DECHEMA

VDI

Trends and Perspectives in Industrial Water Treatment

Raw Water – Process – Waste Water

Position Paper by the ProcessNet Subject Division Production-Integrated Water/Waste Water Technology

ProcessNet

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Summary

Water is vital for the industry sector, both at the national and at the international level. The water technology needs of the industry sector do not only differ fundamentally from those of the municipal sector, they also vary strongly between industries and locations so that standardized solutions are not feasible. Rather, the different needs call for a combination of methodical/technical know-how and customized process technology. In view of the close interaction between production and water technology, integrative technologies and management systems are called for.

The resulting integrated, sustainable industrial water management curbs the dependency of production processes from external water, raw materials and energy sources and from other influencing factors such as the regulatory framework. It is not only relevant for the German market, but also boosts the export of technologies, equipment, engineering and other services and enhances the competitiveness of German companies in the international markets.

In view of the high innovation potential of an integrated, sustainable industrial water management, the ProcessNet Subject Division "Production-Integrated Water and Waste Water Technology" set itself the task of presenting the trends and perspectives in industrial water treatment.

Using the present situation as a basis, a vision for the situation in the year 2030 is derived from the (mega) trends and the R&D targets, challenges and resulting fields of action are defined. In a next step, the research and development needs to realize this vision are described and potential routes to realization are presented (Fig. I).

With a view to the state of the art in the year 2030 the following R&D targets for an integrated, sustainable industrial water management can be defined:

» Smart management systems control the distribution and utilization of water with due consideration of the technical/natural water networks and cycles (smart networks). Waste water is routed to municipal waste water treatment plants and surface waters taking into account the performance capacity of the infrastructure in place with the aim of avoiding damage to natural water bodies and shifts into other environmental compartments. These premises also apply for the emission of heat.

» The continuous optimization of production systems by production-integrated processes results in a progressive reduction of water demand and pollution loads and enhances the economic efficiency of recycling process water, valuable substances and process heat. At the same time, demands on water quality are increasing. Investment decisions are taken on the basis of the Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and other tools to evaluate sustainability.

» The substances contained in industrial waste water and waste water partial flows are largely known. Transformation products resulting from biological/chemical degradation processes as well as the release of substances by water treatment processes are largely avoided or almost completely biodegradable (mineralizable).

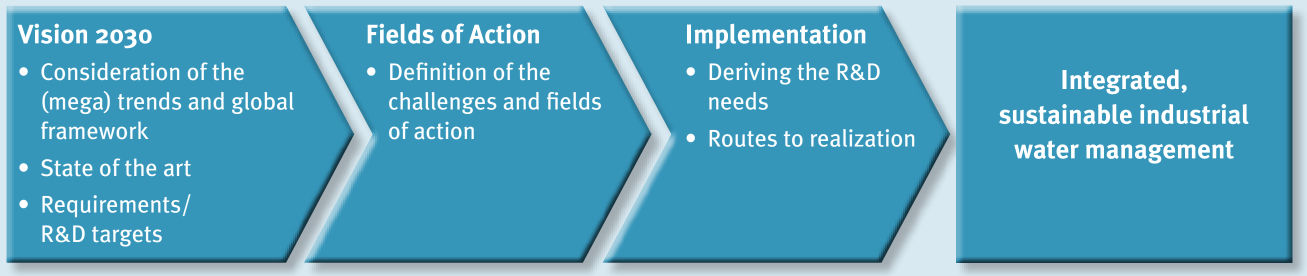


Fig. I: The route towards an integrated, sustainable industrial water management

SUMMARY

Fourteen fields of action with the corresponding R&D needs can be derived from the Vision 2030:

1. Smart water management
2. Water: quantity, quality, resources
3. Waste water: networks, sewage treatment plant, receiving water, waste water levy
4. Pollutants, hygiene: substances, concentrations, limit values
5. Water-energy nexus
6. Technology: integration, efficiency enhancement, transfer
7. Recovery: raw materials, valuables, energy
8. Footprint: CO_2, virtual water, life cycle assessment (LCA)
9. Change of industrial production
10. Environment: climate, residues
11. Salts: regional/global, medial shift, reduction, salt utilization
12. Socioeconomic environment
13. Responsibility for the future: holistic approach, consequences of an optimized water management
14. Qualification and public relations

These fields of action and the resulting development needs in turn lead to R&D focuses for cross-technology approaches and processes that must be addressed already today so as to be able to achieve an integrated, sustainable industrial water management by the year 2030:

» Production-integrated measures targeting an energy-efficient water recycling

» Recovery of valuables

» Handling of salts

» Biological processes

» Advanced oxidation processes

» Membranes for water and waste water treatment

In this position paper, the present situation for these approaches/processes is described, their application potentials characterized, the specific research and development needs are derived, and the anticipated impact of their realization is assessed.

I Trends und Perspektives

1 Introduction

Water is vital for industry, both at the national and at the international level. The water technology of the industrial sector differs fundamentally from that of the municipal sector as a function of the specific needs of each sector. In the industrial sector, these requirements vary strongly between industries and locations so that standardized solutions are not possible (cf. Fig. 1). Rather, the different needs call for a combination of methodical/technical know-how and customized process technology. In view of the close interaction between production and water technology, integrative technologies and management systems are called for.

An integrated, sustainable industrial water management curbs the dependency on natural water resources and other influencing factors such as energy or the regulatory framework. It is therefore not only relevant for the domestic market, but also boosts the export of technologies, equipment, engineering and other services and enhances the competitiveness of German companies in the international markets.

The ProcessNet Subject Division "Production-integrated Water and Waste Water Technology" examines the state-of-the-art of science and technology and new perspectives in the field of production-integrated (waste) water treatment. The division's aim is to integrate the industrial utilization of water into the entire water economy with consideration of sociological effects and to consistently improve its ecological and economic efficiency. The Subject Division offers a forum for the interdisciplinary exchange of ideas and experiences among experts from industrial production, process development, environmental technology, plant engineering and construction as well as from engineering contractors, associations and the relevant authorities. In the process, new needs for R&D and application are identified and the technology transfer from scientific research to commercial implementation is promoted. r aus der Wissenschaft in die industrielle Praxis gefördert.

In view of the high innovation potential of an integrated, sustainable industrial water management, the Subject Division has set itself the task of presenting the trends and perspectives in industrial water technology. The present paper is primarily based on the situation in Germany, but also takes into account the fact that industrial production in the same way as the water technology are embedded in an international context. Based on the present situation, a vision for the situation in the year 2030 is derived from the (mega) trends and development targets are defined. Although forecasts always involve elements of uncertainty, they encourage discussions and open up the opportunity for developing new perspectives and – as a function of the period under review – also systemic solution approaches. With the year 2030, a manageable period of time has been defined that is sufficiently large for developing systemic concepts.

From the vision for the year 2030, the challenges and the corresponding fields of action are derived. To achieve the defined development targets, the research and development needs for the implementation are described and potential routes to realization are shown (cf. Fig. 2).

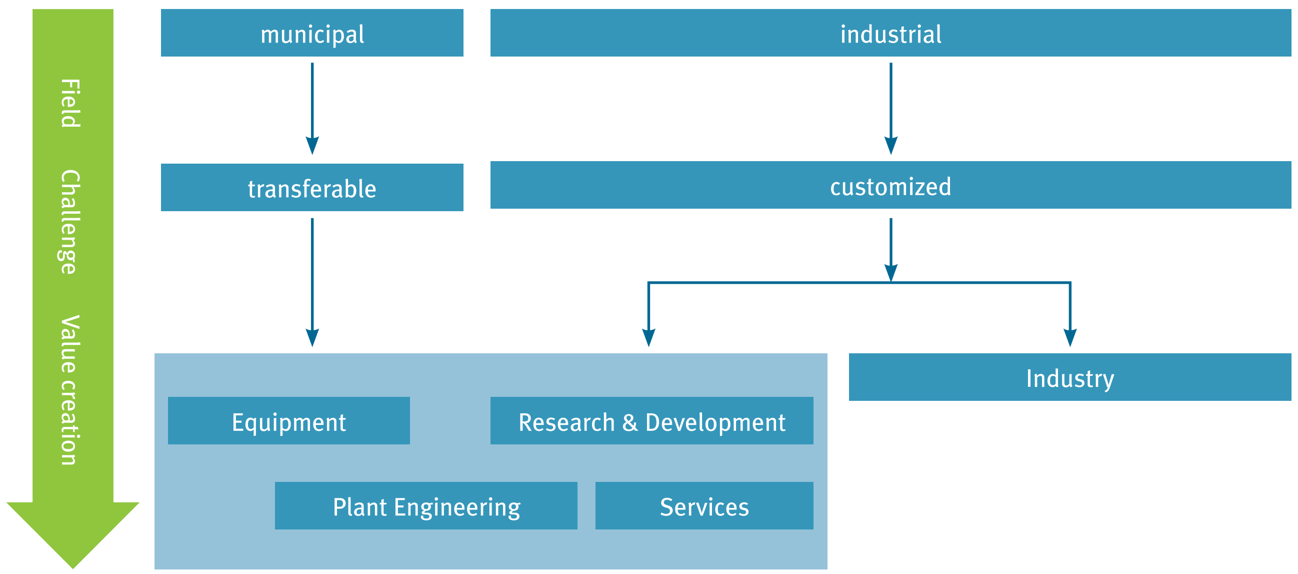


Fig. 1: In the industrial sector, and especially at the international level, a large number of players benefit from innovations in (waste) water technology

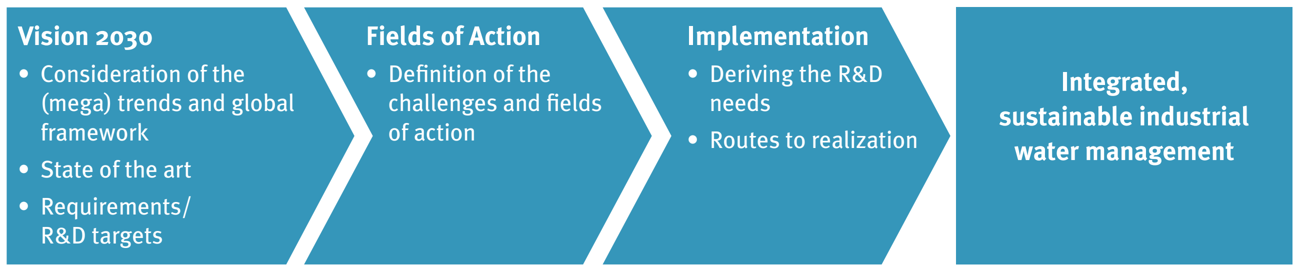


Fig. 2: Methodology for the development of an integrated, sustainable industrial water management: from the vision 2030 to the fields of action through to realization

1.1 Present Situation

The heterogeneous use of water in industrial processes requires different process water qualities. Various treatment processes are used as a function of the raw water available and the process water specifications (cf. Fig. 3).

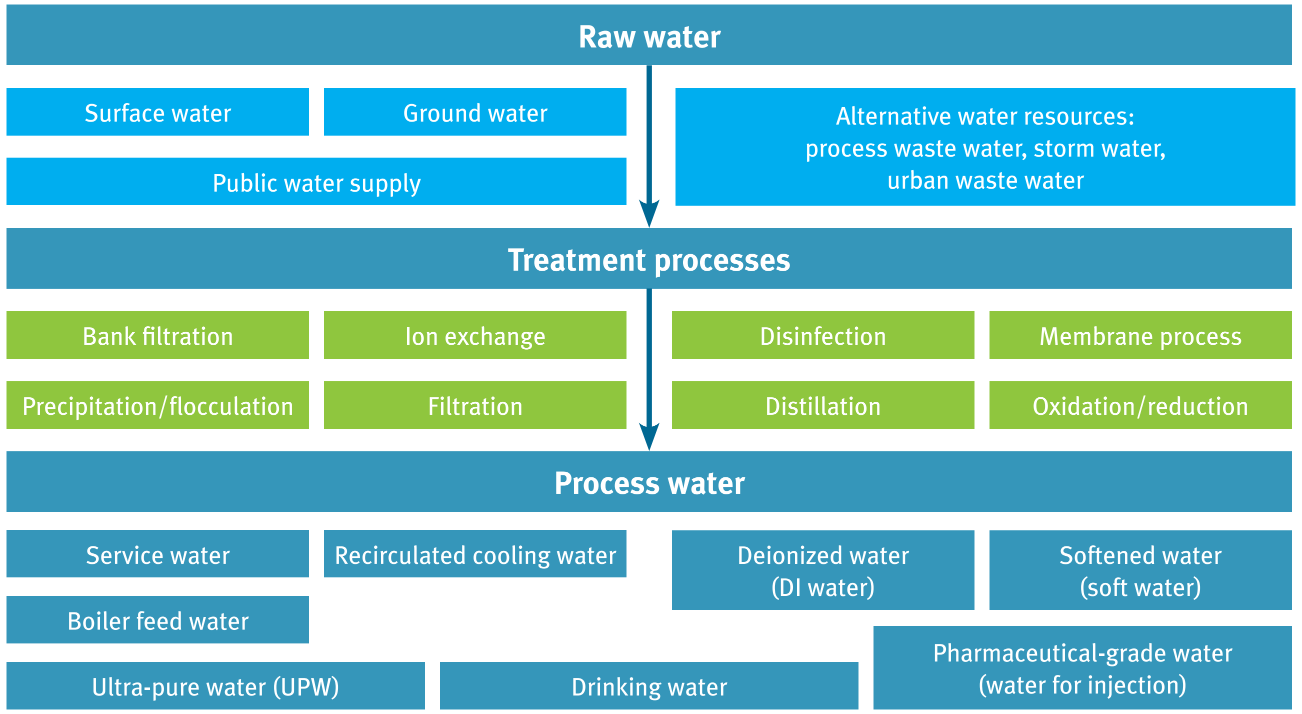


Fig. 3: Industrial process water supply

In Germany, around 90 % of the process water (cf. Fig. 4) is treated after use in line with the statutory requirements and finally discharged into surface waters. The water recycling technologies used for certain applications use water and energy resources sparingly. For an optimal water utilization, process waste water recycling must be combined with water treatment (cf. Fig. 5)

At 26.5 billion m^3/a, the quantity of industrially used water in Germany in 2007[2] amounts to six times the quantity of water used for residential and commercial purposes (4.5 billion m^3/a). Only 1.1 billion m^3/a (4 % of the industrial waste water) are discharged to municipal waste water treatment plants (cf. Fig. 4). This significant difference is attributable to the fact that, especially the cooling water, which accounts for around 92% of the fresh water used, can be directly discharged into the water bodies in the required quality.

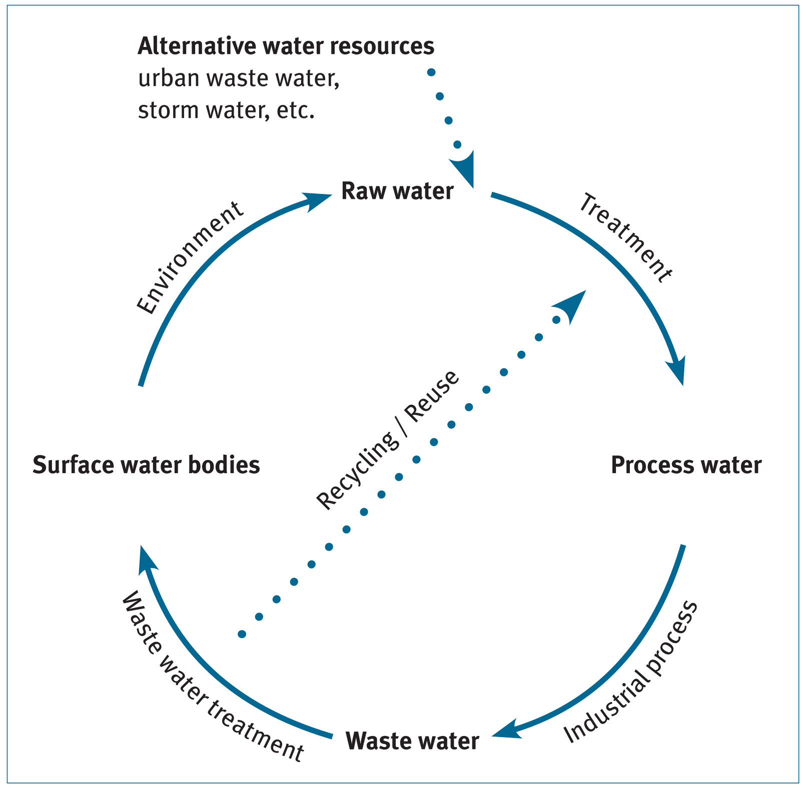


Fig. 5: The industrial water cycle, conservation of natural water resources through recycling/reuse of water and use of alternative water resources

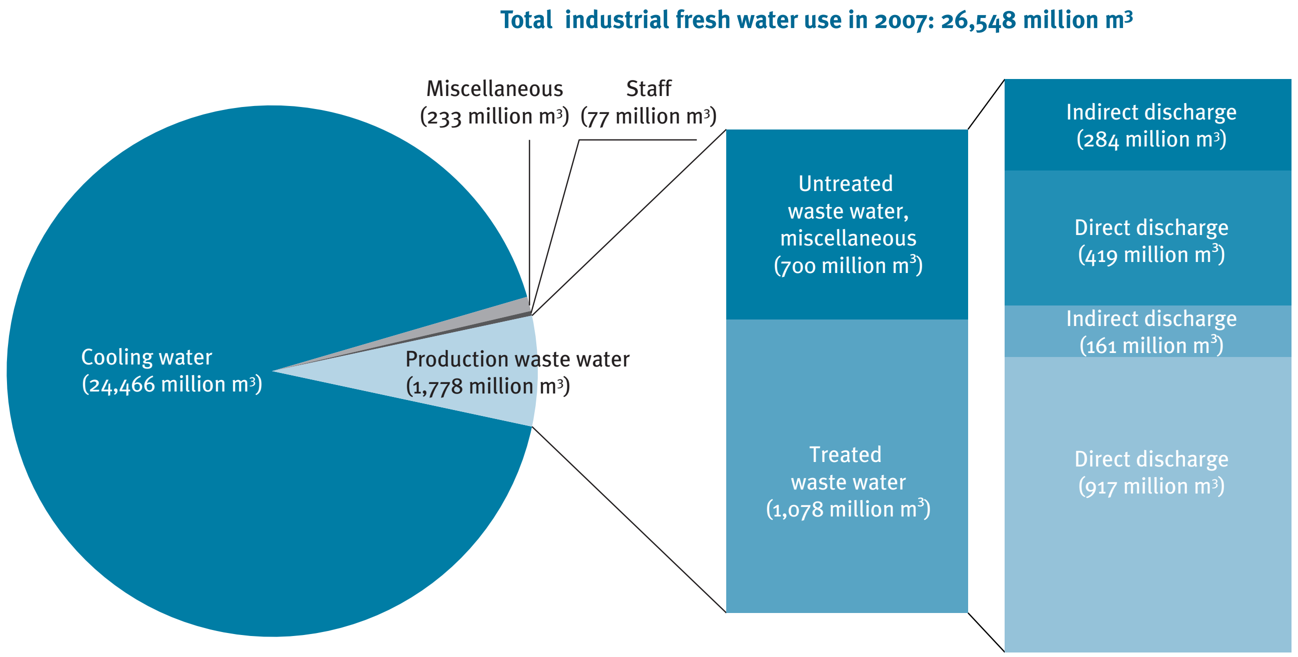


Fig. 4: Fresh water utilization[2]

1 German Federal Statistical Office, Wiesbaden 2009
2 Geißen et al., Chem.Ing. 84 (2012) 7

Over the past decades, optimization of the production processes resulted in a substantial reduction of the production-specific water demand and in an improvement of the waste water quality. From 1991 to 2004, the water intensity factor including cooling water in the chemical industry improved by 25 % to around 90 L/€.[3], for example. In the last decade, this development was accompanied by investments into waste water treatment involving, among others, a growing number of anaerobic cleaning units.

In Germany, the chemical industry together with industrial biotechnology, is considered the leading industry for water use. Presently, it generates the largest waste water quantity (cf. Fig. 6) and will also in future contribute significantly to the growth of industrial production in Germany together with the automotive, electrical and plastics industry as well as with the mechanical engineering sector. Compared against other manufacturing industries, the forecast development until 2030 in this leading sector is more dynamic at 1.8 % growth per annum in Germany[4]. Moreover, the chemical industry, through the development of new process techniques, materials and chemicals, offers a high innovation potential for solutions for (waste) water treatment at the industrial and municipal level.

Besides the further optimization of production processes, currently an intensification of waste water recycling with the aim of curbing demand for fresh water and thus process (waste) water costs can be observed. Also the utilization of the waste water heat and, in individual cases, the recycling of valuables contained in the waste water are recent trends in industrial water utilization. Since first technologies and measurement techniques are now available, the implementation of such process modules can substantially contribute to cost reduction already today.

The motivations for investing into the treatment of process waste water and the reutilization of water are illustrated in Fig. 7. Different countries have different priorities depending on their level of development. Most developing and emerging nations have great demand for an extension of industrial waste water treatment, the implementation of which to a substantial degree depends on the gross domestic product and the availability of water. Moreover, also the strategies of global corporations as well as national (e.g. Chinese mega water projects) and international programs (e.g. European Water Stewardship[6], CEO Water Mandate of the UN Global Compact[7]) play a crucial role.

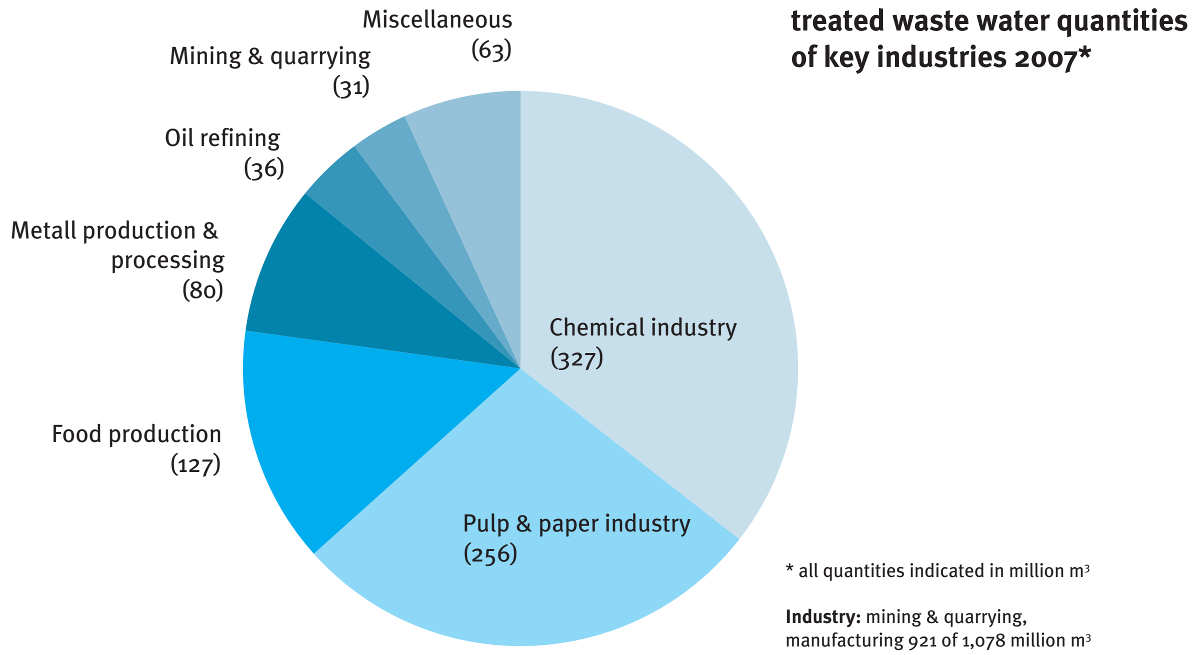


Fig. 6: Waste water volumes in various industry sectors[5]

3 Hillenbrand, T. et al., Technische Trends der industriellen Wassernutzung, Arbeitspapier, Fraunhofer-Institut für System- und Innovationsforschung, Karlsruhe 2008
4 VCI-Prognos Studie, Die deutsche chemische Industrie 2030, VCI, Frankfurt 2012
5 Geißen et al., Chem.Ing. 84 (2012) 7
6 www.ewp.eu/activities/ews
7 http://ceowatermandate.org

To assess the water demand, water availability and associated risks under different conditions around the globe, industry can rely on tools such as the "Water Footprint", the "Global Water Tool" of the World Business Council for Sustainable Development (WBCSD), the "Water Sustainability Tools" of the Global Environmental Management Initiative (GEMI), and the "Aqueduct Tool" of the World Resources Institute[8]. Tools that allow for a holistic assessment, like the Life Cycle Assessment (LCA) and the Life Cycle Costing (LCC), have so far only been applied in isolated cases.

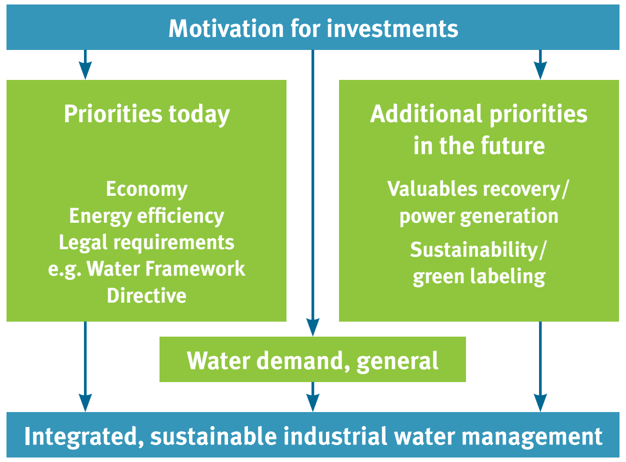


Fig. 7: Investment drivers

1.2 Near Future

In addition to a further reduction of costs, the industrial utilization of water in Germany will over the next five to ten years mainly focus on compliance with the requirements of the European Water Framework Directive and the waste water regulations which are currently under revision. With the planned changes in the national waste water regulations, the integrated approach is for the first time implemented in the form of a cross-environmental compartment analysis of energy efficiency and resource conservation. This principle will also be transferred to the treatment of process waste water.

In waste water recycling, a major part of the costs results from the infrastructure required, which is in most cases very difficult to adjust in existing plants. For this reason and due to the water, heat and valuables recycling processes under development, the production-integrated recycling of waste water will only be realized nation-wide in the years to come. For the implementation of recycling systems it must be considered that the retained concentrates need to be collected and treated. Moreover, the future water demand and heat load for the water bodies will be lower as a consequence of the development and implementation of more efficient cooling systems.

Measures for saving water, treating process waste water and water recycling will increasingly be assessed using the LCA and LCC tools.

8 Overview at http://ceowatermandate.org

2 Vision 2030

Because mega trends such as

- consumption and population growth,
- shortage of resources,
- climate change and
- the growing significance of environmental protection

uare uncontested[9], a look at different scenarios for the year 2030 is not necessary. This notwithstanding, the forecast trends may vary locally in the short to medium term, e.g. as a result of natural disasters, the discovery of new raw materials deposits or political decisions.

The vision for 2030[10] by the European Water Partnership in principle also applies for industrial water treatment:

"We have achieved sustainable water resource management and universal access to modern and safe water supply and sanitation because we value water in all its dimensions – in its economic, social, environmental and cultural importance"

In view of the rising efficiency of industrial production, the specific water demand will be dissociated from production growth even more than before. However, no reliable data exist at present about the magnitude of the economically achievable water savings potential for the German and European industry. In any case, it depends to a high degree on the respective location and industry sector. A reliable evaluation of the achievable reduction of contamination in the process waste water and of the potential for recycling valuables and heat is not possible either. The prerequisites for realizing an integrated, sustainable industrial water management are the financial viability of investments in environmental protection as well as the motivations summarized in Fig. 7.

2.1 General Framework 2030

From the above-listed mega trends, the following globally applicable general framework can be derived that will in all probability also be relevant for Germany in the year 2030:

1) Water remains the main solvent.

2) Across the world, the demand for water will continue to rise (primarily due to a rise in the standard of living, secondarily due to population growth and ageing populations). In this context, the continued strong GDP growth in China, India, Brazil, South Korea and Mexico plays a major role[11]. In Germany, the water demand will drop at constant industrial value added.

3) Owing to climate change, the average annual temperatures will rise ("+2 degree society").

4) The population is better educated and sets greater store by environmental protection. Customer buying and market behavior promotes green /eco labeling.

5) The implementation of technologies is assessed using a holistic approach.

6) New industries (e.g. biorefineries, industrial biotechnology), new materials, new media for energy storage and alternative forms of power generation are established.

7) The cost pressure has increased, also due to the rise in costs for energy and resources and to the strong global competition.

8) Complex and difficult to exploit raw materials deposits are increasingly mined.

9) The demand for mining/recovery of valuables (e.g. phosphorous, rare earths) grows.

10) The European Water Framework Directive and other legal regulations will become increasingly stringent in Germany and similar emission-based laws for the protection of the aquatic environment will be implemented worldwide, thereby improving the raw water quality.

11) A local shortage of skilled labor will occur.

12) The availability and pollution of water varies very strongly from one region to the other. In combination with the continued urbanization, local competition among the different water users will increase.

9 Example: http://www.unesco.de/weltwasserbericht4_kernaussagen.html [UN World Water Development Report 4 – Key Messages]
10 www.ewp.eu
11 VCI-Prognos Study, Die deutsche chemische Industrie 2030 [The German Chemical Industry 2030], VCI, Frankfurt 2012

2.2 State of the Art 2030

AUsing the mega trends and the general framework as a basis, the general state of the art of industrial (waste) water technology in the year 2030 can be derived:

» Smart management systems control the distribution and use of water with due consideration of the technical/natural water networks and cycles (smart networks). Waste water is routed to municipal waste water treatment plants and surface waters in due consideration of the capacity of the infrastructure in place and with the aim of avoiding damage to natural water bodies and shifts into other environmental compartments. These conditions also apply for the release of heat.

» The further optimization of production processes using production-integrated processes allows for a reduction of the water demand and contaminant loads as well as for an increase in the economical recycling of the water, its constituents and its heat. At the same time, the demands on water quality will rise. Capital expenditure will be decided on the basis of LCA, LCC and other tools for evaluating sustainability.

» The substances contained in industrial effluents and waste water flows are largely known. Transformation products from biological/chemical degradation processes as well as the release of substances by water treatment processes are largely avoided or such substances are almost fully biodegradable.

From the forecast status of (waste) water technology, the necessary conditions can be derived that need to be created by 2030:

1. Water management is considered already when developing new industries and processes, user-friendly software systems to this effect are available. The systems used are provided with interfaces to the management systems of other companies, local authorities and for the entire local water balance in the catchment area (smart networks). With such networks, the process and cooling water supply as well as the treatment/recycling of process waste water can be systematically controlled as a function of offer and demand.

2. The ecological efficiency of the water management and the processes involved is described using parameters like the water footprint, carbon footprint, environmental footprint; they are assessed using the LCA and LCC tools. The substance and heat flows form an integral part of the water management.

3. The operation and maintenance of industrial plants is automated. Online measurement and analytical instruments are inexpensive and low-maintenance.

4. Water, heat and substances are stored in a network involving all water users – smart networks are in place.

5. Processes are adapted to climatic, geographic and socio-economic conditions.

6. Treated waste water and storm water is used as a water resource.

7. The manufacturers and operators of plants as well as the approving and surveilling authorities are highly qualified from a technical, (socio-)economical and ecological point of view and their work is supported by expert systems. The population is informed about the technical developments and involved in the decision-making processes.

8. Processes established already today are further optimized and combined in a purposeful way; they require little energy and are flexible in terms of the energy source.

9. The utilization of heat and chemical energy is largely established.

10. High-resolution chemical analysis is supplemented with biological methods and models which, in addition to the concentration of individual substances and aggregate parameters, also describe the effects of complex mixtures in small concentrations on nature and humans.

11. Valuable substances are largely separated and recovered.

12. A salt management for industrial effluents has been established.

13. Water-relevant raw and auxiliary materials as well as products and by-products are largely biodegradable.

3 Fields of Action and R&D Needs

Aus den Megatrends, den daraus entwickelten Randbedingungen sowie dem prognostizierten Stand der Technik für das Jahr 2030 lassen sich für den Bereich der industriellen Wasserwirtschaft Handlungsfelder identifizieren, die zum Erreichen der Vision 2030 bearbeitet werden müssen (s. Fig. 8).

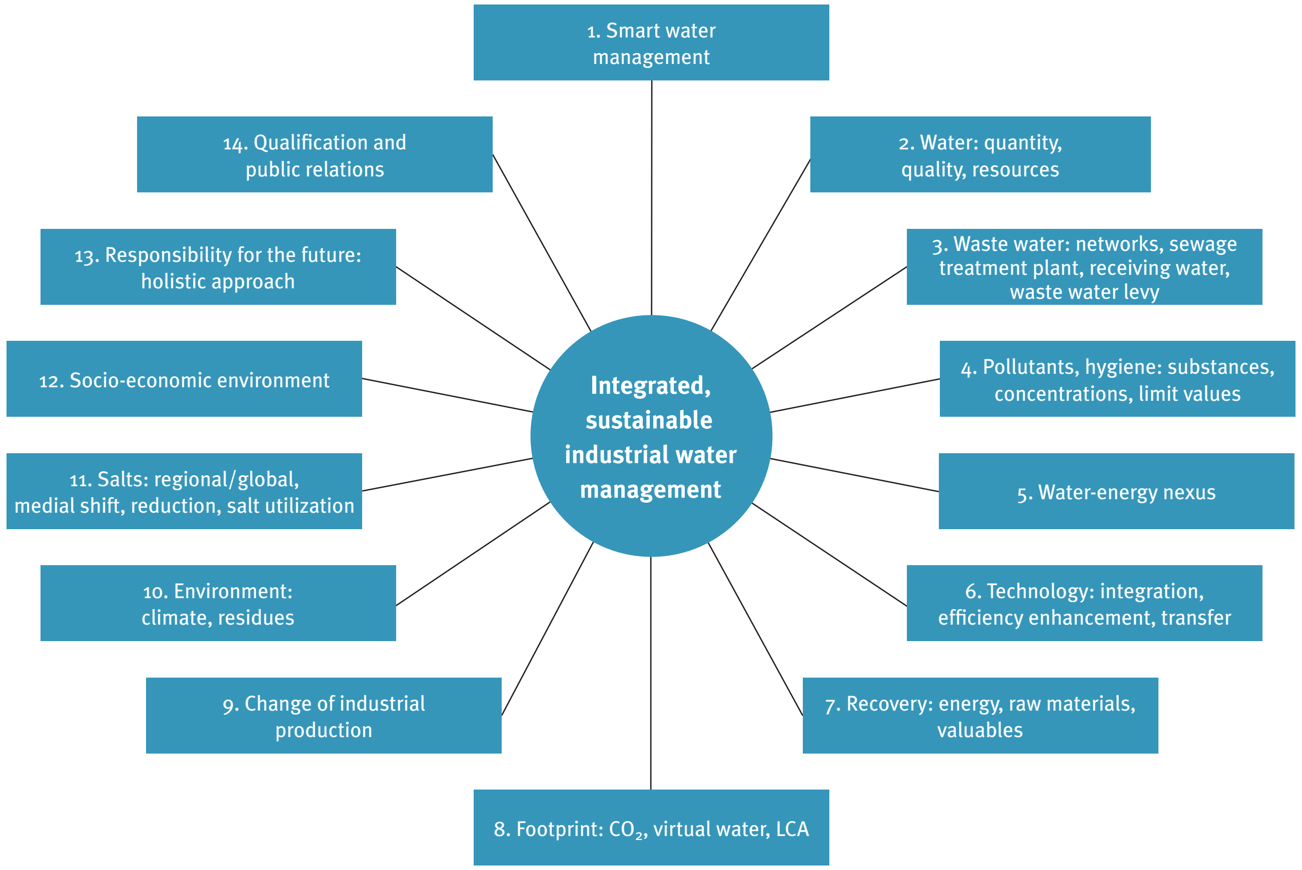


Fig. 8: Fields of action for an integrated, sustainable industrial water management

3.1 Smart water management

Smart water management does not only create a network of users from outside (e.g. local authorities, agriculture, local recreation), but also from within the industry sector. Water management is integrated with the heat and materials flow management. This complexity makes smart water management a multi-faceted, systemic field of action:

» Improvements of single processes only have a limited reach. Therefore, the heat and substance flows must be duly considered for the distribution of water and the treatment of waste water (smart networks). Such an approach guarantees an optimal integration of the in-company and external processes (e.g. sewage sludge digesters) in place.

» All parties responsible for water management must pursue the same sustainable targets.

» Local conditions such as industrial, economic and legal requirements must be considered.

» A systematic approach that is adapted to the system and requires matching software modules in view of the complexity of the processes is purposeful. Such modules must be easy to operate and configure; the interfaces must be compatible with each other and with a water balance master program.

3.2 Water: quantity, quality, resources

Industry's supply with process water depends to a large extent on the location and is also influenced by a vast number of other parameters. One essential aspect is to involve all water resources which results in a complex assessment matrix. Moreover, reduction of the water demand represents an important field of action. In Germany, the availability of water is a limiting factor only at isolated locations and water is only scarce in periods of serious drought. Locations in other countries, including locations in Europe, may be characterized by an extremely limited availability of water. Irrespective of the type of limitation, industry is at a disadvantage compared to the other water users (population, agriculture). With resource-conserving technologies, water can be made available at locations that do not naturally have any water or where it cannot, or not sustainably, be extracted from the underground (e.g. closing of water cycles, multiple use of water in downcycling, municipal waste water). The same applies for locations with a poor water quality (e.g. water contaminated with organic substances, heavy metals, salts). This allows making further land available for industrial or housing purposes.

» As a rule, the "water environment" should be considered. Areas with rich water resources do not require the same technological input as areas with poor water resources.

» The availability of water must be determined at the different locations using the corresponding tools. Adequate instruments for analyzing the availability of water must be developed further. The analysis of worst case scenarios allows taking corrective action in time (e.g. use of alternative water resources, intensification of water recycling). Given the complexity of the processes, such analyses must be performed by models (cf. smart water management).

» For water collection, an evaluation of the resource is required (e.g. ground water vs. surface water).

» Regardless of the raw water resource, qualities and quantities must be made available according to demand. For a cascaded use, domino effects must be considered and implemented in the water management.

» In some industry sectors and countries the trend points towards a further closing of the loops and towards a water-free production (Zero Liquid Discharge – ZLD, e.g. dry vehicle paintworks, pulp and paper industry). These developments are among others triggered by a growing water shortage due to authority regulations and costs.

» A reduction in the cooling water demand must be targeted, e.g. by switching to circulation, hybrid and dry cooling, and by using combined heat and power systems. The demand for cooling water should be included in the holistic assessment of the processes. In addition, blow-down water should be circulated by way of suitable treatment processes. At the same time, the capital expenditure should be reduced and the efficiency enhanced.

» The use of alternative water resources like for example storm water, treated (municipal) waste water and condensate, shall be extended.

» Synergy potentials in water use, in particular between municipalities and industries as well as among the different branches of industry, must be identified. Based on these analyses, technical and management solutions must be developed.

3.3 Waste water: networks, treatment plant, receiving water, waste water levy

High quality requirements must be met irrespective of whether the process effluent is to be reused after treatment or routed to a municipal sewage plant or surface water body.

» Targeted improvements must duly consider the capacities of the receiving water bodies. A change in the water flow volumes (e.g. major variations in the water levels over a year; rainfall decline) and the heat load must be taken into account. The funds from the waste water levy can serve to improve efficiency with a view to footprint minimization.

» Treatment processes must be optimized and/or newly developed. This refers to refractory substances, but also to salts and the heat energy released (cf. Technology).

» Networks for the cleaning of process waste water must be implemented also beyond system battery limits (cf. Smart Water Management).

I TRENDS UND PERSPEKTIVES

3.4 Pollutants, hygiene: substances, concentrations, limit values

The routes of entry for emissions into the water system must be known. An almost complete description of the entry and fate of individual substances all the way to ion distributions and microbial loads will be possible. The assessment of the biological effects, also in larger balance areas, such as water catchment areas, allows for clear quality specifications. Initial levels of water pollution are considered.

» The aim with a view to a most efficient and complete use of raw materials must be to avoid/reduce emissions in the waste water and thereby at the same time increase the yields.

» Improved analytical methods and growing knowledge about the environmental effects of pollutants will further sharpen the focus on (problematic) individual substances (e.g. persistent, bioaccumulative and toxic substances). A biological effects analysis must supplement the chemical analysis, also with a view to defining limit values. Adequate processes for the detection of trace concentrations with consideration of their interaction with other substances and the occurrence of transformation products must be developed to be able to make accurate statements about the behavior of substances in the aquatic environment. This is very important for the authorization and use of substances and also for the downstream waste water treatment and waste water discharge/reuse (e.g. regarding legislation, plant operation). The development of new methods should be accompanied by modeling (in silico).

» A further optimization, fine-tuning and automation of the hygienic detection methods and the corresponding adaptation of the assessment methods is essential. This does not only apply for sensitive industries like the food or pharmaceuticals industry, but also for cooling waters (e.g. detection of Legionella) and for industries with intensified water recycling. The occurrence of pathogenic viral and microbial loads as well as of multi-resistants must be identified early on and their transfer avoided.

» The above-mentioned methods must be translated into chemical and biological online measuring techniques. These online analyses are used for water management, for the control of technical processes and for quality assurance in natural water bodies and recycled water. Online databases are a condition precedent for an efficient and up-to-date water management at all levels.

3.5. Water-energy nexus

The additional requirements in terms of water treatment are coupled to a higher consumption of energy. As energy prices will continue to rise and the carbon footprint represents an important tool for assessing sustainability, the primary objective must be to avoid contamination and the secondary objective must be to reduce the energy demand of water treatment and transport processes. Additionally the chemical and thermal energy contained in the process waste water has to be utilized.

» This requires an evaluation of the energy efficiency of individual treatment and recovery processes with due consideration of the cleaning efficiency achieved. New processes need to be developed that significantly curb the energy demand and utilize the chemically bonded energy (e.g. biological fuel cell, production of valuable materials). Furthermore, the volume of residues requiring energy for treatment should be reduced (e.g. sludge).

» The development of treatment processes operating at a high temperature level (e.g. biology, membranes, sorbents) should be driven forward to avoid heat transfer losses.

» Efforts should be made to integrate chemically bonded and thermal energy as well as transport processes into the water management.

» The use and treatment of cooling water has a great impact on the energy balance and must be optimized on the basis of the above-listed parameters.

3.6 Technology: integration, efficiency enhancement, transfer

Efficient technologies for the treatment of process, cooling and waste water form the basis of a sustainable water management. The efficiency of such technologies is greater when used at the place where emissions form rather than at the end of the chain ("end-of-pipe solution").

» An enhanced efficiency of the production and (waste) water treatment processes in terms of water, products, raw and auxiliary materials, energy, residues and offgas emissions should be targeted.

- » New technologies and the combination of technologies and/or a variation of the process step sequence offer great potential for development.
- » Water treatment processes should be designed for a high temperature level to allow for a direct reuse of materials flows without external temperature adjustment.
- » Production- and process-integrated measures (e.g. contamination-controlled treatment of suds after cleaning processes) shall be supported.
- » The technology potential of the process industry should be leveraged by transfer to other fields of application.
- » Selective separation techniques, e.g. for the recovery of valuable substances or the separation of inhibiting substances, must be developed.
- » Processes for the efficient separation of salt by means of universally applicable, non-toxic extraction agents that are easy to separate shall be devised.
- » The huge potential of biological processes (e.g. generation of power and production of valuable substances, degradation of refractory organic matter) should be leveraged.
- » The energy demand of oxidative and electrochemical processes for the removal of remaining refractory substances and for the improvement of hygienic water quality should be curbed through process optimization, new catalysts and process integration.
- » Membrane processes should be developed further by increasing their selectivity and stability as well as by optimizing the module geometries and process integration. This also includes the downstream treatment of concentrates.
- » New, environmentally sound materials for process intensification and efficiency enhancement, like hybrid materials, catalysts, sorbents, membranes, auxiliary materials (e.g. green flocculants, antiscalants, biocides), should be developed.
- » Measures to accelerate and improve technical developments with due consideration of the value chain must be explored. This requires an improvement of research funding and knowledge management, especially for small and medium-sized enterprises. The construction of demonstration plants in Germany (e.g. via subsidies, test fields) facilitates the market launch of new technologies.

3.7 Recovery: raw materials, valuables, energy

A recovery of substances upstream of conventional process waste water treatment reduces emissions into the environment. In this context, it is important to identify that point in a process chain where the substance is best separated. This depends to a large extent on the specific process conditions and environment. For entropic reasons alone, a separation in the as yet unmixed flow instead of at the end of the pipe is in most cases more efficient. A process intensification may be purposeful (e.g. reduced space demand), but also a utilization of the substances. Conversion of organic substances to biogas, for example, is possible both, at the end of pipe and at the place where they occur.Eine Nutzung der im Abwasser enthaltenen stofflichen Ressourcen (z. B. Phosphor, Ammonium, Polyphenole, Metalle) durch neue hochselektive und effiziente Trennprozesse ist anzustreben. Biologische und chemische Transformationsprozesse (z. B. Lactoseproduktion) sollten entwickelt werden, um die Wertschöpfung zu steigern.

- » A utilization of the substances contained in the waste water (e.g. phosphorous, ammonia, polyphenols, metals) by new, highly selective and efficient separation processes should be targeted. Biological and chemical transformation processes (e.g. production of lactose) should be developed to increase the value added.
- » The recovery of heat through water recycling (cf. Water Management) should be developed further.
- » The generation of power from process effluents using biological/catalytic processes should be fostered.

3.8 Footprint: CO_2, virtual water, LCA

An improvement of the quality of water treatment and circulation should not result in a shift of loads into other compartments. Various footprints can be used to assess the reduction of costs for waste water treatment and the improved efficiency of waste water treatment from an ecological viewpoint. Already today, the water quality can be adjusted arbitrarily at sometimes high energy input and/or costs. As a result, there is a need for adequate tools allowing to objectively balance between the different options available. Which amount of additional CO2 is acceptable or justified to remove a specific amount of organically bonded carbon or NaCl from a water body? How should incineration instead of chemical, physical or biological treatment within or outside of a production process for the removal of substances contained in the water be evaluated energetically?

- » For the holistic assessment of processes it is necessary to consistently apply and further develop the LCA methods by introducing additional indices (e.g. salt, temperature, effect on aquatic organisms).
- » Parameters such as the “water footprint” and “virtual water” must be established by analogy to the “carbon footprint” as quality criteria for industrial manufacturing. For the evaluation, not only the absolute figures shall be regarded, but also the regional availability of the water used (e.g. water stress index). This will require a further development of footprints and indices.

3.9 Change of industrial productionn

The evolution of industrial production will lead to changed and new production methods and industries (e.g. industrial biotechnology, new materials). In this context, the water management can be efficiently integrated.

- » Water management and the required water technologies should develop in parallel to the evolution of production methods and the emergence of new industries (e.g. biorefineries).
- » Existing technologies should be adapted, e.g. to fulfill more stringent requirements for the recycling of valuables while at the same time reducing the amount of raw materials required in production processes. These parameters should be considered already in the development phase of new technologies.
- » New technology and management concepts should allow to further decouple industrial production and water demand.
- » New and environmentally neutral materials and material functionalities should be developed in production processes and industrial water technology, (cf. 6. Technology).

3.10 Environment: climate, residues

In the future, climatic changes will have a growing impact on how we handle water. The availability of water will change at the regional level, resulting in a reduced availability, for example in southern Europe and in northeastern Germany. This influence will intensify as a result of a growing competition between urban, agricultural and industrial users. Moreover, the range and frequency of extreme weather situations like drought and heavy rainfall in combination with a rising temperature level will increase. This will result in periodical restrictions regarding the use of water (e.g. reduced availability of raw water, limited intake capacity for waste heat, organic substances or salts, higher demands on the treatment of process and cooling water). The options for residue disposal will progressively decrease.

- » That is why the task must be to create locational advantages by reducing the dependency on fresh water resources.
- » The availability of water, climatic conditions and opportunities for the recycling of materials must be considered for regional industry development.
- » Technological developments for process water treatment and cooling (e.g. increased circulation, leveraging synergies between industrial and municipal use) must be driven to reduce the dependency on fresh

water resources and waste water discharge into the water bodies.

» Residues from process (waste) water treatment must be reduced to a minimum and new recycling options developed.

3.11 Salts: regional/global, medial shift, reduction, salt utilization

Given the legal requirements specified in the Water Framework Directive, the emission of salt into fresh water is limited so that the natural level is not significantly altered. Dry periods will contribute to increasing the problem of salt disposal as the admissible salt loads must be reduced. This requires a consistent salt management with a removal of salts from the water cycle. Due to the increased exploitation of groundwater in coastal regions, salt water is increasingly entering the aquifer, leading to a degradation of the water quality. The consequence is that coastal regions will increasingly be characterized by water stress. Although the emission of salts is less critical in these regions, the collection of process water is more complex due to the high salt concentrations. Reuse of water is becoming increasingly attractive, both in non-coastal and coastal regions. The reduction in raw water demand and the intensification of recycling will lead to increasingly concentrated, salt-containing material flows.

» Concepts and processes for salt reduction and reuse as well as for the use and treatment of concentrates must be developed.

» Shifts into other environmental compartments must be included in the holistic assessment.

» Energy-efficient desalination processes (e.g. pressure-reduced membrane technologies), the use of salt gradients for power generation and processes for the production of useful, salt-containing products must be established.

3.12 Socio-economic environment

Water is vital for industrial production. The industrial utilization of water is always embedded in an economic, political and social context and must consider these framework conditions for its management approaches. In particular, the task is to sparingly use the scarce fresh water resources and not to affect the water quality by the industrial use of water. On the part of industry, these aspects need to be included in the evaluation of locations with a view to assessing the risk of production limitations and production loss as well as rising treatment costs, for example. Only this way, a cost-efficient use of water that is integrated into its socioeconomic environment will be possible.

» Communication with the public, politics and non-governmental organizations must be intensified.

» Water utilization concepts to reduce the competitive pressure and the dependency on fresh water resources must be developed.

» The development of management and technology concepts for a stronger decoupling of fresh water demand and production must be driven further. They will strengthen industrial water engineering on the global market and give German companies in the manufacturing industry a global competitive edge.

3.13 Responsibility for the future: holistic approach, consequences of an optimized water management

In industrial water technology, technical measures must be assessed and selected using holistic methods. Only this way a strong integration with other areas can be achieved already within the companies. This holistic view is also a societal demand. With this position, a stronger responsibility for the future is assumed. Economic, socio-political and social aspects are included in the assessment of water as a resource. This global perspective ensures that not only local interests are considered. The consequences of applying a new management approach or a new technology are holistically assessed and the effects of a shift of production facilities to other locations are taken into account.

» The LCA and LCC methods must be adapted more precisely to the new technologies.

» New methods must be developed to be able to more accurately assess the environmental impact at the local level.

» Integration with the water management is required to be able to perform assessments in the complex water systems (raw water – process waste water – natural water bodies).

3.14 Qualification and public relations

Given the increasingly complex technologies and systems also the qualification of the staff at all levels must be adjusted in vocational training and also in further education and qualification programs. The same applies for public relations since the public would not support decisions on the implementation of innovative concepts and technologies without sufficient information. As the German industry is export-oriented, the corresponding measures must be supported also at the international level.

» Vocational training and further education and qualification programs must be adapted to the technical progress; this applies for all levels of qualification. It also includes an optimized knowledge transfer in the field of basic scientific and technical know-how. Moreover, models for complex systemic analyses and for the holistic assessment shall be integrated into the curricula. The same applies for socio-economic and social skills. The bases for this can already be taught in general education schools (e.g. integration of these topics into the curriculum, student labs).

» A further development of concepts for promoting young talents and the combination of theoretical and practical training at the academic level should be targeted. Here, teachers with practical experience are indispensable.

» Concepts for measures to curb the shortage of skilled labor at the non-academic level (e.g. communication, qualification, recognition) shall be developed.

» The rising level of automation requires a more intensive vocational training and further education of skilled employees in event-oriented situations (e.g. simulator training).

» An export-oriented water industry needs qualified personnel abroad for the operation of installed plants. Short induction phases during the commissioning period, like those commonly used today, will no longer be sufficient in the future. The combination of theoretical and practical education practiced in Germany must be extended further. Local labor can be better integrated by way of vocational training and further education programs planned in the medium to long term at regional training and qualification centers. To avoid a loss of know-how, long-term motivation and loyalty of employees must be targeted (e.g. career planning, incentives). Also the training and further qualification of public authority representatives shall be included.

» The public must be informed about technical developments and be involved in the decision-making processes wherever possible. Events such as the “Long Night of Science” in Berlin and education modules like the “Student Labs” of the chemical industry must be expanded further.

» Software modules and expert systems with user-friendly and defined interfaces complement these activities.

II Routes to Realization

4 Cross-technology Approaches

In this chapter and based on the different fields of action, the present situation, potential, challenges and the research and development needs for cross-technology approaches are shown by way of examples to allow for an integrated, sustainable industrial water management.

Moreover, an assessment of the achievable impact is provided

4.1 Production-integrated Measures for an Energy-efficient Water Recycling

Present situation

PProduction-integrated measures target the point where waste water is originated. Many processes for the manufacturing, upgrading and cleaning of products require aqueous solutions. The implementation of measures to recycle water into the production process presupposes a detailed analysis and balancing of the relevant substance flows, a water consumption analysis as well as the definition of specifications and quality requirements for the water. This allows to decide whether water is used efficiently, whether a direct reuse is possible and whether recycling requires the implementation of an in-company water treatment system.

Water recycling can leverage synergies

- if it allows to save energy at the same time,
- if an ecologically, economically and technically purposeful solution for the substances separated from the recycled water can be found (resource-conserving handling of useful and valuable substances contained in the water),
- if it allows for rationalization effects and/or
- if the reduction in the waste water volume and contaminant content helps relieve the downstream waste water treatment and avoids or reduces the impact on receiving water bodies.

The option of water recycling is known from all industry sectors.

Water recycling is most beneficial when only weakly contaminated flows can be treated with inexpensive and simple cleaning measures. In the case of flows containing high contaminant concentrations and/or substances with different chemical and physical properties, water recycling in most cases proves to be less efficient. That is why one of the basic requirements for water recycling is usually the implementation of an efficient water management so as to be able to separate waste water flows of different recyclability.

Optimizing a materials flow management is a highly complex process. Generally, neither the analysis nor the development of measures and implementation of new concepts can be performed by the operational staff in place. Especially in situations where new regulations and regulatory requirements are to be implemented, the management requires a high level of technical competence. Measures must not be looked at individually, but shall consider problem shifts into other environmental compartments. For a successful implementation of measures therefore also the effects on the process causing the pollution and on the quality of the process and product must always be taken into account. These requirements, besides the know-how available in the company about the substances used, the production processes, formulations and general process conditions also presuppose knowledge about ecological and economic relationships, like for example the condition of the process water, the consumption of energy and resources as well as the risks and dangers of using hazardous substances. With specific, process-related data (e.g. L water/kg product, chemical oxygen demand (COD)-load/process or process step, kWh thermal energy/kg product or process) it is possible to continually improve the processes and hence also the company's environmental protection. For the development of measures also the long-term effects of (integrated) environmental protection measures must be taken into account, like for example the concentration of substances in the water when reducing the waste water volume, a possible concentration of noxious substances in the water cycle, potential changes of the general conditions for the production location, and also reactions of the stakeholders. An ecological and economic life cycle assessment of the planned changes is helpful for evaluating cause and effect relationships. Especially for medium-sized companies, no tested and

approved methods are available for this assessment. As a consequence, ecological process and product criteria, like for example those relating to resource and energy consumption or climatic factors, are rarely available to the customers and hence largely unknown.

Measures to avoid or reduce emissions into the waste water and to conserve the resources water and energy as well as the efficient use of utilities require a continuous review of the processes with regard to their optimization potential.

In the short term, water, energy and utility savings can be implemented and, as a consequence, also savings in process and environmental expenses. Associated with these savings are improvements of the process and product quality, the introduction of measures for occupational safety, process safety, the implementation of new regulatory requirements or of customer requirements, and the award of eco labels.

In the medium term, the implementation of production-integrated environmental protection measures in new investments or replacement investments for machines and plants is possible

In a long-term perspective, integrated measures are already considered during the planning phase of new products or processes.

Frequently, companies supplement integrated environmental protection measures by additional processes. Unlike in integrated environmental protection, measures of additive environmental protection involve adding a downstream process step. Additive environmental protection requires an additional use of resources, leads to the conversion of emissions, usually with the input of energy, and is frequently linked to subsequent emissions or a shift of emissions into other environmental compartments besides involving capital expenditure and additional operational costs. Additive measures result in a targeted and efficient reduction of the respective environmental impact and may lead to a reduction of emission charges, where applicable.

Numerous examples demonstrate that a smooth transition between additive and integrated measures within companies is possible. A hot nanofiltration step allows recycling the water directly on the dyeing or washing process while at the same time saving energy. Ion exchangers are used for the treatment of rinsing waters in surface finishing.

Water recycling in the steel industry (© atech innovations gmbh)

Also the use of membrane filtration for water recycling in the food and beverage industry represents a successful implementation. Most of these integrated recycling processes are operated close to or directly on the production process because the complexity of the water constituents is limited and the time and costs for additive processes are low. To avoid inefficient processes, such measures must be evaluated with a view to resource conservation and emission reduction (cf. Chapter 4.2 “Recovery of Valuable Substances”).

Vision/assessment of potential
Production-integrated environmental protection measures mostly relate to measures for substituting utilities, enhancing process efficiency and avoiding emissions into the water or other compartments. A direct reuse of water from washing and cleaning processes is particularly beneficial in the case of hot water since the circulation of the water goes hand in hand with energy saving. In this context, the upgrading of existing plants bears as yet untapped potential. Small and medium-sized companies are currently being encouraged with state subsidies to determine their resource savings potentials. In some industries, these potentials amount to up to 30 % of the water used, up to 20 % of the thermal energy required for using the water and up to 10 % of other utilities. The corresponding cost savings are in some cases material and could contribute to improving the profitability of companies. Many of these measures are company-specific and cannot be directly transferred to other situations / other companies.

Experience has shown that integrated measures, if their potential has been identified, are implemented immediately, especially when they involve simple process changes or a substitution of materials that can be realized with low effort and without compromising product quality. The recovery of valuable functional components and/or the retention of properties (e.g. corrosion inhibitors, disinfectants, electrolytes, fertilizers, pesticides or the reduced hardness, sterility and temperature) may be decisive for water recycling. The economic viability of the measures must be evidenced.

Frequently, the implementation of integrated measures goes hand in hand with a higher qualification of the employees involved in the process. The company’s stakeholders receive information about integrated measures from trade associations and from the suppliers of utilities and plants/equipment who act as multipliers. Knowledge about the relationship between waste water contamination and the underlying process, about integrative and additive measures as well as about process optimization and its potential effects makes the stakeholders aware of the opportunities available to improve a company’s fitness for the future.

The in-process application of membrane processes, chemical oxidation with O_3 or H_2O_2/UV and others, adsorption on activated carbon, and ion exchangers offers great potential that has so far only been leveraged to a limited extent and has been developed in the framework of practice-oriented research and funded projects over the past two decades. So far, their implementation mainly failed because the economic viability of the measures was not sufficient, a solution suited for practical application was not found or a commercial-scale implementation met with great reservations on the part of the staff working in the company.

Research and development needs
Similar to what has been described under “Recovery of valuable substances” (cf. Chapter 4.2), also the implementation of new concepts for water recycling processes is very slow.

Despite the availability of cost-effective concepts for production-integrated environmental protection, the need for research and development regarding the redesign of water-consuming and waste water producing processes that carry potential for resource conservation and energy efficiency enhancement remains high.

In view of the shortage of energy resources there is an increasing demand regarding processes for the production of organic chemicals in aqueous media operating at temperatures below 50°C. A combination of process and separation/purification technologies with optimized yields requires hybrid solutions. R&D examples are capsule membranes for the safe transport and release of the encapsulated substances at the target point and hollow fiber membrane reactors for the exploitation of defined reaction conditions.

In the future, water recycling will be more frequently combined with the recovery of substances. To this effect, in-process additive measures will be more widely deployed. R&D demand exists regarding the further development of membrane processes (aggressive, hot media; raising yield and profitability; functionalized membranes; liquid membranes), ion exchangers (selective ion exchangers; ion pair reagents for regeneration and substance recycling, separation of substance mixtures with high concentration gradients), biological processes (selective degradation; increase of the degradation rate), hybrid processes and for process intensification and the combination of in-process additive processes with heat recovery.

With a view to sustainability, the integrated measures besides their present focus on energy and climate will in future also increasingly consider the aspect of resource efficiency:

- reduction of the work, costs and fees for raw water treatment and waste water treatment by curbing the specific water consumption and recycling water (water footprint),
- utilization of the organic carbon contained in the water at the end of processes for the generation of renewable energy and for the reduction of greenhouse gas emissions (carbon footprint),
- conservation of water from ground and surface waters.

Vorrangige Entwicklungsziele für die Optimierung und Entwicklung von Verfahren zur effizienten Wassernutzung sind eine ganzheitliche Betrachtung sowie eine breite Anwendung der ökologisch-ökonomischen Bilanzierung. Softwarebasierte Systeme müssen entwickelt werden, um die Wirkungen der integrierten Maßnahmen beschreiben und eine Bewertung durchführen zu können.

Impact assessment
The efficient use of water contributes to conserving resources, especially in regions with limited water supply. Reduced emissions lead to synergy effects regarding discharge into the water bodies. The implementation of integrated measures for industrial environmental protection is closely related to an improved occupational safety and an improved quality of the processes and products. Analyzing the options of integrated environmental protection measures within a company contributes to enhancing the employees’ know-how and thus to improving their qualification. A proactive management will see industrial environmental protection for protecting the water bodies in the form of an integrated, sustainable industrial water management instead of end-of-pipe solutions as an opportunity to safeguard the future of the company.

Despite the fact that production processes mostly require individual solutions, it will be possible to transfer economical implementations of measures for an integrated, sustainable industrial water management to other companies operating in the same line of business and to comparable conditions in other industry sectors; software-based systems will support this transfer.

4.2 Recovery of Valuable Substances

Present situation
A contamination of the process water with production materials upon direct contact is inevitable. Consequently, the substances are found in the process water in different concentrations (from a few ppb to several %). If the substances are valuable, a recovery may be purposeful, not only from an ecological but also from an economic perspective.

In view of increasingly scarce raw materials and rising raw materials prices this trend is set to grow further in the future. Moreover, some substances should also be recycled for strategic reasons as access to the sources (e.g. mines) may be limited due to monopoly positions (e.g. China for Gallium). Moreover, the German **Closed Cycle and Waste Management Law** must be considered which regulates the recovery of substances in Germany.

Increasingly stringent discharge limit values are another driving force for the optimization of processes for the separation and recovery of substances from waste water and process streams. In the case of some metals classified as “priority hazardous substances” (e.g. mercury, nickel, cadmium, lead), a significant further tightening of the discharge limit values as a consequence of the implementation of the European Water Framework Directive is expected (cf. Chapter 2.1).

The basic requirement for a simple recovery of valuable substances from production is a well-organized separation of process and waste streams (materials flow management) so that concentrated and unmixed substance flows are obtained. A large number of technologies is available for the recovery of valuable substances. The choice of the separation method is primarily governed by the physicochemical properties of the target substance and its concentration and secondarily by the specific matrix of the waste water and the size of the material flow.

Table 1 gives an overview on the recovery methods and application examples. The recovery technologies can generally be broken down into three approaches:

II ROUTES TO REALIZATION

a) **Recovery of valuables:** separation of a valuable substance from a waste water (e.g. precious metals, solvents)

b) **Recovery of a process stream:** treatment of a process stream so that it does not have to be disposed of as or together with the waste water (e.g. electrolytes, pickling acid)

c) **Reuse of water**

As can be seen in Table 1, a wide range of technical processes and interesting raw materials exists. For many raw materials, different recovery methods are available. Which method is best suited generally depends on the respective conditions, such as:

» concentration of the valuable substance and admissible residual amount in the effluent after treatment

» matrix and associated components

» availability of inexpensive energy

» possibilities/requirements for the direct recycling of process streams into production.

In case of a complex waste water mix, processes allowing for a selective separation of the relevant substances should be used, wherever possible.

Recovery of solvents (© EnviroChemie GmbH)

Table 1: Technical methods for the recovery of valuable substances and their possible use (example

	Valuable substance														
Method	Gold, silver and platinum groups, metals	Non-ferrous metals: Cu, Zn, Sn	Metalloids: B, Ga, Ge, As, Sb, Se	Special metals: Co, Ni, Nb, Ta, Mo, V, U, Pb, Cd	Inorganic acids: e.g. HCl, HNO_3, H_2SO_4, HF	Electrolytes for surface treatment: e.g. Cr-, Zn-, Ni-electrolytes	Other electrolytes: NaCl, KCl,	Organic acids: e.g. tartaric acid, acetic acid, EDTA	Organic solvents	Oils	Active pharmaceutical ingredients, pesticides	Phosphorous, nitrogen	Iodine and iodine compounds	Li, rare earth metals: e.g. La, Ce	Water
Hydroxide precipitation		✓		✓			✓							✓	
Sulfide/organosulfide precipitation	✓	✓		✓			✓								
Flocculation and precipitation			✓	✓			✓	✓				✓		✓	
Chemical oxidation/ reduction	✓	✓	✓										✓		✓
Electrochemical recovery	✓	✓		✓		✓								✓	
Cementation	✓	✓													
Electrodialysis	✓		✓		✓			✓							
Diffusion dialysis					✓										
Crystallization (evaporation)	✓	✓			✓							✓		✓	
Distillation/rectification								✓	✓				✓		
Ion exchange (demineralization)									✓	✓					✓
Selective ion exchange	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓
Acid and ion retardation					✓		✓								
Chromatography											✓			✓	
Extraction		✓	✓	✓				✓			✓		✓		
Activated carbon adsorption	✓				✓	✓	✓	✓			✓		✓		✓
Adsorber resin adsorption					✓	✓	✓				✓				
Special adsorbents	✓	✓	✓	✓		✓				✓		✓	✓		
Nanofiltration	✓	✓	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓
Reverse osmosis											✓				✓
Bulk solids and fabric filtration	✓	✓	✓	✓		✓	✓		✓	✓	✓				✓
Sedimentation and centrifugation	✓	✓		✓		✓	✓		✓	✓	✓	✓		✓	✓
Flotation	✓	✓		✓											✓

Vision/assessment of potential

DThe recovery of valuables is becoming increasingly attractive as raw material prices are set to rise further. Given the diverse geopolitical and economic influencing factors, forecasts about the timeline for such developments still involve considerable uncertainties. An increased volume reduction leads to rising concentration levels in the water cycles, thereby facilitating the recovery of valuable substances. Valuable substances include: precious and non-ferrous metals, alkali metals, rare earth metals, metalloids like selenium, tellurium, arsenic, bismuth, boron, gallium, germanium, indium as well as compounds of the elements phosphorous (e.g. phosphate), nitrogen (e.g. ammonia or nitrate), lithium and iodine. In addition, valuables include acids (mineral and organic), surfactants, solvents, extraction agents, phenols, lignins as well as active ingredients from the pharmaceutical industry or crop protection.

Table 2: Industry sectors with a high potential for the recovery of valuable substances

	Valuable substance														
Industry	Gold, silver and platinum group, metals	Non-ferrous metals: Cu, Zn, Sn	Metalloids: B, Ga, Ge, As, Sb, Se	Special metals: Co, Ni, Nb, Ta, Mo, V, U, Pb, Cd,	Inorganic acids: e.g. HCl, HNO_3, H_2SO_4, HF	Electrolytes for surface treatment: e.g. Cr-, Zn-, Ni-electrolytes)	Other electrolytes: NaCl, KCl	Inorganic acids: e.g. tartaric acid, acetic acid, EDTA	Organic solvents	Oils	Complex organic molecules, e.g. active	Phosphat, Stickstoff	Iod und Iodverbindungen	Li, Seltene-Erden-Metalle: z. B. La, Ce	Wasser
Mining	✓	✓		✓	✓									✓	✓
Metal refinery	✓	✓	✓	✓	✓	✓		✓						✓	
Metal and plastic surface finishers (electroplating)	✓	✓		✓	✓	✓		✓							✓
Semiconductor industry	✓		✓												✓
Electronics industry	✓	✓	✓		✓	✓								✓	✓
Solar industry			✓	✓											✓
Machinery										✓					✓
Petrochemicals										✓					✓
Chemical industry	✓			✓	✓		✓	✓	✓	✓	✓		✓		✓
Pharmaceutical industry									✓		✓		✓		
Crop protection									✓		✓				
Textile industry		✓													✓
Battery producers				✓	✓		✓							✓	
Ceramic industry	✓		✓		✓										✓
Waste/waste water disposal	✓	✓		✓						✓					
Agriculture												✓			✓
Food industry								✓		✓	✓				✓
Fertilizer industry												✓			✓

Among the industry segments with a high potential for the recovery of valuables are all sectors where valuable metals are extracted or processed (e.g.: mining, metal refining, steel industries, metal surface treatment and surface finishing, electrical, solar and semiconductor industries), the chemical and pharmaceutical industries, agriculture as well as the wood processing, pulp and food industries (cf. Table 2). These industry sectors account for a significant share in the gross domestic product (GDP).

Research and development needs

Presently, many companies refrain from recovering valuable substances because of the high capital expenditure required for the technical realization of these processes. Moreover, in the case of older plants, significant remodeling would be required, something that is often difficult to implement for lack of space and due to the temporary production downtimes involved and the resulting costs. Consequently, technical concepts for the recovery of valuable substances can primarily be implemented when planning production extensions or new projects.

In addition to these practical and organizational problems it must be considered that individual concepts tailored to the respective application case have to be developed for the realization of valuable substance recovery units. This task is so complex that it usually requires external support (process design including laboratory tests and pilot plant testing).

Practicable solutions are in most cases obtained when combining an adequate materials flow management with a range of established separation processes (cf. Table 1).

It must be examined on a case by case basis whether the recovery of a substance from a waste water is technically feasible and to which extent the recovered valuable substance meets the quality specifications for reuse or processing within or outside the company.

Furthermore, it must be examined to which extent besides the separation of valuables also a reliable compliance with the limit values is achieved. Ultimately, the calculation of the costs and the assessment of the sustainability of a recovery solution will determine whether a reuse is economically and/or ecologically purposeful.

Especially in the case of raw materials with a limited availability, a contact between producers and consumers should be established to promote the exchange of know-how about technologies for the recovery and recycling of raw materials from waste and waste waters.

Within the framework of technical progress, those methods are interesting that selectively can remove valuable substances or contaminants from the contaminated matrix and transfer these substances into a new generated stream of higher concentration. Thereby ideally, a high separation efficiency (99.9 %) combined with a high concentration increase factor (> 100) should be achieved. Any auxiliary material used for this process (e.g. extractants, adsorbents) should be regenerable and reusable.

Based on these requirements and specifications, research and development needs for individual target substances exist regarding new materials and methods for a selective separation from specific process flows. It would, for example, be purposeful to significantly extend the range of selective adsorbents. In this context, new functional groups for selective ion exchangers, metal- or metal oxide-doped polymers or solids with specifically shaped adsorption centers (MIPs: molecularly imprinted polymers) are of great interest.

For historic and also for chemical/physical reasons, the present state of research on the selective adsorption of organic compounds is less advanced than that on the adsorption of inorganic substances so that a substantial need for research and development exists in this field.

Impact assessment

Since most of the above-mentioned valuable substances have toxic, refractory and/or polluting properties, a recovery of such substances is purposeful not only from an economic, but also from an ecological point of view.

The publication of economically successful projects for the recovery of valuable substances in conjunction with an integrated, sustainable industrial water management will drive future projects.

Moreover, also the strategic benefits in the form of a reduced dependency on raw materials suppliers and a weakening of monopolies must be considered for the impact assessment.

4.3 Salts

Present situation

Anorganische Salze gelangen vorwiegend bei der Erzge- Inorganic salts are mainly found in the process effluents from ore mining and dressing, salt and fertilizer production and the chemical, petrochemical and food industries. A special case are concentrates from seawater desalination plants.

The salt concentration is owed to substance losses in production, waste and by-products, reaction products (chemical industry) as well as acids/alkalis used in purification processes, for chemical reactions or in waste air and waste water treatment. In the case of waste water cleaning, the salt concentration rises in particular as a result of neutralization processes.

Relevant ions from inorganic salts mainly include Na^+, K^+, Cl^- und SO_4^{2-}.

In biological waste water treatment, organic salts (e.g. neutralized organic acids) are mostly converted to CO_2 or the corresponding carbonate type and mainly leave the waste water treatment plant in the form of inorganic salts

With a view to industrial water management, salt exhibits the following relevance:

a) **Salt discharge may affect the ecological situation of the water bodies.** In most cases, waste water treatment does not include salt removal which means that salts are discharged into the water bodies together with the waste water treated for the removal of organic substances and nutrients. Mostly, the dilution effect is so large that negative effects on the water bodies are at least acceptable (cf. Fig. 9). Where this is not the case, attempts are made to keep the effects within reasonable limits by way of salt management (e.g. Salt Convention for the River Rhine).

This assessment is of great significance because for the majority of salts hardly any processes are available for their economically feasible removal from waste water. In addition, they nearly always – especially when compared to processes for the removal of organic contaminants – involve a high energy consumption and thus also high costs. Electrical processes and membrane processes are only suited for the first concentration steps which means that, ultimately, basically only thermal processes (evaporation/crystallization) can be used. Precipitation processes exist only for few salts (e.g. sulfate) and in addition also result in a secondary pollution of the process effluent, depending on the water matrix.

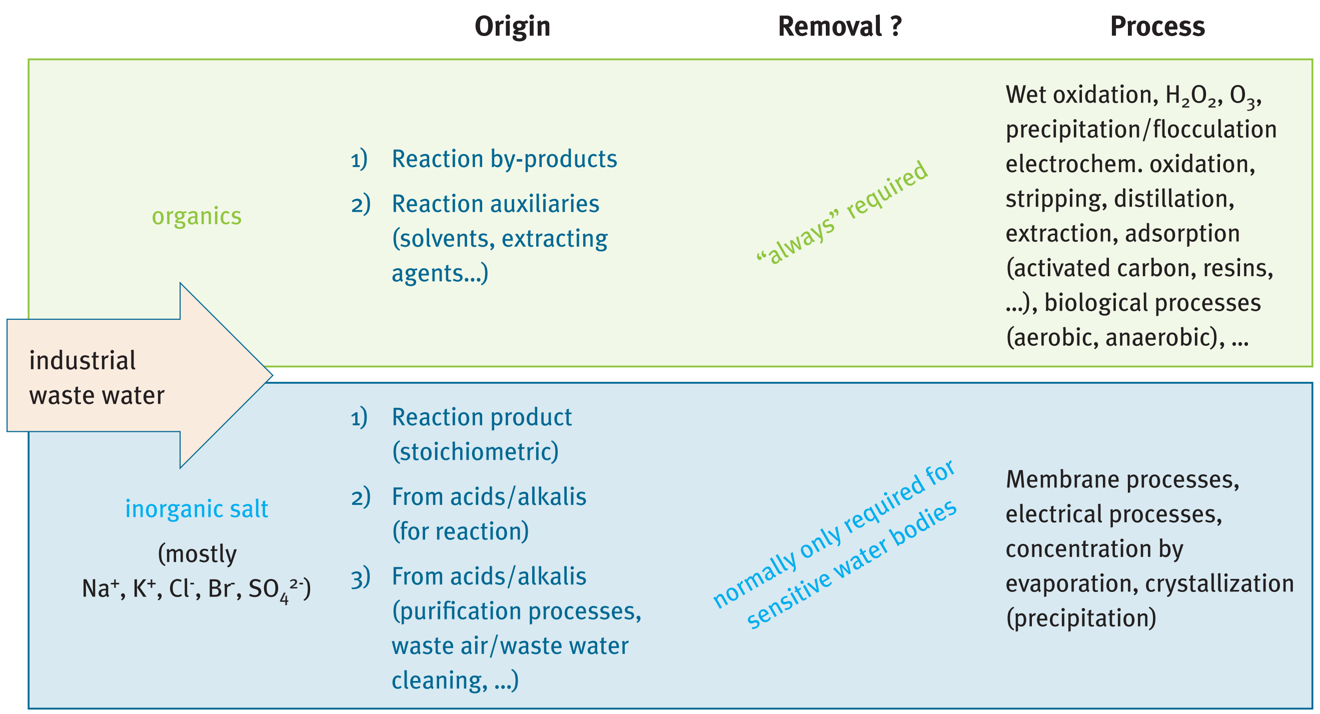


Fig. 9: Salts in industrial process waste water

b) **Salt is a valuable substance.** Salts can be used either directly or as a raw material for further applications (e.g. fertilizer production, chlorine production). However, both options are usually very demanding in terms of the purity of the salt (as a solution or solid). Accordingly, an extensive and complex treatment is required (removal of noxious matrix components, e.g. organic compounds). When using NaCl brines for electrolysis, for example, the usually required purity with regard to organic carbon or nitrogen is normally equal to or below 1 ppm. Therefore, such applications always also require a certain willingness to accept risks on the part of the operators/users.

c) **High salt concentrations inhibit biological waste water treatment.** Practical experience has shown that, depending on the cleaning requirements, concentrations of 2–5 % are still acceptable for biological processes. Despite intensive research and development, processes involving special biotic communities have not proven to be stable and applicable in practice. That is why a limitation of the salt concentration is essential for the application of inexpensive and comparably resource-saving biological processes in process waste water cleaning.

Vision/assessment of potential

The problem of high salt concentrations in process waste waters is growing because of higher concentrations resulting from water saving and closed loop operation. In addition, the requirements on the water body quality and resource conservation aspects are playing an increasingly important role.

Also the limit values for salts and individual ions in drinking water are increasingly having an effect on the admissible emissions into water bodies.

In the future, the salt concentrations in the waste water will decide about the profitability of a recycling process. This applies in particular for regions where the raw water is generated from sea water or brackish water. The waste water from this process exhibits low conductivities and can therefore be treated and recycled at comparably low costs.

In 2030, the need for separating salts from the waste water and recovering them, wherever possible, will be significantly higher. This presupposes processes requiring an energy input that has been drastically reduced as compared to the present state of the art. Here, not only an optimization of the existing process / combinations, but also the development and establishment of completely new process / combinations shall be targeted.

The establishment of life cycle assessments to strike a balance between the conservation of salt resources and the consumption of energy and resources for effluent treatment is essential.

R&D and lab experiences with biological degradation processes in waters with high salt concentrations must be transferred to practical applications. At present, the need is less for specialized microorganisms and more for operational and control strategies.

Despite potential progress, the conflict between saving water and meeting the requirements for a biological process waste water treatment remains unsolved. In many parts of the world the waste water is currently being diluted to allow for a biological treatment.

Research and development needs

a) General R&D need
- Further development of tools for life cycle assessment, standardization and evaluation; consideration of the results for authority approval processes
- Salt management

b) Processes for salt removal / reduction
- Implementation of best practice examples for reducing the use of acids and alkalis (e.g. process control of alkaline washers instead of operation in the "comfort zone")
- Further development of separation processes (e.g. membrane distillation, reverse electrodialysis)
- Concepts for the utilization of waste heat for thermal processes (e.g. heat pumps, energy storage devices)
- Development of strategies for the operation of ion exchangers with the goal of reducing the salt concentration in the regeneration phase (e.g. alternative regeneration agents, direct precipitation during regeneration)
- Basic research for entirely new process approaches (e.g. biological salt accumulation)

c) Processes for the purification of saline solutions
- selective processes for the removal of polar organic substances as well as ions from salt solutions

d) Salt utilization
- robust membrane electrolysis processes allowing for higher concentrations of interfering components and thus for a recycling of the salt (especially Si compounds and organic compounds)
- re-evaluation of the quality specifications for salt-based products. For the return of (salt) resources into the raw materials cycle it is essential to also accept lower qualities wherever possible.

e) Biological processes for cleaning saline waste water
- Further development of anaerobic biological processes, especially with a view to a higher salt tolerance
- Utilization of the salt tolerance of marine algae for waste water treatment
- Development and implementation of process control and plant operation strategies for the utilization of halo-tolerant and/or halophilic biocenoses in biological waste water cleaning

f) Processes for the production of ultra-pure water
- Further development of electrical hybrid processes (e.g. capacitive deionization))

Impact assessment

An optimized strategy for the handling of salts in industrial process waters will first and foremost have an effect on resource conservation. Salt production leads to sometimes significant amounts of waste in solid and liquid form (e.g. for the production of potassium salt according to the state of the art four times the amount of the product volume). A recycling of salts from process effluents may therefore in many cases also have significant indirect benefits.

Biological waste water cleaning is usually the most cost efficient and resource-conserving waste water treatment process and therefore widespread. If we succeed in raising the tolerable salt concentrations, this will have a positive effect on the input of energy, resource consumption and costs. This holds true in particular for anaerobic processes.

5 Processes for Realization

Using the fields of action as a basis, this chapter shows the initial situation, potential and challenges as well as the research and development needs for selected processes by way of example to allow for an integrated and sustainable industrial water management. In addition, the achievable impact will be assessed.

5.1 Biological Processes

5.1.1 Generaln

Present situation

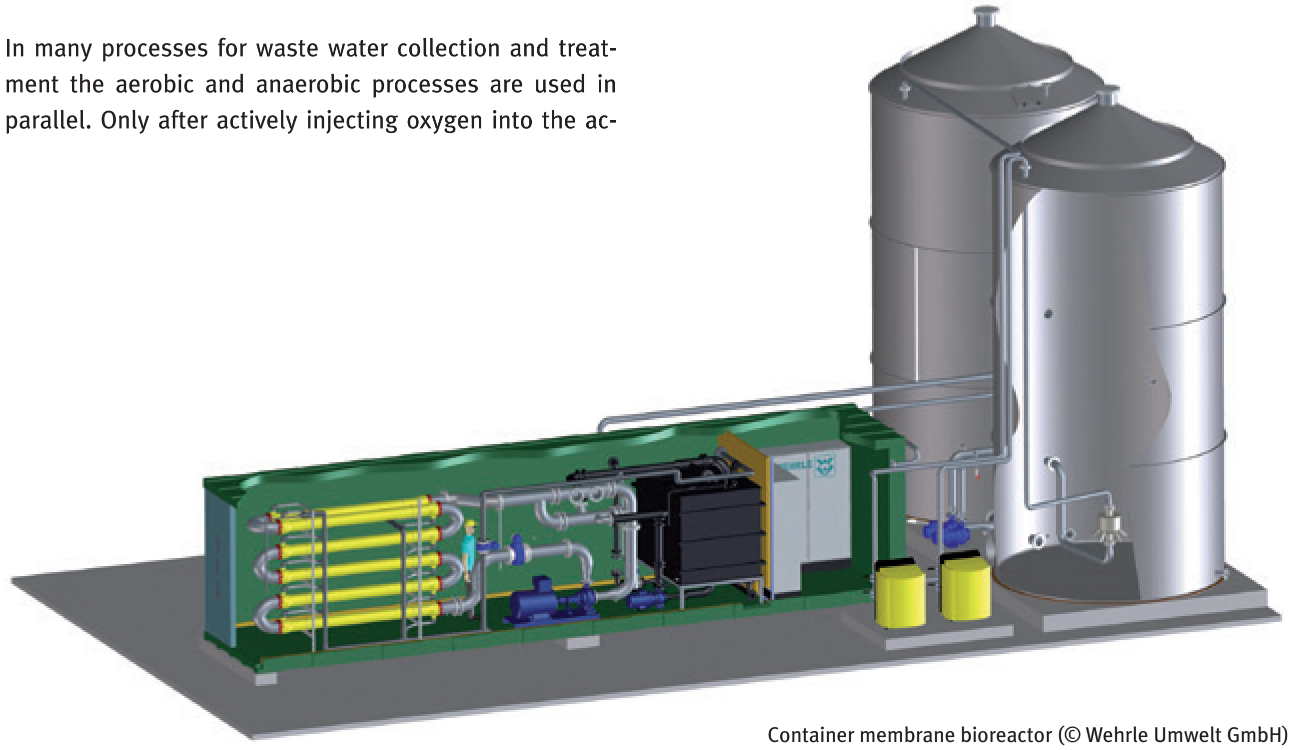
Biological processes have a great relevance in waste water treatment due to the usually lower costs as compared to chemical/physical processes. A large number of different reactor concepts and processes is used to create optimal cultivation conditions for the microorganisms required to achieve the desired degradation and cleaning performance. By varying the different process parameters it is possible to cultivate the desired biomass (e.g. nitrifying, methane-forming organisms) in the reactors. Basically, a distinction is made between the following process control concepts

- » Biomass growth or maintenance metabolism
- » Suspended growth or attached growth
- » Aerobic or anaerobic reaction conditions (availability of an electron acceptor)

In many processes for waste water collection and treatment the aerobic and anaerobic processes are used in parallel. Only after actively injecting oxygen into the activated sludge treatment also aerobic processes will have a major effect. Both in the activated sludge floc and in the biofilms, local oxygen limitations may exist as a result of the metabolic activity and anaerobic zones may develop.

Most biodegradation processes take place in central sewage treatment plants where the production effluents of a plant are jointly treated to use synergy effects (economy of scale, compensation of load and hydraulics, combination of carbon-rich and nitrogen-rich flows, avoidance of toxic concentrations). In this context, the following problems need to be addressed:

a) The **recalcitrance** of certain natural and synthetic substances as well as inhibiting effects lead to an insufficient biodegradation for direct discharge or water reuse. Therefore, chemical/physical processes – usually for partial flows – need to be integrated into the treatment process. Restraints exist regarding the industrial-scale use of special biocenoses, e.g. varying composition of the waste water in terms of substrate and contaminant concentration, irregular occurrence, low growth rates of the biocenoses in conjunction with insufficient knowledge about their composition and the habitat conditions required, operational variations and the presence of toxic compounds (e.g. heavy metals), high salt loads (cf. Chapter 4.3), varying pH and



Container membrane bioreactor (© Wehrle Umwelt GmbH)

II ROUTES TO REALIZATION

temperatures as well as occasional lack of substrates. The majority of biological degradation processes nowadays operate using biomass in its growth phase. For some applications (e.g. dehalogenation, decolorization) it was possible to demonstrate at the laboratory scale that the above-listed problems can be effectively overcome by way of an immobilization, i.e. by fixing the specialists on adequate support materials or by decoupling the waste water retention time from that of the substrate and biomass using membranes. However, this process is presently only implemented at a commercial scale to a negligible extent.

b) The **mechanisms of biologically caused operational problems** (e.g. foaming, floating sludge) are as yet insufficiently understood. Corrective action is in many cases only of limited success or unsatisfactory due to the high volume of chemicals required, for example.

c) The **optimal conditions and kinetics of biological processes that have only recently been introduced** (e.g. deammonification, iron/manganese bacteria) have not yet been fully researched and/or are not implemented.

d) The **adaptation of the reactor design to the requirements and kinetics of the microorganisms** is only insufficiently achieved.

Control of the biological processes used in waste water treatment continues to be based largely on experience and on physical and chemical measurement values. Therefore, the biological processes that are decisive for the processes are only indirectly controlled by measuring the substrate consumption and/or the formation of biomass and product. Only in single cases it has become common practice to directly analyze and measure the microorganisms responsible for certain degradation and/or production processes. One example is the measurement of nitrifying bacteria by way of fluorescence in situ hybridization (FISH).

Vision/assessment of potential

For the transformation of most organic waste water substances microorganisms are available that can be enriched in full-scale plants. This allows for both, a complete mineralization and also the formation of valuable substances (e.g. CH_4, H_2, lactate, oil, power) even at high temperatures and salt concentrations and outside of the neutral pH range, by biological reactions. These processes are based on specialized bacteria (e.g. iron oxidizing and reducing, halophilic, thermophilic organisms) algae, fungi and enzymes that are in part immobilized on support materials with added functionalities (membranes, sorbents). Another option involves a multi-stage process with separation of the biocenoses and adaptation of the cleaning steps to the specialists (competing substrate, co-metabolism, sequential degradation) or specialized reactors (algae reactors, fuel cell, hybrid reactors). Understanding the microbiological reactions allows for an economically viable design and operation of the bioreactors for the treatment of both, concentrates and also low-concentration process effluents with trace substances.

A range of biological processes is available for the treatment of partial flows directly at the point of origin. These processes can be supplemented by chemical/physical processes, as required.

In the case of a mixotrophic metabolism, also some algae are capable of effectively degrading the substances contained in the waste water under certain process conditions without requiring energy-intensive aeration. In sunny regions, these organisms are used in algae/bacteria mixed biocenoses for industrial waste water treatment. Microalgae are successfully used for the selective sorption of certain substances contained in the waste water and for the recovery of heavy metals, for example.

Bio-electrochemical systems allow for a direct production of electricity during the degradation of dissolved or fine-particulate organic substances. Especially waste water with relative low organic loads such as municipal waste water could be treated in an energy-efficient way with such systems.

To avoid possible damage of the biocenoses due to inhibiting and toxic substances in the inflow to the biological waste water treatment stage or in an additional physical-chemical treatment step, toxic substances are identified online with reliable tests and sufficiently fast response times and removed from the biological treatment unit by separation (stacking). These tests are also used for monitoring the quality of the plant processes.

The mechanisms of biologically caused problems in operation are well understood and described. Manageable practical strategies exist to reliably address any problems that may occur by purposefully influencing the biocenoses without the addition of chemicals.

The combination of established and new processes involving specific microbial populations with data on the microbial activity collected online will allow for a significantly more specific and efficient waste water treatment. A targeted influencing of the different subpopulations in the reactors allows to purposefully control their interaction and specific activity. With the help of molecular biological detection methods it is possible to identify the presence and activity of subpopulations that are responsible for specific degradation processes (e.g. nitrification, denitrification, accumulation of phosphates and/or heavy metals) fast and where possible also online, and integrate them into adaptive control concepts for the treatment processes.

In addition to conventional waste water treatment plants, different variants of membrane and biofilm reactors are used with the objective of effectively degrading substances contained in the waste water while at the same time recovering valuable substances and/or energy from the waste water matrix. In this context, processes attaching biomass to media play an important role as they are less sensitive to sub-optimal cultivation conditions and disturbing influences and thereby allow for a better process stability. For the treatment of process effluents containing slowly degradable substances by way of immobilized microorganisms, the use of anaerobic and aerobic fixed bed and moving bed reactors as a function of the requirements has gained acceptance. In the case of sufficient biomass concentrations and short retention times, they can be integrated into the production process as strongly performing units for the treatment of partial flows offering a high operational reliability.

Research and development needs

In the field of biological transformation of the substances contained in process waste waters, research and development needs exist mainly regarding the enrichment of **bacteria, algae, fungi and enzymes with special degradation properties.** The methods currently available for a reliable identification of the composition of mixed cultures must be significantly simplified and adapted for in situ application. Moreover, the population dynamics in defined mixed cultures must be analyzed. This applies in particular for the use of sub-populations that are able to transform trace substances in effluents with easily degradable substrate. The search for critical and useful **transformation products** in the decomposition of harmful substances as well as analyses of their mutual interaction are further important fields for R&D. This work must be supported by kinetic examinations involving both, the individual substances and also the multi-substrate mix (e.g. growth kinetics of individual strains in the mixed culture, co-metabolisms, competitive substrates), to be able to determine the characteristic reaction-kinetic parameters. These parameters are then used for mathematical modeling and simulation of the decomposition processes and for the simulation of incidents. In the same way, **extreme reaction conditions** such as high temperatures and salt concentrations, pH values outside the neutral range and low substrate concentration in the micro- and nanogram range should be analyzed.

For the establishment of processes involving micro algae, basic analyses on the enhancement of the photon utilization, on the behavior of mixed algae-bacteria biocenoses and on the chemical-organic-heterotrophic metabolism ("dark metabolism) under anaerobic conditions shall be conducted (oils as storage substances). The objective should be to increase the energy efficiency of the process waste water treatment and/or generate an algae oil as a valuable substance used for example as a raw material for biogenic fuels. This would result in a process for the production of valuable substances that is not competing with the food chain. The **sorptive separation and recovery** of raw materials by means of algae, bacteria or plants is possible, but using them in an economically viable way would presuppose an improvement of their selectivity, regenerability and service life.

Research and development is not only needed for the development of quick and specific **tests** for the quantification of critical substances, but also for fast and reliable detection and quantification of microorganisms. For this purpose, molecular-biological methods and their application in automatic analyzer systems need to be developed further. In combination with biological and physico-chemical sensors, an **online monitoring** is possible that aims at directly influencing the microorganisms and thereby controlling the process and protecting it from inhibitors. The systems to be developed must be sufficiently robust for application in commercial operation.

A targeted control of certain subpopulations in a bioreactor presupposes a better understanding of the interactions between the microorganisms (communication within and among species, so-called quorum sensing, e.g. for biofilm formation). R&D activities in this field aim at fostering the desired physiological performances of certain subpopulations (e.g. degradation, bio-sorption, accumulation of substances) and at suppressing physiological processes that lead to operational problems like for example scum formation.

Influencing the growth behavior of microorganisms constitutes an important process parameter. To date, it has not yet been possible to determine which factors decide whether, in the case of cell retention, microorganisms change to maintenance metabolism or whether they continue to grow planktonically with formation of food chains (bacteria – protozoa – metazoans). The possibility of controlling the sludge age by directly influencing the microorganisms leads to new options for **reducing the sewage sludge quantity.**

Moreover, not enough knowledge is available about the **mechanisms of biofilm formation** of surface-associated communities (flocculation, aggregation/agglomeration and or adsorption phenomena, exo-polymer matrices, bio-fouling) as well as about substance transport mechanisms in the bio-films. This makes it difficult to directly influence bio-films (e.g. stability of bio-films, biofilm mechanics, physiological modification of the microorganisms, mechanical stress) by adjusting the process parameters.

In the field of bioreactor technology and operation of biological processes, also **basic process research** in moving bed, fixed bed and membrane bioreactors (MBR) with a view to characteristic re-suspension, mixing, residence time distribution, fluid dynamics, oxygen injection, scale-up and, in the case of the MBRs, also on an improved retention of various toxic substances is required. Thereby, the missing basic data for assessing the energy efficiency can be generated. Moreover, also analyses regarding the mechanical stress of shear-sensitive biocenoses by purposefully influencing the shearing forces through reactor elements (such as agitation and gas injection internals) are needed. Know-how about residence time distribution and reaction kinetics must be consistently applied. Moreover, also downstream processes (e.g. sedimentation, filtration, flotation) of conventional treatment plants should be developed further and optimized.

The development of the **bio-electrochemical fuel cell** supplies basic information about the transport of electrons in biofilms, the development of electrodes, the control of electrode potentials, generation of OH radicals, optimization of the series and parallel connection of cells, as well as about scale-up.

Impact assessment

Practical implementation of the above-described processes requires extensive research and new developments in the field of molecular biotechnology, sensor technology, process technology and adaptive process control. All activities must focus on the economic viability of the processes used. The development of new analytical technologies and their combination shall serve as a basis for a novel type of process control and represent a major innovation boost for waste water technology.

Biological processes are already today the most economical variant for the removal of substances contained in the process waste water. The developments of the coming years will extend the applicability of biological processes and improve their process economics; the same applies for the production of valuable substances and energy (e.g. algae, H_2, electricity). The establishment of applications under extreme conditions (temperature, salinity, concentration, pH) will result in an additional spread of the biological processes because it will allow for an efficient treatment of process flows that can to date only be disposed of by thermal or multi-stage treatment. Another aspect that should not be neglected is the process-integrated water and heat recycling that will become possible thanks to these developments and an optimized modularization/automation. It can be assumed that new/improved biological processes in the field of process waste water treatment and recycling will make a significant contribution to low waste water production and in addition reduce production costs as a result of substance, water and energy recycling. They are therefore an important integral element of an integrated, sustainable industrial water management.

5.1.2 Anaerobic Processes

Present situation

Owing to the energy gain while at the same time saving energy for aeration, anaerobic processes are widely used for the treatment of waste waters with high organic loads. They are mostly used as a preliminary treatment upstream of a final aerobic treatment. In the case of a high metabolism of the anaerobic bacteria the work and cost for sludge disposal and the nutrient demand are low, something that is particularly advantageous when treating process effluents with low nitrogen and phosphorous concentrations.

Presently, anaerobic waste water treatment is used when the organic substances in the waste water are present in highly concentrated form, waste water is generated continuously and no or only few inhibitors are contained in the waste water.

The key sectors with mostly anaerobic waste water treatment are the food industry and the pulp and paper industry. Moreover, anaerobic processes are also increasingly used in the chemical industry.

Processes currently used on an industrial scale target the retention of as much biomass as possible with subsequent return to the process since the active biomass is characterized by low growth rates. The following processes are used for the retention of biomass (list not exhaustive):

- Sedimentation process with sludge flocs:
  - Activated sludge process with downstream final sedimentation tank,
  - MBR
- Processes with immobilized biomass
  - Pellets (granulated biomass): Upflow Anaerobic Sludge Blanket (UASB)-, Expanded-Granular-Sludge-Bed (EGSB)-, Internal Circulating (IC)-processes
  - Processes involving a carrier material (fixed bed, moving bed)

The application of anaerobic MBRs is currently tested in pilot plants. The main challenge is the poor filterability of anaerobic sludge. In addition, cover layer control by means of air which is widely used for aerobic MBRs is not possible when operating under anaerobic conditions and the substitution with biogas is complex and risky from a safety point of view.

Vision/assessment of potential

In view of the rising energy costs in the coming years (decades) it is vital to minimize the energy consumption of industrial processes, on the one hand, and optimize industrial processes for energy generation, on the other. Therefore, the recovery of the energy contained in many waste waters in the form of organic substances will strongly gain in significance.

In the future, also low concentrated waste waters will be subjected to anaerobic treatment with a view to the potential energy gain provided a better understanding of the requirements resulting from the metabolism of the anaerobic species and creating adequate milieu conditions. In addition to the mesophilic anaerobic biocenoses commonly used today also thermophilic and psychrophilic as well as halo-tolerant and halophilic anaerobic microorganisms will be used.

Thermophilic organisms are characterized by a higher metabolism which allows increasing the volume-based metabolic rate. Psychrophilic applications are easier to implement, on the one hand, while requiring more space, on the other. The application of halophilic or halo-tolerant biocenoses is mainly interesting for the chemical and also for the petrochemical industry. In addition, also the metabolism potential of special anaerobic species will be utilized, like for example biological sulfate reduction and deammonification for the removal of salts.

Furthermore, some substances contained in the waste water that are refractory when treated under aerobic conditions can be converted better and more efficiently by reduction under anaerobic conditions than by oxidation.

The use of anaerobic MBRs will spread because only the gas is separated at the reactor head and the liquid phase is separated via membrane processes. Separation of the nutrients dissolved in the solids-free permeate is comparatively easy (e.g. nanofiltration/reverse osmosis, precipitation, ion exchange, stripping).

Modular, compact and inexpensive process concepts will significantly drive a more widespread use of anaerobic processes.

Especially companies producing process water flows with strong organic contamination will more frequently be implementing such anaerobic processes. Partial flows with higher contamination will increasingly be subjected to anaerobic pretreatment because these processes will become more robust, effective and cost-efficient.

Process effluents may exhibit very different compositions. This notwithstanding, the processes will be designed on the basis of results that are determined according to a standardized scheme using simple, standardized test facilities.

Research and development needs

Although anaerobic processes are widespread, they have been researched much less than aerobic treatment processes.

The following particularities of anaerobic metabolisms need to be examined most urgently:

- The interaction of the anaerobic decomposition steps which take place in several stages, especially those occurring in hydrolysis, and determine the efficiency of all downstream degradation stages

- The reductive degradation of compounds that are not degradable under aerobic conditions (refractory substances)
- Psychrophilic and thermophilic anaerobic microbes
- Halophilic and/or halo-tolerant anaerobic microbes
- Sulfate reduction and deammonification

Furthermore, process concepts adapted to the anaerobic metabolism mechanisms must be developed:

- Adaptation of the reactor systems to the degradation kinetics (especially to hydrolysis)
- Independent anaerobic treatment (without subsequent aerobic treatment step)
- Processes for the generation of hydrogen, the reduction of sulfate and for deammonification

The objectives to be achieved in terms of process technology are:

- compact, simple anaerobic systems
- treatment of partial flows, also with smaller volume
- intensified energy generation
- reduction of the methane slip

Great research demand exists, for example for the establishment of anaerobic MBR processes, whereby the focus shall be on module and membrane optimization and on the development of an overall concept.

The sulfur separation, too, must be optimized in order to improve recovery and further develop adequate processes for CO_2 separation. With regard to a reliable biological removal of sulfur, research must in particular concentrate on the physiology of the metabolism specialists.

A simplified and quick examination of different waste waters for adaption of the process design to the specific application will boost the widespread use of anaerobic processes.

Impact assessment

As the design safety improves also the application range for anaerobic processes will increase: this relates to the anaerobic treatment of partial flows, on the one hand, and to the of discontinuously occurring process effluents, on the other.

The options for a selective transformation of organic matter to methane as an energy storage medium or to basic chemicals will be utilized.

Given the low specific growth rates of anaerobic biocenoses and the low nutrient demand, the (low-germ) bacteria-free effluents of anaerobic MBRs will be used for the irrigation/fertilization of agricultural areas. This way, anaerobic processes can contribute to the recovery of nutrients in the sense of a pollution-free recycling and help reduce the environmentally harmful and energy-intensive production of nutrients.

5.1.3 Aerobic Membrane Bioreactors

Present situation

The general objective of a biological waste water treatment is to eliminate the carbon and nitrogen compounds by way of biochemical oxidation. Conventional biologic processes are characterized by a high space demand. Their application is limited due to the fact that the substances dissolved in the waste water must be accessible to microbial decomposition under the prevailing conditions and may have neither a toxic nor an inhibiting effect under operating conditions. In addition, a "slip" of non-degraded compounds and microorganisms occurs in traditional process operation that may affect the workflows in the plants.

To bypass these downsides at least in part, aerobic membrane bioreactors (MBR) units have become established process components over the past 20 years.

In the case of a MBR unit the conventional components of an activated sludge process are combined with a membrane separation step in lieu of the final sedimentation basin. In most applications, submerged membrane systems are used.

In 2011, the world's largest MBR with a PDF (peak daily flow) of 150 MLD (million liters per day) went on stream. Around the world, some 20 plants with a capacity of > 60 MLD are in operation.

The main challenges for the conceptualization of MBRs are the altered aeration properties of the enriched biomass, the high amount of energy required for the separation of the biomass, and the optimization of the membrane service life.

When treating highly contaminated industrial waste water flows (or partial flows), a transfer of the processes com-

monly used in municipal waste water treatment is possible only to a limited extent. Individual, frequently changing waste water compositions, the presence of poorly degradable, dissolved substances and the demand for a higher space-time yield require adapted reaction spaces, more efficient aeration systems and economic and/or robust membrane separation steps. Given the generally much lower waste water volumes, different membrane concepts tailored to the individual application can be used. Project-specific conceptualizations must frequently be determined by preliminary tests and adapted to the requirements. The toolbox existing to this effect is characterized by the following elements:

- **Reactor designs:** e.g. loop reactors, pressure reactors, cascaded reactors (e.g. aerobic, anoxic)
- **Aeration systems:** e.g. pure oxygen aeration system, injectors, ejectors, membrane aeration
- **Membrane systems:** submerged or externally installed cross-flow filtration, dead-end filtration, ceramic or organic membranes, plate membranes, tube membranes or capillary membranes, micro-, ultra- or nanofiltration

Aerobic MBRs are widely used in industrial waste water cleaning on the grounds of their reliability, high cleaning performance, compactness and adaptability. Possible applications are not limited to the final treatment of water prior to discharge, but also include systems for the internal re-use of water and closing of water loops.

Across Europe, numerous applications for industrial MBR units are found. Here are some examples:

- Landfill leachate, waste water from waste treatment plants (>250 installations)
- Chemical waste water, cleaning of tank trucks (> 25 installations)
- Dairy industry (> 25 installations)
- Hospital waste water, pharmaceutical industry (> 10 installations)
- Slaughterhouse waste water, rendering plants (> 10 installations)
- Pulp and paper industry (> 10 installations, some with waste water recycling)
- Food industry (> 10 installations)
- Brewery waste water (> 5 installations)
- Laundry waste water (> 5 installations with waste water recycling)
- Cosmetics industry (> 5 installations)

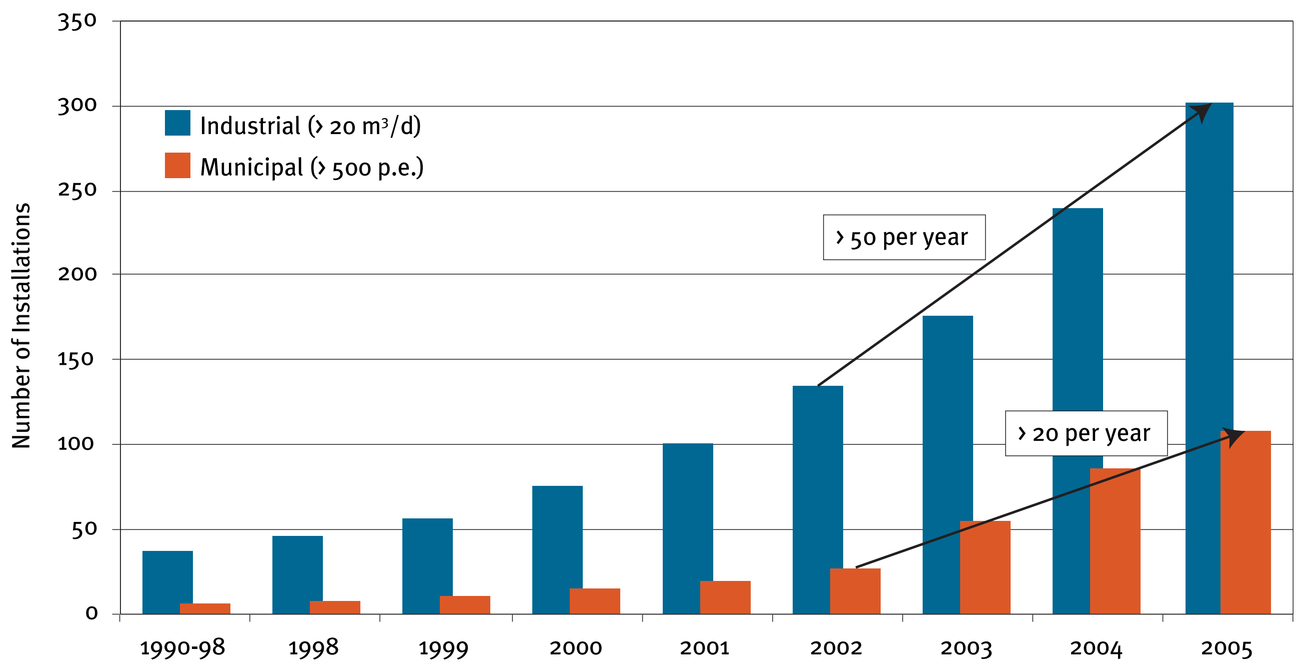


Fig. 10: Number of installed membrane bioreactor/aeration units[12]

12 Lesjan B. und Huisjes E.H. (2008): Survey of the European MBR market: trends and perspectives; Desalination 231, 71-81

The evermore popular strategy of recovering valuable substances from the waste water at the place of occurrence or removing contaminants from a partial flow with technologies designed specifically to the substance to be removed leads to a situation where aerobic MBR units are increasingly used as a first step in a multi-stage waste water treatment.

Consequently, demand for MBRs continues to rise also 20 years after the first implementation of technical MBR systems in the 1990s (cf. Fig. 10).

Vision/assessment of potential

Effluents containing valuable substances or contaminated with substances that are not biodegradable or poorly biodegradable, are collected separately and specifically treated. Thereby, the focus is on the recovery of valuable substances. Substances that are not biodegradable or only poorly biodegradable in conventional sewage treatment plants are removed in partial flows by physico-chemical treatment or in an upstream aerobic MBR unit.

When using an aerobic MBR for the treatment of highly contaminated industrial waste waters or for the treatment of partial flows, different sub-processes are combined in a purposeful sequence. The reactor designs are adapted to the waste waters produced in the upstream production process which may in some cases exhibit an unbalanced composition. Efficient aeration systems and their intelligent control require significantly less energy. New and in some cases specific membrane cleaning strategies have been developed. For the membrane materials and module concepts, durable, flexible and powerful systems are preferred over inexpensive mass products. Aerobic MBRs are frequently combined with other physical or chemical treatment steps, thus resulting in specific, tailor-made "hybrid systems".

Research and development needs

The treatment of highly contaminated industrial waste waters requires the development of individual solution concepts tailored to the specific application. The main focus is on the aspects of operational and process stability of the biological treatment as well as on membrane separation.

Reaction spaces and aeration facilities shall be combined in such a way that the higher solids concentrations in the MBR units can be optimally supplied with oxygen. In this context, the process shall not be adapted to a complex waste water mix, but to individual substances contained in partial flows and/or in the highly contaminated industrial waste water. Purposeful control mechanisms for oxygen supply must be developed. Accumulation mechanisms in the MBR or in the process in the case of water reuse systems shall be evaluated separately. Below is a list of the areas with a high demand for research and development:

- Adequate aeration systems for higher biomass contents
- Impact of the reaction room geometry on the aeration efficiency and metabolism rate
- Decomposition behavior of individual substances
- Control of the oxygen supply in aerobic MBRs
- Substance accumulation in the reactor and in water loops in the case of aerobic MBRs

Adequate membrane concepts shall be developed taking due account of membrane cleaning, membrane service lives and the energy required for filtration. Especially for the cleaning of membranes new and interesting options have been found:

- Ultrasonic cleaning of membranes
- Cleaning by changing the electric potential
- Cleaning by pulsating flows
- Development of new membrane cleaning chemicals
- *In situ* mechanical membrane cleaning

For the design and engineering, in addition to databases with relevant kinetic and physiological data also standardized laboratory tests combined with modeling tools need to be developed. A particularly important aspect is the adaptation and integration of the aerobic membrane process into an overall treatment concept or into the overall production process. The adaptation of different systems and their interfaces represent one of the great challenges for the future.

Impact assessment

The further development of MBRs enables a production-integrated approach for the treatment of partial flows and the reuse of water. The consistent treatment of partial flows will allow plants to operate at a higher concentration and temperature level and avoid higher capital expenditure for infrastructure (e.g. storage volumes, piping). The physical and chemical processes used for the elimination

of some substances can be applied more economically with an aerobic MBR pretreatment. MBR therefore constitutes an important element for an integrated, sustainable industry water management.

In countries and regions with insufficiently developed infrastructure or where water is only available to a limited extent and in poor quality, the (pre-) treatment of highly contaminated industrial effluents and partial flows will be even more important than in the highly developed industrialized nations. For Germany as one of the leading export nations a pioneering role in this field would be beneficial.

5.2 Advanced Oxidation Processes (AOP)

Present situation

AOP offer a broad application potential and are used in the treatment of industrial and municipal waste water, in the treatment and recovery of industrial water, but also in the treatment of ground water and potable water[13]. They are characterized by the involvement of radicals, mainly hydroxyl radicals, in the reactions. In view of the radical reactions with a high oxidation potential, these processes are interesting for the degradation of anthropogenic and toxic organic substances contained in the water. In addition, the parallel disinfection, discoloration and deodorization of the (waste) water is advantageous.

One particularity of the oxidation process is the formation of intermediates and by-products. These transformation products might have toxic effects so that an exact analysis of the processes and a precise design of such plants are required prior to a possible application.

AOPs need a higher energy input than other processes like biological or membrane processes, e.g. for electric energy and/or chemically bound energy (oxidants). Economical applications of AOP are therefore still restricted to comparably small pollution loads, identifiable production advantages (e.g. improved product quality or reduced dependence on the availability of water) and to combinations with other processes (e.g. biological, membrane-based and adsorptive processes).

One application option with a substantial economic potential for AOP is the post-treatment of treated process water (e.g. polishing: elimination of trace substances, discoloration, disinfection), because these processes only involve a low oxidant demand.

Vision/assessment of potential

With AOP, a residue-free water treatment with regard to organic compounds is possible. They are therefore well suited as a sub-process in the framework of processes for the recovery of valuable substances and water. Usually both the quality of the recoverable valuables and also that of the process water to be reused is improved and in addition the volume of residues and/or concentrates is reduced. For example, the quality of the metal salts that can be recovered in a precipitation step can be improved by introducing a (co-) precipitation/flocculation of organic substances in the form of an upstream oxidation step. Therefore, it can be reasonably expected that the significance of AOP in water treatment is set to rise.

Potential exists in particular regarding

- a reduction of the energy demand for the provision of oxidants,
- a purposeful use of intermediaries or prevention of their formation,
- an improvement of the water recycling efficiency by means of a combination of processes.

Photocatalysis could become increasingly interesting, especially for regions with little water and lots of sunshine. This would require the development of stable and highly efficient catalysts.

Research and development needs

Current research approaches target the following fields of application:

- a more energy- and cost-efficient production and use of oxidants (hydrogen peroxide, ozone)
- reduction of the oxidant demand (purposeful facilitation of chain reactions, catalysts)
- increased use and control of photons from solar radiation
- application of new, more efficient materials for electrical, chemical and photo-catalysis
- improved reactor concepts and technologies
- combinations with other processes
- supporting process optimization by way of improved reaction models, in particular for the reactions of rad-

13 Sievers M. (2011): Advanced Oxidation Processes. In: Peter Wilderer (ed.) Treatise on Water Science, vol. 4, pp. 377-408 Oxford; Academic Press

icals and the interaction with substances contained in the water

With a view to minimizing the volume of by-products it will probably be possible to use research approaches on the risk assessment of micro-contaminants for developing test methods and automation concepts for AOP applications.

Future research and development needs exist regarding quality improvement in the recovery of valuable substances from aqueous solutions because it is assumed that this involves a great potential. A first practical example from printed circuit board production shows five benefits: (1) minimization of the waste and (2) waste water volume (zero-emission), (3) recovery of a high-quality electrolyte solution, (4) improvement of the energy efficiency and – something that is also very decisive – (5) an enhancement of the product quality[14].

Impact assessment

The plans for an energy- and cost-efficient application of AOP which are still considered visionary today can be leveraged in the future. This will create new, economically viable application options. Since not only the recovery of valuable substances but in particular also the recovery of water will gain increasing importance in the future, it is to be expected that AOP will in many areas make an essential contribution to the closing of (industrial) water loops, for example as an element of "multi-barrier concepts" or in the treatment of sidestream flows.

5.3 Membranes for Water and Waste Water Treatment

Present situation

As a physical separation method with low energy consumption, membranes play an important role in water and waste water treatment. At present, polymer membranes are successfully used for the treatment of large potable and waste water flows. Preferably, spiral wound membrane modules in cross-flow filtration and immersed membranes as membrane bioreactors (MBRs) are used. With polymer membranes, not only suspended substances and germs, but also dissolved salts and low-molecular molecules can be separated. In the chemical and pharmaceutical industries, comparably small process flows must be treated with specific and functional membranes. In this context, ceramic membranes are increasingly used which, given their high mechanical, chemical and thermal stability, allow for an application in aggressive media and the use of efficient chemical cleaners all the way to hot steam sterilization. With these properties, a production-integrated application of membrane technology is possible where only sidestream flows are treated and cycles are frequently closed while avoiding heat losses. Examples include the maintenance of contaminated oil-in-water emulsions by microfiltration membranes, the maintenance of highly alkaline baths for the cleaning of returnable bottles with ultrafiltration membranes or the discoloration of chemically aggressive and hot effluents from textile finishing using nanofiltration membranes.

14 Dams S, Sörensen M, Weckenmann J, and Csik G (2008): Continuous nickel recycling with integrated electrolyte purifying. Galvanotechnik 2, 320-328.

Vision/assessment of potential

- Membrane processes are the dominating separation processes in the field of waste water cleaning and water treatment. They are mainly used in combination with other separation processes.
- The gap between polymer membranes and ceramic membranes is largely closed. Polymer membranes are much more stable and durable while ceramic membranes can be inexpensively fabricated with large areas.
- The propensity of membranes and modules to scaling and fouling is significantly reduced; this allows for longer membrane service lives at reduced cleaning effort.
- New membranes with specific selectivities for certain substances contained in the water and/or with additional functionalities (e.g. catalytic self-cleaning, suited for switching between hydrophobic/hydrophilic) are available.

Implementation of ozone electrodes (© Xylem Inc.)

Research and development needs

- Improvement of the chemical, mechanical and thermal stability of polymer membranes
- Ceramic membrane geometries with high volume-specific membrane area for a significant reduction of specific membrane costs
- Higher throughput capacities of the modules at lower energy input
- Availability of ceramic nanofiltration (NF) membranes with a cut-off of 200 g/mol
- Improvement of the selectivity of membranes without impairing their productivity
- Functionalizing of membranes
- Availability of ultrafiltration (UF) and NF membranes with a high resistivity to acids and alkaline substances (15–20 % acid and alkaline solutions)
- Enhancing the stability and selectivity of membranes in organic solvents
- Combining membrane treatment with other separation and enrichment processes
- Developing integrated solutions including the treatment of concentrates
- New module concepts and membranes for applications for the better utilization of renewable energy (e.g. biofuel and biogas, synthesis gas and natural gas cleaning, osmotic distillation, direct osmosis, water recovery from flue gases)

Impact assessment

The use of membranes offers the following benefits:

- Saving water by means of production-integrated waste water cleaning and cycle closing
- Enhancing the quality of water bodies by efficient waste water cleaning
- Energy savings thanks to low-energy separation processes
- Possibility for a combination with other processes (e.g. membrane aeration for biological waste water treatment)

The demand for clean potable water which has been growing for years and the demand for microbiologically safe water in combination with a successful further development of the membranes will lead to a significant rise in the membrane area installed. If a clear reduction of ceramic membrane fabrication costs can be achieved, their proliferation will rise significantly. The same also applies for biotechnological processes for the production of special base and fine chemicals, e.g. on the basis of renewables. Compared against chemical processes, membrane treatment offers the benefit of lower energy costs. In addition, there is a growing demand for the recovery of vitally important substances that are not produced as bulk raw materials directly in the production process, and/or for their distribution into different outflows and thereby prevent their loss from the value chain. In this context, new opportunities open up for the use of membranes with a high substance-specific selectivity and/or added functionality.

Hollow fiber membranes in industrial wastewater treatment (© Bayer Pharma AG)

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