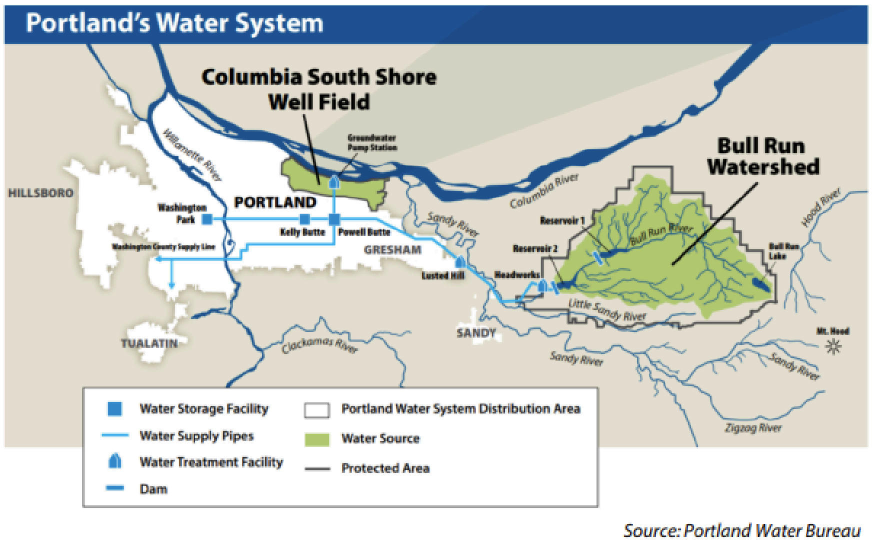

Figure 26. Map of the Bull Run Watershed and Portland's water distribution. Source: City of Portland[267]

Portland Water Bureau (PWB) provides drinking water to 1 million customers, relying on the Bull Run Watershed for surface water and the Columbia South Shore Well Field as a backup. PWB prepares an annual Seasonal Water Supply Augmentation and Contingency Plan to forecast and manage water resources.[268]

8.1.1. Driving Legislation

PWB is a leader in decarbonization and renewable energy. Since 2007, it has tracked carbon emissions, identifying electricity as the primary source, accounting for 75% of operational emissions. Climate and energy goals set by the City of Portland since the 2000s, including a 2020 Climate Emergency Declaration, guide PWB's actions. The declaration outlines targets for a safe future and Net Zero emissions by 2050[269], followed by the Climate Emergency Workplan, which provides actionable steps for municipal agencies.[270]

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[266] Portland, Oregon. (n.d.). *Climate change resilience and your drinking water*. Portland.gov. https://www.portland.gov/water/about-portlands-water-system/climate-change-resilience
[267] *Groundwater: City identified risks, must develop a long-term plan to address them*. City of Portland. (2020). https://www.portland.gov/sites/default/files/2021/groundwater-report-6-30-2020.pdf
[268] Johnson, B. (n.d.). *Inline micro-hydro: Portland Water Bureau*. Water Utility Climate Alliance. https://www.wucaonline.org/assets/pdf/greenhouse-gas-case-study-portland.pdf
[269] Ibid., 262.
[270] City of Portland. (2022, July). *Climate Emergency Workplan*. City of Portland. https://www.portland.gov/bps/climate-action/climate-emergency/documents/climate-emergency-workplan-2022-2025/download

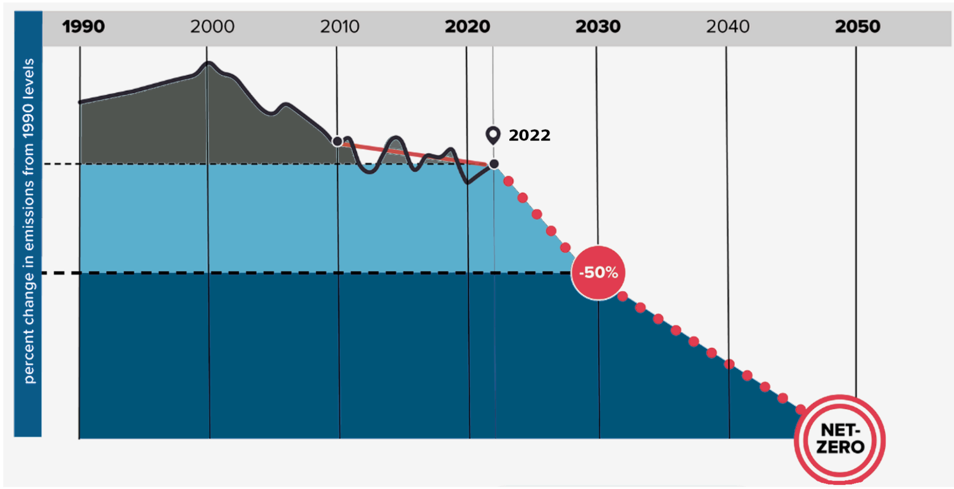

Figure 27. Carbon emission reduction targeted through the Climate Emergency Workplan. Source: Climate Emergency Workplan[271]

In 2021, Oregon passed the Clean Energy Targets Bill that requires energy utilities to reduce their greenhouse gas emissions completely by 2040. To support this goal, PWB is developing its own clean energy projects that can contribute to the utilities' targets.[272]

8.1.2. Actions

PWB's Net Zero Strategy aims to eliminate greenhouse gas emissions by 2050, marking its first formal policy mandate for climate change mitigation. Key to its success is embedding the strategy within the utility's operations.[273] The primary focus is on reducing energy use by eliminating water loss, leveraging energy savings contracts, and improving industrial efficiency. From 2007-2022, electricity accounted for 79% of PWB's emissions, and from 2016-2021, 15% of all produced water was lost due to leaks or bursts. To address this, PWB is deploying advanced metering infrastructure to detect leaks faster.

The next priority is the generation of energy from renewable sources.[274] PWB has already installed solar panels on the roofs of some of its facilities and has a working micro-hydro installation at one plant. The inline micro-hydro was an exploratory and innovative project that explored the application of a renewable energy source within the civil water infrastructure.[275] This innovative project required collaboration with the City of Portland, private contractors, and energy utilities. The hydropower system continues to generate energy sold under a power purchase agreement (PPA)[276], with plans for a new hydropower project underway.[277]

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[271] Ibid., 266.
[272] *Department of Environmental Quality : Oregon Clean Energy Targets : Action on Climate Change : State of Oregon*. (n.d.). Oregon Clean Energy Targets : Department of Environmental Quality. https://www.oregon.gov/deq/ghgp/pages/clean-energy-targets.aspx
[273] Ibid., 45.
[274] *Portland Water Bureau climate action*. (n.d.). Portland.gov. https://www.portland.gov/water/about-us/climate-action#:~:text=At%20the%20Portland%20Water%20Bureau,net%20zero%20emissions%20by%202050
[275] Ibid., 264.
[276] Ibid., 264.
[277] Ibid., 45.

The Portland Water Bureau Strategic Plan is a five-year plan that prioritizes water management goals based on data. The plan identifies five areas of focus, including system reliability that addresses response to climate change and groundwater resilience. Topics of cybersecurity and effective technology are also discussed, and the position of a Water Bureau Technology Manager is suggested to address such issues.[278]

8.1.3. Key Factors

To enact the changes that PWB has led, partnerships have provided necessary resources, perspectives, and professional capacity. At the municipal level, the City of Portland fosters partnerships with research institutions and climate scientists. PWB collaborates with academia to understand how climate change could impact water infrastructure and systems, as well as to develop tools to address the changes. PWB also works closely with other utilities across the United States that are focusing on water management and adaptation through the Water Utility Climate Alliance (WUCA). WUCA enables leaders in this sector to learn from each other and exchange best practices; currently, PWB holds a leadership position in the organization.[279] Integrating expertise from multiple fields and contexts allows PWB to make more informed and strategic decisions and plans.

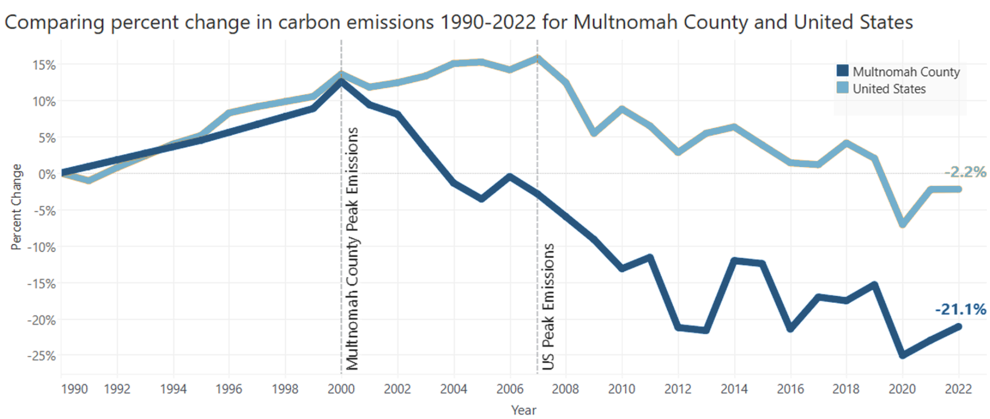

Figure 28. Comparing percent change in carbon emissions 1990-2022 for Multnomah County and the United States. Source: Portland Bureau Planning & Sustainability[280]

8.1.4. Funding Mechanisms

PWB leverages funding from local, state, and national sources.[281] A notable example is the micro-hydro installation, National programs, such as the 2009 American Recovery and Reinvestment Act, provided funds to stimulate economic recovery and support infrastructure projects. Similarly, the American Rescue Plan Act and the Inflation Reduction Act (IRA) allocated resources to renewable energy development.[282] Through the IRA, PWB anticipates recovering 30-40% of its renewable energy investments as direct payments.[283]

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[278] *Portland Water Bureau Strategic Plan*. (2019). Portland Water Bureau. https://www.portland.gov/water/documents/2020-2024-portland-water-bureau-strategic-plan/download
[279] Ibid., 264.
[280] Portland Bureau of Planning & Sustainability. (2022). *Portland's Climate and Energy Dashboard*. Tableau Public. https://public.tableau.com/app/profile/portland.bps/viz/ClimateandEnergyDashboard/ClimateandEnergyDashboard
[281] Ibid., 264.
[282] Loans Program Office. (2023). INFLATION REDUCTION ACT OF 2022. Energy.gov. https://www.energy.gov/lpo/inflation-reduction-act-2022
[283] Interview with Elise Guinee-Cooper, City of Portland Water Bureau, August 2024

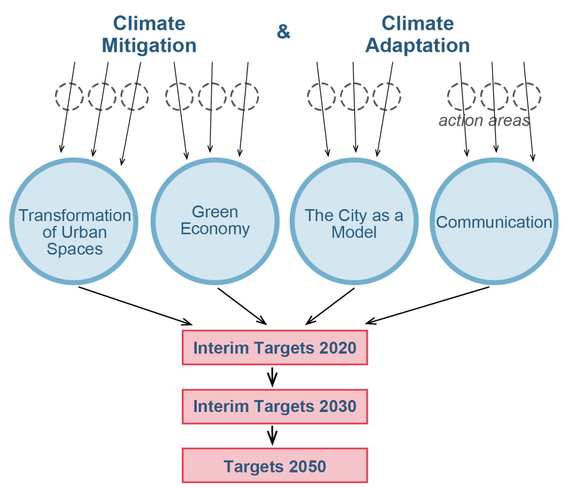
At the state level, the Energy Trust of Oregon supports energy conservation projects by pooling resources from state-wide energy utilities.[284] Locally, the Portland Clean Energy Community Benefits Fund (PCEF) offers sustained climate equity support, focusing on historically marginalized communities. The PCEF was established through a community-driven ballot measure, reflecting strong local commitment to climate initiatives.[285]

8.2. Best Practices: HAMBURG WASSER, Germany

Hamburg, a major port city in northern Germany, faces climate challenges including rising temperatures, heavy rainfall, and sea-level rise. Despite these challenges, groundwater sources remain unaffected.[286] HAMBURG WASSER (HW) supplies drinking water to 800,000 customers and connects 2.2 million people. The utility has significantly reduced CO_2 emissions from 180,000 tons in 1990 to 4,000 tons in 2021[287], achieving 100% renewable energy production since 2011.[288]

8.2.1. Driving Legislation

The Hamburg Climate Plan, integrates climate mitigation and adaptation goals, aiming for an 80% reduction in CO_2 emissions by 2050. The plan evolved into the Climate Action Master Plan, raising targets to a 90% reduction in emissions and achieving 90% energy self-sufficiency. By 2025, €50 million will be invested in renewable energy systems.[289] All levels of municipal policy are engaged to achieve this goal and meet guidelines set by the federal government.[290] The city's strategy, informed by the Klimainformationssystem Hamburg research, emphasizes ongoing evaluation and updates to meet federal guidelines and adapt to climate realities.[291]



[284] Ibid., 45.
[285] City of Portland. (n.d.). *About PCEF*. City of Portland. https://www.portland.gov/bps/cleanenergy/about
[286] Senate. (n.d.). *Hamburger Klimaplan - hamburg.de*. Hamburg. https://www.hamburg.de/contentblob/4658414/b246fbfbbf114918443170697270 9508/data/d-21-2521-hamburger-klimaplan.pdf
[287] Winkler, G. (2023). *HAMBURG WASSER's contribution to carbon neutrality*. Water 4. https://www.uniacque.bg.it/export/sites/default/waterweek/.galleries/documenti/WaterSeminar4/Acqua-e-transizione-ecologica/04.-GUDRUN-WINKLER.pdf
[288] Ibid., 282.
[289] Aqua Publica Europea. (2020). *Hamburg Wasser presents its climate strategic plan for 2025*. Aqua Publica Europea. https://www.aquapublica.eu/article/members-activities/hamburg-wasser-presents-its-climate-strategic-plan-2025
[290] Ibid., 282.
[291] Hamburg. (2023). *Hamburg gets new online information system on climate change*. Hamburg News. https://hamburg-business.com/en/news/hamburg-gets-new-online-information-system-climate-change

Figure 29. Transformation Process proposed by the Hamburg Climate Plan. Adapted from: Hamburger Klimaplan[292]

8.2.2. Actions

HAMBURG WASSER aims to be fully energy self-sufficient by 2030, currently achieving ~80% self-sufficiency. The three driving actions to reach energy independence are: generating heat from sewage sludge incineration, using energy-efficient processes, and increasing renewable energy production.[293] HW generates its own power through wind turbines and solar power, as well as captures some energy from the drinking water system. The renewable energy is used internally, and any additional energy produced is sent to the public grid.[294] Additional energy consumed is purchased green energy, and the utility continues to advance energy-saving projects.[295]

Environmental impact assessments and an Integrated Management System guide HW's continuous improvement. A digital database tracks CO_2 savings potential in municipal buildings, fostering centralized energy consumption records and facilitating public access through an online knowledge portal.[296]

Community engagement is integral to HW's approach. Through partnerships with local schools and educational programs, HW raises awareness about climate change, water conservation, and energy efficiency. The Water Agents program involves children and youth as ambassadors for sustainable water management. Participants engage in workshops, excursions, and hands-on projects, promoting environmental stewardship and awareness of water conservation.[297]

8.2.3. Key Factors

The City of Hamburg has taken national leadership surrounding climate change research and adaptation strategies. The City's Climate Action Policies started originally in the 1990s, and this work continues to be updated and refined. This has led to the integration of related policies and goals within the municipal agencies, including HAMBURG WASSER.[298]

[292] Ibid., 282.
[293] Hamburg. (2023). *HAMBURG WASSER continues to expand renewable energy production*. Hamburg. https://www.hamburg.de/politik-und-verwaltung/behoerden/bukea/aktuelles/pressemeldungen/2023-04-27-bukea-windenergieanlage-522100
[294] Hamburg Wasser. (2022). *Hamburg Wasser - Nachhaltigkeitsbericht 2022*. Hamburg Wasser. https://www.hamburgwasser.de/fileadmin/Redakteur/Downloads/nachhaltigkeitsbericht/HW_Nachhaltigkeitsbericht_2022.pdf
[295] Hafen Hamburg. (2023). *New climate plan and climate protection law for Hamburg: Senate adopts concrete measures for the next 10 years and sets new climate goals*. *https://www.hafen-hamburg.de/en/press/news/new-climate-plan-and-climate-protection-law-for-hamburg-senate-adopts-concrete-measures-for-the-next-10-years-and-sets-new-c-365/*
[296] Ibid., 287.
[297] HAMBURG WASSER. (n.d.). Aqua agents. Retrieved from https://www.hamburgwasser.de/unternehmen/gesellschaftliches-engagement/kita-schule/aqua-agenten
[298] Ibid., 287.

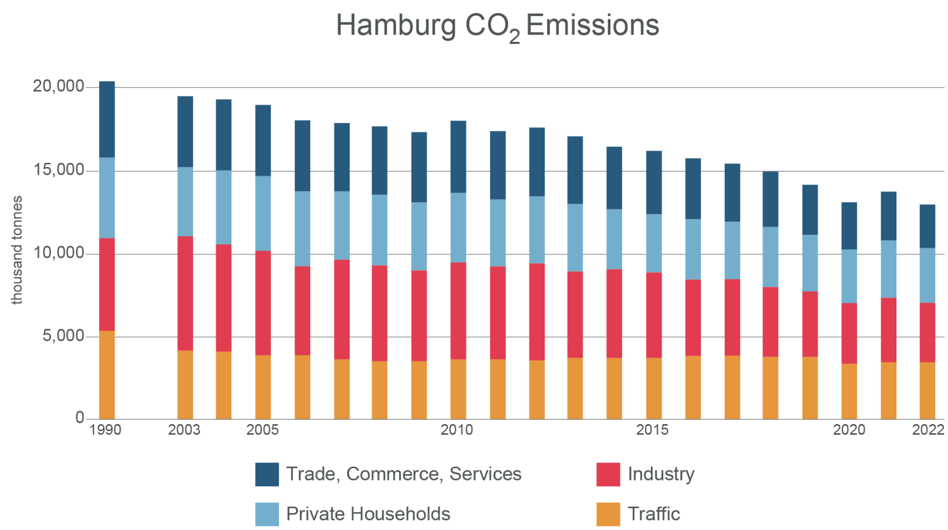


Figure 30. CO_2 Emissions for the City of Hamburg, 1990-2022. Adapted from: City of Hamburg[299]

Hamburg collaborates on EU-wide research projects with other cities, especially other ports, on topics of climate change adaptation. The focus of these projects has tended to be on issues of infrastructure adaptation, such as coastal flooding and protection from intense storms.[300] Further, HW exchanges knowledge with other cities and utilities, through physical exchanges and through international conferences and collaborations.[301]

8.2.4. Funding Mechanisms

To reach targets laid out by the City of Hamburg, they set aside funding specifically for strategies discussed in the plans. For example, between 2024 and 2026, the City has allocated €3.5 million to expand renewable energy. Along with public and private partners, the City is investing billions of euros into its energy goals, including €2 billion to develop a hydrogen industry and €1.9 billion to eliminate the use of coal as an energy source.[302]

The Hamburg Investitions- und Förderbank (IFB) is the central bank of the City of Hamburg, and it provides financial support through grants, subsidies, and low-interest loans. The IFB is the funding mechanism behind the municipal policy directives, and it assists with funding initiatives from other levels of government, too.[303] Regarding current energy programs, the IFB is supporting companies and individuals to replace carbon-intensive heating systems with renewable-based heat.[304] Regarding water, the IFB is providing grants surrounding rainwater infiltration, storage cisterns, and land use reversal.[305]

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[299] Hamburg. (2022). *Deutliche CO2-Minderung in Hamburg*. CO2-Emissionen in Hamburg. https://www.hamburg.de/politik-und-verwaltung/behoerden/bukea/themen/klimaschutz/klimaanpassung/co2-bilanz-hh-2022-169240
[300] Ibid., 285.
[301] Ibid., 281.
[302] Hamburg. (2023). *Senate continues to advance CO_2-neutral transformation of the city*. Climate Plan and Climate Protection Act. https://www.hamburg.de/politik-und-verwaltung/behoerden/bukea/aktuelles/pressemeldungen/2023-08-29-bukea-klimapolitik-522580
[303] Hamburgische Investitions- und Förderbank. (n.d.). *IFB Hamburg*. Hamburgische Investitions- und Förderbank. https://www.ifbhh.de/
[304] Ibid., 282.
[305] IFB Hamburg. (n.d.). *Nichtwohngebäude Modernisieren*. Nichtwohngebäude modernisieren. https://www.ifbhh.de/programme/gruender-and-unternehmen/energie-und-ressourcen-einsparen-gu/nichtwohngebaeude-modernisieren-gu

HAMBURG WASSER has established a comprehensive Green Finance Framework to support its sustainability and decarbonization initiatives. This framework reflects the utility's commitment to aligning its financial strategies with environmental goals and is an integral part of the broader climate action objectives set by the City of Hamburg. The Green Finance Framework outlines specific categories of eligible projects, which include renewable energy production, water and wastewater management, and infrastructure development aimed at improving energy efficiency and reducing greenhouse gas emissions. Investments in renewable energy, such as wind and solar projects, are prioritized to ensure that a significant portion of HAMBURG WASSER's energy comes from sustainable sources. Additionally, the utility has committed to upgrading existing facilities to enhance their efficiency and overall environmental performance.[306]

In adherence to international standards, the framework complies with the Green Bond Principles established by the International Capital Market Association (ICMA). This compliance ensures transparency and accountability regarding the allocation of funds and the environmental impact of financed projects. HAMBURG WASSER also emphasizes community engagement in its sustainability initiatives, involving local residents in educational programs that promote awareness of climate action and sustainable practices.

Notable projects funded through the Green Finance Framework include the installation of solar energy systems at various water treatment facilities, which have significantly increased the share of renewable energy in the utility's operations. Additionally, the implementation of smart water management systems has optimized water distribution and waste management processes, thereby contributing to HAMBURG WASSER's decarbonization efforts.[307]

[306] HAMBURG WASSER. (n.d.). *Green Finance Framework*. *https://www.hamburgwasser.de/fileadmin/Redakteur/Downloads/Green_Finance_Framework/Green_Finance_Framework.pdf*
[307] Ibid., 298.

9. Recommendations

To enhance the decarbonization and digitalization of the water sector in both the United States and Germany, targeted policy reforms and strategic investments are essential. These recommendations focus on overcoming current challenges, leveraging funding opportunities, and promoting standardized practices that support innovation and sustainability.

1. Strengthen and Streamline Funding Mechanisms: The United States has implemented significant funding initiatives, such as the Direct Pay mechanism from the Inflation Reduction Act. This initiative provides direct financial support instead of tax credits, making it more accessible for public and non-profit water utilities to adopt digital and energy-efficient technologies.[308] Additionally, the Hydroelectric Production Incentive Program (Section 242)[309] and state-specific programs like California's Self-Generation Incentive Program (SGIP)[310] facilitate the integration of renewable energy and energy storage solutions within water management systems.

Expanding funding mechanisms across more states and for a broader range of digital tools can encourage investments in predictive maintenance, smart metering, and real-time water quality monitoring. These measures collectively reduce carbon emissions and improve system resilience by modernizing infrastructure.

2. Foster Policy Clarity and Standardization in the EU: In Germany, EU policies shape national water management regulations, but fragmented digital policies hinder the full potential of digitalization. Clear, cohesive policies defining digital frameworks and standards are essential for streamlined adoption of new technologies. Programs like the EU Pre-commercial Procurement (PCP) can help bridge gaps by stimulating market-driven innovation and ensuring digital solutions align with public sector needs, promoting uniform adoption across member states.[311]

3. Advance Knowledge Digitalization for Water Operators: Water and wastewater operators increasingly rely on digital tools such as SCADA, GIS, data historians, laboratory information systems, and predictive maintenance technologies like leak detection and drone surveys. However, most operators gain proficiency through informal, on-the-job training, as few utilities provide formal instruction on these tools. Programs like Northwest Ohio's Water Workforce Coalition offer a model, combining specialized digital training with certification and job placement support for aspiring water professionals. To meet the growing need for digital skills, expanding such initiatives nationwide, in collaboration with educational institutions, utilities, and governments, can enhance digital literacy and create a strong IT talent pipeline to keep pace with the sector's digital transformation.[312]

4. Implement Robust Cybersecurity Practices: Protecting water infrastructure from cyber threats requires a multifaceted strategy grounded in governance, secure architecture, risk management, and comprehensive staff training. Water utilities should align with industry standards like AWWA, NIST, and ISO-27001, prioritizing

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[308] The United States Government. (2024). *Direct pay*. The White House. https://www.whitehouse.gov/cleanenergy/directpay/

[309] *Section 242: Hydroelectric Production Incentive Program*. Department of Energy. (2024). https://www.energy.gov/gdo/section-242-hydroelectric-production-incentive-program

[310] *Self-generation incentive program (SGIP)*. California Public Utilities Commission. (2023). https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/self-generation-incentive-program

[311] European Commission. (n.d.). *Pre-commercial procurement*. Research and innovation. https://research-and-innovation.ec.europa.eu/strategy/support-policy-making/shaping-eu-research-and-innovation-policy/new-european-innovation-agenda/innovation-procurement/pre-commercial-procurement_en

[312] Environmental Protection Agency. Office of Wastewater Management. (2024). Preparing Your Workforce for the Future through Innovative Technology and Intelligent Systems. https://www.epa.gov/system/files/documents/2024-06/water-workforce-innovation-presentation.pdf

practices such as routine vulnerability assessments, thorough asset inventories, and robust system hardening techniques. These include removing outdated devices, disabling unnecessary ports, and enforcing strong access controls like multi-factor authentication and VPNs. Addressing knowledge gaps with CISA's cybersecurity resources and EPA's "Top Cyber Actions for Securing Water Systems" can foster a culture of cybersecurity awareness among utility staff, reducing risks and preparing utilities to counter emerging cyber threats effectively.[313]

5. Promote Interdisciplinary Collaboration: Collaboration across all levels of water management, encompassing government agencies, utilities, educational institutions, and private businesses, is critical to creating resilient water systems and driving innovation. Interdisciplinary efforts, such as competency-based programs and peer-to-peer learning, can provide essential hands-on training and skill-building for professionals. For example, the EPA and USDA's partnership on the "Promoting Sustainable Rural Water and Wastewater Systems" initiative offers apprenticeships and funding for rural communities. These partnerships also aid in developing long-term workforce planning by sharing best practices and anticipating skill needs, ensuring that water systems are managed by capable professionals who can meet modern challenges.[314]

6. Encourage Standardization for Unified Water Data: In the EU, fragmented policies and inconsistent digital standards across member states limit the water sector's digitalization potential. Establishing a standardized water ontology—such as SAREF4WATR, which serves as a semantic model for IoT data—can facilitate consistent data sharing and interpretation. Collaborative efforts with bodies like ETSI, ISO, and ITU-T, along with alignment with EU water legislation, could establish a framework for seamless information exchange. This would enable cohesive adoption of digital tools across EU member states, ensuring that data integration initiatives operate efficiently and securely, supporting a more resilient and sustainable water sector.[315]

7. Enhance Public Engagement through Digital Education: Education systems and digital tools play a pivotal role in increasing public awareness of water-related issues. Leveraging digital platforms to share data and insights, presenting complex water management data in engaging and accessible formats, and incorporating tools like augmented and virtual reality can foster public trust and transparency. For example, VR simulations of water conservation efforts or interactive online resources can encourage citizens to engage meaningfully with water policy. By making scientific data approachable and relevant, water agencies can inspire communities to support sustainable water practices and advocate for conservation efforts, helping to build a broad, informed base of stakeholders who value and actively participate in water stewardship.[316]

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[313] West Yost Associates. (2019). Water Sector Cybersecurity Risk Management Guidance. https://www.awwa.org/wp-content/uploads/AWWA-Cybersecurity-Guidance-2019-1.pdf

[314] Environmental Protection Agency. (2020). America's Water Sector Workforce Initiative: A Call to Action https://www.epa.gov/sites/default/files/2020-11/documents/americas_water_sector_workforce_initative_final.pdf

[315] Ulf Stein et al. (2022). Digitalisation in the water sector: Recommendations for policy developments at EU level. Publications Office o f the European Union. doi: 10.2848/915867

[316] Ibid., 310.

10. Advancing Decarbonization through Digitalization

Digital tools are advancing the workflows of the water sector, while providing data at scales previously not possible. Such tools and the insights that they provide can be applied to drive strategic decarbonization efforts in water supply. Decarbonization and resilience efforts are necessary for the water sectors in Germany and the United States as the impacts of climate change become more intense and affect groundwater and surface water supply, extreme events, and infrastructure itself. Best practices from leading utilities in both countries provide insights in how to drive change within public organizations, find necessary funding, advocate for larger issues, and align efforts across agencies or offices.

As utilities advance to meet trends in technology, the tools can be applied to assist in meeting emission targets; targets that are set internally or mandated from a higher authority. Recommendations for utilities to incorporate digital tools and make progress on decarbonization goals include efforts in workforce training, interdisciplinary collaboration, and specific funding sources.

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