

# **Sustainable separations by membranes: from performance potential to industrial implementation**

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## **Abstract**

Separation processes are responsible for a large share of industrial energy consumption, particularly in thermally driven operations such as distillation and evaporation. Membranes can play a key role in enabling the transition toward more sustainable and circular industrial systems. Compared to conventional separation techniques, they can significantly reduce energy demand while allowing selective recovery of valuable components from complex streams. This makes them particularly suitable for applications such as water reuse, resource recovery, and emission control. In addition, membrane processes can be integrated into hybrid systems, where they complement existing technologies to improve overall process efficiency and support compliance with increasingly stringent environmental regulations.

Despite their strong potential, many membrane innovations remain confined to the laboratory scale. Challenges related to fouling, stability, larger scale membrane production, and economic feasibility often hinder successful scale-up and industrial adoption. Bridging this gap requires not only advances in membrane materials, but also system-level understanding, pilot-scale validation, and close collaboration between research and industry.

In this context, demonstration cases from the INNOMEM network illustrate how these challenges can be addressed in practice. Contributions from partners such as EMI Twente, VITO, TecNALIA, Fraunhofer IKTS, PNO Innovation and Helmholtz-Zentrum Hereon showcase membrane applications in areas including water reuse, selective separations, and circular process streams. These cases highlight the importance of testing under realistic operating conditions to assess performance, fouling behaviour, and long-term stability.

By providing access to pilot infrastructure, process expertise, and application-driven research, INNOMEM acts as an Open Innovation Test Bed (OITB) that bridges the gap between academic development and industrial deployment. The presented work demonstrates that accelerating the implementation of membrane technologies requires not only material innovation, but an integrated approach combining testing, validation, and collaboration across the value chain.

## **Keywords**

Membrane processes, Sustainable separation, Scale-up, Pilot validation

## 1. Membranes as enablers for sustainable separation

Separation processes account for a substantial portion of global industrial energy consumption, particularly in thermally driven operations such as distillation, evaporation, and solvent recovery. As industries move towards decarbonisation and improved resource efficiency, there is increasing interest in alternative separation technologies capable of reducing both energy demand and environmental impact. Membrane-based processes have gained considerable attention in this context due to their non-thermal operation, modularity, and selective transport characteristics.

Compared to conventional thermal separations, membrane processes often operate under milder conditions and can reduce energy consumption while maintaining high selectivity. Their applicability spans water treatment, gas separation, solvent recovery, carbon capture, and resource recovery applications. In addition, membrane systems can be integrated into hybrid process schemes, enabling process intensification and more circular use of industrial streams<sup>1-3</sup>.

Beyond energy reduction, the role of membranes in supporting circular industrial processes has gained increasing attention. Membrane systems can enable the recovery and reuse of valuable compounds from industrial side streams, thereby reducing waste generation and raw material consumption. Applications such as solvent recovery<sup>4,5</sup>, purification of industrial process streams, nutrient recovery<sup>6</sup>, and recycling of battery-related materials<sup>7,8</sup> demonstrate how membrane technologies can contribute to circular economy strategies.

Additionally, membranes are playing an important role in energy-related applications and industrial decarbonisation strategies. Gas separation membranes are being used for biogas upgrading, hydrogen purification, carbon dioxide capture and in fuel cell systems. Compared to other gas separation technologies, membrane systems offer advantages such as compact design, continuous operation, and easier process integration. Particularly in carbon capture and renewable gas applications, membrane technologies are considered promising tools for reducing emissions while improving process efficiency.

Despite the significant progress achieved in membrane materials and module development, many promising membrane concepts remain confined to laboratory-scale research. Challenges associated with membrane production, long-term stability, process integration, and techno-economic validation continue to hinder large-scale implementation. Bridging this gap requires testing and validation under realistic operating conditions, combined with close collaboration between research organisations, technology developers, and industrial stakeholders.

### 1.1 The scale-up gap

From a practical perspective, several aspects are frequently encountered when moving toward larger-scale systems. One of these concerns the scale-up of membrane production, where fabrication methods developed at laboratory scale are not always directly transferable to industrial manufacturing, particularly when advanced materials or multi-step preparation routes are involved. In parallel, process performance may evolve with increasing scale, as differences in hydrodynamics, module configuration,

and system integration can influence mass transfer and separation behaviour compared to controlled laboratory conditions.

The evolution of performance over time is another relevant aspect in this context. During extended operation, membranes may be subjected to fouling, ageing, or gradual material changes, affecting permeability and selectivity. Fouling phenomena, resulting from the accumulation of organic, inorganic, or biological matter, are widely reported to influence membrane performance and operational lifetime.<sup>9</sup>

In addition, membrane processes are often initially evaluated using simplified feed streams, while industrial applications involve more complex and variable compositions. The presence of multiple components and fluctuating operating conditions can affect separation performance and robustness, making it necessary to assess systems under representative conditions.<sup>10</sup>

Finally, the economic performance of membrane processes is strongly linked to system-level considerations, including membrane lifetime, energy consumption, and overall process configuration. Techno-economic analyses show that operational aspects such as energy use and membrane replacement can have a significant influence on overall feasibility, and that these depend strongly on scale and process design.

These considerations illustrate that, while membrane technologies show considerable potential across many applications, their successful implementation requires evaluation beyond laboratory performance alone, taking into account production, operation, and system integration under realistic conditions.

## 2. Bridging the gap using an OITB approach

In response to the challenges associated with translating membrane technologies from laboratory development to industrial application, collaborative innovation frameworks have been established at European level. One of these is the concept of Open Innovation Test Beds (OITBs), which bring together facilities, expertise, and support services required to develop, test, and scale new technologies under conditions relevant for industrial use. By providing coordinated access to these resources, OITBs aim to facilitate the progression from early-stage validation toward higher levels of technological readiness, while reducing both development time and investment risk, particularly for small and medium-sized enterprises.<sup>11</sup>

Within this framework, the INNOMEM project was initiated under the Horizon 2020 programme with the goal of establishing an OITB focused on membrane technologies. Starting in 2020, INNOMEM represents one of the earlier initiatives within this programme and is recognised as the first OITB dedicated specifically to membranes. The project brought together a network of research organisations and industrial partners, combining pilot-scale facilities, material development, characterisation techniques, and modelling capabilities into a coordinated service structure.

Over time, this structure has evolved into a more integrated platform that provides access to both technical services—including membrane fabrication, testing, and process validation—and supporting activities, such as techno-economic evaluation

and guidance toward implementation. A central feature of this approach is the use of a single entry point, through which relevant stakeholders can access the distributed expertise and infrastructure within the network. This facilitates the development and evaluation of membrane processes under conditions that better reflect industrial practice.

The relevance of this approach is illustrated through a series of demonstration cases developed within INNOMEM. These cases, carried out in collaboration with industrial partners, show how membrane technologies can be assessed beyond laboratory conditions, taking into account aspects such as process performance, integration into existing systems, and overall feasibility.

The demonstration cases are grouped into three thematic areas: (i) separation efficiency and energy reduction, (ii) resource recovery and circular processes, and (iii) membrane development towards industrial implementation. For each area, selected cases are presented to illustrate how membrane technologies are evaluated in practice and how different aspects of development, integration, and scale-up are addressed.

## **2.1 Separation efficiency and energy reduction**

Membrane processes are increasingly explored as alternatives or complements to thermally driven separations, particularly in applications where energy demand and process efficiency play a dominant role. By enabling selective transport without phase change, membrane technologies offer opportunities to reduce both energy consumption and associated emissions.

### **Case: Techno-economic assessment of pervaporation for solvent dehydration <sup>12</sup>**

A techno-economic assessment was conducted to evaluate the use of pervaporation as an alternative to conventional distillation for solvent dehydration. The study covered several industrially relevant solvent systems, including isopropanol, acetonitrile, tetrahydrofuran, acetic acid, and N-methylpyrrolidone, and compared different process configurations, including stand-alone distillation, stand-alone pervaporation, and hybrid distillation–pervaporation systems.

The analysis was based on process modelling supported by experimental membrane data, and included both capital (CAPEX) and operational expenditure (OPEX). In hybrid configurations, pervaporation was used to overcome separation limitations such as azeotropic behaviour, allowing for more efficient downstream processing.

The results indicate that, for several solvent systems, pervaporation-based approaches can reduce separation costs and energy demand compared to conventional azeotropic distillation, particularly when implemented as part of a hybrid process. For example, significant reductions in energy consumption were observed for systems such as isopropanol and acetonitrile dehydration, which are typically energy-intensive when treated by distillation alone (Figure 1). These improvements translate into reductions in process-related CO<sub>2</sub> emissions, with values reported up to approximately 80–85% depending on the configuration, while maintaining solvent recoveries of more than 90%.

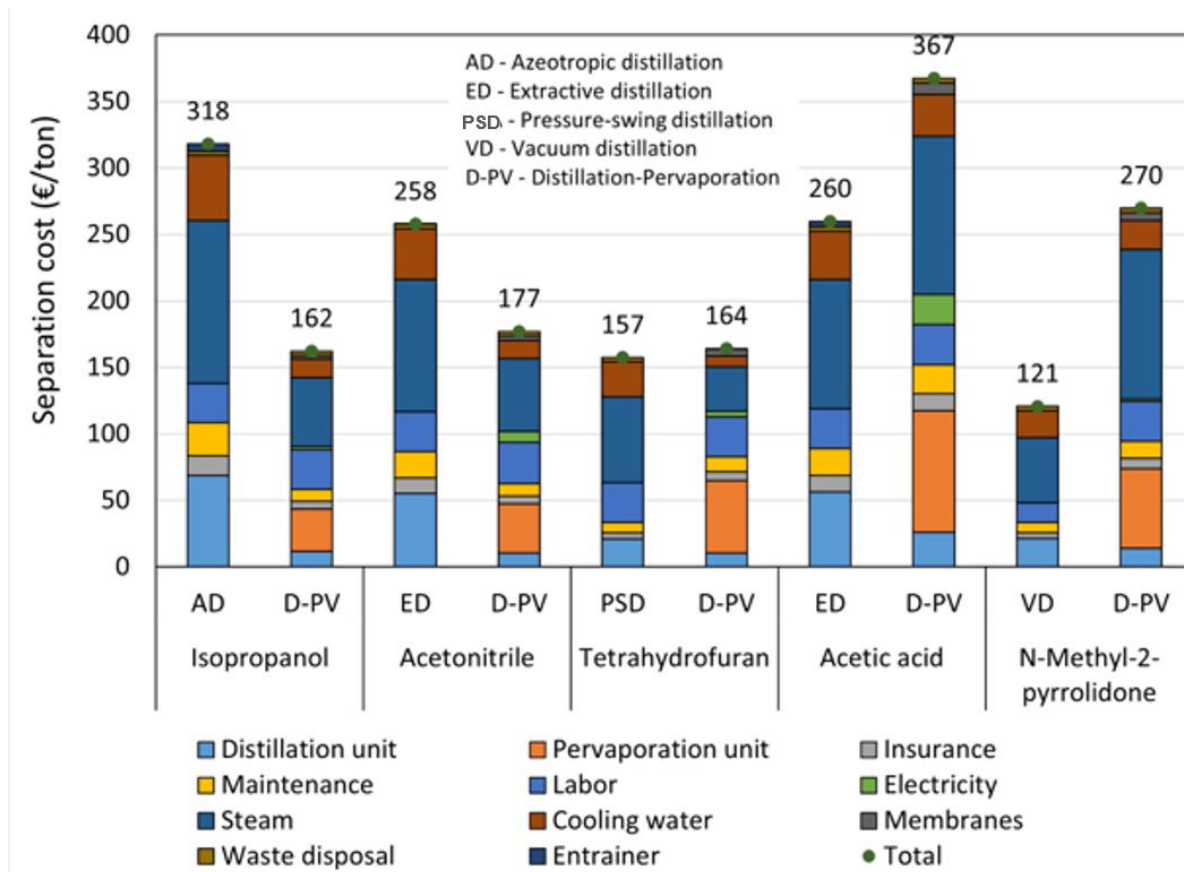


Figure 1 – Separation costs for different solvent/water mixtures, comparing different separation approaches.

At the same time, the assessment highlights that the benefits of membrane integration are system-dependent. While pervaporation shows clear advantages for certain mixtures, its applicability is more limited for high-boiling solvents, where economic benefits are less pronounced. This underlines the importance of applying membrane processes in a targeted manner and evaluating performance within the context of the full process configuration.

This case demonstrates how membrane technologies can contribute to improved separation efficiency and reduced environmental impact, while also emphasizing the importance of techno-economic evaluation and process integration when assessing their potential as alternatives to conventional separation technologies.

## 2.2 Resource recovery and circular processes

Membrane technologies are increasingly applied in processes aiming to recover valuable components from industrial side streams and to enable circular use of resources. In such applications, the focus shifts from separation as a purification step towards separation as a means of valorisation, where both recovery efficiency and product quality are relevant for downstream utilisation.

**Case: Recovery and purification of glucose from residual streams (PureGluc) <sup>13</sup>**

The PureGluc project addresses the recovery of high-purity glucose from hydrolysates derived from residual cellulose streams. These streams typically contain a complex mixture of dissolved compounds, making downstream separation and purification challenging. Membrane filtration was investigated as a potential post-treatment step to concentrate and purify glucose for reuse as a chemical feedstock.

The proposed process combines ultrafiltration (UF) and nanofiltration (NF) to separate residual macromolecules while retaining and concentrating glucose. Experimental results demonstrate that UF membranes can achieve high retention of raw materials (>99%), while allowing the permeation of glucose. Subsequent NF treatment enables further concentration and purification, with glucose retentions exceeding 95% for selected membranes. In extended testing under more realistic conditions, the achievable concentration and recovery levels appeared to depend on process configuration and operating conditions.

This case illustrates how membrane processes can enable the conversion of complex waste streams into valuable intermediates, supporting circular value chains. At the same time, it highlights the need to consider process optimisation and hybridisation when targeting high recovery and concentration levels.

#### **Case: Selective removal of PFAS from wastewater streams (PFASSELECT) <sup>14</sup>**

In contrast to valorisation-focused applications, membranes are also applied to selectively remove contaminants. The PFASSELECT project investigated the use of nanofiltration (NF) and reverse osmosis (RO) membranes for the removal of per- and polyfluoroalkyl substances (PFAS) from wastewater matrices with varying compositions.

Membrane screening and proof-of-concept testing were performed using real and spiked wastewater streams. The results show that polymeric NF membranes can achieve PFAS retentions in the range of approximately 50–95% (Figure 2), depending on molecular size and operating conditions. In addition, tailoring membrane selection and operating parameters allows for selective retention of PFAS while maintaining permeability for other components, thereby enabling downstream treatment or reuse strategies. Ceramic NF membranes, with a Grignard graft modification, demonstrated stable performance and robustness, particularly in more complex feed streams.

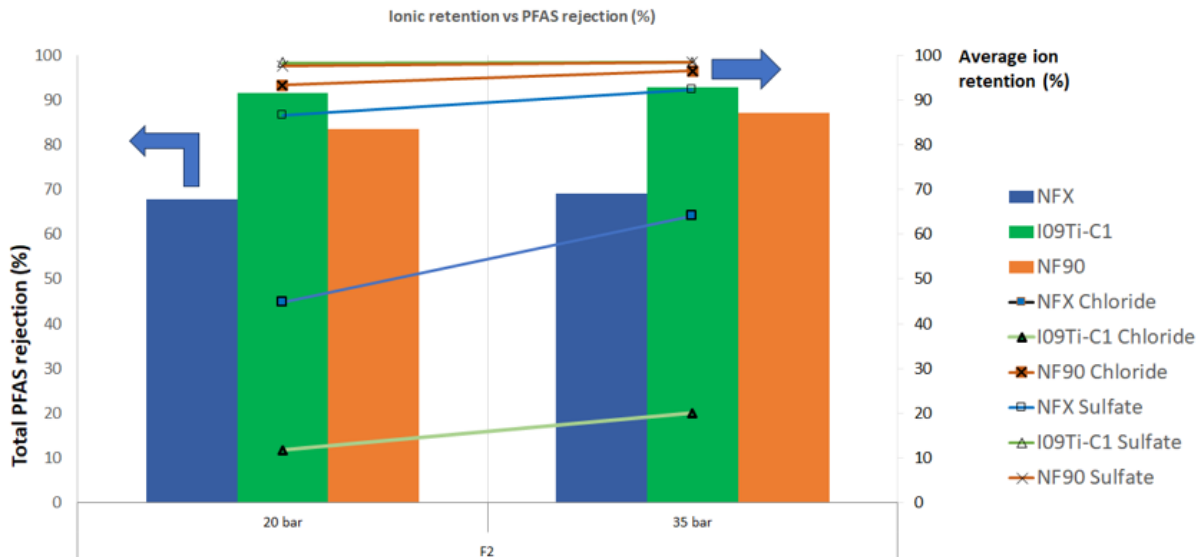


Figure 2 – PFAS rejection vs ion retention for three different membranes. NFX is the commercial hollow fiber membrane by NX Filtration, IO9Ti-C1 is the Grignard modified tubular ceramic membrane and NF90 is a commercial polymeric flat sheet membrane.

Taken together, these cases illustrate how membrane technologies can be applied both for recovery of valuable components and for removal of contaminants in the context of circular process schemes. They also show that process performance is influenced by factors such as process integration, membrane selection, and the characteristics of the feed stream.

### 2.3 From membrane development to industrial application

In addition to demonstrating performance in specific applications, the transition of membrane technologies from laboratory development to industrial use requires validation at larger scale and under representative operating conditions. This involves not only the evaluation of membrane materials, but also the scaling of manufacturing processes, module design, and system integration.

#### Case: Upscaling of electrodialysis system for direct air capture applications <sup>15</sup>

The case focuses on the development of a standardised testing protocol in combination with process modelling to support the scale-up of membrane-based separation systems. Rather than addressing membrane fabrication, the work aims to improve the ability to translate experimental membrane performance into reliable predictions at system scale, in this case for an electrodialysis (ED) stack.

A key aspect of this work is the establishment of a consistent testing methodology for membrane performance, ensuring that experimental data obtained at laboratory scale can be used as input for numerical simulations. These simulations are then used to predict process behaviour of the full ED stack under a range of operating conditions, including variations in feed composition, current density, and flow configuration.

The approach highlights that membrane performance at system scale is not only determined by intrinsic material properties, but also by the interaction between

membrane behaviour, stack configuration, and operating conditions. As a result, modelling plays an important role in understanding how local transport phenomena scale up to overall process performance.

The combined use of standardised testing and simulation provides a basis for assessing process performance prior to large-scale implementation. At the same time, the case illustrates that the accuracy of such predictions depends on the quality and representativeness of the experimental input data, as well as on the assumptions used in the modelling approach.

### **Case: Development of new potting technology for gas separation hollow fiber membranes (IMCEPO) <sup>16</sup>**

The IMCEPO case addresses a practical aspect of scaling membrane technologies, namely the development of larger hollow fibre membrane modules. In this context, the work focused on the selection of suitable resin materials to enable the production of mechanically stable modules at increased size.

The use of larger membrane modules allows for a reduction in the total number of modules required in a system, which can simplify system design and reduce overall system complexity. However, increasing module size introduces constraints related to mechanical stability, manufacturability, and material compatibility. The selection of appropriate resin materials is therefore an important factor in enabling the production of larger modules while maintaining structural integrity.

The study involved evaluation of different resin options with respect to their suitability for module fabrication, taking into account factors such as durability and compatibility with operating conditions. The results indicate that material selection at module level can influence not only manufacturability but also the practical feasibility of scaling membrane systems.

This case illustrates that, in addition to membrane material performance, aspects such as module design and material choice play a role in the transition from laboratory-scale concepts to larger-scale systems.

These cases show that scaling membranes is not just about the membrane—it's also about how you build and design the system around it

## **3. Discussion**

The presented cases illustrate membrane applications across different contexts, including process efficiency, resource recovery, and technology development. Although these cases differ in scope, they show that membrane performance is typically evaluated in relation to the overall process rather than as an isolated parameter.

Across the cases, results are influenced by factors such as feed composition, process configuration, and scale. This is observed, for example, in the solvent dehydration study where performance depends on integration within hybrid systems, and in the resource recovery cases where complex feed streams affect separation behaviour. In

the upscaling cases, both modelling approaches and module design are shown to affect system-level performance.

Within this context, the role of INNOMEM is reflected in how these different aspects are addressed in combination. The cases show that INNOMEM provides access to facilities and expertise for testing under realistic conditions, for example by enabling membrane evaluation on complex industrial streams rather than model solutions. In addition, INNOMEM supports the integration of experimental work with modelling and techno-economic assessment, as illustrated in the solvent dehydration and electrodialysis cases. Furthermore, INNOMEM enables development beyond laboratory scale, including pilot testing, module development, and the evaluation of process configurations.

By combining these elements within a single framework, INNOMEM allows different steps of technology development—testing, modelling, and upscaling—to be addressed together. The cases suggest that this combined approach provides a more complete basis for evaluating membrane processes in view of their intended application.

#### 4. Conclusion

Membrane technologies offer potential to improve separation processes across different applications, including energy-efficient separations, resource recovery, and system development. The presented cases show that performance depends not only on membrane properties but also on process configuration, feed conditions, and scale.

The results further indicate that implementation requires consideration of system-level aspects such as integration, module design, and predictive capability. In this context, the OITB framework enables the combined evaluation of testing, modelling, and scale-up activities within a single structure.

Overall, the work highlights that the application of membrane technologies is determined by how they are developed and integrated within practical process conditions.

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