Final Publishable Summary Report

Executive summary

NAWADES project united a high-level European consortium in membrane production and application to target their research on seawater desalination enhancement starting at the very base: the membrane and including the complete process from seawater intake to effluent streams. The initial NAWADES idea foresaw the combination of ultrafiltration (UF) and reverse osmosis (RO) in one single membrane cast on top and bottom of UV-light distributing glass fibre matting. It further included lithographically produced electrodes on UF and RO membrane for fouling and scaling monitoring by impedance comparison and controlled UV dose to the TiO_2 photo-catalyst in the self-cleaning membrane sandwich. Further, a positive influence of a low strength electric field for the reduction of concentration polarization and RO-scaling was expected.

Detailed interface mapping of production procedures however updated the concept even prior to the kick-off meeting and the following break-through technologies and their combination options were evaluated during the research and development phase of the NAWADES project:

- Layer by layer assembly of catalyst on flat polyethersulfone/polyvinylpyrrolidone (PES/PVP) membrane, production of mixed matrix hollow fibre ultrafiltration membranes made of PES/PVP and titanium dioxide (TiO_2) catalyst, polyvinylidene fluoride (PVDF) and TiO_2 catalyst and aluminium oxide and TiO_2 catalyst. The last two going into demonstration.
- UV-A irradiation by black light, LED flat array, LED submergible light sticks and LED curved coats. The last going into demonstration. Light propagation by side emitting quartz fibres and quartz glass surface integrated into the membrane housing with exchangeable membrane cartridge. The last going into demonstration.
- Lithographically produced impedance electrodes on perforated foil and also directly on flat ultrafiltration membranes.
- Influence of a low strength electric field for the reduction of concentration polarization and RO-scaling and implementation options.
- Fouling and scaling reduction by plasma surface modification of reverse osmosis membranes including the development of online testing procedures.

Several of these new technologies were further developed into demonstration prototypes and tested on-site. The demonstrated technologies were also subjected to economic, energetic and environmental evaluation in the application case of seawater desalination.

In June 2015 the pilot phase of NAWADES project started at the water catchment system in the desalination plant of El Prat de Llobregat (Barcelona, Spain). The demo phase continued until the end of September 2016 testing both work settings (dead end and cross flow) and 4 different hollow fibre ultrafiltration membranes, with and without LED-UV-A irradiation.

The partners have signed an exploitation agreement on NAWADES technology and continue development of specific technologies in bilateral and trilateral partnership. Partner MANN+HUMMEL is just setting up series production for ceramic hollow fibre membranes.

The project has included individual marketing plans for each technology; >10 conference presentations; >8 poster presentations; >7 exhibition participations; 2 industrial workshops; 1patent application and 1granted patent; 1 peer reviewed publication and 3 further submissions including two book chapters on mixed matrix membranes.

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Summary description of the project context and the main objectives

Pollution and over-exploitation of natural resources, damage to the aquatic ecosystems, climate and global change as well as security aspects are challenging the sustainability of the European water systems. With average economic growth, the 2030 Water Resource Group reports that the worldwide water supply-to-demand gap is likely to reach approximately 40% by 2030 unless significant efficiency gains can be made. Further the Intergovernmental Panel on Climate Change (IPCC) predicts that by the year 2050, around 60% of the world's population could experience severe water shortages, with 33% thought to be already under stress.
Consequently, there is a need to protect the diminishing clean water resources and to upgrade/develop alternative water sources by promoting investments in water treatment and desalination.
In this regard, there are also several initiatives at European and national level aimed at establishing a framework for the management, protection and improvement of the quality of water resources across the EU. One of the objectives set by the Water Framework Directive (WFD) is that all surface water and groundwater should meet certain standards for the ecology, chemistry, morphology and quantity of waters. Already some countries are well on the way to resolving their water shortages using desalination; two examples of this are Israel with over 40% of its fresh water, and Saudi Arabia with 70% of water to its cities, coming from desalination.

Desalination is a process of removing dissolved salts to produce fresh water for consumption. Reverse osmosis is a predominant form of membrane-based desalination. RO is currently the most widely used method for desalination. In 2012, it accounted for 63% of the desalination production capacity worldwide. Desalination technologies are specialized in nature, they operate very efficiently but in a defined range of situations.
Desalination is a mature technology applied to 63 million m^3 of water in over 14 000 plants each day and on a dramatic growth path. It is used worldwide to reduce salinity gaining potable water from seawater or brackish water, for wastewater reclamation, and in industrial applications.

The water type, its salt concentration but also the pre-treatment of the water defines the reverse osmosis energy requirement. Standard pre-treatment includes the seawater intake system, coarse pre-filtration, chemicals addition (biocides, acid and flocculants), inline coagulation, single or double-stage sand filtration and subsequent microfiltration (MF), de-chlorination and the dosing of anti-scalants. Advanced pre-treatment with combined microfiltration / ultrafiltration (MF/UF) can reduce cost and enhance process stability depending on operation conditions and water quality.

The main objective of the NAWADES project was to study, design, produce, and test new water desalination membrane technology from four points of view:

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1. The structure of multi-layer membrane filter, including UV light distribution inside the membrane stack for control and reduction of fouling

2. The materials used to build the membrane system, including fouling and scaling monitoring

3. The coating treatments applied to the surfaces of the membranes; using plasma, layer by layer technology and and nano-TiO_2

4. The membrane process with integrated removal of fouling

The new membrane technologies shall provide long-life and antifouling properties.

The project goals were monitored by a set of milestones covering:

Successful lab demonstration of active RO membrane; successful lab demonstration of photo-catalytic anti-fouling; successful lab demonstration of anti-fouling sensor system; proof of principle of integrated membrane system; high capacity plant installation and operability; energy use, system reliability, economics and LCA report and competitive advantage evaluation in agreement with the industrial partners and the set-up of the technology specific marketing concepts.

The NAWADES consortium consists of eleven partners with complementary expertise located in six different EU27 states:

1)Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V - Fraunhofer.; 2)Hidroquimia Tractaments I Quimica Industrial SLU - Hidroquimia; 3)Acondicionamiento Tarrasense Associacion- Leitat; 4)Sico Technology GmbH- SICO; 5)Virtualpie LTD – VPiE; 6)Consiglio Nazionale Delle Ricerche – Institute on Membrane Technology (ITM-CNR); 7)MANN+HUMMEL GmbH – M+H; 8)Knowledge Innovation Market S.L. – KIM; 9)Exergy LTD – Exergy; 10)Eilenburger Elektrolyse- und Umwelttechnik GmbH – EUT; 11)IVL Svenska Miljoeinstitutet AB – IVL;

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To give a rough overview the partner roles are summarised in very reduced form below:

RESEARCH PERFORMERS

Fraunhofer (RTD, DE)
Who: Research organisation, interfacial/material/electrokinetics science experts
Role: Coordinator, provider of anti-scaling technology for the system membrane

Leitat (RTD, ES)
Who: Non profit research centre, experts in membrane reactors & associated methods
Role: Developers of the photo catalytic anti-fouling function of the NAWADES system

ITM (RTD, IT)
Who: International reference in membrane science and technology
Role: Provider of reverse osmosis system expertise and the system economic validation

INDUSTRIAL SERVICE SECTOR

Exergy (SME, UK)
Who: Research based technical SME consultancy with a core competence in energy efficiency
Role: Monitoring and assessment of the NAWADES system energy consumption/efficiency

VPiE (SME, UK)
Who: expert in fluid dynamics in the seawater desalination processes
Role: Provide computation models of the system during the planning and validation phase

IVL (RTD, SE)
Who: Expert on Life cycle assessment and sustainability assessment
Role: Life cycle assessment of the NAWADES system

KIM (OTH, ES)
Who: IP right consulting, patent research and market evaluation specialists
Role: Review, evaluate and protect the consortium wide IP created by the project

SUPPLY CHAIN PARTNERS

HIDRO (SME, ES)
Who: SME project originator, provider of water treatment systems
Role: Provide "voice of the customer" or market demand for the filtration system

Sico Technology (SME, AT)
Who: SME producer of optical components to be used in the NAWADES system
Role: Provide UV-light distribution technology into the membrane module

M&H (OTH, DE)
Who: Large scale industrial producer of filter media and membrane technology
Role: Future intended production partner for the membrane elemet in the NAWADES system

EUT (SME, DE)
Who: Specialists in production and sales of electrolysis technology
Role: Production partner for the electric field based anti-scaling technology

1. FRAUNHOFER (non-profit research organization): Electrode deposition, plasma, electro-kinetics and membrane characterization. NAWADES collaborative project management.

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2. HIDROQIMIA: SME provider of water treatment systems with focus on seawater desalination and environmental engineering innovation. Leader of NAWADES demonstration.
3. Leitat (non-profit research centre): membrane reactors, nanotechnology, photo-catalysis and photo-catalysis membrane reactor design, desalination and water treatment.
4. SICO: SME producer of optical components used in the NAWADES system with special knowhow in quartz glass manufacturing, shaping and application for novel technologies, highly experienced in UV light systems for water treatment.
5. VPiE: SME expert in fluid dynamics in the seawater desalination processes.
6. ITM-CNR Institute on Membrane Technology, Consiglio Nazionale delle Ricerche (research organization): membrane production, membrane characterization, and economic aspects of the overall process.
7. M+H: Large-scale industrial producer of filter media, filter elements, filters and membrane technology.
8. KIM (company): technology based innovation services. IP right consulting, patent search, market evaluation and dissemination.
9. Exergy: SME expert on energy efficiency calculation and evaluation of renewable energy options.
10. EUT: SME developer and manufacturer of electrochemical equipment focussing on electrochemical and electro-physical technologies.
11. IVL Swedish Environmental Research Institute (non-profit research organization): Life cycle assessment and environmental technology verification.

Scientific manager of the NAWADES project is Prof. Steffen Schütz, Director New Filtration Applications at MANN+HUMMEL GmbH supported by the NAWADES advisory board: Prof. Hermann Nirschl, Head of the Section Process Machines Group at Karlsruhe Institute of Technology and Dr. Carsten Schellenberg, LANXESS - BU Liquid Purification Technologies R&D Membranes, IAB Ionenaustauscher GmbH. The honorary contribution and time investment of our advisors is most gratefully acknowledged.

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Main Scientific & Technological results/foregrounds

The NAWADES project united the high-level consortium, described above, in membrane production and application to target their research on seawater desalination enhancement starting with the membrane and including the complete process from seawater intake to effluent streams.

The definition phase included the detailed mapping of the desalination process, membrane production processes, and technology ranges along with measurement protocol harmonization. It was followed by the research and development phase.

Research and Development Phase

The initial NAWADES idea foresaw the combination of ultrafiltration and reverse osmosis in one single membrane cast on top and bottom of UV-light distributing glass fibre matting. It further included lithographically produced electrodes on UF and RO membrane for fouling and scaling monitoring by impedance comparison and controlled UV dose to the TiO_2 photo-catalyst in the self-cleaning membrane sandwich. Further, a positive influence of a low strength electric field for the reduction of concentration polarization and RO-scaling was expected.

The detailed interface mapping of production procedures however updated the concept even prior to the kick-off meeting and the following break-through technologies and their evaluation and combination options were tested:

Membrane Development

- Self-cleaning, photo active, hollow fibre mixed-matrix membranes
    - Polyethersulfone (PES) based hollow fibre ultrafiltration (UF) membranes with TiO_2 photo-catalyst
    - Polyvinylidene fluoride (PVDF) based hollow fibre ultrafiltration (UF) membranes with TiO_2 photo-catalyst
- Self-cleaning, photo active, hollow fibre double layer membranes
    - Ceramic Al_2O_3 based hollow fibre ultrafiltration (UF) membranes with TiO_2 photo-catalyst
    - Polyethersulfone (PES) based flat ultrafiltration (UF) membrane with TiO_2 photo-catalyst top layer (layer by layer)

Membrane Enhancement

- Plasma etching on commercial reverse osmosis membranes
- Plasma deposition on commercial reverse osmosis membranes
- Plasma etching followed by plasma deposition on commercial reverse osmosis membranes

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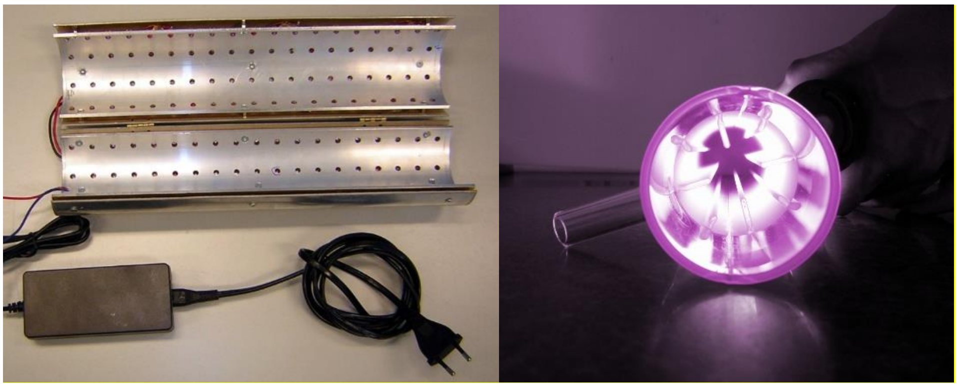
Membrane Characterization Methods

- Development of characterization methods for online salt retention and scaling measurement of reverse osmosis membranes
- Development of characterization method for online fouling measurement of reverse osmosis membranes and fouling reduction by cleaning measures
- Development of UV-A resistance measurement for ultrafiltration (UF) hollow fibre membranes
- Development of catalytic activity measurement for ultrafiltration (UF) hollow fibre membranes
- Harmonization of membrane characterization procedures between ITM-CNR, Fraunhofer IGB and Leitat

Light System Development

- Theoretical study (PMMA vs quartz glass fibres) availability and light loss
- Coupling of UV-A LED into fibre bundle
- Production of quartz fibres emitting on the side - homogeneously
- Simulation of light emission of side emitting quartz fibres
- Simulation of light distribution in a hollow fibre/quartz fibre bundle
- Simulation of light distribution in segmented membrane housings (The rib-module Sico developed in the NAWADES project has been patented as A78/2015 Pat.No.: 516 374 B1. "Device to irradiate objects with electromagnetic radiation")
- Market analysis of UV-A sources (lamps and LEDs)
- Development of submersible LED-light strips
- Development of LED-light coat



Physico-Electric Effects

- Measurement of fouling layers on flat ultrafiltration membranes

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- Measurement of scaling reduction by 2V electric field over reverse osmosis membrane

Several of these new technologies were developed into demonstration prototypes and integrated into the complete test system.

The first system included one filtration line with automation for control and assessment. It operated in both constant flux and constant pressure mode. A backwash as well as a chemical enhanced backwash (CEB) was performed in automatic mode. Remote control was installed.

The technologies and process parameters (e.g. cleaning frequencies) were tested with seawater from the water catchment system of the desalination plant of El Prat de Llobregat.

Three membrane systems were tested in this set-up with one filtration line:

- TiO_2 coated ceramic hollow fibre membranes with an integrated light technology
- TiO_2 coated ceramic hollow fibre membranes
- Al_2O_3 coated ceramic hollow fibre membranes

Demonstration and Evaluation Phases:

In March 2014 the complete consortium visited the desalination plant of El Prat de Llobregat (Barcelona, Spain) and the partners received reference data of the site in a dedicated technical meeting.

In June 2015 the pilot phase of NAWADES project started at the water catchment system in the desalination plant of El Prat de Llobregat (Barcelona, Spain) with an ultrafiltration pilot, in order to validate the correct operation and autonomy of the pilot system.

In parallel with the production and testing of the first plant a second filtration line was planned. The experimental results gained with the first plant in the Leitat laboratories were included into the planning.

The second line operates in cross-flow mode inside-out filtration. This allows for direct comparison testing. In the following optimization the back-flush rate could be reduced and cleaning procedure was adapted due to the good membrane behaviour.

The chemical enhanced backwash (CEB) is independent in each line of the prototype plant. This enabled testing of different (optimized) cleaning strategies in parallel, varying base/acid concentrations and CEB periodicity. The permeate generated in both ultrafiltration modules was stored separately in independent tanks for analysis.

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Additional membrane modules with ceramic hollow fibres and TiO_2 doped PVDF fibres were fabricated by M+H. The integration of the two filtration lines (high capacity system) was realized at the demonstration site.

A formal access authorization was reached and detail information on the desalination plant was shared by the plant operators during and in the follow-up of the two dedicated meetings in March 2014 and June 2015.

The consortium visited the demonstration site again in June 2016 and the demo phase was prolonged until the end of September 2016 optimizing and testing both work settings (dead end and cross flow) and 4 different hollow fibre ultrafiltration membranes (a-d).

a) Seawater pre-filtration with ceramic membranes outside-in

b) Seawater pre-filtration with ceramic membranes inside-out

c) Seawater pre-filtration with UV-A irradiated TiO_2 coated ceramic hollow fibre membranes

d) Seawater pre-filtration with UV-A irradiated TiO_2 doped PVDF membranes

Partners Exergy, ITM-CNR and IVL evaluated the demonstrated technologies in terms of energetic, economic, and environmental performance for the application of seawater desalination in comparison to a jointly defined best practice MF/UF/RO reference case.

The energy analysis performed in the NAWADES project has identified the energy impact of the innovative pre-treatment membrane in a real environment. The work showed that the energy consumption of the overall SWRO operation is mainly associated with the reverse osmosis operation due to intermediate pumping required to overcome the water osmotic pressure. On the other hand, the UF pre-treatment technology application ensures a stable feed water quality to the RO membrane system. Conventional pre-treatment may not ensure a good permeate quality when the raw seawater to be treated has very high fouling capacity. In that case, the energy consumption in a traditional ultrafiltration based pre-treatment is thus slightly higher, so in terms of energy efficiency, the performance of UF technology is determined by the raw seawater quality.

Energy Analysis	
Average energy consumption of an industrial RO desalination plant	3.7 kWh/m³
Pretreatment accounts for	2- 5% of total energy consumption
RO accounts for	65% - 80% of total energy consumption
NAWADES solution could provide	0,073 to 0,29 kWh/m³ savings
	Equal to 20,608 MWh/year (max) 7,300 MWh/year (min)

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The implementation of UF technologies could achieve benefits such as power consumption reduction and less RO membrane replacement in the overall SWRO process when the quality of the seawater is very low, by allowing more efficient RO stage pressure configurations and reducing RO membrane fouling. When the quality of the seawater is fairly good, the implementation of UF technologies may be not necessary in terms of assuring a more efficient RO operation, as it is the case in the SWRO facility located in Llobregat, where after six years of operation no membrane had been substituted due to fouling even when it operates in a single stage, 7 elements per vessel configuration.

The Life Cycle Analysis (LCA), Strengths, Weaknesses, Opportunities and Threats analysis (SWOT) and Political, Economic, Social and Technological analysis (PEST) work performed in the NAWADES project has significantly contributed to identify the potential of the technology both for what concerns its environmental impact and its realization potential. As the technology is new and not yet mature, the results must be interpreted as indications rather than exact results. They point in directions towards which further development should be directed in order to develop the technology to market.

The LCA clearly shows that the environmental hot spots of the new NAWADES UF concept are electricity consumption in the UF step and materials for the production of UF membranes and modules. Out of six analysed impact categories, acidification and climate change categories presented, for all scenarios, the largest share of impacts originated from electricity production; while the remaining four impact categories displayed greater dissimilarity in the impact distribution, depending on the scenario analysed.

Freshwater eutrophication category, mostly impacted by water emissions of phosphorus, showed operating chemicals for the RO step as the largest impact contributor for our standard UF+RO desalination process. Marine eutrophication by its turn was greatly impacted by electricity use.

The production of UV lamps (if assumed as medium pressure mercury bulbs) and ceramic membranes affect the category human toxicity and cancer effects.

A sensitivity analysis showed that the usually important parameters such as life span of membranes (if varied by 1 year) and UF electricity consumption did only to a limited extent affect the environmental impact of the NAWADES setup.

SWOT+PEST analysis discussed the technology from other aspects than strictly technological (a technological aspect is comprised in such an analysis but other aspects dominate).

The main conclusion from this analysis is that desalination is an emerging technique in the EU. Although desalinated water is still considered expensive, the costs of other water supply techniques are increasing. As supplies of fresh water shrink, desalinated water has become a viable solution and is economically competitive with other options for water supply. However, there are

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two critical challenges that need to be tackled for desalination to reach mass commercialization in the EU: Cost and environmental concerns. Desalination requires large investment and operation costs. For what concerns the environment, details are given above under LCA results.

Economic analysis has motivated the partners to invest into 2 patent applications and to detail plan and conclude an agreement on post project exploitation.

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

Potential impact, including the socio-economic impact and the wider societal implications

NAWADES strengthened its small and medium enterprise partners and enhanced their Europe wide professional network. The cooperation and knowledge build up during the project has strengthened the position of all partners and will enable them to maintain and create new sustainable jobs in Europe in the coming years.

Permission to publish many positive and negative research results has kindly been granted by the industrial partners to the benefit of the wider scientific and professional community. The project has also supported the scientific and professional development of young researchers for the benefit of the European economy.

All technologies developed in the NAWADES project support sustainable water treatment. The focus in the project has been set on seawater desalination. However, the scientific and technological advances reached in NAWADES will also benefit other water treatment applications in the medium and long term.

This will support a reduction of pressure on conventional fresh water sources (i.e. surface and ground sources) and thereby preservation of original flora and fauna and also a reduction of the associated environmental footprint in terms of energy consumed, greenhouse gas emissions, consumable burden and chemical disposal.

Dissemination activities and Exploitation of project results

For a relevant socio-economic impact, it is necessary to be fully aware of the importance of effective communication of results. The NAWADES consortium in fact during the 4 years disseminated the project and the achievements through different tools:

- Website (http://nawades.eu/)
- Newsletters
- Press release
- Policy brief
- Industrial Workshops in two European countries (Paris + Barcelona)
- Conference participations

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- Informational factsheet
- Publications
- A video with motion graphics
- Advertising materials (posters, brochures, flyers, etc).

The intention was to disseminate the goals and achievements of the project to stakeholders from different fields, such as: scientific, industrial, public and political.

In fact an effective dissemination is essential to make sure that the presentation of research results is well-tailored for target audiences. Through analysis, stakeholders were classified in the following categories:

- Policy-maker (includes governmental bodies, such as ministries and national agencies, local/regional authorities, etc.)
- Business support organization (includes chambers of commerce, local/regional development agencies, etc.)
- Academic/research institute (includes universities, colleges, research units etc.)
- Non-Governmental Associations (includes industry, companies)

Once the stakeholders were identified, KIM prepared a specific list of all contacts and the entities' contact person that was circulated to all the partners in order to allow them to add or remove specific contacts. The consortium prepared a definitive list used for sending the newsletters in order to create awareness of the project, to invite the stakeholders to events and to disseminate project results.

In order to shape the exploitation strategy, the dissemination of the project goes through a previous phase of IP management. In NAWADES the IP management was structured similar to the IP process in larger companies by the partners compilation of technology information requests including: technology description, application description, General Maturity Level (GML) and Technology Readiness Level (TRL) classification, work plan leading to market deployment, intellectual property owner definition and preferred knowledge protection method, documentation, key application, target geographical market, potential barriers and specific exploitation plan. A draft Plan for Use and Dissemination of Foreground (PUD) was created by the middle of the project and a final PUD by the end of the project. The PUD defines responsibilities and activities of all the partners post-project for the exploitation of the results from the NAWADES project.

The partners have signed an exploitation agreement on NAWADES technology and continue development of several specific technologies in bilateral and trilateral partnership. Partner MANN+HUMMEL has taken ceramic membrane hollow fibres into series production.

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The project has included individual marketing plans for each technology; >10 conference presentations; >8 poster presentations; >7 exhibition participations; 2 industrial workshops; 1patent application and 1granted patent; 1 peer reviewed publication and 3 further submissions including two book chapters on mixed matrix membranes.

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