PROJECT FINAL REPORT

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Executive Summary

The chemical industry is a keystone of the European economy. It converts raw materials into thousands of different products and is both a major water user and a solution provider for the key strategic European process industry sectors. The chemical industry offers significant potential for increasing eco-efficiency in industrial water management also for other industrial sectors.

Primary contribution of E4Water includes a paradigm shift in chemical industry to create a breakthrough in industrial water treatment and management. The project has addressed crucial process industry needs to overcome bottle necks and barriers for an integrated and energy efficient water management. The main objective is to develop, test and validate new integrated approaches, methodologies and process technologies for a more efficient and sustainable management of water in chemical industry with cross-fertilization possibilities to other industrial sectors. International partners, namely industry stakeholders, research partners and end users, dealt with reduction of water use, wastewater production and energy use in the chemical industry with the objective of more eco-efficiency and sustainability. Particularly the societal, environmental and economic challenges were on focus where innovative solutions are needed to uncouple growth from water use.

E4Water has built on state-of-the-art and new basic R&D concepts. Their realization, improvement, utilization and validation, with the compromise of early industrial adaptors, are clearly innovative. E4Water has realized this by

- creating water loop interfaces, synergies and symbiosis: (a) in industry (b) with urban & agricultural water management
- developing and testing innovative materials, process technologies, tools and methodologies for an integrated water management,
- providing an open innovation approach for testing E4Water developments with respect to other industries,
- implementing and validating the developments in 6 industrial case studies, representing critical problems for the chemical industry and other process industries,
- implementing improved tools for process efficiency optimization, linking water processes with production processes and eco-efficiency assessment.

The E4Water concept was following an integrated, multi-disciplinary and holistic approach in different industrial scales and across sectors. The six case studies (CS) were chosen as prototypical examples for generic challenges in order to show the generality and broad impact of the concept. They were designed to ensure and demonstrate the relevance of the E4Water approach to the chemical industry.

The work was supported by a policy framework analysis, to ensure later regulatory compliance. Further modelling and assessment tools have provided an important information basis for industrial decision making.

Summary description of project context and objectives

PROJECT CONTEXT

Water is a key pan-European concern for industry. Despite the vast amount of water on the planet scare fresh water resources or water stress of aquatic ecosystems are up-to-date in Europe and the world. They are the result of environmental, political, economic, and social forces. Europe is confronted with urgent challenges related to water: adapting to climate change, including mitigation of floods and droughts risks, reaching good status of surface water, ensuring availability of water to deliver multiple benefits to nature and to the economy. In view of the requirements of water related policies, eco-efficient and sustainable industrial water management is considered to be one of the main strategies for environmental protection in many European countries.

The chemical industry is a keystone of the European economy. It converts raw materials into thousands of different products and is both a major water user and a solution provider for the key strategic European process industry sectors such as mining, industrial biotechnology, health, food, electronic, pulp and paper and energy. The chemical industry offers significant potential for increasing eco-efficiency in industrial water management also for other industrial sectors.

How to come to an economically and ecologically efficient water management in the European chemical industry? How to realize an integrated industrial water management approach?

A sustainable integrated water system is essential for an efficient water management in chemical and process industries. Integrated management considers interactions, interdependencies and synergy potentials between different measures of water use and water/wastewater treatment in and across various scales. It concerns measures directly linked with single production processes as well as measures and cooperation that go far beyond one industrial unit or even site (e.g. neighbourhood industrial sites, municipal wastewater treatment units, water resources management institutions up to catchment scale). To come to an integrated water management the technology options are getting manifold.

OBJECTIVES

Primary contribution of E4Water includes a paradigm shift in chemical industry to create a breakthrough in industrial water treatment and management. The project has addressed crucial process industry needs to overcome bottle necks and barriers for an integrated and energy efficient water management. International partners, namely industry stakeholders, research partners and end users, dealt with reduction of water use, wastewater production and energy use in the chemical industry with the objective of more eco-efficiency and sustainability. Particularly the societal, environmental and economic challenges were on focus where innovative solutions are needed to uncouple growth from water use.

Main objective was to develop, implement and validate new integrated approaches, methodologies and process technologies for a more efficient and sustainable management of water in Chemical Industry achieving solutions that are eco-efficient, cost-effective and industrially relevant. This was reached by the close cooperation between research organizations and industry and by the high industrial involvement in all the steps of the process. In this way the scientific and technological excellence was assured.

E4Water has built on state-of-the-art and new basic R&D concepts. Their realization, improvement, utilization and validation, with the compromise of early industrial adaptors, are clearly innovative. E4Water has realized this by

- creating water loop interfaces, synergies and symbiosis: (a) in industry (b) with urban & agricultural water management
- developing and testing innovative materials, process technologies, tools and methodologies for an integrated water management,
- providing an open innovation approach for testing E4Water developments with respect to other industries,
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- implementing improved tools for process efficiency optimization, linking water processes with production processes- and eco-efficiency assessment.

E4WATER CONCEPT

The E4Water concept was following an integrated, multi-disciplinary and holistic approach in different industrial scales and across sectors. The six study cases (CS) were designed to ensure and demonstrate the relevance of the E4Water approach to the chemical industry:

- The chemical site of case study 1 (CS1) is located in the coastal area of the Netherlands. Due to shortage of fresh water the partners were working on facilitating the use of reclaimed water in industrial water management process. For this a "Mild Desalination" concept was developed.
- The case study 2 (CS2) is located in the Port of Antwerp (Belgium), a multi-company site. Due to pressure on fresh water resources and regulatory demands for waste water, water reuse and identification of synergies are of interest. For this approach an "Industrial experimental Garden" was developed and synergy effects with a neighbor company were made possible.
- The coastal area of northern Spain with small river basin facing periodical water shortages. Case study 3 (CS3) has focused on ensuring process continuation by closing the water loop and minimizing fresh water use.
- Case study 4 (CS4) dealt with recycling of wash water streams that incurred in the production process of household chemicals. Innovative ways to enhance in-process water loop closure by integrating biocidal with wastewater treatment technologies were on focus.
- In case study 5 (CS5) an integrated waste water management on a petrochemical site in northern France was elaborated. Optimisation of water management and the further treatment of concentrates were on focus.
- Case study 6 (CS6) is located at an industrial symbiosis site in Denmark. Focus is to develop innovative symbiotic treatment concepts for high-loaded organic waste water streams coming from industrial fermentation processes by creating added value.

The case studies were chosen as prototypical examples for generic challenges in these fields in order to show the generality and broad impact of the E4Water concept. The work was supported by a policy framework analysis, to ensure later regulatory compliance. Further modelling and assessment tools have provided an important information basis for industrial decision making.

The results were elaborated in close cooperation between developer and provider of water treatment technologies and the process/ chemical industry. It is clearly shown that individual solutions are needed for the optimisation of an integrated water management. Especially in water scarcity regions (quantitative/ qualitative) individual solutions improve the competitiveness of companies.

E4Water provides a toolbox with technical solutions and concepts that support the European chemical industry but also other European industry sectors regarding approach and solutions for an integrated water management. The implementation of E4Water developments help to decouple the increase of industrial production from the use of water, natural resources and energy. The outcome of E4Water strengthens both, the leadership of the European Water

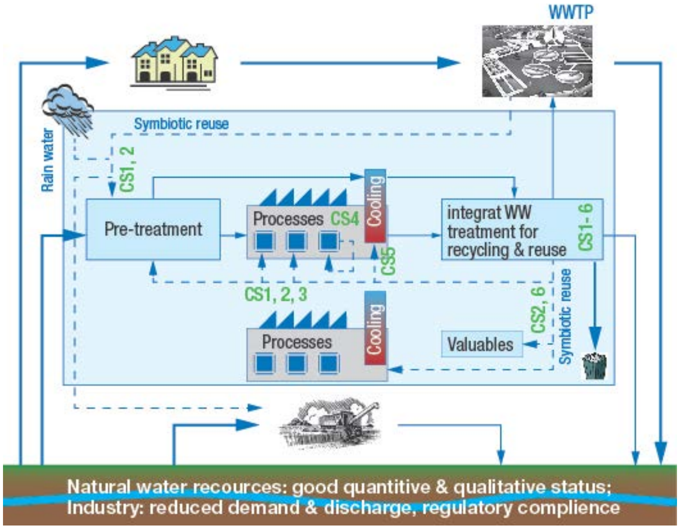

Figure: The E4Water concept, following an integrated, multi-disciplinary and holistic approach in different industrial scales and across sectors. The dashed lines indicate the impact by E4Water, CS (= case study) indicate where on site industrial pilot testing and demonstration are focused on, the number allows their identification.

Description of the main S&T results/ foregrounds

THE DOW CASE: MILD DESALINATION OF WATER STREAMS FOR OPTIMUM REUSE IN INDUSTRY OR AGRICULTURE AT AFFORDABLE COSTS

Case study description

As a chemical site Dow Benelux has a significant demand for fresh water with major applications in cooling and heating (via producing steam) to run its processes. Situated at the river Scheldt estuary, the region where Dow is located suffers from an intrinsic lack of fresh water (with a WRI overall water risk index of 3.1, indicating a medium to high water stress).

Various water streams currently discharged to the river Scheldt have been selected on their reuse potential, both from a quantitative and qualitative point of view. However, these streams contain varying amounts of inorganic salts, which make them unfit for direct usage in industrial applications or agriculture. Hence, the E4Water case study 1 (CS1) demo is designed to develop commercial applications for a mild desalination of these different raw water streams. The required degree of desalination depends on the specific acceptance specifications for the final application of the mild desalinated water by the end-user, which can either be industry (Dow or another nearby facility) or agriculture. In the Dow case study the target was to produce a process water quality fit to use as make-up water for cooling towers at affordable costs (approx. 0.4 €/m^3 of produced product).

Results

The first stage of the case study has focused on market screening and laboratory studies to evaluate and select the most suitable and promising techniques to achieve the project objectives.

Next a pilot facility was constructed at the Dow/Evides site and operated by Evides Industriewater over a period of thirty months. As feed streams three different brackish water sources were directly connected to the pilot unit. These were 1) Collected rain/surface (Spuikom) water, 2) Treated process wastewater (Biox effluent), and 3) Blow down from process cooling towers. The test rig consisted of two parallel desalination trains, one based on NF (Nanofiltration), the second on EDR (Electrodialysis Reversal), preceded by a combined robust raw water pre-treatment (scheme on p.4).

Major results of the different technologies vs. feed streams were summarized. Ultrafiltration (UF) was tested with inside/out multibore polyethersulphone Inge membranes and outside/in polyvinylidene difluoride (PVDF) Dow membranes. Fluxes of 45-70 L/m2.h were possible for all tested water sources. Iron dosing was needed for Spuikom and Biox effluent to obtain a stable performance. NF in all cases provides a superior product quality, but is sensitive to fouling and scaling, especially when treating cooling tower blow down (CTBD) water and to a lesser extent with Biox effluent. EDR appears to be a robust technique yielding high recoveries, but non-charged constituents like most organic compounds (TOC) are poorly removed and require an additional treatment step.

Several process and cost optimizations seem possible, but are only tested to a limited extent:

- Reduced Fe dosage especially when using Dow UF membranes
- Simplify pre-treatment of Biox- and Spuikom-water by using multimedia filtration instead of UF

Towards future implementation three concepts were developed, with different ratios of feed streams and combination of technologies. These were

1a) Full delivery by a mix of Biox effluent and Spuikom water treated with NF

1b) Full delivery by a mix of Biox effluent and Spuikom water treated with EDR

2) Partial delivery by a mix of Biox effluent and Spuikom water treated with EDR with additional delivery of CTBD water treated with EDR followed by Ion Exchange (IX) for organic carbon removal

A multi criteria analysis was done to compare these alternatives with respect to robustness of operation, product quality, water source security, and environmental impact.

In addition preliminary full scale designs (excluding connecting infrastructure) were generated for each of these concepts, including estimates for operational costs (chemicals, energy) and direct equipment investment. The relative costs of the different alternatives were shown with concept 2 as a reference (100%). In addition to this high level Opex and Capex also costs for operation & maintenance, capital interest, analyses and others will have to be included to determine absolute levels of production costs. Total costs then may range from 0.45 to 0.65 €/m³ of product for the best option.

Both from a cost and performance perspective the reuse of CTBD water is the least attractive among different options and should be discarded as long as other sources are available in sufficient quantities. EDR appears to be the more robust mild desalination technology, but is more costly than NF.

Perspectives for the future

The Dow Terneuzen case study shows that mild desalination technology of miscellaneous brackish water streams is feasible and can be an attractive approach to produce water for industrial applications in delta areas across the world, which typically are characterized by the presence of limited fresh but abundant brackish water sources.

Case study related technologies

Ultrafiltration

In the coagulation/flocculation process step a dosage of 5-10 ppm of Iron (Fe) is effective to realize a stable performance in the down-stream (UF) unit. The UF performance was evaluated by transmembrane pressure (TMP). The prime objective of UF is to remove suspended solids. Both, Inge and Dow membranes can be operated in a stable and acceptable way, when taking into account constraints in feed water quality. A flux of 70 L/m2.h was achieved with all water sources for the Inge membranes, accepting a filtration run time of 20 minutes for Spuikom- and CTBD water) and of 45 minutes for Biox-effluent. This resulted in an acceptable recovery of 83-92%. The recovery was higher on all feed water sources for the Dow membranes, resulting in a recovery of 87-96%. The higher recovery is mainly the result of the lower chemical enhanced backwash frequency. Iron dosage in the pretreated feed water was in most cases not required for the Dow membranes. Where the applied flux was 45-50 L/m2.h for CTBD and Spuikom water respectively. The applied flux on Biox-effluent was similar for both membranes.

UF: Very reliable application for new mix of raw water streams (TRL 8).

Electrodialysis Reversal

EDR is performing well with respect to the key performance indicators developed in the course of this project: normalized pressure drop (NPD), normalized current efficiency (NCE) and normalized membrane resistance (NMR) on all feed water sources. These key performance indicators were developed together with the E4Water project partners and recently published in Water Resource and Industry. The results are leading towards the conclusion that EDR is performing better in terms of operational stability for CTBD water and Biox effluent than (NF). Possibly EDR can be operated more stable due to the reversal of electrical current and “selectively” removes the ions when compared to NF where the water is pushed through the membrane. With CTBD water there is more fouling in terms of NPD and NMR, compared to Spuikom water and Biox-effluent, which is resulting a different CIP frequency. The quality of the EDR regarding TOC removal is not meeting the specification when treating CTBD water, however by applying an additional treatment step (ion exchange) at the diluate the specification of < 15 mg/L C can be reached.

Innovation: Combination of suitable pretreatment and EDR in Mild desalination on a mix of surface water and industrial streams to produce industrial quality water (TRL 7)

Nanofiltration

Operation of the NF membrane system is stable for Spuikomwater at an acceptable recovery of 75%. With CTBD water the fouling of NF membranes is substantial and is negatively impacting the NF process by fouling of the membrane. Consequently the higher feed pressure accounts for more than 40% of the energy consumption of the entire system. This at even low recovery rates of 40-65%. Membrane autopsy revealed an irreversible hydrocarbon fouling/biofouling. This membrane fouling could thus not be removed even when applying different cleaning chemicals at the laboratory. Both the observations on pilot results, theoretical background of chemical use in the cooling tower, and the membrane autopsy results lead to the conclusion that CTBD water treated by polyamide NF membranes causes an unstable process performance. A final conclusion on the process stability of Biox-effluent is still uncertain, given some periods with a steep decline in permeability, while CIPs are not completely restoring the membrane performance.

Combination of coagulation and UF as pre-treatment for NF on CTBD and industrial wastewater was not sufficient.

Membrane Distillation

Desalination using membrane distillation (MD) is investigated on small pilot scale. MD is an attractive desalination technology for cooling tower blow down water as residual heat at a temperature level of 60-80 °C, which is often available on industrial sites, can be used for the process. This makes MD a potentially cheap desalination technology. However, this is not yet common practice. Pilot experiments were performed using spiral wound modules with a PE membrane with a surface area of about 12 m2. The MD process was operated at a temperature of 70 °C with a temperature difference across the membrane of 10 °C. The pilot ran for more than three months, testing different parameters and set-ups.

Innovation: MD is a promising technology, especially for treating difficult process water streams – not economically feasible yet on the required scale (TRL 5).

Major conclusions comprised:

- The presence of biocides and organic components did not pose problems for the membrane distillation. A constant low distillate conductivity (100 μS/cm) was observed in the pilot experiments.
- Addition of antiscalant did not improve MD performance
- 80 % of the cooling tower blow down water could be recovered as clean water.

THE INOVYN BELGIUM CASE: ENHANCE THE WATER REUSE BY GLOBAL MANAGEMENT AND SYNERGY IDENTIFICATION ON A MULTI-COMPANY SITE

Case study description

The aim of the INOVYN case study (CS2, former Solvic) is to ultimately deploy, in a step-wise approach, a water management concept that will save large volumes of drinking water intake and come close to zero salt waste and zero liquid discharge. Enabling synergy in water savings with neighborhood industries in the Port of Antwerp Chemical Cluster is the key to significantly reduce consumption of potable water in this area. The three main objectives are:

- Scenario evaluation and step wise implementation of innovation plan to reach gradual reduction of drinking water intake from 20% to 60%
- Reduction of emission load in final effluent by replacing waste-generating steps or applying advanced treatment options for concentrate streams (application of waste design and zero waste concepts)
- Transition of demo unit into ‘Industrial experimental garden’ to serve as open infrastructure to enhance innovation with regard to water reuse in the chemical sector leading companies to a symbiotic cooperation in terms of reuse.

The INOVYN site is located in this coastal region and faces pressure on fresh water uptake (Flanders “Integral Water Policy” and “Rainwater Decree”). This case study of the project was divided in three modules with each a DEMO-installation:

- Module/DEMO 1: Producing high quality water (< 5 µS/cm, 6,5 < pH < 8,5) from phreatic water and wastewater (> 2000 µS/ cm) from an external company
- Module/DEMO 2: Producing high quality water (< 5 µS/cm, 6,5 < pH < 8,5) from brackish surface water (> 15000 µS/cm)
- Module/DEMO 3: Reuse concentrated salty water (5-14% NaCl) from an external company for the membrane electrolysis process of INOVYN Manufacturing Belgium site.

Evides Industriewater operated DEMO 1 for 4 years and was leading the research. DEMO 2 was designed, built and owned by Evides Industriewater and operated for 2.5 years.

Results

With DEMO 1 the possibility of reusing wastewater from an external company and phreatic water was tested to produce high quality water for the INOVYN site. The DEMO unit consists of a disc filter as pre-treatment and an UF-RO module. In this case only the technological evaluation has been done. 100% treatment of the wastewater wasn’t possible with the current DEMO 1 setup due to the wastewater quality. The largest problem was the very small (< 50 µm) black carbon particles (difficult to remove from UF) and small plastic fibers (leading to plugging of the UF). Due to this the unit was only in operation for a limited period of time. The tests of reusing the wastewater and phreatic water were continued with phase 2 on DEMO 2.

With DEMO 2 the possibility was tested to produce high quality water from brackish surface water for the INOVYN site. The DEMO unit consists of an Amiad-strainer as pre-treatment and an UF- and RO-modules. A stable operation was achieved with 100% brackish surface water as feed during phase 1.

Phase 2 started when the tests were executed according to a research plan of DEMO 1 & 2, which is the integration of the wastewater from the external company and phreatic water into DEMO 2.

The unit operates with a mixture of the 3 water types:

- Brackish surface water
- Wastewater
- Phreatic water (rainwater)

The technological evaluation of the DEMO unit shows a stable process performance. The economical evaluation was also done for DEMO unit 2.

Innovation DEMO 2: deminwater production by UF-RO-RO on a mix of difficult to treat wastewater, freatic water and brackish surface water (TRL 8)

With DEMO 3 the possibility was tested to reuse concentrated salty water from an external company for the membrane-electrolysis of INOVYN. To evaluate the direct injecting of concentrated salty water stream into the INOVYN process, a mini-electrolysis was built to test this water type and to shield the hazards of testing in a production environment. The

DEMO unit was designed and built with a “plant on truck” concept. After commissioning the unit was first fed with a vacuum salt/demin water mixture. A first promising water type (10-14% NaCl) was tested during phase 1. Due to unforeseen complications of the external water, modifications were needed to achieve a stable process operation. The technical evaluation looks promising after the test results with 8 consecutive loads. A final conclusion was made after a membrane-autopsy at the end of the tests: the first water type was suited for reuse in the INOVYN process.

After the membrane autopsy, maintenance of the DEMO unit and new membranes of the same type were placed in the cell of the unit to test a second promising water type with a lower salt concentration (5-8% NaCl). The preliminary results gave a stable operation and cell performance. A final conclusion will also be made after a membrane autopsy.

Innovation DEMO 3: Reuse concentrated water into a chlor-alkali plant thanks to industry symbiosis (TRL 7)

Perspectives for the future

The DEMO studies describe the technical and economic feasibility of a full-scale installation to working up of wastewater, phreatic & dock water to high quality water and to reuse the concentrated salty water from an external company. The results of DEMO units 1 & 2 will also study the basis to generate the design parameters for a possible full-scale plant for the production of process water & demineralized water.

It was difficult to compete with the relatively “low cost price” of water in the region of INOVYN Manufacturing Belgium with the DEMO 1 & 2 units. But we are confident to compete this with a full scale installation when also an intermediate water quality can be delivered. An additional benefit is the knowledge gained from the DEMO units which can be valuable for other partners/companies facing “high water costs” or water scarcity.

An economical study of reusing the concentrated salty water shows a relatively high CAPEX and OPEX costs to integrate the concentrated salty water from the external company into the INOVYN Manufacturing Belgium site. One of the main key factors for a rapid evaluation is the payback time (PBT). The PBT is high and between 5.8 years and 7.8 years. It is clear that a further reduction of the PBT has to be obtained before the realization of the project will be decided by the management of the both companies.

Case study related technologies

Strategies to deal with high concentrated brines

Three strategies (Electro-dialysis with bipolar membranes (EDBM), Membrane distillation crystallisation (MDC) and electrolysis) were evaluated to avoid discharge of brines to surface water and to valorize the sodium chloride. The use of a new 5 compartment EDBM stack configuration increase the tolerance for calcium slightly but still fails to enable long term process stability. Membrane distillation enables to concentrate NaCl brines at stable flux up to almost saturation and during this process a clean water stream is generated. After reaching saturation, crystallization started and a strong decrease in the flux was observed for both MDC and osmotic distillation (OD). The use of high concentrated NaCl brines as feed for a chlor-alkali plant is the most promising. The subsequent electrolysation process was stable and no differences were observed in comparison with the use of pure sodium chloride.

THE INOVYN SPAIN CASE: ENSURE PROCESS CONTINUATION BY CLOSING THE WATER LOOP AND MINIMIZING FRESH WATER USE

Case study description

The aim during the development of this case study (CS3) was to increase the sustainable water use in a chemical production line through the development and demonstration of effluent reuse and closure of circuits in a PVC production plant. Technical and economic aspects were considered for the implementation of the project results at industrial scale.

The main bottleneck for the implementation of closure concept in this type of industries is the presence of polyvinyl alcohol (PVA) within the mother water, because it interferes in membrane separation. In general, the effluent from these industries is characterized by neutral pH, low COD values, high PVA/COD ratio and almost no solids.

Results

The work has been developed in several steps:

1. Evaluation of different scenarios and treatment alternatives at laboratory scale for the reclamation of this effluent with the aim of finding the most optimum treatment train to be implemented at pilot scale. After an exhaustive bibliography study different technologies were tested and optimized. A membrane aerobic bioreactor (MBR) with different membranes (flat sheet and hollow fiber) was tested as pre-treatment to the desalination step. Reverse osmosis (RO), capacitive desalination (CDI) and electrodialysis were evaluated as possible desalination technologies with the aim of achieving the target values needed for the PVC polymerization plant: conductivity < 10 µScm-1, Al < 0.1 mgL-1 and TOC < 10 mgL-1.

2. Based on the laboratory study, the pilot design and initial operational values were selected. Pilot plant results during 15 months have shown the robustness of the proposed solution. MBR effluent characteristics were suitable to feed the RO. RO permeate and reject characteristics were assessed. Final RO permeate fitted the quality demanded for water reclamation in terms of target values during all the piloting period. RO membranes showed quite good performance in terms of permeability and transmembrane pressure values. Concentrates also fulfil the limits for discharge.

Feasibility study

An economic estimation was done using Discounted Payback Period (DPP) value calculation. Thus, after finishing the pilot studies, a computational simulator was built to make full scale-up extrapolation in terms of raw materials and utilities consumption, i.e., to determine variable costs. The purpose of this study was to have an estimation of the required CAPEX for the deployment, OPEX for regular operation as well as DPP and some other key strategic points such as minimum recycled water or fresh demineralized water cost to make this project profitable from an economical point of view.

According to the estimations and based on different offers, DPP is 5 years, with an initial investment of 2.5 M€. Nevertheless, this technology cannot be only considered as CAPEX project but also as strategic one.

Innovation:

- ***Water usage strategy improvement in areas with water scarcity (TRL 7).***
- ***New concept to reclaim PVC effluent to reuse them in the polymerization process (TRL 7).***

Perspectives for the future

If DPP is lower than depreciation time of the active, this alternative can be interesting from an economic point of view. Hence, According to the results, for sites where fresh demineralized water production cost is higher than 1.5 €/m3, and with a treatment flowrate greater than 50 m3/h, this recovery system is potentially profitable. On the other hand considering the water risk of a severe drought with a 3% limitation of the production, the payback time of the investment will be only 1 year. Therefore the driver for the industrial implementation would be justified by the minimization of the water risks becoming independent of external water suppliers.

Innovation: Decoupling production from external water supply.

Case study related technologies

Membrane Bioreactor

Three MBRs were working in parallel (one at lab scale treating synthetic wastewater and two treating industrial wastewater from a PVC plant). The optimization of operational parameters (pH, temperature, oxygen, F/M ratio, PVA/COD ratio, nitrification and nitrogen removal, nutrients and bacteria cultures) were evaluated. Different membrane technologies were tested in the MBRs: flat-sheet, flat-sheet with back-flush and hollow fiber. All tested technologies proved to deliver similar stable results after an adaptation phase of the biomass to the specific COD (mainly PVA) and under classical operating conditions (0.15 g COD/g MLSS.day at 35°C). The parameters that must be carefully monitored and controlled during the MBR operation are: mass load, temperature (< 40ºC), pH control and foaming tendency.

Good membrane performance was observed during the membranes test as TMP and permeability showed great stability. Moreover, after the trials the membrane can recover the initial permeability values.

After the treatment a suitable permeate, for feeding membrane desalination to reuse the effluent for the PVC polymerization step, may be obtained. PVA was totally removed, avoiding membrane blockage episodes. Furthermore, BOD5 removal efficiencies close to 100% and ammonia nitrification show a good performance in terms of membrane bio-fouling and effluent quality.

Innovation: Extending the limits of biological treatments (TRL 5-6)

Desalination

To recycle the effluent from the MBR as process water for polymerization, additional specifications (PVA < 1 mg/L, NH3 removal – N-NH4 < 2 mg/L) are required.

The desalination was performed applying 6 different technologies: membrane distillation (MD), RO, capacitive deionization (CDI), ionic exchange resins and electrodialysis. The best quality in terms of conductivity (10 µS/cm) was reached with MD, 2-pass RO and two-stage CDI; good performance (20 µS/cm) is possible with electrodialysis; the one-pass RO produced water with a slightly lower water quality (conductivity =40-100 µS/cm). The cost per m3 varies between 1.01 and 11.76 euro/m3 for the different techniques tested at laboratory scale.

Thanks to the wide review of the desalination technologies, the input for up-scaling to on-site pilot trials was very well documented and permitted to write trustful datasets.

Reverse osmosis

Due to the much lower production cost (investment & operation) of the RO technology this technology was chosen for the pilot trials.

Polyamide RO membranes gave the best results in terms of conductivity removal. The conductivity in the final effluent was slightly above the target specification using the best polyamide membrane (about 40 µS/cm with 85% recovery). Two pass RO experiments achieved the target value (10 µS/cm) with conductivities below 2 µS/cm. The different membrane tested were evaluated in terms of fouling, recovery, permeability and cost obtaining good results.

MBR technology for treatment of complex industrial wastewater streams

Industrial wastewater streams may contain specific components which are detrimental for application of membrane technology. During the E4Water project MBR tests were performed on two types of industrial wastewater which contained respectively polymeric components and detergents. VITO tested its proprietary Integrated Permeate Channel membranes (IPC) for these specific applications. They are especially designed as high performing membranes for MBR applications. IPC-membranes are the first fully back-washable flat sheet membranes. The IPC membranes were benchmarked against commercially available flat sheet membranes at lab scale. After adaptation of the sludge a stable biological process was observed. High removal rates of COD (< 15 mgL-1) were reached at an average sludge load of 0.15 g COD/g MLSS.day. During the test a stable membrane performance was observed. Both membranes (IPC and benchmark) were operated at a fixed flux of 25 L/m2.h. The commercial flat sheet membrane was cleaned 8 times during the total test period corresponding to an average cleaning every 22 days of operation. The initial permeability could never be restored after each cleaning showing that the filtration flux of 25 L/m2.h (net flux of 20 L/m2.h) is slightly too high for full scale operation and results in irreversible fouling of the membrane. The VITO-IPC membrane needed only 3 cleaning operations during the whole test campaign. After each cleaning the initial permeability could be restored.

One can conclude that the IPC membranes outperformed the benchmark flat sheet membranes resulting in a more stable process operation and lower cleaning frequency. The VITO IPC membranes will be commercially available by mid-2016.

Innovation: development of back-washable IPC membrane for MBR (TRL 4)

THE PROCTER & GAMBLE CASE: ENHANCE IN-PROCESS WATER LOOP CLOSURE BY INTEGRATING BIOCIDAL WITH WASTEWATER TREATMENT TECHNOLOGIES

Case study description

A typical manufacturing plant at P&G produces a variety of detergent products. Rinsing of equipment between different batch production cycles generates a high detergent loaded wash water. This stream is difficult to treat; mainly because more efficient CIP approaches are reducing the water volume and as such generate high loaded COD wash water (15-50 g/L). Some of these wash water streams are treated on site before being discharged. This typically involves physical- chemical treatment and/or advanced oxidation processes (AOP), biological treatment and where needed additional polishing. Other wash water streams are collected and sent for an external treatment by e.g. wet oxidation or incineration with energy recovery. In both cases, the wash water is seen as a wastewater which needs to be treated. Chemicals and energy are added to transform the wash water into 'water which can be discharged' and 'sludge' which is removed as waste. The cost for treating these wastewater streams can be significant.

The European E4Water project has focused to find alternative solutions and approaches. Within this project, the wash water streams were considered as a mixture of water and product. Three innovation pathways are investigated and partly combined. The aim is to combine segregation/separation technologies with traditional wastewater treatment technology and biocidal technologies:

- Membrane technology is used to extract the raw materials (mainly surfactants) back out of the water and split the wash water into a water fraction and a concentrate. Trials have shown that tubular nanofiltration (NF) membranes are giving the best performance.
- The concentrate is a mixture of surfactants and other raw materials and can be recycled into a variety of applications (e.g. lower grade surfactants for industrial use). Where micro contamination is an issue, Ohmic heating has been qualified to pasteurize the concentrate stream.

- The water stream is treated in order to meet the legal discharge requirements or, in the ideal case, reuse the water in the process after an additional polishing step. Several polishing steps have been identified to give the required results. The ideal set-up will depend on the membrane chosen and the type of surfactant system. Typical solution will be MBR and activated carbon but also AOP (Ozone) can be used to polish the permeate from the membranes.

Results

Lab trials and pilot trials were done at several P&G locations to cover the wide range of surfactant combinations (cationic, anionic, non-ionic, amphoteric). Based on the results, the treatment train has been developed and qualified at pilot scale.

After the successful pilots, P&G decided to use this approach into its manufacturing sites. First industrial unit of tubular membrane combined with MBR has been designed as a containerized ‘plug-in and start ‘system and is built by European SME’s. The target capacity is 12-16 tons/day. The first unit has been shipped to a P&G facility in China and is running since Feb 2015. Since then, more than 3000 ton of high concentrated wash water has been treated with the performance.

Ohmic Heating trials have been completed in the UK at industrial scale (equivalent to 300-500kg/h for P&G manufacturing plant). These trials demonstrated that ohmic heater can successfully be used for P&G concentrated wash water with high product content at a much lower energy consumption and smaller footprint than traditional technologies such as Heat Exchanger etc.

The trials indicated there was no negative transformation due to ohmic heater i.e. the product properties remained the same throughout the trials.

Perspectives for the future

P&G is investigating to introduce this concept in several production facilities across the globe:

- A 16 ton/day tubular membrane-MBR unit has been shipped out of Europe to P&G Brazil and is currently been started-up.
- A 16 ton/day tubular membrane unit has been installed in P&G Czech Republic and is currently been started up.
- A first industrial ohmic heater will likely be installed in a P&G manufacturing plant in the UK by the end of 2016.
- We are looking to scale-up the concept to higher capacities, up to 150-500 tons/day. This is creating additional challenges:
  - Smart selection and combination of membranes will be needed to reduce the capital investment and the energy consumption. Multi-stage set-ups, where different types of membranes are combined, could be a more economical solution at higher capacities.
  - Specific supply chain outlets need to be looked at to be able to reuse the concentrated streams.

Case study related technologies

Recovering wash water from cleaning in place by tubular membrane filtration

Within E4Water we applied membrane technology in order to concentrate the diluted wash water stream back towards the initial product concentration. During the E4Water project the influence of operational parameters and membrane cleaning procedures were evaluated for various streams. Conventional spiral wound membranes proved to be applicable, but in general the use of tubular membranes was selected due to the higher reliability for long term stability and easiness of cleaning. Depending on the type of ingredients present in the product formulation UF, NF or RO membranes are recommended in order to achieve maximum retention of the detergents.

Innovation: treatment line designed for full recycling (TRL 9)

Ohmic Heating as pasteurization technology for concentrate streams

Within E4Water we looked at several pasteurization technologies. The winning one was ohmic heating due to low energy consumption and high/efficient heating capabilities. 2 main

legs of work were studied:

1. How effective the Ohmic heating technology kills potential microorganisms.

2. How effective the technology compares to similar technology and what modifications are needed to comply with P&G manufacturing requirements.

Pilot trails were conducted with P&G detergents and important parameters such as conductivity, footprint, cost, operability were tested/ estimated.

Innovation: recycling without micro contamination risk (TRL 7)

THE TOTAL CASE: TOWARDS INTEGRATED WATER MANAGEMENT SYSTEM IN PETROCHEMICAL SITES

Case study description

The case study 5 (CS5) takes place at the TOTAL Gonfreville Plant – A petrochemical site located in Normandy, France – since June 2013. It aims at developing a new water management system based on the application of technologies for water recycling and reuse with the major objective to reduce freshwater withdrawal by 40%.

The current water scheme already involves recycling in the cooling circuit and steam segregation for direct discharge. The new water management system focuses treatment trains based on complementary and synergetic technologies that can combine pollution concentration and degradation to enable on one hand resulting water streams fitting for reuse and recycling and on the other hand low liquid discharge of water with quality compliant with the Water Framework Directive.

Research works have begun with a site audit during which all water streams were investigated on quality and quantity aspect in order to identify possible water recycling and reuse points and related requirements.

As a result, E4Water CS5 addresses development of water treatment at three points:

- The extension of the deoiling waste water treatment plant with 4 treatment stages: ozonation, biofiltration, ultrafiltration (UF) and rreverse osmosis (RO).
- The cooling water circuit treatment line with three technologies investigated: sand filtration and alternative disinfection using UV irradiation and ozonation.
- The cooling water blowdown treatment line within two stages: UF and RO.

Results

On the cooling water circuit, technologies employed were evaluated in industrial environment. The sand filtration afforded total suspended solids under 5 mg/L making possible efficient application of downstream disinfection techniques as UV and ozone. Microorganisms in a circulating water system are effectively inactivated provided the application of UV at 350 mJ/cm2 or of ozone at dose as low as 0.5 mg/L. The circulating water disinfection took place while biofilm growth was controlled.

The treatment of cooling water blowdown was developed using membrane techniques at lab scale. Direct UF application allows Silt Density Index (SDI) below 2. Further RO separation reaches the water quality for cooling tower make-up. RO operation however requires scaling inhibition.

On the extended wastewater treatment plant (WWTP), assessment was carried out at pilot scale over one year. Performances of aerobic biofiltration associated with upstream ozonation meet the current emission limits values for wastewater discharge. Under optimized conditions, coupling ozonation to biofiltration promotes COD removal up to 70% and provides outlet concentrations below quantification limits for all PAHs quantified, BTEX and styrene removal rates as high as 99% and 98% respectively. Further ultrafiltration with in-line coagulation allows outlet turbidity under 1 NTU and SDI of 3.4 found suitable for successful operation of next RO stage. RO gives an average conductivity around 7 μ S/cm. The permeate can be used in the petrochemical plant for make-up water in cooling tower with high concentration rate or in entry of demineralization plant. Recycling at inlet of 50% of RO brine does not affect the performances of the treatment line. Tests on RO brines at bench scale also show that these last can be biotreated in 40 % admixture with existing refinery influent.

Several options for the new water management system were designed according to the technical performances in-field proven. The system finally selected balances achievement of quality and quantity objectives, costs and environmental impacts related to the technical solutions:

- Extended wastewater treatment using ozonation, biofiltration, UF and partial RO; reuse of UF and RO permeates mixture as cooling make-up.
- Cooling water treatment using side-stream filtration and inline ozonation.
- RO/Side streams management.

This system achieves the expected reduction rate of freshwater intake and results in a high reduction of the wastewater discharge. It thus constitutes a Low Liquid Discharge scheme from which only small saline streams are issued. This clear environmental benefit is connected to the reduction of major pollution emissions as expressed by COD, TSS and AOX. In addition, residual saline effluents can be managed in a neighbor biological treatment by mixing with its usual influent.

Due to the large number of treatment stages involved, the related capital and operating expenses are important in this particular case. These costs might be computed using a convenient depreciation method. They should be compared to savings on freshwater withdrawal fees and on possible costs for non-production due to local restriction of access to water.

Perspectives for the future

TOTAL and its partners consider the project approach valuable and its outcomes significant to better tackle potential water saving measures in Europe, Middle-East and China as well as to balance even more expending freshwater fees.

Case study related technologies

Treatment of RO brines

The implementation of the developed treatment train at industrial scale to reuse the water within CS5 is limited if RO brines are not fully managed because they do not comply with discharge limits. The neighbor refinery offers the opportunity to admit part of them in its WWTP biological treatment. Different possibilities have then been considered at lab scale: biological treatments with and without prior advanced oxidation processes (AOP) for biodegradability enhancement.

AOP pre-treatment using ozonation or electrooxidation does not significantly increase biodegradability of brines. COD is however biodegraded at high rate upon biomass acclimatation. The operation of a bench scale MBR demonstrated that the biotreatment of RO brines is successful when performed in presence of easily biodegradable carbon source. An optimum ratio at 40/60 of brines/refinery wastewater appears feasible (COD removals: 80-90% for inlet COD: 50-100 mg/L). Variations in organic load of brines can however decrease the MBR permeate quality. AOP post-treatment can then be used to meet the discharge limits: ozonation and electro-oxidation are able to remove residual COD by 50% and 40%, using 270 mgO3/L and 700 Wh/m3, respectively.

Innovation: RO brine management thanks to industry symbiosis (TRL 5).

Mitigation of cooling circuit biocontamination

The current water management in the cooling circuit involves the use of a mixture of chemicals (control of scaling, biofilm growth….). It was challenged considering technologies selected according to their suitability with respect with targets and further applied at pilot scale to cooling water blowdown as model water:

- Cross flow microsand filtration for the retention of fine and low density particles.
- Disinfection technologies using ozone or UV for control of circuit and water biocontamination.

Research works on the new cross flow microsand filtration show the need to meet hydraulic constraints. Under optimized flowrate, this technology provides TSS content as low as 5 mg/L convenient to preserve downstream disinfection performances. Another advantage is the very low water loss (< 0.5%) generated by washing (TRL 6). Ultraviolet (UV) and ozone were investigated considering their biocidal effect (175 and 350 mJ/cm2 for UV, 2, 0.9 and 0.5 mg/L for O3). Regarding disinfection efficiency, application of UV at 175 mJ/cm2 appears not sufficient while all other conditions can fully inactivate microorganisms and permit to control the biofilm growth. Of interest, ozonation improves global water quality and both disinfection processes do not produce noticeable changes in corrosion behavior of the materials used. The results support that both disinfection processes (TRL 6) may be appropriate alternatives or supplements to chemical biocides.

Innovation: Reliable treatment line based on "green" technologies for this specific application (TRL6)

Treatment of complex wastewaters and high volume streams: chemical and biological oxidation prior to desalting by ultrafiltration/reverse osmosis

Water outlet of the WWTP mainly contains organics including micropollutants (HAP, BTEX) and salts. The examination of the water qualities to be reached from its treatment for further discharge and reuse highlights as major treatment roles, demineralization using usual RO technology with prior protection thanks to UF separation and enhanced degradation of organics using oxidation according to a process combining ozonation and aerated biofiltration for controlling membrane fouling and emissions of microcontaminants of concern.

Direct application of biofiltration almost fully remove biodegradable organic content, achieves high TSS retention and shows very good efficiencies for most of the micropollutants detected inlet like BTEX (> 97%) when nonylphenols are still detected (< 1 µg/L). Regarding ozonation, the variation of the ozone dose makes possible COD reduction by more than 40% for 78 mg/L transferred. Observations on the oxidation extent and rate are consistent with a fast shift towards the accumulation of compounds more easily biodegradable.

Ozonation was then applied with the lowest dose prior to biotreatment for a synergetic oxidation. This combination enhances COD removal from 50 to 70%. Balances confirm that ozone mainly serves to make recalcitrant compounds more sensitive to biodegradation. The control of biofiltration performances is also made easier as highlighted by the reduction of its washing frequency. In this application field, the implementation of the synergetic oxidation (TRL6) upgrades the water quality to a sufficient extent to anticipate fouling issues for reliable operation of next UF/RO train and allow brine recycling.

Innovation: New Low Liquid Discharge system (TRL 6).

The technical developments carried out can be made beneficial in many other industrial sectors:

- By offering technical solutions to drawbacks, in the fields of high quality water production using membrane technologies, of cooling as largest point of water use in industry, of brine treatment,
- By enabling the close integration of the water system in the production process according to the “fit for use” concept.
- By highlighting that sustainable water management system results from the integration of combined degradation/ concentration water treatment technologies not only for substantial water resource savings but also for reduction of emissions into the environment and for the best reliability of the global operation.

THE KALUNDBORG CASE: BIOEXTRACTION TECHNOLOGY IN A SYMBIOTIC INDUSTRIAL PROCESS WATER TREATMENT CONCEPT CREATING ADDED VALUE

Short description

The conceptual approach in the Kalundborg case (CS6) revolves around the inclusion of industrial symbiosis, where one companies “waste” is considered a potential resource into another company, thereby creating mutual benefits and added value for the partners involved. Within the context of E4Water focus is on water reuse, but also includes possible added value that could be generated by reusing residuals in industrial process water streams that supports the utilization of e.g. “new” microorganisms in the exploitation of our common water resources.

In this specific case mixotrophic microalgae were utilized as a means of bio extracting nutrients out of an industrial process water resource, while performing CO2 sequestration. The overall aim was to test and demonstrate microalgae efficiency in nutrient removal from a relevant industrial process water stream available within the Kalundborg Symbiosis, with the purpose of creating added value from the process water, as a growth media, into microalgae biomass production, and cleaned water for potential reuse within the local symbiosis.

In order to realize this a treatment train was identified and tested involving:

1) pre-treatment of industrial process water suitable as a microalgae growth media

2) nutrient and CO2 removal and upcycling in large-scale photobioreactors

3) separation of remediated water and produced microalgae biomass for generating added value

Results

Based on nutrient and chemical composition, a one million m3/year resource was identified, representing pre-gasified Process water (ICW) from the local Novozymes wastewater treatment plant (WWTP).

Microfiltration (MF, 0.2 µm) by dynamic crossflow filtration (TRL 6) was demonstrated as a valid and cost effective means of mechanically converting the pre-gasified process water into a near-sterile growth media with no light inhibition within the photosynthetic active range (400-700nm).

Upscaling tests at meso-scale (5-140L) and large-scale (3.800L) supported lab screening results and demonstrated the process water resource as a suitable microalgae growth media.

Process optimization was performed to support optimal growth conditions in batch and semi-continuous mode for improved nutrient removal and microalgae biomass quality.

Water quality was evaluated based on regulatory requirements for free disposal (Kalundborg WWTP), including total phosphorous (TP), total nitrogen (TN) and COD. Based on the tests performed requirements for TP and TN were met without exceptions, but not for COD.

Depending on the dilution rate and growth conditions (primarily sunlight and temperature) more than 98% of TP was removed within 24-48 hours, where as > 90% of TN could be removed, but took between 8-48 days. COD removal was very variable (30-85%) and followed the trend of TN removal. COD removal also showed some variability between process waterbatches. The latter also relates to the fact that the easier digestible fraction of the original COD would already have been removed in the pre-gasification step resulting in a higher content of "inert" COD in the growth media, also not readily available for microalgae metabolism.

In terms of water reuse the water quality coming from the microalgae process was identified as sufficient to be considered as a water resource into the local Tissø water works, which produces technical water to local industry. It therefore represents a potential local water resource of up to 1 million m3/year, and could support a current increase in demand for technical water from the water works. This increase in water demand could therefore be met without increasing the environmental impact on Lake Tissø or drinking water reserves.

The microalgae biomass produced on the pre-gasified industrial process water resource was grown as a means of creating added value from the water cleaning process. For this purpose strains grown at different condition in meso- and large-scale were screened for biochemical composition in order to evaluate the potential. Nannochloropsis salina grown in a combination of saltwater (25g/L) and up to 20 vol% ICW resulted in a production of 40% lipid of which up to 47% represented the long-chained omega-3 fatty acid EPA, with the highest content produces at low light and low temperature conditions. Chlorella pyrenoidosa and Chlorella vulgaris could both be grown in 30-100 vol% ICW. At 60 vol% ICW C. pyrenoidosa produced up to 65% protein, and C. vulgaris 20-60 mg/g lutein.

Harvesting microalgae away from the waterfraction is normally involving high cost centrifugation procedure. This is mainly due to the low biomass content that can be achieved in phototrophic microalgae production. Our harvesting concept at large-scale included a first pre-filtration step before centrifugation using tubular cross-flow ultrafiltration (0.04 µm). Our Pre-filtration tests performed on 1-3m3 batches of 1-2 g DM/L, resulted in > 90 vol% water removal at an energy consumption of 3-4 kW/m3 clearly out compeating that of centrifugation. Fouling did occur but over the 1 year of sporadic testing CIP procedures and preventive cleaning kept TMP at a maximum of 1.25 during harvesting trials.

Perspectives for the future

From this study we have demonstrated that pre-gasified industrial process water could be redefined as a plant substrate and support a local production of microalgae biomass and produce water fit for reuse. Furthermore, this represents a development of the concept of Industrial Symbiosis and sustainability, where nutrients (e.g. phosphorous) and CO2 are not only removed from the water resources but also upcycled to higher value biocomponents such as plant protein, plant lipids (e.g. EPA), and pigments (e.g. luten). In addition it has been demonstrated that a pre-filtration step can cost-effectively improve water and microalgae separation without compromising quality of the two value streams, water and microalgae biomass.

The future perspectives are pointing towards a potential commercial exploitation of industrial process water and CO2 in a production of new plant biomass and new water and placing microalgae industry as a future water prosumer.

Important bottlenecks are consumer acceptance, food safety and related regulatory issues in order to include industrial residual streams as a resource in production of higher value components, as there is still a need to target the higher end market in order to make a solid business case for microalgae production.

Production costs, improved photobioreactor technology and automization have to be further improved, but in addition the implementation of a biorefinery approach should be developed in order to cash in the added value from introducing refined products to the consumers.

Case study related technologies

Microalgae screening method

A microalgae screening assay based on microplates was developed. Aim of this screening method is the simultaneous determination of the growth rate of different species of microalgae, in order to choose, for each specific wastewater, the species that correspond to the highest growth rate and, therefore, the highest removal of nutrients and the highest production of high added value products.

The strategy is schematized as follows:

Microplates (each well with a capacity of 2 mL) are used to simultaneously test the different dilutions and, possibly, combinations of specific wastewaters against different species of microalgae. The inoculation takes place in a laminar flow cabinet to minimize contaminations. The plates are incubated in the shaker with a 24:0 light-dark cycle and the cultures are periodically monitored using the Synergy Mx reader® so to measure the increase of optical density and/or of the in vivo fluorescence (IVF) to determine for each wastewater/species combination the corresponding growth rate.

Innovation: A novel method to estimate the concentration of microalgal biomass based on on-line chord length distribution (TRL 4)

Lab scale photobioreactors

A number of experiments were performed using two types of lab-scale photobioreactors: the Algaemist flat panel reactor and an ePBR (pond-simulating) reactor.

In the frame of E4Water, these photobioreactors were used to test and simulate (in batch and in continuous mode) a number of conditions, improve microalgal cultivation and define a number of parameters that could be useful for the pilot microalgaefacility that has been built within Kalundborg WWTP. Using the species C. sorokiniana and the same anaerobic digestate that is used in Kalundborg, it was possible to provide information about the relationship between culture dilution rate and productivity of biomass or desired biochemicals. The effect of dilution rate on biomass productivity, photosynthetic yield and nutrient removal and utilization efficiency was investigated by deceleration-stat experiments in the flat panel reactors at both high (2100 µmol photons m-2s-1) and low (200 µmol photons m-2s-1) irradiance with 100% wastewater.

Innovation: Harvesting of microalgae cultivated in wastewater with sustainable flocculants (TRL 5)

Large scale photobioreactors

Large scale photobioreactors were tested in a biological process, utilizing mixotrophic microalgae for the combined removal and upcycling of nutrients, CO2 and the reduction of COD. This was performed on pregasified industrial wastewater from Novozymes and Novo Nordisk, partners within the Kalundborg Symbiosis. Process optimization was performed to achieve optimal growth conditions for microalgae biomass production and nutrient removal, in order to evaluate the potential of utilizing industrial wastewater as a resource in the production of added value in the form of microalgae biomass and water for reuse.

Reactors are based on a rotating mechanical system to track and optimize the sun for the photosynthetic process. Mechanical sterilized industrial wastewater and algae are continuously mixed and pumped through the serially connected plates by an airlift effect. The effect is caused by the uprising of small gas bubbles of premixed air and CO2. Consequently CO2 is introduced as an inorganic carbon source, also acting in the down-regulation control of pH for optimal growth. Off-gas from the process (primarily oxygen) is released via the top tubular manifold.

Innovation: overall concept, industrial process water in algae production, photobioreactor design (TRL 5)

Algae concentration by membrane filtration

VITO selected submerged membrane filtration for algae concentration as it operates at low shear rate and in the meantime it produces clean permeate ready for medium recycle. VITO has tested its proprietary IPC (integrated permeate channel) membranes in parallel with commercial membranes. One of the main features of the VITO membranes is their ability to backwash whereas the commercial ones are not back-washable. The membrane filtration test yielded promising results. The permeate was free of algae corresponding to a harvesting efficiency of 100 %. The permeate is sterile and can directly be reused in the algae production. For an initial algae concentration of 1 g/L, the filtration flux started at 30 L/h m2 and decreased gradually to 15 L/h m2. The final concentration of algae was 16 times higher compared to the feed concentration.

One can conclude that the IPC membranes outperformed the benchmark membranes resulting in a lower amount of membrane surface that needs to be installed. The operational cost for a full scale installation was estimated at 0.2 to 0.4 euro/m3 at an algae feed concentration of 1 g/L.

Innovation: Algae concentration by membrane filtration (TRL 4)

Microalgal harvesting through flocculation

UCM studied the harvesting of microalgal cells through flocculation employing flocculants compatible with biomass uses that require low toxicity, namely chitosan and cationic starch. The microalgae were cultivated with two different media, TAP medium and IC wastewater in 5.5 L photobiorreactors maintained at pH 7.5 through the controlled bubbling of CO2. The flocculation experiments were carried out at different biomass concentrations and pH with both flocculants.

The optimal doses of flocculant was established in each case by monitoring the aggregation process with a focused beam reflectance measurement (FBRM) probe. Both flocculants performed reasonably well. Chitosan presented the best performance of the two species at pH 5.5 (over 98 % recovery for all biomass concentrations) whereas cationic starch was the most effective flocculant at the pH of the medium (over 97 % recovery for all biomass concentrations studied). In this latter case, for biomass concentrations below 1.6 g L-1 the optimal doses of cationic starch remained below 8.5 mg starch/g biomass.

Furthermore, a novel method to estimate the concentration of microalgal biomass was developed. The method employs the chord length distribution information gathered by means of an FBRM probe immersed in the culture sample, and processes the data through a feedforward multilayer perceptron. The optimal multilayer perceptron architecture was systematically selected through the application of a simulated annealing algorithm. The method developed can predict the concentration of microalgae with acceptable accuracy and it could be implemented online to monitor the aggregation status and concentration of microalgal cultures.

DEVELOPMENT OF A TOOL FOR THE MANAGEMENT OF INDUSTRIAL WATER, RELATED MASS AND HEAT FLOWS

Description

The Integrated Water and Energy Management Model (IWEMM) has been developed, using the Simba software platform, to simulate water, heat and related substance flows within a production site. A PVC production plant has been chosen as master site. The model is block based and includes mass and energy balance models, and blocks for the polymerization reactor, cooling tower, heat exchangers, Membrane Bioreactor (MBR) and Reverse Osmosis (RO). Model blocks for ultrafiltration, electrodialysis, membrane distillation and activated carbon, are available too for other applications. The blocks can be connected according to an existing or planned water/wastewater scheme. IWEMM can visualize the water, heat and substance flows in the production and wastewater treatment processes by a Sankey diagram. Moreover, it can be used to optimize the wastewater recycling process in terms of water quality, operational costs of the MBR and RO, heat reuse and cooling water savings. While part of the model is specifically adapted to the PVC production site (e.g. water flows within the production) other parts (respectively blocks) are designed more general and can be used for other PVC sites or other industrial sectors. IWEMM can also provide essential information for Life Cycle Assessment (LCA) to predict the economical and ecological effects (e.g. impact on water bodies) of water recycling and the related technologies.

Results

The calculation of different scenarios for the master site identified:

- The optimum recycling rate of 60% with respect to permeate quality, costs, operation limits of the RO, concentrate handling, heat management
- The costs savings due to reduced process water processing and heat energy recovery
- Auxiliary substances which are added to water negatively influencing the processes (e.g. flocculants)

The results include the additional operation costs (energy, chemicals) of the MBR and RO.

Exemplary, selected substances are plotted as a function of the water recycling rate. The concentrations increases strongly at higher recycling rates resulting in poorer permeate quality and potentially in scaling effects. At the optimum recycling rate of 60 % the water demand can be reduced by 80%, with related savings for process water treatment and the required heat for the polymerization reaction by approximately 50%.

Future perspectives

There are several directions in which this work might be continued. Due to the modular approach, using different blocks for different processes, the existing models can be adapted to different wastewater streams. The next steps could be to verify the IWEMM for other PVC production sites and then to extend it to other industries. To further improve the quality of the implemented models experiments might be necessary, e.g. the description of ions removal in RO could be developed in more detail for specific membranes or types of operation. Additionally, more unit operation modules should be developed to broaden the field of application of the IWEMM. Another direction of future work might be applying the IWEMM to address wastewater-reuse policy issues more extensively e.g. by BREFs.

ENVIRONMENTAL AND ECONOMIC EVALUATION

When implementing new solutions for efficient water management, tools such as Life-cycle-assessment (LCA) and water footprint methods are relevant decision support tools.

LCA provides information about the environmental performance of processes and supports optimisation of these going beyond direct and obvious effects. In combination with process modelling LCA can be used for further process optimisation and scenarios.

Water footprint methods can be used either in a more local context to assess effects on local water scarcity and quality or on a broader scope taking water effects along the value chain into account. The most relevant method depends on the question to be answered in each case.

Cost assessment in a life-cycle approach includes both investment and operating costs giving the total cost of operation. Costs for avoided risks should be included.

Description

The environmental efficiency of water management technologies has been evaluated with life-cycle assessment methodology. The whole process chain from procurement of equipment and consumables to impacts in the receiving waters was considered (environmental cost/benefit analysis), meaning that not only the environmental effects downstream and from use of equipment for treatment of wastewater were investigated, but also the effects from supply of water for the process. The concept included the assessments as an integral part of process design to support the development of environmentally optimized treatment processes and water system designs. Process modelling was used in combination with LCA as a powerful optimisation tool to investigate the possibilities to integrate LCA in optimisation. In addition to the environmental efficiency of the water management, cost aspects are important. Investment and operational costs have to be taken into account.

For many companies and production sites, use of water is a limiting factor, making efficient water use necessary. Water footprint methods have been used to assess the efficiency of water management options with new technologies both locally and for the processes lying upstream of the supply chain.

Results

LCA has been performed for 5 of the cases by comparing the current situation with a future situation when new technology is implemented. For one case, INOVYN in Spain, a more in depth study has been performed in combination with process modelling.

Each of the cases had different approaches to improve water management with innovative technologies. These have been reported as part of the project deliverables. In several cases, future scenarios would increase energy use leading to environmental effects, while there are positive effects that differ from case to case.

In the following, we provide more information for the case of INOVYN in Spain, where a more detailed work took place and included different scenarios. In principle, a combination of membrane bioreactor (MBR) and membrane filtration is used to produce water for reuse in the production of PVC where today local ground water is used. As there is a calculated risk of a drought every seventh year it is crucial to secure the production and also to save ground water as there is a restriction on how much ground water that can be used by INOVYN. Based on data for the present and future process water systems at INOVYN in Martorell, Spain, the environmental impact on different environmental categories has been assessed. The impact assessment is divided into a number of different common impact categories that cover different environmental aspects.

For different parameters, the effect of a possible installation varies. While there is a reduced impact on e.g. acidification and climate change, there is an increased impact for the future scenarios regarding freshwater ecotoxicity and eutrophication. The results can be used in different ways. One is to optimize the process by analysing the origin of different environmental impacts of future scenarios and recommend corrective actions. Another is to use the results for decision support, where LCA experts together with the company make an assessment of the total situation. A common way is to weight the parameters in accordance to their importance for the specific case.

Some conclusions from the assessment are:

• The dominating environmental effects are not caused by the treatment systems as such but by the necessary commodities delivered to the system such as electricity and chemicals. The main effects coming from the actual treatment systems are the magnitude and the composition of the effluent water. In addition, heat recovering from effluent wastewater leads to great differences in the results. Since, within the LCA calculations, the effect of heat recovery from the effluent waste water actually is influence by change of use of thermal energy from natural gas, a higher recycling rate of waste water is favourable.

• Saving water comes with the price of increased consumption of other resources which leads to a higher impact for some of the investigated impact categories.

• Among the chemicals, sodium hydroxide contributes considerably to the induced impacts in several investigated impact categories, also depending on the production method of sodium hydroxide.

• Materials for infrastructure are not causing such high impacts compared to other resource inputs. The materials that are actually causing the highest impacts are materials used in large quantities such as concrete and consumables. For consumables such as membranes the impact is caused by the shorter lifetime of these materials compared to other materials

In addition to LCA that gives an overview of the environmental performance of the system, the aspects of water use, availability and scarcity were of importance for the project. Water use per se is covered in an LCA; however the water footprint concept may provide a more comprehensive perspective over issues related to water use. At the moment there is no unanimity on a single water footprint method, but a number of methods with different approaches. In the project, we compared, for one case, Total, 3 different water footprint methods; one based on local water use and scarcity; and two methods taking a broader perspective, based on a water stress weighted approach and an impact assessment approach. Results for the local water use method showed that water reuse leads to a lower amount of wastewater discharge and a lower amount of water intake compared to the current situation. However the total water consumption, which is the amount of water intake minus water outlet, would increase in the future scenario. The broader water footprint methods agreed on showing that there are considerable upstream effects, while also showing that the local emissions play the most important role in the water footprint results of the analysed system.

The economic evaluation included investment (CAPEX) and operating costs (OPEX) for the individual cases has been performed in tight cooperation with and out of the case studies. The results vary from case to case, e.g. necessary payback times. More information can be found in the case study chapters.

Perspectives for the future

The overall objective of assessing water treatment processes is to find the ecologically most sustainable and economically most feasible treatment systems to supply process water. Thus, entire systems shall be assessed and optimized, not just individual process steps.

The results from the case studies show clearly that each case has individual pre-requisites and results, thus the conclusions from the LCA work for the future are case specific. In several cases, the water scarcity in a specific area can be the one crucial factor that will determine whether actions are taken. In such cases, life cycle tools provide input for optimization of the future processes. For example in the INOVYN case, if sodium hydroxide from a more efficient production facility can be used, this will already improve the environmental performance. In other cases, the assessment will be a comparison between local effects on water recovery in comparison to local or even global environmental effects, if for example water savings lead to more climate change effects.

In general, the life-cycle approach for environmental and costs aspects gains more and more attention, as it provides a more comprehensive base for decision making and process optimisation. The quality of the output is directly dependent on the quality of the input data. Thus, increased understanding of the LCA approach and its needs and benefits will allow for more efficient work in the future. It is also necessary to engage several company levels and include suppliers of technologies early in the work, which is not always the case in the current situation. In many situations it will be interesting to investigate a limited number of scenarios. Here, the combination of process modelling and LCA provides a potential for optimisation that can be developed and used further.

Cost aspects are crucial for assessment of investments in water treatment. It is important to include investment as well as operational costs. In many cases of this project, these costs were very uncertain in the beginning, making it more difficult to provide decision support early in the development process. In addition to investment and operating costs, it has been shown to be difficult to assess costs of potential risks, e.g. production shut-downs due to the risk of drought, as there are often no established methods in the companies. This is a point to be addressed more in the future.

For the water footprint methods, it is necessary to provide more guiding on the right choice of method depending on the question to be answered. The water footprint methods as such provide additional information that can be used for optimisation of water management measures either with a local or a more holistic perspective. In addition, LCA provides information on the resource use and emissions from a holistic perspective, providing an overview of environmental effects and benefits of different solutions. Thus, LCA and water footprint can be used complementary for decision making in water management.

EU POLICIES

Description

The European chemical industry operates in a fairly complex set of rules and legislations, continuously shaped and influenced by global megatrends. A stable and supportive EU policy and legislative framework is a prerequisite to stimulate companies to invest in business practices seeking to enhance sustainable water management and to ensure a broad uptake of innovative solutions.

Unfortunately legislation can also create barriers hindering sustainable, innovative developments and solutions. In this regards it is important to identify potential legislative barriers stemming from existing regulations and to see how they can be turned into a supportive framework taking into account the specificities and objectives of the existing legislation.

Results

Identification of legislative barriers potentially relevant for the project as also of interest for the chemical sector in general, was done according a step-wise approach and finally resulted in 3 main identified potential legislative barriers.

For each of the main legislative barriers, potential solutions to overcome these barriers has been explored and raised towards policy-makers.

Compliance with operating permit

What is the issue?

Water saving measures may potentially lead to a higher concentration of pollutants in wastewater. This increase may prevent companies to meet emission limit values as included in the operating permit as required by the Industrial Emission Directive (IED – 2010/75/EU) or as set by national legislation. Potentially incompliance with legislation may limit water reuse within industrial applications.

Potential solutions?

• Take into account the potential impact of water saving measures on the composition of wastewater when deriving emission levels associated with the application of best available technologies (BAT).

• Include a provision in BAT-conclusions allowing national authorities to take into account the effect of water saving measures when setting emission limit values in order to anticipate to new technologies.

Valorisation of high concentrated streams

What is the issue?

Extensive reuse or purification of (waste) water may result in high concentrated material streams. EU waste legislation or the REACH regulation may limit the reuse of such high concentrated wastewater streams and therefore indirectly also the implementation of innovative water use and treatment solutions as the potential to valorize these streams is often decisive.

Potential solutions?

• Clarify rules on by-products and end-of-waste criteria to facilitate valorization of high concentrated material streams and to ensure a harmonized application across Europe.

• Explore policy options to limit unnecessary burden for companies aiming to valorize high concentrated streams.

Water reuse standard

What is the issue?

Treated industrial wastewater can be reused for industrial and non-industrial applications (e.g. land irrigation). Whereas industry sets its own environmental/health/quality standards to ensure safe and sustainable reuse of water within industrial applications, external reuse for non-industrial applications often lacks such a supportive framework.

Absence of a (EU-wide) a supportive framework, in particular common EU environmental/health standards is preventing a broader uptake of water reuse for non-industrial applications.

Potential solutions?

• Setting EU minimum requirements related to water reuse for non-industrial applications like land irrigation.

Perspectives for the future

On 2 December 2015 the Commission published its Circular Economy package. This policy package includes an action plan to support the transition towards a more circular economy which is seen as an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy.

The Circular Economy action plan includes several actions (in)directly addressing legislative barriers identified by the E4Water project. Further deployment of the action plan (2015 – 2019) will offer the opportunity to create a legislative framework supporting Economically and Ecologically Efficient Water Management in the European Chemical Industry.

Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

E4Water has addressed a wide range of aspects relevant for an efficient integrated industrial water management in practice by focusing on increased water-, wastewater-, energy-, economical- and ecological efficiency. Developments provided and demonstrated in the six E4Water case studies comprise:

- utilisation of alternative water sources
- treatment of organic and inorganic wastewater streams and concentrates
- recovery of valuables and energy from wastewater
- linking process water and cooling water networks
- combining different scales in water management (process – plant – site – local - regional)
- introducing tools to optimse water management
- Life Cycle Assessment of selected measures
- considering regulatory framework aspects

A sustainable integrated water system is essential for an efficient water management in chemical and process industries. It is also a key element in circular economy approaches. Integrated management considers interactions, interdependencies and synergy potentials between different measures of water use and water/wastewater treatment in and across various scales. It concerns measures directly linked with single production processes as well as measures and cooperation far beyond one industrial process, unit or even site (e.g. neighbourhood industrial sites, municipal wastewater treatment units, water resources management institutions up to catchment scale). To come to an efficient integrated industrial water management the technology options are getting manifold.

The results in E4Water were elaborated in close cooperation between developer and provider of water treatment technologies and water users in process/chemical industry. Other than in the municipal sector process industry requires individual solutions, focused on their processes and surrounding environment for an efficient integrated water management. Especially in water stress and scarcity regions (quantitative/ qualitative) integrated water management solutions help to decouple an increasing industrial production from the use of fresh water resources. This contributes to the competitiveness of industry and a sustainable use of natural resources.

The E4Water case studies and developments represent a toolbox with technical solutions and concepts that support the European chemical industry but also other European process industry sectors realizing an integrated industrial water management.

The impact of the achieved project results can be described at three distinctive and interlinked levels at European scale: technological, economic and social, and environmental:

Technological Impact

Each case study contains 3 levels: the integrated industrial water management, the treatment train (combination of technologies to solve the challenges at site), and the technologies (that represents the basic module for the integrated water management). Innovation in E4Water has been reached in all 3 levels. The highest degree of innovation can be found in the integrated industrial water management.

Examples from different levels are:

Technology: IPC (integrated permeate channel) membranes (VITO): more stable process operation + lower cleaning frequency for industrial WW containing polymeric components and detergents; also promising for algae concentration
→ cost reduction (mainly OPEX), appropriate qualities of permeates for reuse, purity and concentration of retaining product (algae)
→ commercially available in mid-2016

New concept: enhance in-process water loop closure by combining segregation/ separation technologies with traditional WW treatment technology and biocidal technologies
→ already used in several production facilities (P&G) across the globe

Integrated approaches: reuse of brine from neighbor company; Industrial Symbiosis: WW treatment band algae production in a symbiotic industrial WW treatment concept; Use of alternative water sources (rain water, municipal WW, brackish water, cooling tower blowdown water…)
→ reducing costs, increasing supply reliability and sustainability, creating valuables

New treatment trains: optimize industrial water management by developing new treatment trains, based on proven and new technologies for new application fields, e.g. mild desalination in delta areas or integrated water management in petrochemical sites etc.
→ high industrial acceptance, low/medium risk of failure, cost reduction.

The TLR of technologies or treatment trains ranges from 4 (technology validated in lab) up to 9 (actual system proven in operational environment).Some trains are already applied in practice by industrial partners.

Economic/ Social Impact

The results in E4Water show a significant direct economic benefit (up to ~ 30%), further a decreased dependency from fresh water resources (see examples under “technological impact”). The results strengthen the competitive position for Europe’s process industry and water industry. Further they keep Europe an attractive location for industry.

As the E4Water sites represent a wide range of application areas for the technologies, tools and integrated concepts developed, the economic benefits in E4Water seem to be achievable in Chemical Industry and related sectors to a high degree.

Examples for the economic and social impacts are as follow:

- With E4Water case study 3 up to 0,4 Hm^3/year of water extraction from the well can be reduced, allowing this water use for other socio-economic activities **(INOVYN Spain)**. Furthermore employments can be created as people will be needed in case of the installation is commissioned. In addition industry in Catalonia (Spain) can be reinforced with this project and others similar to this.
- **P&G** (case study 4) has the ability to produce at affordable cost in locations where ZLD is a requirement**.** They developed a cost effective way to handle certain wash waters and as such eliminate the roadblock to further increase water efficiency of a plant. They now see wash water as a source of surfactants and water; not was a waste.
  Furthermore SME's in Germany and UK building the industrial installations: ability to produce skid based systems and have these exported and installed across the globe. A membrane manufacturer in Poland has done the development of a new application area for his membrane.
- Mild desalination technologies as defined in case study 1 (**Dow-Evides**) offer an affordable effective measure to reuse a broad range of water supply sources - the pilot study in E4Water have validated the boundaries for use and exploitation. Electrodialysis reversal has proven to be a robust technology enabling fit-for-use reuse water quality for industrial applications.

- The knowledge can be used for making better defined offers to industrial clients **(Evides)**.
- **Ondeo** describes the following impacts: Expertise and business opportunities related to the implementation of wastewater reuse scheme at industrial sites facing water scarcity by collaborating with such sites to continue their business activities vs shutdown; collaboration with European process industries for their international growth; better and better acceptance of extended water treatment solutions; sharing of a common vision of the benefits of the close integration of the water management system in the industry process, of local synergies between water users.
- Using the integrated modeling tool optimise water consumption on a site **(TUB)**. Due to the reduced water consumption the production itself gets cheaper and more competitive. The industrial sites are saving money that can be used to maintain or create new jobs and the local GDP will be increased.
- Under the lead of **DECHEMA** a group out of the E4Water consortium has summarized the practical lessons learned within the project in the CEN Workshop agreement SustainWATER "Sustainable Integrated Water Use and Treatment in Process Industry – a practical guidance" (www.cen.eu/news/workshops/Pages/default.aspx). SustainWATER supports company stakeholders in the implementation of sustainable integrated industrial water management. It describes the overall process to move towards a sustainable integrated industrial water use and treatment.

<u>Environmental Impact</u>

E4Water aims a reduction of > 20% in water use, reduction of > 30% in wastewater production, 15% reduction in energy use.

E4Water achieved a significant reduction of water uptake and waste water production due to the use of alternative water resources, reuse of water, water loop closure, industrial symbiosis, on site integrated water management:

- **Independency from fresh water:** up to ~ 40-80% in water use, 100% for one case (loop closure)
- **Less waste water production:** up to ~ 30-80% in wastewater production, 100% for one case (loop closure)
- **Less energy use:** up to ~ 20% reduction in energy use could be shown by considering low energy using technology, heat recovery, etc. or optimize the process by using modelling.

<u>The transfer across process industries and other industry sectors possible</u>

The applicability of the E4Water developments is possible at non case study sites of the industrial partners and non-consortium chemical industry. Cross-fertilization of the approaches to other industrial sectors is possible. Examples are:

- **Regional approach**: Concept for „Mild Desalination" → applicable to delta regions
- Enhanced water management: **Symbiotic concept for reuse of concentrated water streams** from neighbouring company – towards zero liquid/ zero waste discharge
- PVC production: new concept with adapted/ optimized technologies going **towards zero fresh water dependency in a water scarcity region →** applicable to PVC sites
- **Circular economy**: full recycling of water and surfactants – in- process water loop closure
- **Integrated water management** in a petrochemical site

- Overall concept inside an **industrial symbiosis**: Industrial proceswater in algae production, PPP/innovation

E4Water reached its aims to overcome bottle necks and barriers in close-loop recovery and to realize an integrated management of industrial water. With its open innovation approach (e.g. via the industrial testbed of CS2) to other process industry sectors, the impact was realized there as well.

Contribution to Circular Economy

Identification of legislative barriers potentially relevant for the project as also of interest for the chemical sector in general, was done according a step-wise approach and finally resulted in 3 main identified potential legislative barriers: (1) Complience with operating permit, (2) Valorization of high concentrated streams, and (3) Water reuse standard.

For each of the main legislative barriers, potential solutions to overcome these barriers has been explored and raised towards policy-makers.

On 2 December 2015 the Commission published its Circular Economy package. This policy package includes an action plan to support the transition towards a more circular economy which is seen as an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy.

The Circular Economy action plan includes several actions (in)directly addressing legislative barriers identified by the E4Water project. Further deployment of the action plan (2015 – 2019) will offer the opportunity to create a legislative framework supporting Economically and Ecologically Efficient Water Management in the European Chemical Industry.

Wider societal implications

Following the E4Water results and the impacts described above the following wider societal impacts are achieved:

Socio-political impact

- ✓ The results of E4Water facilitate a **long-term technology planning** within the **industrial water sector value chain** in **responding** to its environmental impact and in particular to **"great societal challenges"** such as climate change and sustainable use of resources (e.g. reduction of and production of those).
    - o Examples are the reuse of brine from neighbor company; algae production in a symbiotic industrial WW treatment concept
    - o Dow: As salt intrusion is expected to progress with seawater level rise due to climate change scenarios, multiple delta areas around the world will face increasing shortage of fresh water sources - as a result of salt intrusion former fresh water sources will turn into brackish and thus demanding a mild desalination prior to use as a source for a wide range of applications in both industry and other sectors like agri and horticulture - this exactly is the area where the concept and technology assessment of "Mild Desalination" in E4Water has been focusing on.
- ✓ **The results of E4Water help to meet the targets set** by the EU and different member States Governments on **water quality** by the introduction and demonstration of leading-edge technology developed for industrially relevant solutions at the case study sites.
- ✓ The results of E4Water contribute (also in the upcoming years) to the **public dialogue between the stakeholders in the water management value chain** (i.e. technology providers, end users), Government bodies, regulatory authorities and the general public

about the **value of water** and challenges faced in the coming years for companies, consumers and society in general. With dissemination material, publications events etc. DECHEMA, CEFIC and the whole consortium could ensure the dialogue during the project (ongoing process).

- ✓ The results of E4Water ensure the **proper inclusion** of social, economic, climatic, environmental, political, authority concerns in the **decision making process** used for selecting **global and site-specific water solutions for the industry** (via, CWA Sustainwater and contibutions to CE and BREF).

Scientific and technological impact

- ✓ E4Water provides a **platform of technological incentives** that will **drive the water-related industry value chain** (i.e. R&D, solution providers and end-users) to **innovate** in the crucial area of sustainable management of water in chemical industry, related industry sectors and wider process industries. – The E4Water case studies and developments represent a toolbox with technical solutions and concepts that support the European chemical industry but also other European process industry sectors realizing an integrated industrial water management.
- ✓ E4Water promote and implement **solutions towards a sustainable use of water** within the Chemical Industry while ensuring efficient management and possible recovery of other resources required in the production such as raw materials and energy (with the demonstration of technology solutions at case study sites, by publishing the CWA SustainWATER, etc.).
- ✓ E4Water has settled with its results and activities the basis for a **cross-fertilizing and technology sharing methodology** inside and outside the Chemical Industry sector leveraging on the best suitable solutions and practices for an **integrated approach** to eco-efficient management of industrial water resources and use.

Economic impact

- ✓ During E4Water it was developed and evaluated **cost-effective and eco-efficient** integrated industrial water management approaches, treatment trains and technologies to support sustainable water resources management. All were demonstrated in **pilot demonstrations** of industrial relevance. Innovation in E4Water has been reached in all 3 levels. The highest degree of innovation can be found in the integrated industrial water management approaches.
- ✓ E4Water has shown by example an **appropriate Enabling Framework** for the **cost-effective and eco-efficient** implementation of systemic **integrated water management** solutions to link industrial water management with alternative sources and to solve the major industrial water issue of managing concentrates resulting out of increased recycling and reuse within and outside the Chemical Industry sector.
- ✓ E4Water facilitate the **breaking of the major barriers** for impeding the deployment of integrated water management solutions at the local, regional, national or transnational level. One example is the regional approach at CS1.
- ✓ The results of E4Water **improve the competitiveness of European industries**. The holistic approach of E4Water makes the major water-consuming industries in Europe (and their global engagement) less dependent on natural water resources and strongly reduces the impact of wastewater discharges to the environment: Europe is the world market leader in chemical industry, generating employment, social well-being and economic benefits in Europe and globally. European chemical industry is taking care of its responsibility in all regions of its international engagement. The E4Water results ensure the fulfillment of this engagement in an eco-efficient way.

- ✓ The results of E4Water lead to **less risk on production interruption by shortage of water** (this is shown e.g. at CS3, INOVYN Spain ("*Improve environment avoiding excess water use*")).

The implementation of E4Water developments and know how helps to decouple an increasing industrial production from the use of fresh water, natural resources and energy. The outcome of E4Water strengthens both, the leadership of the European Water Technology Industry and of European Process Industries in the global competition.

The impact was closely linked with the dissemination and exploitation strategy of E4WATER. This accounts especially for the impact to the whole EU chemical industry, to technology providers and to other industry sectors. The communication of the success of the E4Water developments, testing and demonstration to industrial decision makers –during and after the project - was crucial to fully realise the impact and ensure the exploitation. Important measures are the work for policy compliance and for the BREF update (ongoing process), the contribution to Circular Economy, trainings (internal and external), the CEN Workshop Agreement SustainWATER, the industrial testbed of CS2/ INOVYN Belgium site, the demonstration at the E4Water case studies etc. The industrial partners, the advisory board and the European Technology Platforms have ensured together with DECHMEA and CEFIC that industrial decision makers are properly involved.

Via scientific publications, the networks of the 19 partners in E4Water, the website with the presentations of the final conference as mp4, the final brochure etc. a wide dissemination could be ensured.

<u>Main dissemination activities and exploitation of results</u>

With the E4Water dissemination and exploitation strategy Europe's leading position in chemical and other process industry sectors was strengthened and extended in an increasing international competition in an eco-efficient way.

Within its development, testing and demonstration segment E4Water focused on a strong interaction between (I) industrial demands, (II) development of solutions, (III) assessment and modelling tools that allow the supply of informed decisions and (IV) policy compliance.

The E4Water dissemination and exploitation strategy aimed to foster the exploitation and implementation of results at E4Water partners, in chemical industry and other sectors. The dissemination to industry, technology provider and the application oriented R&D community was fostered.

<u>Demonstration/ Industrial testbed</u>

The basis for implementation of results at E4Water partners was the **strong testing and demonstration focus** of the project. Combined with the modelling and assessment tools this **provided the knowledge base for informed decisions by high level decision makers of the industrial partners**.

The information about successful demonstrations gives evidence on the eco-efficiency of E4Water developments to exploit them outside the project. Cefic, by representing 29.000 European chemical companies and DECHEMA providing the link to over 500 SME and applied research, has foster this.

The industrial testbed (WP3) is open to other industries as an open innovation approach beyond the project.

Internal and external training

The sites directly involved in E4Water the **industrial partners operate around 40 sites in Europe and more than 80 sites globally** where E4Water results can be implemented. The aim of the internal training was to “train the trainers” – thus the target groups are the responsible for water management and -technology implementation strategies at industrial partners.

The chemical process industry partners have organised internal trainings and has successfully disseminated and exploited their results inside the own company, in Europe and globally. Audience were industries CEO, hierarchy, and management, (responsible for water management and -technology implementation strategies), but also people responsible for waste water plant operations, young and experienced engineers, analyst in the lab. etc. Also the neighbours (external company) involved in the project (INOVYN Belgium CS2), or engineering/ manufacturing organization and etc, were informed. The training occur e.g. via internal communications, internal meetings, webinars, info-sessions, lectures, visits, one-pagers, 1-week trainings, companies face-to-face meetings etc.

With this concept the expected impact was realized within the E4Water industrial partners.

During the final conference members of the E4Water consortium presented the final results of E4Water project. These presentations were recorded and combined with the ppt documents. These video files are available at the E4Water website for a broad audience. The presentations show lessons learnt, the E4Water outcome, the applicability of the solutions to other industry, the innovations, the overall approaches and more. It is shown that there is the possibility to transfer new solutions into practice, and further the advantages and need of integrated water management in the future. With this **external training the full chemical industry sector and industry sectors with high implementation potentials** is and will further be reached with the help of SusChem, WssTP, EIP water and other networks.

Policy compliance and BREF contribution:

Policy compliance has ensured that the E4Water developments are in conformity with and contribute to the conformity with European policies. **Ensuring this compliance increases the acceptance of new solutions to be applied in practice**. Especially via Cefic it was ensured that the **E4Water results feed into the next BREF update for chemical industry**.

On 2 December 2015 the Commission published its Circular Economy package. This policy package includes an action plan to support the transition towards a more circular economy which is seen as an essential contribution to the EU’s efforts to develop a sustainable, low carbon, resource efficient and competitive economy.

The Circular Economy action plan includes several actions (in)directly addressing legislative barriers identified by the E4Water project. Further deployment of the action plan (2015 – 2019) will offer the opportunity to create a legislative framework supporting Economically and Ecologically Efficient Water Management in the European Chemical Industry.

Potential relevant BREF’s to address the technical solutions stemming from the E4Water project have been identified. Revisions of these relevant BREF’s are scheduled for the coming years (in fact it’s a continuous exercise) offering to bring forward the results from the E4Water project.

Policy compliance and BREF contribution are of the same importance for industry beyond the E4Water consortium.

CWA:

E4Water has summarized the practical lessons learned within the project in the CEN Workshop agreement SustainWATER “Sustainable Integrated Water Use and Treatment in Process Industry – a practical guidance” (www.cen. eu/news/workshops/Pages/default.aspx). SustainWATER supports company stakeholders in the implementation of sustainable integrated industrial water management. It describes the overall process to move towards a sustainable integrated industrial water use and treatment.

Dissemination

For communication E4Water has used several communication and dissemination tools:

- A web platform was created and updated during the project time. It will exist minimum 2 years beyond the project.
- 6 newsletters were produced to give information about actual results, project partners, and the progress at the case study sites Further several newsletter were sent to announce events, brochures or documents like the CWA.
- 3 Brochures were produced (I) to introduce the reader to the project approach, (II) to show more detailed first results and (III) to provide a summary of the RTD and demonstration results.
- 3 workshops were organized
    - „Industrial Water Management on the edge to HORIZON 2020“ - Defining actions towards the Industrial Water Vision 2050
    - Eco-efficient industrial water use and reuse, Can we decouple productivity from demand and manage industrial water in an eco-efficient way?
    - The Economic benefits of innovation - Challenges and opportunities for the chemical sector
- A final conference were organized
- dissemination material were produced and spread
- a film was produced by Euronews TV FUTURIS (http://www.euronews.com/2015/05/11/saving-water-from-waste-in-chemical-plants/)
- E4Water partners existing social media networks were used to spread dissemination material (Dechema Twitter, Dechema Newsletter, SusChem Blog, Cefic Newsletter, YouTube etc.) was used as additional routes
- Several presentations of the E4Water results were held on technical and end-user oriented symposia.
- Stakeholder meetings were used to disseminate and discuss results.
- There were produced several scientific publications.

Address of the project public website, if applicable as well as relevant contact details

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www.e4water.eu

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