Integrated Industrial Water Management – Challenges, Solutions, and Future Priorities

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Water is used intensively by various sectors such as agriculture, industry, and the public. Increasing global water demand and the effects of climate change are leading to overuse of water resources in many regions. One strategy to meet these challenges is to implement an integrated industrial water management, e.g., by water reuse or the use of alternative water resources. The development of new concepts and technical, digital, and nontechnical innovations together with priorities will continue to set the course for future integrated water management, particularly in the industrial environment.

Keywords: Alternative water resources, Digitization, Holistic approach, Integrated solutions, Water reuse

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1 Introduction

Water is one of the most important resources on earth for daily use in many different ways. However, water resources are affected by overexploitation and pollution, and the increasing demand for water with limited resources is a major challenge. This and the climate change lead to water shortages due to, e.g., population growth, migration to cities, and higher per capita water consumption in growing urban, domestic, and industrial water sectors as well as the increasing establishment of industrial estates and intensification of agriculture [1]. This situation will continue to worsen worldwide [2]. Already today, half of the world's population lives in urban areas [3]. Global water demand is expected to increase by around 55 % by 2050, mainly due to growing demand from production, thermal power generation, and household use [4]. Consequently, the availability of fresh water will be increasingly negatively impacted. More than 40 % of the world's population is expected to live in areas of severe water stress by 2050 [4]. The World Economic Forum predicts that water crises will have the greatest social impact in the next 10 years [5]. Owing to these circumstances, a new way of thinking is necessary, and innovations can help to solve the situation. A comprehensive and integrative research approach to the management of the water system is a more effective way of dealing with these challenges. It is necessary to recognize diversity in society and environment, to include water resources that are less accessible to control, and to consider adaptive approaches to go beyond supply-side regulation [6].

An example of an integrative approach is the consideration of water and energy. Water and energy are closely linked and strongly interdependent. Decisions taken in one area have direct and indirect effects on the other, positive or negative. With the development of the energy mix of a country or region, e.g., from fossil fuels to renewable energies, the impact on water and its supporting ecosystem services also evolves. About 90 % of the world's electricity generation is water-intensive. At the same time, the availability and allocation of freshwater resources determine how much (or how little) water can be provided for energy production [4]. The focus in this article will be more on water aspects without addressing in detail all energy aspects.

In UN Resolution 71/222, the General Assembly proclaims the period from 2018 to 2028 as the International Decade for Action, "Water for Sustainable Development" [7]. One of the objectives of the decade is to focus more attention on "sustainable development and integrated management of water resources for the achievement of social, economic and environmental objectives" [7]. The challenge for governance in the 21st century is to take into account the multiple aspects, roles, and benefits of water and place water at the center of decision-making in all water-dependent sectors, including energy [4]. Among the most important global trends for water is a stronger commitment to sustainability.

1.1 Integrated Industrial Water Management

Water is used intensively by various sectors such as agriculture, industry, and the public. This makes water management a difficult issue that cannot be solved by one sector alone. To implement effective water governance, a considerable number of challenges have to be addressed. One strategy for improving water management is the implementa-

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tion of integrated water resources management (IWRM). The Global Water Partnership has defined this as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital ecosystems" [8]. In other words, IWRM is a holistic strategy to address the impacts of water-related challenges such as climate change and urbanization to ensure sustainable water security.

Water security plays a major role in IWRM. The concept of water security was developed in response to the complexity of the global water crisis. The core idea is to balance the water needs of humans and the environment [9]. Water security and access to modern water supply and sanitation, as described as an important global trend [10], are linked to technological and industrial development and, more generally, to economic development. As a measure within IWRM, besides urban water management and agricultural water management, the integrated industrial water management [11] is a priority. With regard to the requirements of water policy, eco-efficient and sustainable industrial water management is regarded as one of the most important strategies for environmental protection in many European countries. Water is a key element for the process industry and a core component for recycling and sustainable management. In industry, water fulfils many functions, including its use as raw material, as means of transport as well as its use for cleaning and cooling [3].

Water-intensive industries are primarily the chemical industry, followed by the metal, food and beverage, paper, and textile industries. The chemical industry offers the highest potential for increasing eco-efficiency in industrial water management: on the one hand, it is the largest industrial consumer of water; on the other hand, the chemical industry offers innovative products and technologies for efficient water management [11]. The process industry in total offers a high potential for reducing freshwater demand and wastewater release as well as increasing eco-efficiency in industrial water management. These are actions that are directly linked to individual production processes as well as actions and collaborations far beyond an industrial process, unit, or even site [11]. The expected increase in energy and water consumption in the upcoming decades will result in changes regarding the general integrated water management, which will in turn also influence the industrial integrated water management.

To achieve a sustainable water management in chemical industry and related process industry sectors, technological and non-technological aspects must be taken into account. Integrated industrial water management considers interactions, interdependencies, and synergy potentials between different measures of water use and water/wastewater treatment in and across various scales: process – plant – site – local – regional. A guidance document for efficient and sustainable water use and treatment, i.e., management [12], was compiled from results, experiences, and case studies in the EU project E4Water [13]. The main objective of this project was to develop, test, and validate new integrated approaches, methodologies, and process technologies for a more efficient and sustainable management of water in chemical industry with transfer potential to other sectors. Another current example of integrated industrial water management is the EU project INSPIREWATER [14], in which holistic approaches from E4Water are adopted and further elaborated and validated (Fig. 1). INSPIREWATER aims to increase water and raw material efficiency in the process industry. New and established resource-efficient technologies are applied to reduce water consumption, energy, use of chemicals, and waste. This will be underpinned by a holistic water management framework, which will complement existing management structures in process industry companies. A snapshot of the INSPIREWATER process and targets for resource efficiency is shown in Fig. 1.

The most important ways to increase efficiency are the decrease of water abstraction and the associated reduction in wastewater disposal by fostering the reuse of water and integrating alternative water resources, e.g., brackish water and municipal wastewater (Sect. 2.3). This needs to be considered especially in view of the rising energy costs in the future and the close link between water and energy. These measures will contribute substantially to the desired increase in profitability and ecological efficiency. Integrated industrial water management can contribute to making the use of new technologies more profitable or even possible, which is a clear advantage. This integrated water management is increasingly considered by industry. When reducing freshwater demand and wastewater release towards closing water loops, economic and ecological limitations have to be considered, especially in the case of zero liquid discharge (see Sect. 2.4).

1.2 Challenges and Drivers for an Integrated Industrial Water Management

According to experts at the World Economic Forum, the most important social impacts in the next 10 years are likely to result from water crises [5]. Energy and food security are requirements that are particularly important for water management. Energy production, water, food security, and climate change are interlinked through interactions and feedback [1]. Dealing with these challenges becomes one of the most important tasks in integrated water management, especially for industry, as public water supply and food security (agriculture) are always of the highest priority.

The specific challenges for industry in this respect are: increasing resource efficiency (water, energy, raw materials) while decoupling the increase in production, and developing wastewater management for circular economy. New concepts and innovative technologies need to be applied to address these challenges. Industry tends to focus on maxi-

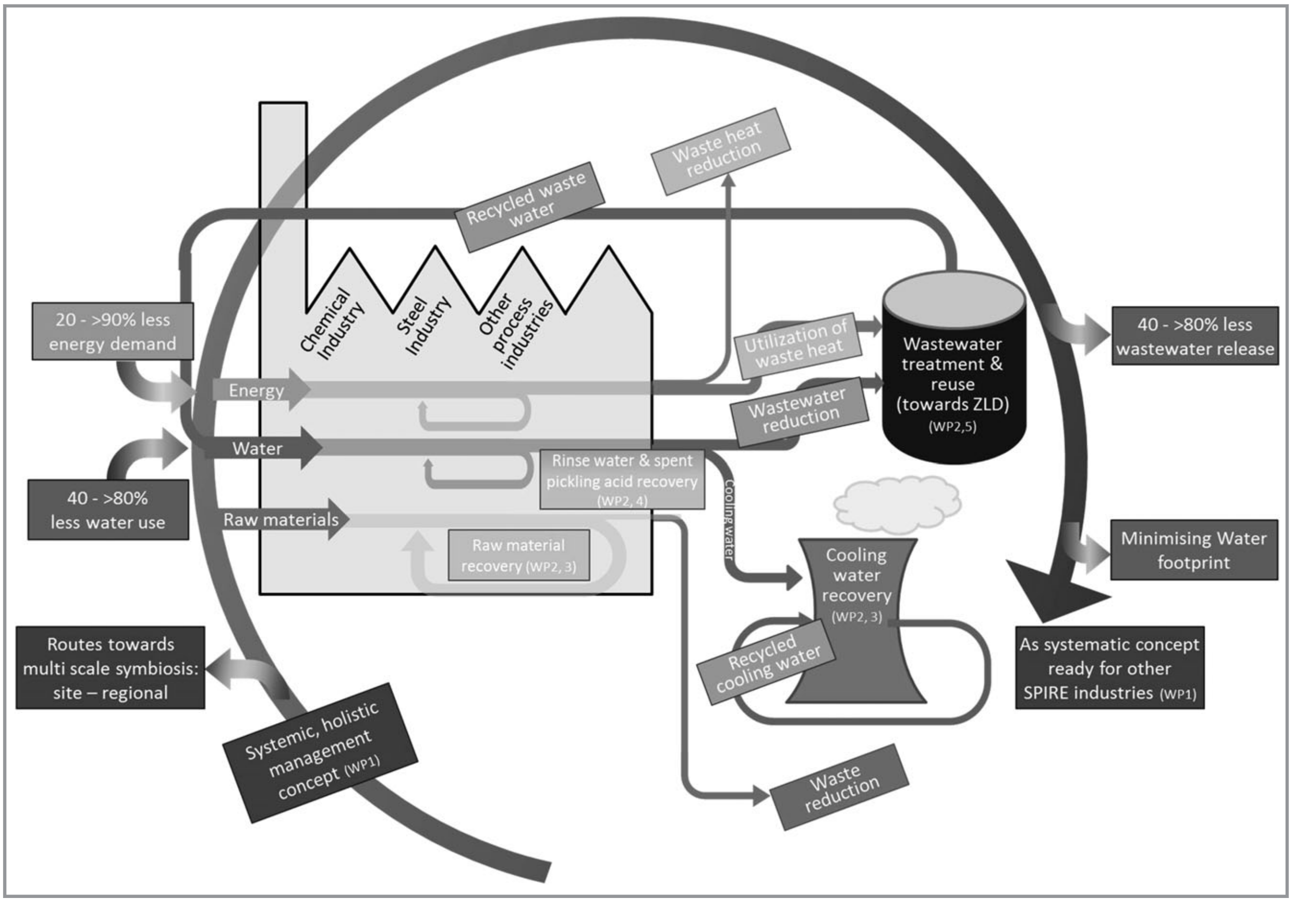

Figure 1. An example of integrated industrial water management used in the EU project INSPIREWATER [14].

mizing production and minimizing costs, and due to the very low economic price of water, minimizing water consumption is rarely a priority [3]. Moreover, company-specific information on water flows and actual water-related indirect and hidden[1)] costs is limited or not included, which makes it difficult to estimate the actual costs/values of water. An example of this could be that a company has to reduce its production due to water shortages, which is accompanied by a tremendous economic deficit. There is currently no standardized methodology or framework, the estimation of the value of water must be based on an integrated approach.

Some challenges can also be drivers for an integrated water management. There are drivers of natural or man-made origin; the most important natural factor is water scarcity, but human factors are also important, such as regulatory frameworks, e.g., stricter discharge limits, sustainability, or economic aspects. With regard to water security, the most important driver is water scarcity. Moreover, water stress is caused by usage competition – several actors, such as municipalities, agriculture, industry with several water functions, such as resources for supply, transport, and ecosystem services, are drivers for integrated industrial water management. These drivers are risk-based. Physical risks (water quality/quantity), regulatory risks (restrictions on water withdrawal/discharge, rising water prices), and strategic risks (securing production capacity, negative image in the media) play an important role here.

Integrated water management is not only important in countries facing severe water scarcity due to climate conditions, e.g., Mediterranean countries. Water stress can occur on different scales; therefore, regional/local water shortages can also occur, e.g., in Germany, especially in areas with different use scenarios, i.e., industry, large communities, and agricultural land, as well as coastal areas and saline groundwater.

2 Solutions: Examples for Integrated Industrial Water Management

Solutions can include water reuse, industrial symbiosis, the use of alternative water resources and, under certain circumstances, the utilization of resources up to zero liquid discharge.

1) Costs relating to water shortages, risks, and societal impacts.

2.1 Water Reuse

Reusing water in industry is becoming increasingly important, especially in view of the concepts of circular economy. The paradigm of wastewater management is shifting from treatment and disposal to reuse, recycle, and resource recovery [15]. This trend is especially evident in the process industry. As an essential part of circular economy, the reuse of wastewater, can be cost-efficient and the recovery of by-products can open up new business opportunities, e.g., for nutrients, metals, and other valuables [12]. In industry, wastewater is increasingly being considered as a potential resource and its use or recycling after suitable treatment as a potential way to generate economic benefits, reduce pressure on water resources, or to complement corporate social responsibility. Particularly in areas with severe water stress, examples and case studies for water reuse in industry exist [16]. In regions where supplies are plentiful and water costs are low, investments in water reuse are often non-existent in the absence of a driver.

In Germany, water reuse and recycling in industry already plays a major role in various industrial sectors. Several process industries, which require large quantities of water, have been recycling or reusing water for a long time, e.g., the chemical [17], paper [18], or steel industry [19]. In the process industry, the largest consumer of water is the chemical industry; water is used multiple times, mainly for cooling processes. The reuse of water in other areas of application has played a subordinate role at German sites to date [20]. Reasons for this are sufficient freshwater availability or missing incentives, e.g., economic efficiency or highly polluted wastewater, which requires high effort and costs for treatment [4]. There is no universal solution for water reuse. Depending on the type of industry, location, existing infrastructure, and boundary conditions, individual solutions have to be developed and demonstrated.

The German Federal Ministry of Education and Research (BMBF) has recognized the importance of water reuse early on. Its funding measure "Future-oriented Technologies and Concepts to Increase Water Availability by Water Reuse and Desalination – WavE" [21] shows the importance of water reuse amongst others for the industrial sector. In eight out of 13 joint research projects, water reuse for industry is addressed from different perspectives and with different approaches. The high level of industry participation and relation to practice is particularly noteworthy. Solutions are to be developed for various sectors, including chemicals, steel, automotive, and mining. Also, concepts for industrial parks, industrial symbiosis, and management of concentrates or residual materials are on focus.

2.2 Industrial Symbiosis

Water can be reused within a business itself or integrated as an element in a wider network of users through industrial symbiosis. In an industrial symbiosis, one company uses underutilized resources, e.g., waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment, and materials, from another and generates benefits for itself and all parties involved. The benefit can be economic, but also a reduction of environmental impacts and the increase of operational efficiency in a certain area can be achieved [22].

Especially within the chemical industry, the industrial symbiosis concept has long been implemented at production sites. Chemical parks can be seen as prototypical examples of industrial symbiosis in which symbiotic links have already been optimized to a very large extent [23]. One example for an industrial symbiosis approach is the Shanghai Chemical Industry Park, one of Asia's largest chemical and petrochemical platforms. With an integrated symbiotic approach, 580 000 m^3 of clean water per year are saved. [24]. The supply of drinking and industrial water, treatment of highly polluted effluents and management of hazardous waste is done by one company, SUEZ. With a public-private partnership and a contract duration of 50 years an independent water supply, wastewater treatment and waste incineration are possible. The goal is to reduce industry's impact on the environment by preventing pollution. This is implemented with a reduce, recycle, and reuse approach. As a master of all the water and waste facilities of the chemical industry park, the company is following the goal to produce industrial water (390 000 m^3d^{-1}), treat combined industrial wastewaters (50 000 m^3d^{-1}), and produce recycled water, incinerate hazardous waste (150 000 $t\,a^{-1}$), and produce recycled heat [24].

For a further increase in efficiency in densely populated countries like Germany, industrial symbiosis offers great potential, e.g., at the borders of a chemical park. A symbiotic exchange between different industry branches or also sectors, e.g., between industry and municipalities, can be particularly useful for already existing industrial settlements.

2.3 Alternative Water Resources

The use of alternative water resources for water reuse, such as specifically treated municipal wastewater, is another option to reduce the pressure on water resources. Within the BMBF funding measure WavE, the joint research project MULTI-ReUse currently investigates this possibility in the northern part of Germany. The project aims at developing flexible and modular process chains for the production of defined water qualities and quantities starting from conventionally treated wastewater [25].

Another already implemented use of treated wastewater is realized in the city of Terneuzen, the Netherlands (Fig. 2). Terneuzen, a major seaport in the south-western Netherlands, lays approximately at sea level and faces a constant threat of saltwater intrusion into the shallow aquifers. Dow Chemical Company operates the world's second largest site

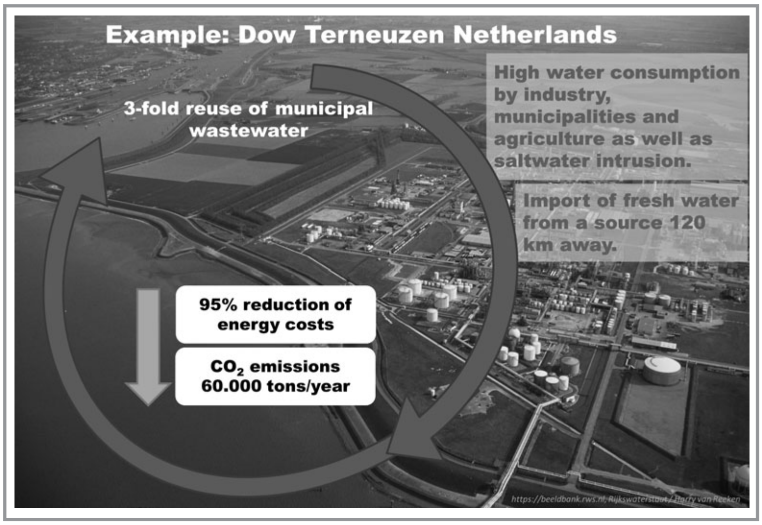

Figure 2. Water reuse example Terneuzen, the Netherlands, adapted and modified from [26].

here, with high consumption of cooling water and process water for steam generation.

The region on the delta of the river Scheldt is increasingly suffering from water stress due to the high water demands of industry, agriculture, communities, and recreational areas. The region has been importing fresh water from a source 120 km away for decades to meet the demand for drinking and industrial water. The water to be reused is first used by the municipality, then passes through the treatment of the municipal wastewater treatment plant and is then further treated by membrane filtration for industrial reuse as boiler feed water and cooling tower make-up water. After use, it is finally evaporated into the atmosphere or, after renewed treatment, discharged into the river [16, 26].

An example for the use of treated industrial wastewater as an alternative resource for agriculture can be found in the north-east of Lower Saxony, namely, in Uelzen, Germany: since 1987, purified production wastewater from sugar production has been made available to agriculture. In two reservoirs of the Uelzen Water Association, water, which is produced and anaerobically purified annually in the winter half year at the Uelzen plant of Nordzucker AG, is stored and used by agriculture for irrigation during the growing season [27].

2.4 Zero Liquid Discharge

Zero Liquid discharge (ZLD) is an ambitious wastewater management strategy that prevents liquid waste from leaving the plant boundary to recover and reuse most of the water. No wastewater leaves the system, but sludge, brine, steam, aerosols, or water by leaching. The solids are recycled or separated to be disposed. In general, the ZLD process is characterized by intensive energy use (resulting in higher CO_2 emissions) and high costs for concentration, concentrate treatment, and disposal [11, 28, 29]. Stricter regulations, rising wastewater disposal costs, and increasing scarcity of water in specific areas are the main drivers for ZLD (Fig. 3).

Globally, the United States, China, and India are the most important ZLD markets; in Europe, Germany and Italy are leading the way [28, 30]. The impetus for ZLD has resulted from an increase in scarcity of fresh water and, also, a tightening of regulations and restrictions relating to discharges. The capital cost associated with the technology investment can be significant; however, the savings over time can be substantial. Once the true cost is determinable, the savings can be estimated accurately, and the investment can be justified [3]. Life cycle analysis can be a valuable tool in this regard.

An actual example for the implementation of water reuse and concentrate treatment towards ZLD is shown in Tarragona, Spain, in a case study from the EU-project INSPIREWATER [14]. This region is facing the severe problem of water scarcity. With full reuse of water, this offers the possibility of saving more than 70 % of fresh water, which offers great potential for environmental benefits in areas with polluted water, such as Tarragona.

The handling of concentrates and residues resulting out of increasing water loop closure down to ZLD is one of the main bottlenecks for both approaches. High costs for concentrate treatment combined with limited opportunities for valorization of the resulting residues or significant disposal costs are the reason. This challenge is currently being addressed by the joint research project "Resource Recovery from Concentrates Arising from Industrial Water Reuse – HighCon" [31] within the BMBF funding measure WavE. HighCon is developing innovative, multi-stage, and selective processes for the reuse of industrial wastewater up to the recycling of the concentrate ingredients.

3 Future Priorities

The aforementioned challenges, drivers, and solutions towards an integrated industrial water management result on the one hand from the main anthropogenic developments such as climate change and increasing water stress. On the other hand, increasing social attention to clean water and sanitation (Sustainable Development Goal 6), water safety, stricter regulations (health and ecology), and corporate responsibility are among the priorities of the future. They prepare the ground for technical, digital, and nontechnical innovations. These developments and priorities will continue to set the course for future integrated water management, especially in the industrial environment.

Most notably, digitization will play an increasingly important role in this context. Today, we are on the cusp of the

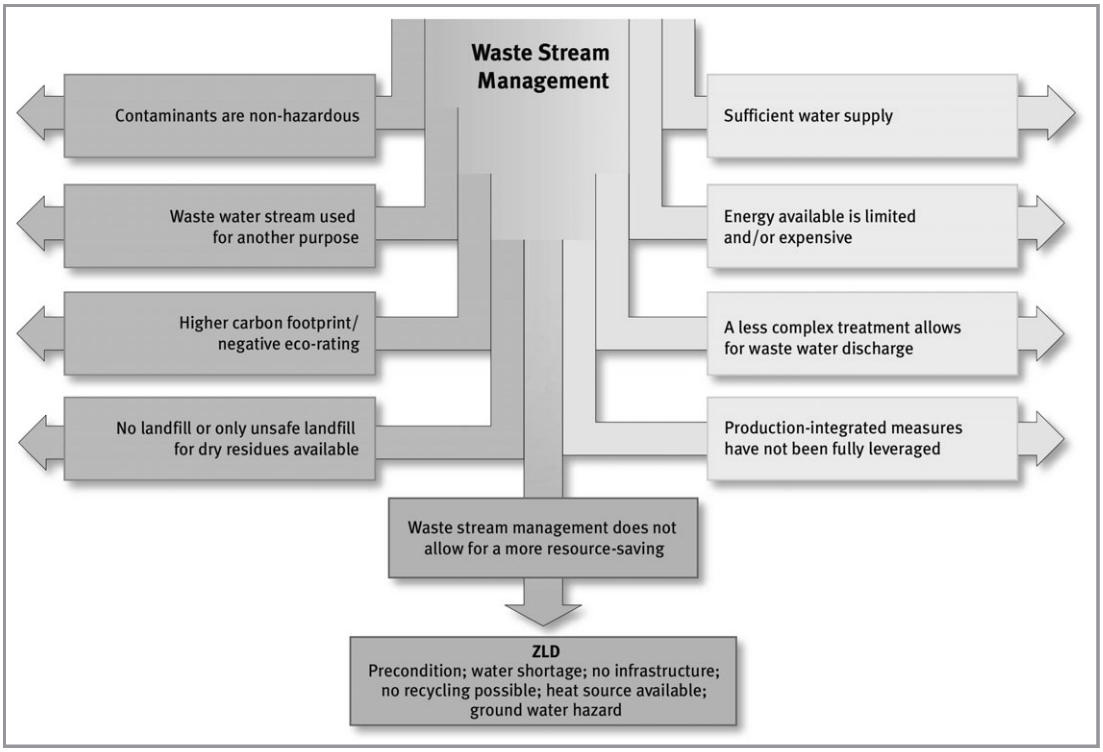

Figure 3. Drivers and benefits of zero liquid discharge (ZLD), reprint from [29].

fourth industrial revolution. In 2013, amongst one of 10 future projects identified by the German government as part of its High-Tech Strategy 2020 Action Plan, the Industry 4.0 project is considered to be a major endeavor for Germany to establish itself as a leader of integrated industry [32]. During the fourth industrial revolution, the use of cyber-physical systems (CPS) has triggered a paradigm shift in industries, in particular the manufacturing sector [33]. While digitization in industrial production and the process industry is progressing rapidly, the level of digitization in water management has not yet reached a comparable level. This requires water management, especially in industry, to become more flexible and integrated in industrial production (Fig. 4). Experts from process industry, digitization, and industrial water management have described in detail how this can be achieved in the position paper on Industriewasser 4.0 [34].

Alongside the challenges associated with digitization, aspects such as stricter regulation and increasing water scarcity will set the tone for developments in water reuse and effective integrated industrial water management. One example are the stricter environmental regulations in China, which put pressure on industrial sites with regard to their emissions. The government is increasingly focusing its attention on industrial water management. The Environmental Protection Law, which came into force in 2015, calls for greater transparency and stricter monitoring. Companies that meet the legal requirements are rewarded with financial incentives, e.g., tax relief, while other companies face high administrative and financial penalties, including closure of the production plant [35]. Furthermore, costs for fresh water will most likely increase in the future [36]. Reasons are the aggravating water stress, e.g., caused by water usage competition, the increasing energy demands, and the concept of the value of water.

Companies are expected to declare a water footprint in a similar manner to the declaration of a carbon footprint presently. This footprint will be applicable to products, processes, and organizations and will be based on life cycle assessments (LCAs). It will be necessary to accurately quantify the water used, in a verifiable and consistent manner. To facilitate this, a new international standard, ISO14046, entitled Environmental Management: Water Footprint, was launched in July 2014 [3, 37]. Water may also be managed in a modus similar to energy. Certain organizations have already adopted water as a form of energy and successfully managed the demand-side using standards including ISO50001, the Energy Management standard [38], and have proven it to be successful [39]. Decisions are taken on the basis of the LCA, life cycle costing (LCC), and other tools to evaluate sustainability; knowing the substances contained in industrial wastewater and wastewater partial flows and avoiding transformation products resulting from biological/chemical degradation processes as well as the release of substances by water treatment processes [11].

Continuing the transformation of our economy towards a biobased economy will also require efficient water management solutions for biobased production processes. A lot is

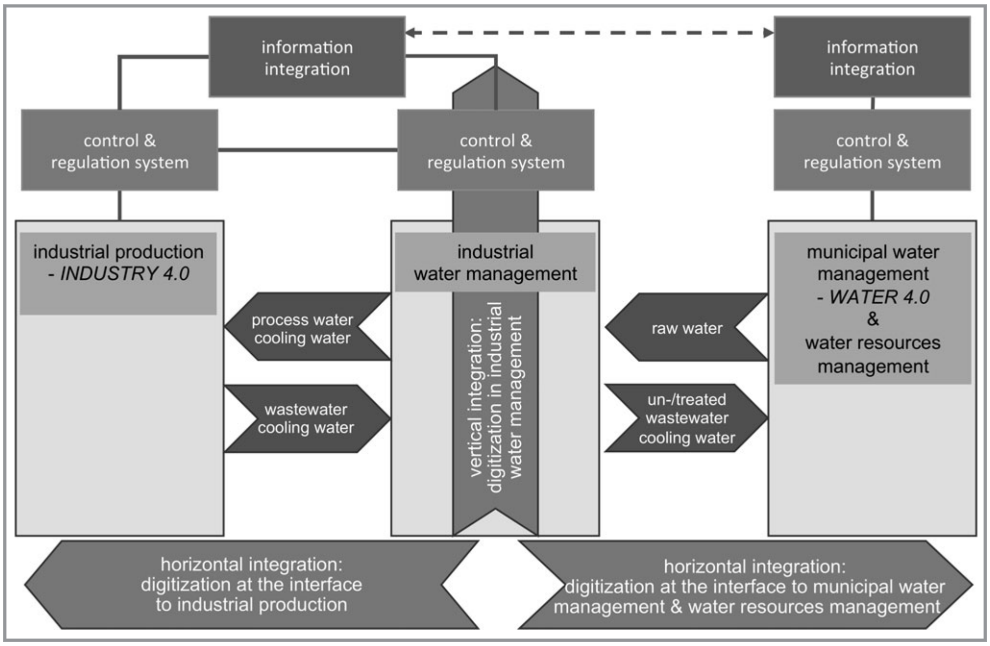

Figure 4. The integration of Industrial Water 4.0 (Industriewasser 4.0) in industrial production and municipal/water resources management, modified from [34].

already done in this sector but realizing the aforementioned targets also for this sector is an important future development path.

The drivers mentioned before are pushing the development of innovative and integrated technologies for a more economical and ecological treatment of water for recycling and reuse, which is one of the cornerstones of successful realization. In industry, the development of these technologies and management systems is of great importance because of the particularly strong link between water and energy demand, raw material input, and resource recovery in industrial production processes. A tailor-made process management adapted to the respective industry can improve resource efficiency while taking the value chain into account and avoiding material inputs into the natural water cycle.

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