Project title	MEMBRANE SCALE UP FOR CHEMICAL INDUSTRIES		
Project acronym	MEASURED		
Project number	101091887		
Project start date	01-01-2023	**Duration**	48 months

D1. 1 – MARKET AND STAKEHOLDER ANALYSIS

Due date	31/12/2023	**Delivery date**	22/12/2023
Work package	WP1		
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Version	V03		
Dissemination level	Public		

VERSION AND AMENDMENTS HISTORY

Version	Date	Created by	Changes
V01	01/12/2023	CIAOTECH	Draft writing
V02	17/12/2023	TUE	Revision
V03	22/12/2023	CIAOTECH	Final version

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List of Abbreviations

Abbreviation	Description
GS	GAS SEPARATION
PV	PERVAPORATION
MD	MEMBRANE DISTILLATION
KER	KEY EXPLOITABLE RESULT
R&D	RESEARCH AND DEVELOPMENT
R&D&I	RESEARCH, DEVELOPMENT AND INNOVATION
C&I	COMMERCIAL AND INNOVATION
IP	INTELLECTUAL PROPERTY
HYBRSI	HYBRID SILICA
CMSM	CARBON MOLECULAR SIEVE MEMBRANE
PVDF	POLYVINYLIDENE FLUORIDE
PD	PALLADIUM
CPC	COOPERATIVE PATENT CLASSIFICATION
HQ	HEADQUARTER
CAGR	COMPOUND ANNUAL GROWTH RATE
PSA	PRESSURE SWING ADSORPTION
OPEX	OPERATIONAL EXPENDITURE
CAPEX	CAPITAL EXPENDITURE
RO	REVERSE OSMOSIS
FO	FORWARD OSMOSIS
MBR	MEMBRANE BIOREACTOR
HDH	HUMIDIFICATION-DEHUMIDIFICATION
PFAS	PER- AND POLYFLUOROALKYL SUBSTANCES
GWI	GLOBAL WATER INTELLIGENCE
EBA	EUROPEAN BIOGAS ASSOCIATION
B2B	BUSINESS TO BUSINESS
SDG	SUSTAINABLE DEVELOPMENT GOALS
VC	VENTURE CAPITAL
PE	PRIVATE EQUITY
IPO	INITIAL PUBLIC OFFERING
M&A	MERGERS AND ACQUISITIONS
TRL	TECHNOLOGY READINESS LEVEL
PP	POLYPROPYLENE
PTFE	POLYTETRAFLUOROETHYLENE
LCA	LIFE CYCLE ASSESSMENT
LCC	LIFE CYCLE COST
EPC	ENGINEERING, PROCUREMENT AND CONSTRUCTION
NG	NATURAL GAS
SME	SMALL-MEDIUM ENTERPRISE
H2	HYDROGEN
CH4	METHANE
CO2	CARBON DIOXIDE
N2	NITROGEN
VIP	VISION AND INNOVATION POTENTIAL
MT	MILLION TONNE
MLN	MILLION

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1 EXECUTIVE SUMMARY

Membrane technology is a dynamic rapidly evolving field with significant implications for various industries such as chemicals, water and gas. It involves the use of permeable membranes to separate, purify, and concentrate different components within a mixture. These membranes allow certain molecules or particles to pass through while blocking others based on their size or other characteristics.

A convergence of legislative, environmental, and economic factors is directing these sectors to push strongly towards the use of innovative technological solutions with an excellent balance between cost-effectiveness and sustainability.

Over the last ten years in Europe, continuous research, development and innovation activities, powered by a number of factors such as a constant increase in public and private funding, commercial initiatives and investments into intellectual property, are pervading the membrane sector to respond to customer needs like improved separation processes, increased energy efficiency, and reduced environmental impact, witnessing substantial progress in material science, manufacturing techniques, and engineering have led to the development of highly efficient and specialized membranes for a wide range of applications such as **gas separation (GS), pervaporation (PV)** and **membrane distillation (MD)**. Highly innovative solutions such as the **carbon, ceramic and polymeric membranes** developed in **MEASURED** fit into this context and are proposed as high added value solutions capable of integrating or replacing existing ones.

Within the sectors covered by **MEASURED**, in fact, membrane technology finds itself competing against conventional methods that are much more expensive, energy-intensive, sometimes even less performing, and represents a valid alternative to respond to the current needs of industries both in terms of environmental and economic sustainability.

All this translates into an ecosystem rich in players well established and positioned into innovation landscape, composed by public funding bodies, private investors, sector associations, research centres, universities, visionary small companies and startups, large industries that collaborate into the network and enrich the entire ecosystem from time to time.

Therefore, the objective of this project deliverable is to offer a general vision of the markets and the innovation ecosystem of membrane technology at a European level and beyond, with a focus mainly aimed at the technological segments and the three business cases of interest to the **MEASURED** project (GS, PV and MD).

Firstly, an overview of the most critical aspects related to the market will be offered investigating for each project’s business case and membrane segment the current sizes and future market and innovation trends, potential applications of the technologies developed in the project, main business drivers and barriers to entry, customer needs and comparison with other competitive and alternative solutions. Secondly, the analysis of the innovation ecosystem that moves around the **MEASURED** project will be investigated, with the aim of identifying the main relevant players that operate in this panorama, some of whom were reached through external interviews to gather their opinion on some critical aspects linked to this business.

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2 SCOPE, METHODOLOGY AND CONTENT OF THE MARKET AND STAKEHOLDER ANALYSIS

In this chapter is described the scope of the market and stakeholder analysis, the relation with other project's tasks and the general methodology of the work.

2.1 SCOPE OF THE REPORT AND RELATION TO THE OTHER TASKS

The market and stakeholder analysis included in this work aims to provide from one hand an **overview of the markets** and, from other, an outlook on the main **innovation trends** in the field of the three **MEASURED**'s business cases (Gas Separation, Pervaporation and Membrane Distillation). It is intended to be a tool to support project's dissemination and exploitation and to identify:

I. Market size, potential growth, trends and segmentation where the project focuses - Gas Separation (GS), Pervaporation (PV) and Membrane Distillation (MD).
II. Market drivers and barriers.
III. Research, development, innovation and investing trends.
IV. Current EU key players in the three project's business cases.
V. Target customers and their needs.
VI. Competing solutions.

The work in this deliverable is also the first step in the context of WP1, paving the way to the D&C tasks during the project. A concept workflow is shown in the figure below.

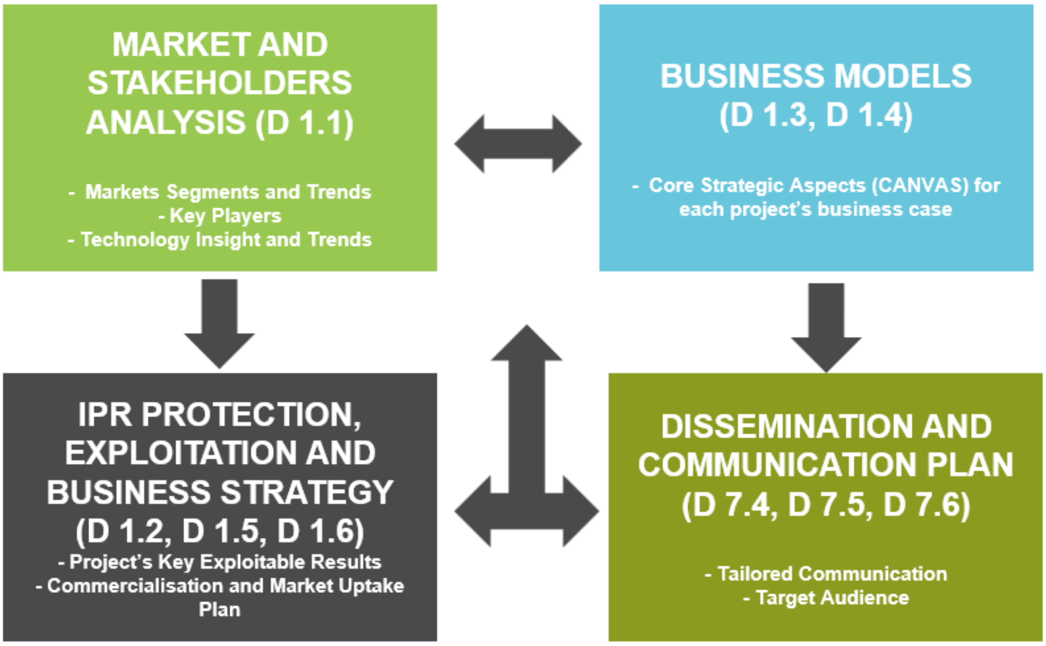

Figure 1: Relation of Market and Stakeholders Analysis with other Project's Deliverables

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2.2 General Methodology Outline

A **5-step data-driven analytical approach** was performed to carry out the work that can be summarized in three points below.

- The first step of the work was to define the main **project outcomes for each business case** and, on the basis of these, identify the most correct **taxonomy of keywords**, subsequently validated by the consortium partners, to conduct targeted searches in the three business cases of project.
- Based on the established framework, the core activity has been carried out by a thorough desktop analysis by PNO's analysts and consultants, where multiple databases have been used to tap into public as well as not public data which allowed to collect a **corpus of relevant data** and to conduct a **mixed market & innovation intelligence** analysis **based on public and private funding, scientific papers and patents research** and identify the **key stakeholders**. Some relevant key players identified through the analyses have been interviewed in order to understand their perspective on the technologies of interest for **MEASURED** project.
- Finally, the main **players** in the **MEASURED** ecosystem have been **mapped and positioned** according to different perspectives such as the collaboration network, positioning with respect to innovation and investment capabilities and gender equality.

Geographical and **temporal research boundaries** have been considered regarding to both the analyses, in particular:

a **global scale overview of the general markets** of the three business cases has been considered with a **tailored focus on Europe where possible** based on the available sources. From the point of view of **research, development and innovation trends**, instead, the **geographical focus has been limited to Europe**, **over the last ten years**.

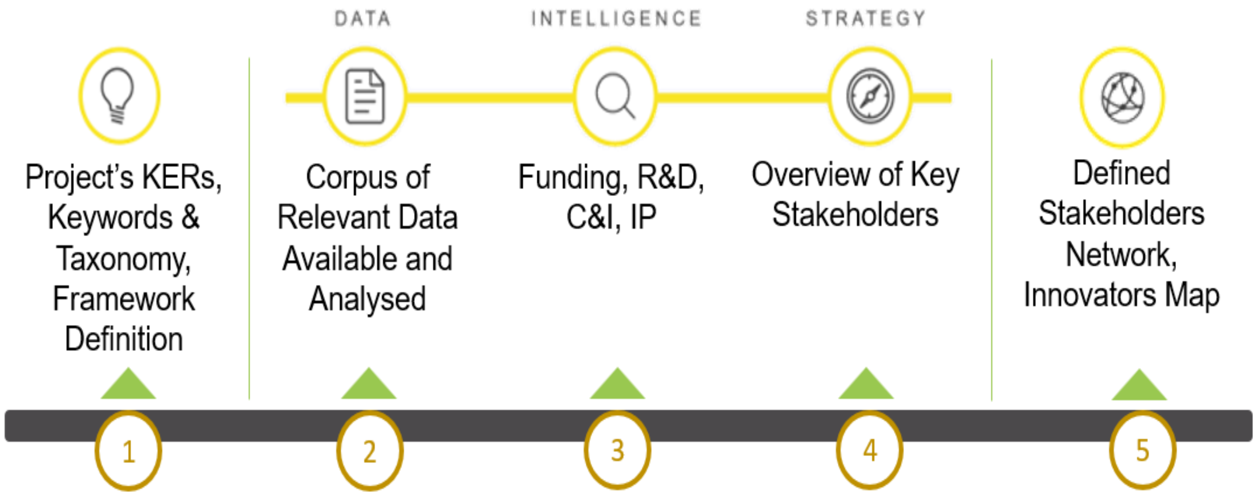

Figure 2: Methodology Concept

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2.3 CONTENT OF THE REPORT

The analysis' core of the report is included in the next chapters, whose content is anticipated in the following:

- **Chapter 3** – a Market analysis is carried out for the three project's business cases of interest, providing markets sizes and trends, business drivers and barriers to entry, customers needs and comparisons with other alternative competing solutions. In this chapter the relevant outcomes emerged from the interviews are included.

- **Chapter 4** – the **MEASURED** innovation ecosystem is described, focusing on its value-chain's definition and building on R&D&I projects, mature private C&I initiatives, IP registrations and finance (private as well as public). Topics, maturity and general trends are elaborated.

- **Chapter 5** - key players mapping and insights, with a review of the analysed stakeholders from a innovation/investing capacity, collaborations network and gender equality perspective.

3 MEASURED MARKET ANALYSIS

The market analysis carried out for **MEASURED** provides a broad description of the membrane technology markets centred on the three project's business cases (gas separation, pervaporation and membrane distillation), their size, growth rate, trends affecting the industries and major segments.

In the context of this study based on the analysis of market data from secondary public sources, the supply and potential application markets, alternative technologies, barriers to entry and business drivers are examined for each business case with respect to membrane technology segment, highlighting the driving forces, any limitations, growth opportunities and possible challenges that could influence success and adoption on the market of the main outcomes developed in each **MEASURED** business case, and a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is included to complete the overview.

3.1 MEASURED BUSINESS CASES AND MAIN OUTCOMES

The **MEASURED** project is based on three business cases:

- **Gas Separation:** Gas separation (**GS**) is a critical process in various industries and applications, involving the separation of different gases from a mixture for specific purposes. By harnessing various techniques and technologies, gas separation enables the extraction of valuable gases, removal of contaminants, and the production of high-purity gases for a wide array of industrial and commercial uses.

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- **Pervaporation:** Pervaporation (**PV**) is an innovative and highly efficient membrane separation process that holds great promise for a wide range of industrial applications. This method is particularly effective in separating liquid mixtures, where a selective membrane allows certain components to permeate through it, leaving behind a more concentrated product on the other side.

- **Membrane Distillation:** Membrane Distillation (**MD**) is an emerging and innovative separation process that shows great promise in addressing complex challenges related to the purification of liquids. At the heart of membrane distillation is a porous hydrophobic membrane that allows only water vapor to pass through, while rejecting contaminants and other impurities.

In each of these business cases, **MEASURED** partners develop specific outcomes described below.

3 Outcomes concern the **pervaporation** business case, **2 Outcomes** related to **gas separation**, **3 Outcomes** centred on **membrane distillation** and a further **3 Outcomes** are **transversal to all three project business cases.**

For each project business case, the outcomes have meticulously defined pertaining to both the membranes and the separation units.

The outcomes associated with the membranes encompass a range of critical functionalities and performance metrics. Each outcome has been strategically designed to address specific industry needs and challenges, ensuring that the membranes contribute significantly to the overall efficiency and effectiveness of the separation process.

The Outcomes related to the separation units encompass factors such as throughput capacity, energy efficiency, scalability, and adaptability to varying feedstock compositions. This meticulous definition of outcomes for both membranes and separation units underscores our commitment to delivering solutions that not only meet but exceed industry expectations. Presented below is a comprehensive overview of the identified outcomes of the project's business cases.

Table 1: MEASURED's Outcomes for the Three Business Cases

#	Outcomes	TYPE OF PRODUCT	BUSINESS CASE
1	Membranes for Pervaporation	Membrane	Pervaporation
2	Membrane Modules for Pervaporation	Membrane Module	Pervaporation
3	Pervaporation Unit	Pilot Unit	Pervaporation
4	Membranes for Gas Separation	Membrane	Gas Separation
5	Gas Separation Unit	Pilot Unit	Gas Separation
6	Membrane and Module Manufacturing for MD plant	Membrane and Module	Membrane Distillation
7	Membrane Distillation Unit	Pilot Unit	Membrane Distillation
8	Coating and Green Solvent	Coating and Solvent	Membrane Distillation
9	Multi-scalar Separation Digital Twin Toolbox	Software	All Business Cases

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10	Circularity Assessment of the MEASURED Solutions	Dataset	All Business Cases
11	Process design Modelling Toolbox	Software	All Business Cases

The main peculiar characteristics of the identified outcomes in each business case of the project are explained in detail:

- **Pervaporation's Outcomes**: The project features acid-resistant and 55-channel ceramic hybrid silica (HybSi) membranes capable of accommodating particular flow conditions (1 m2 of membrane processing H2O flux > 1.0 kg/m2·hr) and specifically designed for pervaporation in order to effectively separate liquid mixtures, aligning with the project's goal of isolating water from solvents and organic compounds. Example of feed composition can concern mixtures like butanol/water, ethanol/water, ester acrylate/alcohol/acrylic acid/water but other mixtures can be considered. In the project two type of membrane modules are developed, with different areas depending on the number of membranes included in the modules. The pervaporation unit, made by acid-resistant materials and operating in continuous mode, plays a pivotal role in extracting water during esterification process. It's engineered to operate at high temperature level and certain pressure and is able to achieve an high expected permeate flow rate of water in the permeate.

- **Gas Separation's Outcomes**: Hidrophilic, 61-channel tube and thin carbon molecular sieves membranes (CMSM) for gas separation with high selectivity and permeation properties able to operate in a wide range of pressure and temperature and to separate different gas mixtures including H2, CO2, CO, CH4, N2 in one step. The Gas separation unit designed includes different membrane modules (1.2 m2/module). The prototype operates with real off-gas of the methanation unit. A dedicated heating jacket will allow to achieve the desired temperature for the gas separation. The gas separation unit will allow to inject high purified methane into gas grids.

- **Membrane Distillation's Outcomes**: Porous polymeric Polyvinylidene fluoride (PVDF) membranes for membrane distillation, with anti-wetting, superhydrophobicity chemical resistance and anti-fouling performances for recovery and recycle of water/alcohol mixtures. PVDF membranes are prepared based on green and more sustainable solvents instead of conventional toxic solvents and the coatings is hybrid (inorganic as inner layer and organic as outlet layer). Two different sizes of the modules accommodates aforementioned membranes. Membrane distillation unit, powered by 100 solar/photovoltaic collectors, is able to process many liters per hour (70 L/h) and is a complex system equipped with auxiliary equipment like heat exchangers, pumps, tanks, control system, piping and fittings and sensors.

- **Other Outcomes transversal to three business cases**: transversally to those mentioned above, another 3 Outcomes are developed within **MEASURED**. a) atom–mesoscale digital twin model for commercial membranes by a seamlessly linked density functional theory (DFT)/molecular dynamics (MD) simulations where the digital characteristics catalogue is an onset of a database that is able to aid developers in emerging intensified operations, so as to tackle solutions/mixtures that have been less extensively experimented on to date; b) Dataset of

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the three sustainability pillars to attain a general overview of benefits and impacts related to the assessed 3 case studies by a set of circularity indicators; c) Process design models developed for the techno-economic analyses and performance modelling studies within **MEASURED** for all three business cases in software such as Aspen Plus, where the models are used to address the potential, the strengths & the weaknesses of the full-scale plant and the technical hurdles and challenges, related to the full-scale realization of novel/critical components, including legal aspects, local gas distribution system compatibility and plant integration.

3.2 Market Potential for Gas Separation

In this section an insight of market potential for membrane technology in the **gas separation industry** is provided, highlighting the market size and forecasts, the demand driving forces, barrier to entry, other alternative and competitive solutions and the major application segments.

The **global gas separation membrane market is evaluated € 2,08 billion in 2023 and it will grow at compound annual growth rate (CAGR) of 7,3% in the next ten years reaching € 4,26 billion in 2033** [1]. **Europe** is an attractive market for gas separation membranes with **50% of market share** in 2023 [2].

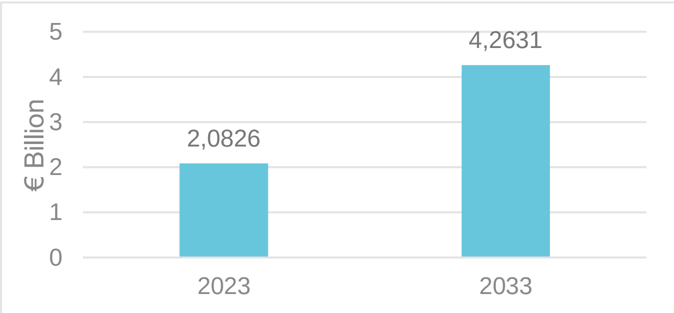

Figure 3: Global Gas Separation Membrane Market by Value

The gas separation membranes find a wide range of applications across various market segments due to their ability to selectively allow certain gases to pass through while blocking others.

The most common applications of gas separation membranes concern **Natural gas sweetening, hydrogen purification, biogas upgrading, nitrogen generation, helium recovery and vapor recovery**. Considering the application segments, currently the **53% of the global gas separation membrane market belong to nitrogen generation** segment, followed by **natural gas treatment with 20%** of the total market.

Other emerging and niche markets are represented by hydrogen purification, vapor and helium recovery and biogas upgrading [3]. **Polymeric membranes dominate the market with over 93,5% of the share**. The remaining part concern other inorganic membranes like zeolite and metal-based [4]. While significant research and development efforts are currently focused on **carbon membranes**, it's important to note that this type **have not yet reached the stage of production at large scale and related commercialization**.

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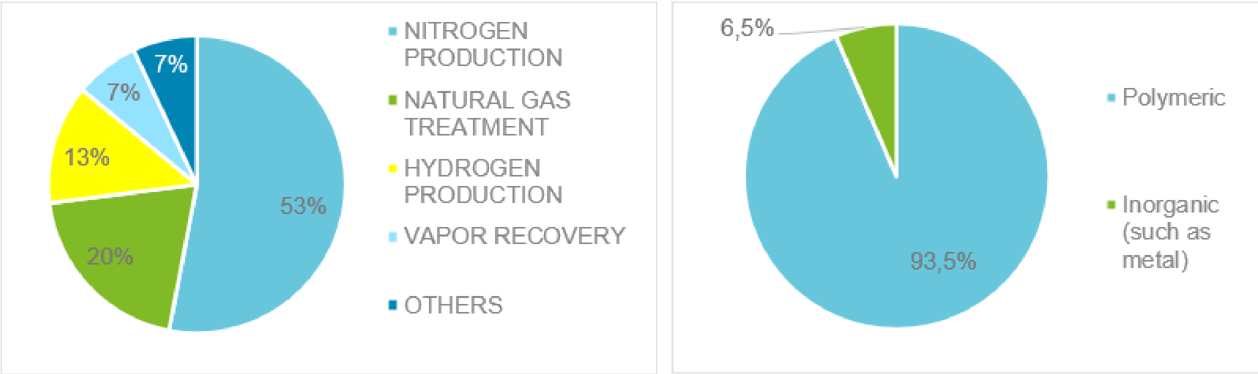

Figure 4: Gas Separation Membrane Market by Application Segments (left) and by Type of Membrane (Right)

Although gas separation membranes can be applied to multiple market segments as seen before, **almost all gas separation market segments are still dominated by conventional technologies like pressure swing absorption (PSA), cryogenic distillation and amines**. **Today the only gas separation market segment in which membrane technology excels among others is biogas upgrading, where the market share of membranes is 39%**, followed by water scrubbing with 22%, chemical absorption with 18% and PSA 12% (see Figure 8) [5].

In the remaining application markets, membrane technology still represents a niche and emerging technological segment. For example, to date, **hydrogen purification** is carried out mainly through PSA which holds 86% of the market segment [6], while the most used technology in **natural gas sweetening** concerns amine absorption which covers 60% of the market [7]. Finally, PSA and cryogenic distillation dominate the **helium recovery** market where membrane technology hold less than 5% of the market [8] and the **nitrogen generation**.

To understand whether membranes can increase their adoption in the market and replace the conventional gas separation technologies in the future, it is necessary to comprehend what are the main driving forces of the demand for gas separation technologies in the different segments and the needs of the market segments. In general, the **demand for gas separation technologies, like membranes, is influenced by several factors ranging from end-products demand to evolving industrial needs to regulatory changes and growing environmental concerns** over greenhouse gas emissions and air pollution which are pushing industries to adopt gas separation membranes as a means to reduce harmful gas emissions.

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One of the most important application segments of gas separation membranes is **the sector of natural gas, where the membranes are used to separate methane from other gases**. Despite recent problems with supply and price fluctuations linked to the war in Ukraine, the natural gas represents one of the most consumed products in Europe where its **demand was 360 bcm in 2022 which will grow at 395 bcm in 2023** [9], while the estimates indicate that there is a supply–demand gap of 200 bcm. Although production is much lower than demand, **Europe is pushing strongly towards an expansion of internal production with 95 active gas processing plants** [10] **and 64 methanation plants** [11] [12] in Europe. The high and increasing demand of natural gas followed by an increase of internal production capacity is a positive factor for gas separation technologies since there would be a greater need for technologies to separate methane from other unreacted gases and obtain high levels of purity in accordance with EU regulations. In fact, **to be compliant with EU regulation, the natural gas sector requires high purity of methane to be injected into gas grids**. Synthetic natural gas produced has to respect the gas grid specifications (0.5-10 vol% for H_2, 2.5-10 vol% for CO_2) in different countries. Increasingly stringent regulations regarding the purity level of the methane consequently require the implementation of more advanced and performing gas separation technologies.

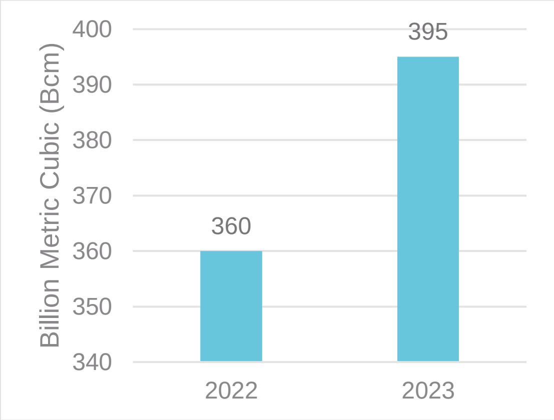

Figure 5: Natural Gas Demand in Europe

In addition to natural gas, the membranes developed in **MEASURED** can also be applied to other sectors such as biogas upgrading and hydrogen purification. There is a **growing interest in renewable energy sources such as biogas, biomethane and hydrogen**. The increase in demand for these products is driving the requirement for gas separation technologies.

Over the last decade, the **European biomethane production has increased by 540%.** In 2020, 18 bcm of biogas and biomethane were produced in the Europe. According to the EBA databases [13] [14] [15] **it is expected that from 30 to 40% of the total gas consumption in Europe will be covered by biomethane by 2050**. The European biogas and biomethane sectors are committed to delivering up to 41 bcm of biomethane by 2030 and up to **151 bcm in 2050**, supporting the EU in the achievement of climate goals and energy security alike. This is also supported by the fact that in the last five years there has been a huge **increase in the number of biomethane plants in Europe, going from 483 in 2018 to 1322 in April 2023**.

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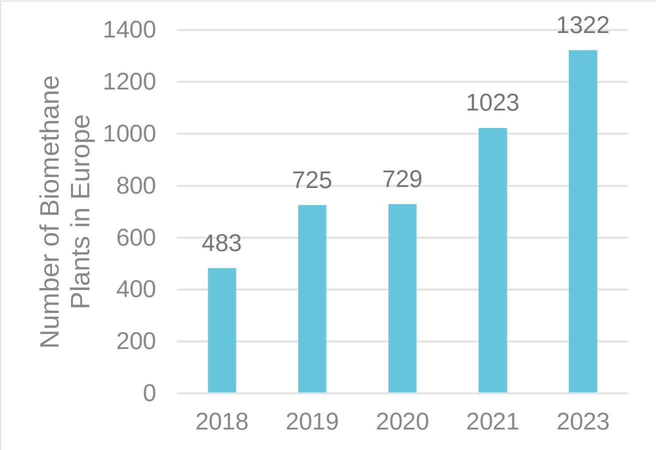

Figure 7: Number of European Biomethane Plants by Year

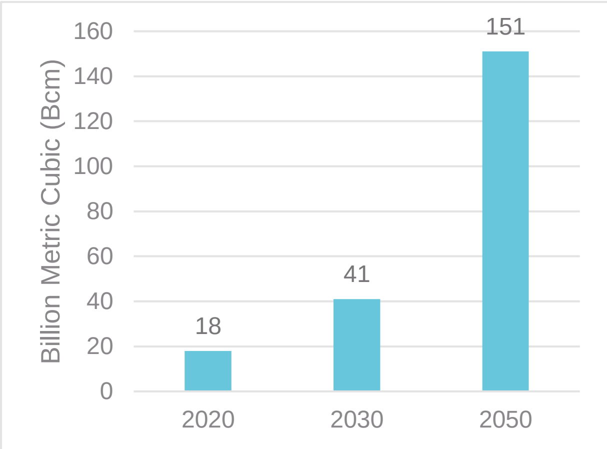

Figure 6: EU Biomethane Production Forecasts

The growing production of biomethane in Europe and the consequently increase of number of biogas upgrading plants help to **consolidate membrane technology in this segment**. The global biogas upgrading technologies market was evaluated € 1,29 billion in 2022 and is estimated to grow at CAGR of 21,1% from 2022 to 2027 reaching a value of € 3,5 billion at the end of this period [16]. Europe has 41% of the market share [17].

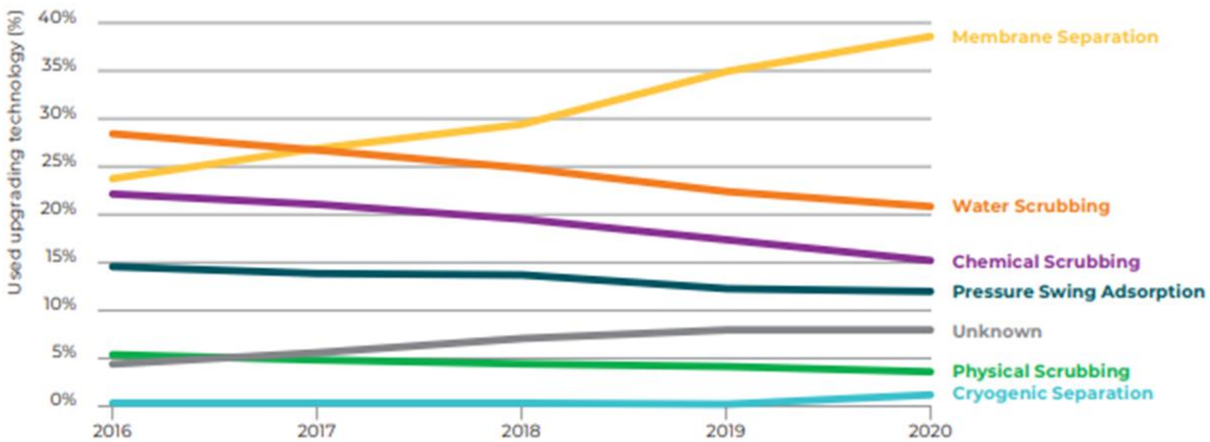

Figure 8: Upgrading Technologies used in EU Biomethane Plants.

Equally promising is the growth **in hydrogen consumption which in 2021 amounted to 92 Mt. It is estimated that the demand for hydrogen will be around 152 Mt in 2030** [19] **and 793 Mt in 2050** [20]. This growth is associated to the increase of sectors which will use hydrogen in the future and represents surely the main driving force towards high-performance purification technologies. Although electrolysis technology is advancing rapidly to produce clean hydrogen with high purity (99.9999%), today the majority of hydrogen (over 90% of global production) is still produced from fossil fuels from which generally 99% pure hydrogen emerges with 1% impurities due to the presence of CO2 which must subsequently be separated. In Europe 504 production sites have a total production capacity of 11.5 Mt per year [21].

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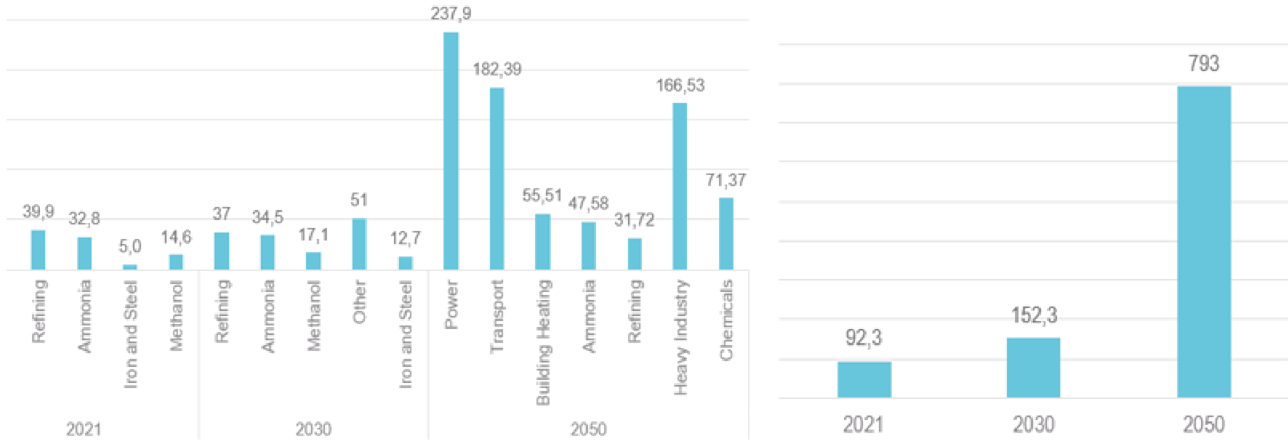

Figure 9: Hydrogen Demand in Mt by Sector and during the Time.

In addition to the government regulatory factor related to high purity of gases, growing interest for renewable sources and the growth in production and consumption of these types of gas, which are certainly some of the main factors driving the demand for separation technologies, these sectors also **require advanced gas separation solutions with excellent balance between affordability and sustainability to improve processes above all in terms of energy consumption, reducing OPEX and CAPEX**. In these terms, with respect to the conventional technologies for gas separation, membrane technology represents a valid and better solutions, and it could replace many of them since technologies like **cryogenic distillation and PSA are in general more expensive in terms of CAPEX, and amines in terms of OPEX and overall all less performing and energy-intensive compared with membranes**.

Each of these conventional separation technologies has advantages and disadvantages. The main advantage of **PSA** is its ability to filter out impurities down to parts per million (ppm) producing gas like hydrogen with high purities > 99.999%. The PSA can be used for large and medium industrial scales as well as for small scale portable systems. Its main disadvantage is the high material loss (~20%) resulting from the pressure release during desorption (for example H2 recovery ~80%). **Cryogenic distillation** relies on the partial condensation of gas mixtures, at low temperatures and high pressures, to be separated by distillation. One major disadvantage is the limited purity levels (~99%) of the extracted gas like hydrogen. The process is very expensive as it requires the use of numerous equipment and devices. Cryogenic distillation is ideal for large industrial scales, but unsuitable for small portable applications. PSA and more notably cryogenic distillation involve high equipment cost and high energy consumption being therefore very expensive methods. In this context, membrane separation technology appears as an emerging and very promising industrial process, that will be able to compete, integrate and eventually replace the traditional separation techniques, due to its many associated advantages. Membrane technology appears as an obvious energy efficient alternative for producing the ultra-pure gases required.

However, **membrane technology need to overcome some barrier to entry like high initial capital costs, technical complexity, long-term durability, fouling and degradation issues and market education and awareness respect to conventional separation methods and, in some cases like hydrogen, need still to reach the maturity level for the adoption at large scale**.

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Compared to traditional separation processes, membrane technology is able to offer simpler operation, higher adaptability, higher purity of gas, compactness and lightweight, modular design with simpler up- and down-scaling, lower labour intensity, lower operating and maintenance costs, higher energy efficiency and a much lower environmental impact [22].

3.2.1 Interviews with Relevant Stakeholders in Gas Separation

In the gas separation business case an interview has been conducted with a **large-size Italian company** that is specialised in innovative and sustainable processes from non-fossil feedstock. The company, which preferred to remain anonymous, has implemented the use of membrane technology in some R&D projects in the recent period.

Its R&D department is **interested in membrane technology from the perspective of membrane reactors** rather than the separation of gaseous mixtures. In the projects where they have been involved in the past **the company evaluated the use of metallic membranes (Pd and Pd/Ag based)**.

After discussing their involvement in the membrane technology, the focus of the interview has been targeted on the main market barriers for membrane technology in the gas separation segment. The company stated that the segment of the metallic membranes (Pd and Pd/Ag) has as its **main problem the stability of the membrane during the process**.
The company identified as the best membrane class for gas separation the Pd-based metallic membranes, especially for applications such as low temperature Steam Methane reforming.

The interviewed stakeholder listed the **main membrane technology applications for gas separation** as the following:

a) Separation of gases under pressure,
b) recovery of CO_2 from natural gas,
c) recovery of CO_2 from bio-gas to bio-methane,
d) Low temperature Steam Methane Reforming.

In addition to the major application listed above, the stakeholder also mentioned **propane dehydrogenation to propylene** as and **emerging application** for the membrane technology.

The interview concluded with a discussion on the main **customer needs** in the gas separation field. Regarding this aspect, the interviewed stakeholder indicates the **stability of membrane over time and the competitive prices** as the key needs to be addressed.

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3.3 MARKET POTENTIAL FOR MEMBRANE DISTILLATION

In this section an insight of market potential for **membrane distillation industry** is provided, highlighting the market size and forecasts, the demand driving forces, barrier to entry, other alternative and competitive solutions and the major application segments.

The **global membrane distillation market** is still a niche market, **valued at €0.05 in 2022 billion** but destined to **grow strongly in the next 5 years at a CAGR of 49.97% reaching a value of €0.57 billion in 2028.** This market is characterised by high concentration level, where the top 3 companies hold 36% of the total market [23].

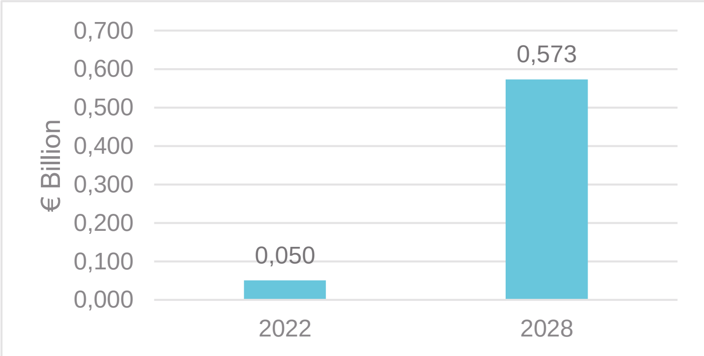

Figure 10: Global Membrane Distillation Market by Value

Many **driving forces** are contributing to the adoption of more advanced and sustainable water purification technologies like membrane distillation. Among the factors there are the growing demand for pure water related to the increasing world population and water stress due to the accelerating process of urbanization, the growing need for water treatment technologies that can provide high quality purified water for industrial, agricultural and domestic purposes, the need to develop efficient treatments of seawater which is fundamental in many regions of the world with scarcity of fresh water, the demand of many industrial sectors for effective separation and concentration processes to produce high quality ingredients and products, concerns about the environment and more stringent wastewater and water treatment regulations.

Membrane distillation has a broad spectrum of possible applications. One of the possible applications of membrane distillation is the **desalination** of saline waters such as seawater or brines. However, other possible applications of MD concern the **treatment of municipal wastewater and industrial wastewater** in different sectors like food industry, electronic industry, metal finishing industry, chemical and pharmaceutical industries, and removal of specific gas streams such as hydrogen sulfide from process water. These industries focus more on recovering the value-added products or removal of key contaminants. Finally, membrane distillation can also be integrated with other advanced water treatment technologies such as membrane bioreactor (MBR), forward osmosis (FO), Reverse osmosis (RO) and humidification-dehumidification (HDH) creating more business opportunities [24].

As reported by GVS in the deliverable D1.3 (preliminary business model) of **MEASURED** project, a qualitative survey was submitted by Thomas et al. (2017) to researchers/academics and industry experts in order to understand the major applications of Membrane distillation. From the survey the general consensus was that MD can play important role in desalination in combination with RO to work on increased recovery. Similarly, as the concentration ability is high for MD, resource recovery is on the top list of potential areas where the technology can have a competitive edge. Wastewater treatment applications are also of great interest, including textile dye effluent, produced water, olive mill wastewater, mining industry, dairy industry, among many others. It was agreed by both type of

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experts that food processing and stand-alone desalination are the least favored for commercial potential.

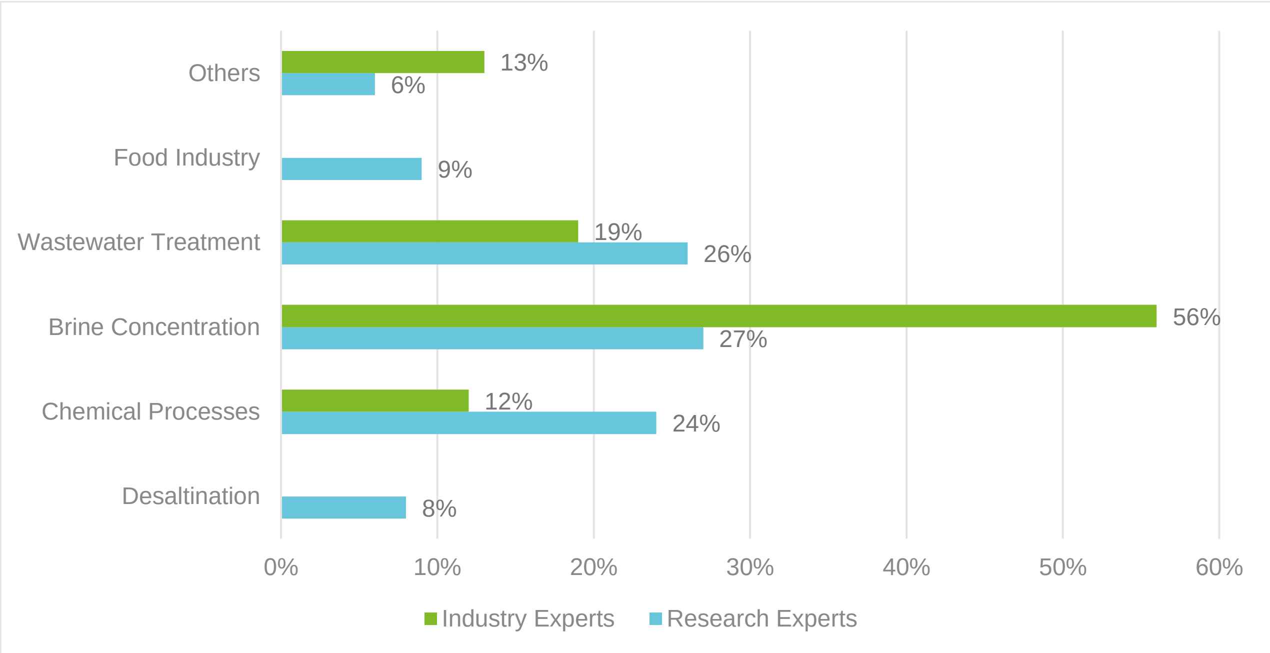

Figure 11: survey responses from the industry and research experts on the most potential commercial application for MD in the future

To understand the application potential of MD systems in Europe it is reasonable to consider the number of plants that can include membrane distillation. Regarding the **desalination market**, there are **1,200 plants in Europe**, that provide a capacity of 2.37 billion m3 and the 82 % are sited in Mediterranean Countries, mainly Italy, Spain and Greece. In the North of Europe Netherlands is the main Country [25]. In addition to the desalination plants, other **26,523 wastewater treatment plants in Europe** have to be considered that process wastewater from 447 million inhabitants and from industries that discharge into public sewers [26].

Figure 12: Total Number of Desalination and Wastewater Plants in Europe

Broadening the geographical spectrum of analysis, instead, there are currently around **16,000 desalination plants worldwide**, with a total global operating capacity of roughly 95.37 million m3/day and brine production of 142 million m3/day [27], and **over 58,000 wastewater plants distributed globally** [28].

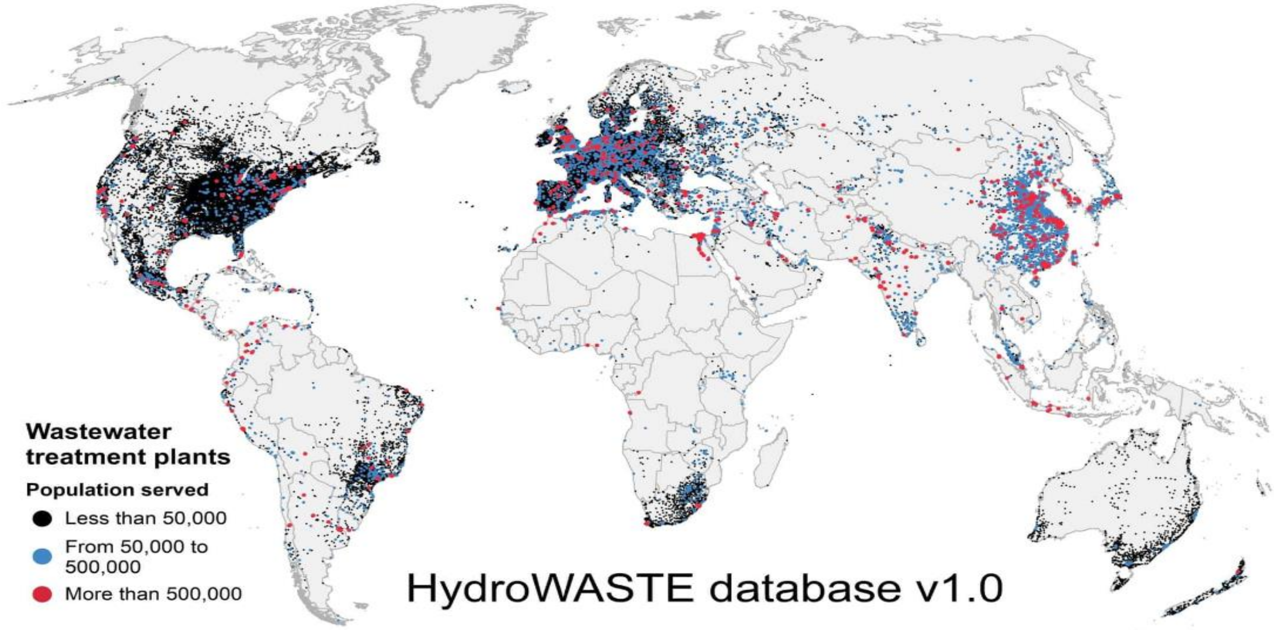

Figure 13: Wastewater Treatment Plants Worldwide. Source: HydroWASTE Database

In addition to desalination plants, therefore, membrane distillation can encompass the entire water and wastewater market which is valuated about €800 billion at global level in 2020. In particular, the 74% of the market value belong to the municipal category, while the remaining 26% belong to the industrial.

According to GWI, the industrial wastewater market consists of the following segments: oil & gas representing approximately 16% of the total industrial wastewater market, power generation with 15% of the market share, food & beverage having approximately 14%, refining & petrochemicals holding 10%, mining representing approximately 7%, pulp & paper recording 6%, micro-electronics having 6%, pharmaceuticals representing approximately 4% and other segments with 22% of the market [29]. Based on technology, the biological treatment segment dominated the global industrial wastewater treatment market with 34.45% share in 2021 [30].

Despite the existence of multiple push factors and relevant advantages of the use of membrane distillation systems, the market size is still modest due to the presence of numerous alternative technologies in the main application segments which guarantee important performances in the segments where MD is inserting. **MBR, Reverse Osmosis and other membrane-based filtration systems** compete with membrane distillation for water and wastewater treatment.

Focusing on desalination, the current desalination plants are majorly based on thermal and membrane processes. At present, around 25% of water desalination processes are based on distillation [38], while **reverse osmosis (RO) membrane technology, being the largest**

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contributor, contributes about 69%. These desalination techniques operate at high temperatures or consume high electrical energy, which are currently fulfilled by fossil fuels such as coal, petroleum, etc. As these fossil fuels are non-sustainable and rapidly depleting, an alternative desalination technique with a minimum energy requirement involving sustainable energy sources is needed for freshwater production [31].

Membrane distillation presents relevant **advantages** compared with conventional technologies like reverse osmosis. Notably, MD presents high salinity rejection, excels in treating wastewater with an unparalleled level of purity, ensuring the retention of solid or nonvolatile contaminants up to 100% on the retentate side. Additionally, operating at relatively low temperatures between 30°C to 90°C, it requires lower pressure. Membrane distillation, furthermore, can use waste heat as a driving force for the process and typically involves fewer process steps compared to other water treatment technologies, potentially reducing its environmental footprint and contributing to the sustainability. These characteristics collectively underscore MD's significant potential in revolutionizing water treatment and desalination efforts. Despite these strengths, MD faces **challenges** that hinder its widespread industrial application. These include the development of membranes with enhanced hydrophobicity, reduced wetting issues and liquid entry pressure values for long-term stability, as well as the creation of modules with reduced thermal and mass transfer resistances. Another vital parameter is improving the water recovery ratio achieved in a single pass, as MD modules typically exhibit low recovery ratios. Achieving a higher water recovery ratio in a single pass is a crucial parameter for large-scale implementation of MD. The energy efficiency remains the key bottleneck for future deployment of MD since membrane distillation has higher total energy consumption compared to RO. In this sense, efforts are underway to decrease the specific thermal energy consumption through the utilization of renewable energy sources. These barriers entails the lack of widespread industrial applications of MD for water desalination and wastewater treatments [24] [32] [33]. A comparison of different membrane desalination technologies [31] is shown in the Table 2.

Table 2: Comparison of Different Membrane Desalination Technologies

Technology	Energy Consumption (KWh/m3)	Advantages	Disadvantages
Reverse Osmosis	(2-6)	Technology maturity; Low space necessities; Easy to operate and scale; No phase change is involved; Does not require the use of expensive chemicals	Membrane fouling, scaling and lack of durability; water recovery drop with growth of scale
Forward Osmosis	21	Production of concentrated brine; Lower environmental influence	High energy ingesting due to the abstraction solution recovery process
Electrodialysis	(1-12)	Low vulnerability to scale formation; High salt elimination	High capital costs; Unable to remove neutral toxic components such as microbes
Multi-Stage Flash	(14-25)	Lower operating cost; Less prone to scaling problems; High quality water produced	Higher energy consumption; Low recovery; High capital costs

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Multi-Effect Desalination	(7-25)	Technology maturity	Significant Energy use; Momentous scaling problems
Membrane Distillation	(1-900)	High salinity rejection; Uses low-grade heat; Reduces fouling and concentration polarization; Modular technology; Low pressure and temperature	Low water recovery; Possibility of membrane wetting; High energy consumption

Recent technological developments and advancements in membrane distillation are indicated in the table below [24].

Table 3: Performances Comparison of Different Membrane Distillation Systems

Case history	Vendor	Year	Membrane material	Membrane configuration	Application	Feed TDS (mg/L)	Product water TDS (mg/L)	MD flux ($L/m^2 h$)	Recovery (%)	GOR	Energy consumption (kWh/m^3)
1	Memstill	2010	PTFE	DCMD	Seawater	35000	< 2	0.25–3	10	10–17	154–38
2	Fraunhofer	2012	PTFE	AGMD	Seawater	43,600	21	1.5	18–44	3.4	140–350
3	Memsys	2014	PTFE	VMD	Thermal brine	71,031	6	5.7	52	2.5	260
	Memsys	2014	PTFE	VMD	Seawater	44,701	9	4.8	NA	2.5	260
	Xzero	2014	PTFE	AGMD	Thermal brine	68,529	1472	2.5	NA	0.74	1031
4	Memsys	2016	PTFE	VMD	Hypersaline ground water	62,592	< 5	5	40	2.5	260
5	Aquastill	2016	LDPE	AGMD	Seawater	35,000	50	1.0	5	6–7	90–95
6	Memsys	2016	PTFE	VMD	Brackish water	1000	2	1.6–2.5	NA	NA	ND
7	Memsys	2017	PTFE	VMD	Saline water	15,000	NA	1.7	76	2.0	340
8	Fraunhofer	2017	PTFE	AGMD	Seawater	35,000	< 1	1.1	4–10	3.18	207
9	Solarspring	2018	PTFE	AGMD	Saline water	240,000	128	0.7	NA	3.64	200–800
10	Memsys	2018	PTFE	VMD	Seawater	25,600	< 2	8.5	36	3.3	200
11	Solarspring	2019	PTFE	AGMD	Saline water	35,000	< 1	1.5	NA	NA	NA
12	Aquastill	2020	LDPE	VEMD	Hypersaline solution	35,000–292,000	508	1–3	NA	8.5–13.5	48–77

Since **hydrophobicity is the basic requirement for membrane distillation process**, the membrane material must be intrinsically hydrophobic, or its surface must be modified to be hydrophobic. **For this reason the most used membranes for MD are polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF)**.

Among these, PTFE has advantages such as high chemical stability, high crystallinity, low intermolecular attraction, low surface energy, and high hydrophobicity. However, the major challenge with PTFE is its insolubility in any solvent. PP is a low-cost crystalline polymer with good thermal and mechanical properties, and good chemical stability, thus suitable for membrane applications. However, compared with PVDF, PP has high surface energy and hence lower hydrophobicity. PVDF is a semi-crystalline polymer with good chemical stability, moderate thermal and mechanical properties, and similar surface energy to PP. Compared to PTFE and PP, PVDF is easily soluble in most organic solvents such as n-methyl-2-pyrrolidone (NMP), dimethylacetamide (DMAC), and

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dimethylformamide (DMF), thus making membrane preparation very easy. Because of this ease of processability, PVDF has been extensively investigated for membrane distillation [34].

All the mentioned advantages of PVDF membranes respect to the other contribute to the growth of the **global PVDF membrane market which is valued at €0.7 billion in 2022 and is destined to grow strongly in the next 4 years at a CAGR of 7,7% reaching a value of €1,013 billion in 2027** [35].

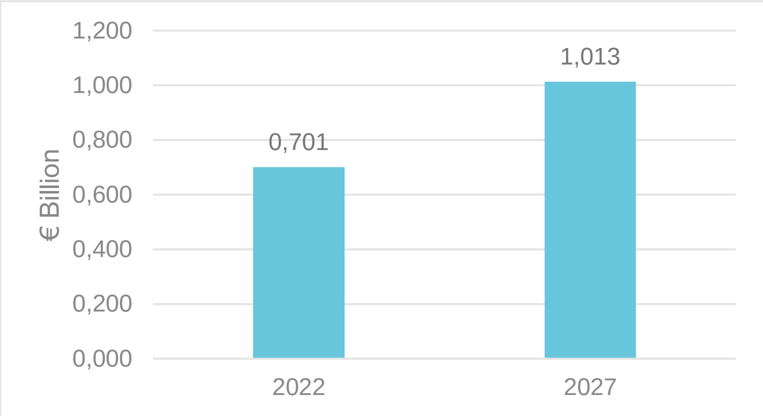

Figure 14: Global PVDF Membrane Market

Potential restrictions on PFAS levels in water represent the main market barrier for PVDF membranes, limiting their growth. In fact, PVDF membranes can potentially release components or degrade into PFAS chemicals, thus contributing to water contamination. So, the membrane itself may not comply with the restrictions imposed by the regulations even if the question still remains open without a definitive rejection [36].

Despite this concern, an emerging trend in the membrane production market, as in the case of PVDF membranes, concerns the adoption of **green solvents** to replace toxic ones. This change is driven by environmental and health reasons, highlighting a growing sensitivity towards sustainability in the industrial sector. The most investigated green solvents for the membrane production are CyreneTM, isosorbide, methyl lactate, γ-valerolactone (GVL), N,N-dimethyl lactamide, succindiamide, glycerol derivatives and 2-methyl tetrahydrofuran (2-MeTHF) [37]. γ-valerolactone (GVL) is one of the most biggest green solvents markets, valuated €660 million in 2022 at global level destined to remain constant in the coming years. China is the largest market, with a share over 85%, followed by Japan, and USA, both have a share about 10%. It is a high concentrated market where the global top three manufacturers hold a share over 75% [39]. One of the challenges related to the expansion of the green solvent markets for membrane production is constituted by the high sale prices of the materials. In fact, in the case of GVL, the minimum selling price is estimated to be 3076 €/ton.

During the **interview with one of the potential customers of membrane distillation operating in the Italian agri-food industry**, which manages over 300,000 tons of incoming wastewater and the same number of internal ones deriving from the distillation process, particular industrial needs, barriers that hinder possible investments in membrane solution and advantages linked to this technology emerged.

Among the company's main needs is the objective of **reducing water consumption** and **investing in environmentally sustainable solutions that allow it to comply with legislative parameters on emissions in sewage systems, while optimizing the entire process**. However, some significant barriers to the widespread adoption of membranes have also emerged. Firstly, reference is made to **energy and operating costs**, which are still considered too high compared to the environmental benefits obtainable, especially in comparison with other alternative systems such as

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water softeners. Secondly, the problems related to **membrane fouling caused by organic residues and the management of these residues downstream** of the process are highlighted.

However, several **advantages** of using membranes for wastewater treatment are recognized. These include the **possibility of reusing water**, **reducing discharge into public sewers** and **decreasing additional extraction of water from aquifers**, which would still result in additional costs.

Therefore, an investment in a technology such as the membrane distillation must guarantee players a balanced ratio between environmental and economic sustainability, with a view to optimizing the entire process.

3.3.1 Interviews with Relevant Stakeholders in Membrane Distillation

<table>
<tr><td>SolarSpring membrane solutions</td><td>Respondents: Rebecca Schwantes

Role: CEO</td></tr>
<tr><td colspan="2">Rebecca Schwantes is the CEO of Solarspring, a small German company specialised in membrane distillation technology. The company based in Freiburg, produces spiral modules for membrane distillation. The MD modules are made of fiber glass, the support is made in PP and the membrane itself is made of PTFE. Their modules have size between 1 to 50/60 m2 and their cost (to be competitive) should be lower than 80 euro/m2. The company is targeting not specific solutions but a range of solutions for customers, where MD can be versatile and provide benefits compared to current technologies.
According to Rebecca membrane distillation has business potential and consequent economical benefit in the following areas:

1)Recover of acidic products in several industrial processes – “this process is feasible when waste heat is present as for example in piro-hydrolysis”.
2)Purification of water solutions with a high salt/mineral content – “in the field of desalinization MD is an additional step to reverse osmosis, MD enables the content of salt and/or mineral is water to be much lower than reverse osmosis and therefore in line with the current law. Hence, MD can be a technology for salt reduction and/or reduction in water solution and recovery of rare and precious minerals”.
3)Ammonia recovery, especially in the industry of fertilizers. “MD is a good technology for ammonia recovery in processes that actually produce solution with high NH3 concentration and can be couple for example with anaerobic digestion that produce waste heat”.
4)Clean water production in hydrogen production, both from fresh and seawater. “The process is economically viable if waste heat is available and they have calculated that for PEM electrolyzers, the amount of waste heat is more than enough to “feed” the energy requirement of the MD process. This application field being a breakthrough for MD expansion and exploitation”.</td></tr>
</table>

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"*Lately there is also an interest of the pharma and chemical industries, although in such cases the processes are more challenging. In all these markets MD can take a share of the markets. Anyway the MD as process is feasible when there is waste heat*".
Often membrane distillation is compared with reverse osmosis in terms of competitivity. According to the Solarspring's CEO, "*MD does not compete reverse osmosis, they are different and have different problems (e.g. when it comes to the type of fouling in the process), target processes and application, as well as the volumes that can be purifies and "purity" of the product.*
"The two technologies can complement each other, and actually MD might complement reverse osmosis when higher purity of the product is required.

After to discussed the main applications of membrane distillation and the comparison with RO, the interview moved on the main barriers to market penetration of MD implementation for new applications. According to Rebecca Schwantes, there are three main barriers:

1)The first concerns the longevity of the membrane module. *"This value is something difficult to be predicted and tested. The module can last between one week up to years and the lifetime of the membrane depends on the conditions of the process – cleaning cycles, opportune and suitable cleaning strategies and so on. Beside membrane stability, the problem is fouling connected with below aspect and with the difficulty in set-up methods to regenerate the membrane in situ*".

2)The second regards the membrane hydrophobicity. *"Actually is still not enough and should be improved by developing new coatings*".

3)The third is related to the costs. "*At moment the CAPEX is very high and there is a lack of large reference system that enable pilot test in large scale and for long time, ideally 1-3 years*".

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VEOLIA	**Respondents:** Pierre jean Remize **Role:** R&D Engineer
Veolia is a large company focused to ensure clean water for population in France and Worldwide. The engineer interviewed, Pierre Jean Remize, is working with the public part that takes care of the drinking water production at the municipal plant of the municipality of 80.000 people. The plants they manage treat volume of water per day in the range: 100 m3 up to 50.000 m3. Before that he was in an R&D department for desalinization process based on reverse osmosis which represent its expertise area, but also was involved in some MD R&D projects some years ago. The focus of interview has been on comparison between alternatives technologies. According with him, "*many customers which have to treat their wastewaters could be interested to invest in membrane distillation, principally as MD is interesting from energy consumption point of view. However it is still not ready-to-market technology. Normally, this technology competes with traditional processes to purify water (removal of ions, demineralization, removal of organic pollutants such as sulphates, as well as pesticides, PFAS, and also removal of micropollutants), like Activated carbons*". "*Activated carbon-based processes compared to processes that use membranes as reverse osmosis, nanofiltration or MD have lower CAPEX and this, coupled with high efficiency rates, constitutes the main competitive advantage. However, although activated carbon technology has excellent levels of efficiency, it has much higher OPEX than reverse osmosis and other technologies that use membranes since they saturate very quickly, therefore have a very short lifetime and require a very fast renovation which currently constitutes a huge problem since the main supplier of these materials is China. Although reverse osmosis has higher CAPEX and OPEX, especially due to water losses, brine disposal and related costs, it has the best removal efficiency rate for different kinds of molecules*". Considering the possibility of investment in MD technology, he said that "*the best solution in which to invest for a company like Veolia is the one that guarantees an excellent balance between economic and environmental sustainability, in which the CAPEX and OPEX are repaid by the efficiency of the solution in terms of water purification*".	

3.4 MARKET POTENTIAL FOR PERVAPORATION

An overview of the market potential for membrane technology in **pervaporation** as a separation process in industry is provided in this section. The market size and its forecast, as the driving forces for demand are reported along with the competitive solutions and the application segments.

Membrane pervaporation, which reached commercial application since 1983 with polymeric membranes, today is a mature technology. Europe, and in particular Italian researchers have had a key role in the development of membrane for pervaporation process.

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The **global market for pervaporation membranes** was evaluated to be ca. € 1 billion in 2021 and with a CARG of 9.60% will reach € 2,30 billion in 2030 [40]. Despite having been commercially available for some time, it is a modest-size market, indeed at a global level there was **only 100 plants that perform pervaporation until 2017** [41]. However, as emerged from an interview with DELTAMEM AG, a small company working on pervaporation technology, in the **last five years** the number of pervaporation plants increased to **about 200 operating units at global level**, particularly in **Italy which represent one of the top EU markets for pervaporation with the highest number of pervaporation plants**. The diffusion of pervaporation plants in Italy is a consequence of the historical, strong attention of the Italian industry and research endeavors to the implementation of processes with a better energy balance.

On the basis of types of membranes, the market is segmented into **organic pervaporation membranes such as polymeric**, and **inorganic pervaporation membranes such as ceramic**, which represent the two major classes, together with mixed matrix membranes and 2D material membranes [42].

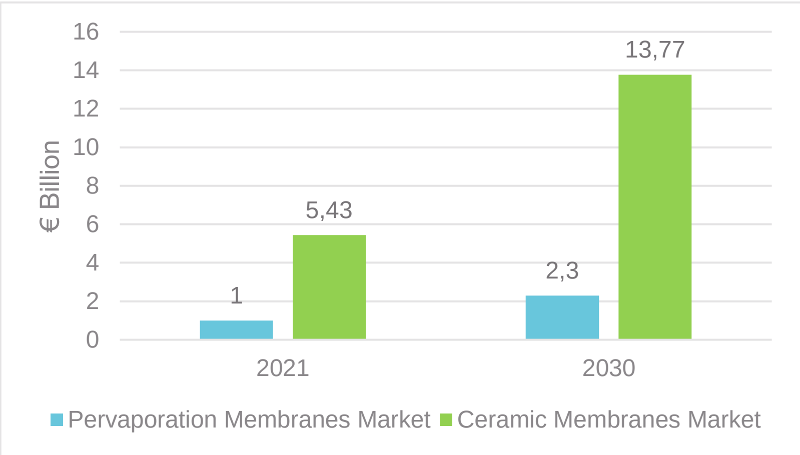

Figure 15: Global Pervaporation and Ceramic Membrane Market

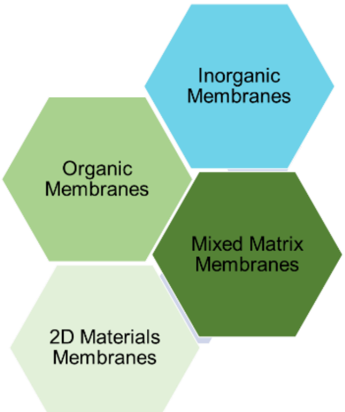

Figure 16: Type of Membranes for Pervaporation

Although **polymeric membranes** (with PVA being the main component of polymeric membranes for pervaporation) **dominate the market** since 1983 due to their low cost and simplicity in the manufacturing processes, late 1999, beginning of 2000 inorganic membranes, mainly ceramic one, have been introduced on the market. The **MEASURED** project aims to develop **ceramic membranes**, which belong to the inorganic class and are also used for pervaporation. Their total market value has a CARG of 10.90%, and its size was evaluated to be ca. € 5,43 billion in 2021 and forecasted to be ca. € 13,77 billion in 2030 [43]. According to the stakeholder interviewed, ceramic membranes have well-defined and rigid pores, thus, they exhibit greater separation performance and selectivity (given the same surface area) towards water than polymeric membranes, enabling higher volumes of solvents to be dehydrated in a more compact plant and in less time. The other difference with polymeric membranes is the operational temperature, while polymeric membranes can operate up to 95-103°C, ceramic membranes are stable up to 130 °C and show overall higher stability in a broader range of operative conditions. Polymeric membranes are however compatible with the dehydration of solvent mixtures that might contain higher amount of water. Ceramic membranes can be used for

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mixture that contain up to 20 % V/V of water, compared to polymeric membrane that are suitable for mixtures that contain up to 80-90% V/V of water. Hence, polymeric membranes can be used for the purification of not only solvents from water, but also for the reverse process, i.e. the purification of solvated water from organic solvents. In general, the pervaporation membrane technology market is segmented according to the **main applications** in **the following sectors**: organic dehydration, recovery and separation. One application is for instance the purification of aqueous mixture used to produce biopolymers.

The growth factors of the pervaporation membranes market are indeed: the increasing demands of pervaporation membranes in the sectors listed above, the growing food and beverage industry, and the quest for energy-efficient and environment-friendly technologies. According to DELTAMEM, among the three sectors **organic dehydration is the most important** and the one in which membrane pervaporation finds its key application.

For instance, the **global dehydration membrane market** is rapidly growing with a CARG of 7,5% and it is forecasted to have a size of ca. € 1,21 billion in 2021 and 2,32 in 2030 [44].

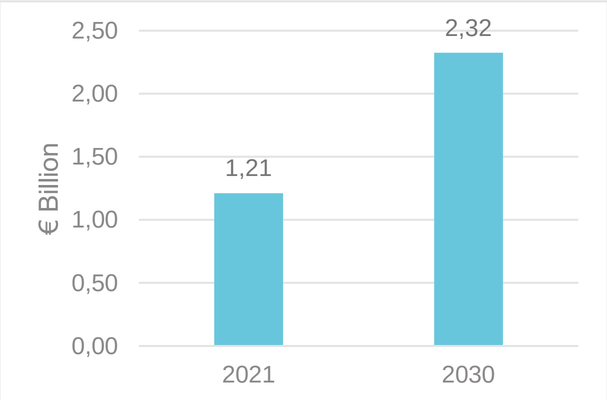

Figure 17: Global Dehydration Membrane Market

Solvent dehydration is one example of an organic dehydration process and **accounts for 63% of all organic dehydration processes**, while gas dehydration represents the remaining percentage of this class of separation process.

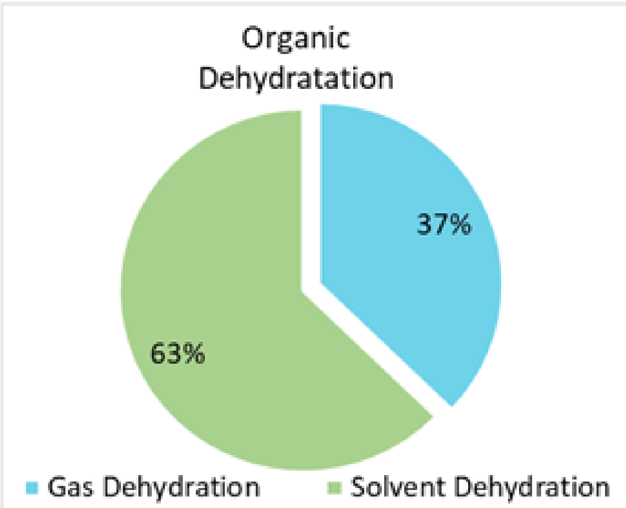

Figure 18: Organic Dehydration Process by Market Share

Pervaporation for solvent dehydration, as mentioned by the stakeholder, can operate on mixtures that are both in the liquid or vapor phases. In the first approach only the water content is in the vapour phase and hence, separated from the solvent. In the second approach, all the components of the mixture are in the vapor phase. This second approach is very suitable when the mixture to be separated is already available in the vapor phase – such as at the exit of a distillation column. In this case, energy is saved because the distilled vapor is not condensed and sent to a further purification step/stage but fed directly into the pervaporation system. This is the so-called hybrid process or plant, and it is energetically advantageous.

Although the most common technology for solvent dehydration is **distillation**, which is an energy-intense operation, about **two hundred pervaporation plants are operating worldwide**, most of

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them **dehydrating solvents such as ethanol, isopropanol, tetrahydrofuran (THF), methyl ethyl ketone (MEK), ethyl acetate as well as separation of methanol from other solvents**. Pervaporation provides higher purity (for instance ethanol with a concentration of 99.9 %V/V is achievable) by utilizing 1/5 of the energy required for distillation.

The main and potential end-users are the **pharmaceutical** (such as nutraceutical) and the **fine chemicals industries**. According to DELTAMEM, pervaporation is more sustainable than extractive distillation and safer since thus not require the use of a third, in some cases toxic, components. Moreover, the OPEX associated with a pervaporation plant is lower than the costs of distillation. Membrane pervaporation requires less energy, can be coupled with waste heat recovery, as well as less operational assistance than distillation. Today pervaporation plants can dehydrate on average a quantity of 100 kg/h of solvent. **One barrier to the implementation of pervaporation is the high initial CAPEX required to install a plant** and the general idea that membranes as something that require often replacement or in general more often than a distillation plant. While a distillation column is to be replaced after 10 years of operation, today's membranes for pervaporation have a lifetime of up to 4 years, while a pervaporation plant can continuously operate for more than 20 years.

At the EU level, 5 million tonnes of solvents are sold per year, an amount that corresponds to a € 4 billion per year of contribution to the economy, with 1 million companies involved and € 28 billion spent in R&D per year [45].

Table 4: EU Solvents Industry Numbers

Total solvents sold per year in Europe (tonnes)	5,000,000 tonnes
European companies use solvents	Over 1 Million of companies
Solvents industry contributing to the economy	€ 4 billion per year

Among the organic solvents, ethanol, and isopropanol are the most common and represent ca. 80% of the solvent volume for which pervaporation is utilized. The distillation of ethanol enables in fact a purity of 92-93%, due to the formation of the azeotrope with water. The further purification of the solvent to reach a purity of 99.1-99-.5 % requires the use of a further and more complicated distillation step, so-called extractive distillation or azeotropic distillation, which involves the use of a third component: a higher boiling solvent, such as cyclohexane or aromatic solvents that in turn from azeotropes with water removing it from the ethanol. The cost associated with the process, the high energy and resource demand, and the potential risks of contamination make pervaporation a better separation technology to achieve solvents with very high purity, meaning a very low water content << 0.5% V/V.

In very recent years, some factors have shaped the solvent industry, especially for ethanol and isopropanol: in 2022 the solvent industry was not prepared for the significantly increased quest that COVID-19 caused for these solvents that are the main ingredients of sanitizers. The solvent industry experienced significant price inflation in the second half of 2021 and in 2022, with each product in the solvent range becoming 100-300% more expensive than in 2019. COVID-19 has indeed had an effect on the membrane pervaporation market in 2022.

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According to stakeholder, a future potential application of membrane pervaporation is related to the dehydration of ethanol, as well as methanol in the production of biofuel. The market size for the production of bioethanol is indeed fast growing and it is expected to reach € 135 billion by 2030 [48]. Bioethanol has to be very vey pure and containing a very low water content to ensure mixability with gasoline, high heat of combustion and prevent corrosion of the engine. The high CAPEX associated with the pervaporation plant installation might represent a barrier for the implementation of membrane pervaporation to the product of bioethanol.

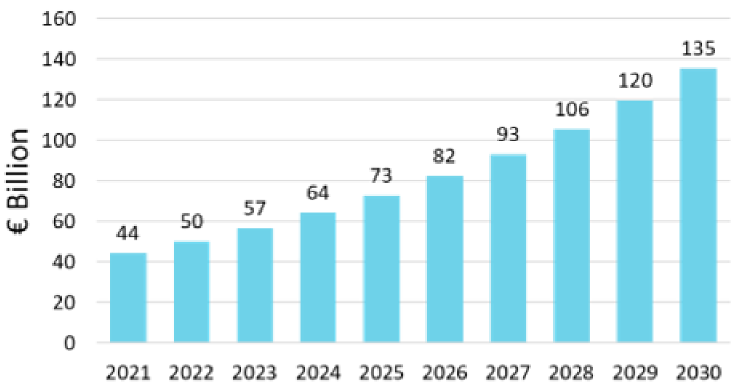

Figure 19: Bioethanol Market

Another market sector where membrane pervaporation has found a key application is the **acrylic ester industry**. Acrylic acids and their derivatives as indeed, esters, are the starting materials in a broad range of chemicals and materials industrial sectors: **paintings, coatings, adhesives, ink, textiles, and diapers to mention the most relevant**. **Membrane pervaporation is used for the organic dehydration of the acrylic acids and esters**. The increase in the market size of the acrylic esters, is estimated to grow from € 8,4 to 10,4 billion in the period 2022-2028 with a CAGR of 7.2%**,** which represents a driver also for the membrane pervaporation market growth [46].

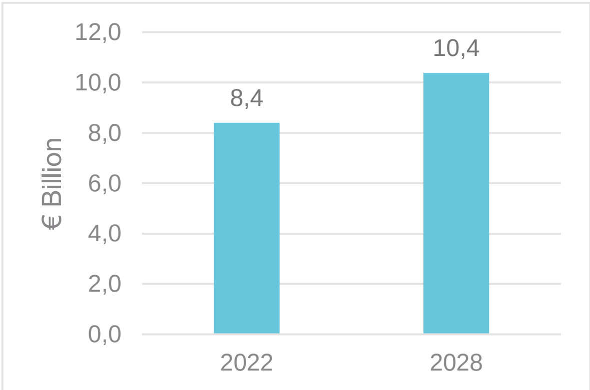

Figure 20: Acrylic Esters Market

Another driver for the increasing market potential for membrane pervaporation is not only the continuous growth of the annual consumption of solvents but also the quest to separate, purify, and recover them (processed that belong to the sectors of organic recovery and separation). Sustainability is the biggest opportunity for the solvent industry and technology that enable product recovery and recycling to reduce the environmental footprint. Solvent recovery, purification and recycling is however not performed by the industries that actually produce exhausted solvents but performed by a dedicated industry and companies that for example buy the exhausted solvent from pharmaceutical and chemical industries, purify and re-sell them for lower grade application, such as diluent.

Indeed, at a global scale, the market of equipment for **solvent recovery is also growing at a CAGR of 5% over the current decades and accounting for € 4,4 billion by 2028**, which demands a higher supply of technologies for such a process, i.e., being pervaporation one of them together with adsorption, condensation, and distillation [47].

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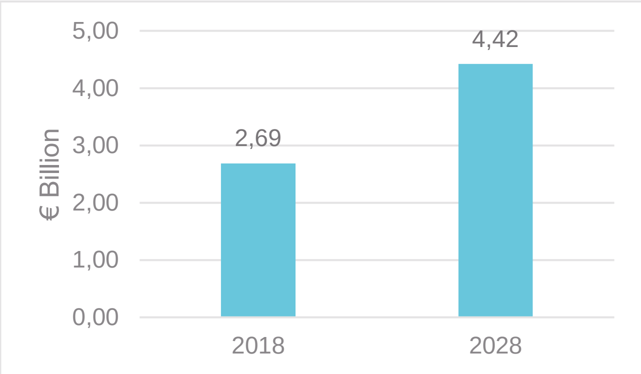

Figure 21: Global Solvents Recovery Equipment Market

The growth of the solvent recovery equipment market is a consequence of the growing demand for such a process from end-use industries in the printing, painting and coating, oil and chemical, pharmaceuticals, and related sectors.

Although most of the exhausted solvents today are still used in incinerators for energy recovery, the use of recovered solvents guarantees energy savings and a lower impact on the environment: The distillation of the solvent requires less energy than its production from scratch and membrane pervaporation is a lower energy intensity than distillation. One of the **fastest-growing sectors in separation processes is the combination of membrane pervaporation with distillation** which has the potential for application when high purity of the products is demanded. This combination minimizes energy consumption while enabling separations that would otherwise be impossible.

3.4.1 Interviews with Relevant Stakeholders in Pervaporation

<table>
<tr><td>Speichim processing
Séché global solutions</td><td>Respondents: Fady Boutros

Role: R&D director</td></tr>
<tr><td colspan="2">Speichim Processing SA is a French company specialised for more than 50 years in the solvent purification. The company works with all the possible organic solvents on the market from oxygenated solvents e.g. alcohol and acetone, THF, to aromatic to halo and so on. Speichim do not uses membrane technology in their processing but prefer other traditional separation and purification processes typical of organic separation like extraction and distillation for instance.
Fady Boutros, R&D director of Speichim, sees the possible implementation of membrane technology difficult for purification of aggressive solvents that can damage the membranes (acetone and THF being one example) – it is also not feasible to clean the membrane module every time and ensure that is clean for the next purification cycle. The only advantage that he can see is to replace distillation or use pervaporation together with distillation to reduce the energy consumption of the process.
In their decision-making processes they usually focus on the CAPEX and try to minimise the OPEX and go towards processes that help sustainability.
“As organic chemist, I can say that it is very difficult to use membrane technology for at least large part of the solvents commonly utilized and that some like THF are also aggressive for polymeric membranes, made of PP or PTFE. I think that the problem is not the deterioration of the membrane, but its swelling in presence of these solvents, something that can be avoided with inorganic membranes. I see that the problem is rather the simplicity of processes such as separation or distillation, that although might take more energy than e.g. pervaporation require less equipment and time”.</td></tr>
</table>

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Respondents: Luigi Leva

Role: Co-founder and Managing Director

Deltamem AG is a small size Swiss company focused on pervaporation and vapour permeation membrane technologies for the dehydration of organic solvents in the pharmaceutical, biotechnology, biofuel and fine chemical industries. The company is specialised in pilot plants and commercial plants for pervaporation and produces polymeric membrane modules, where the main polymeric component is poly(vinyl alcohol), PVA, but they have also know how in ceramic membranes. The company has collaborated with TNO and other actors, such as CNR in Rende, involved into **MEASURED** project.

DeltaMem has worked a lot on developing and improving the technology, especially from the process side and the engineering of the process, while the membrane is the same after 50 years. DeltaMem is continuously working on R&D both internally and by collaboration at EU level, they host several students. Their membranes have today a lifetime of 4 years under good operational practical, while the pervaporation plant has a lifetime of 20 years. They ensure the membrane stability for the customer's needs by performing accelerated compatibility tests that mimic the customer's process and can give an estimation of the lifetime of the membrane under the process conditions of the user. They have 225 m2 of laboratory for pervaporation tests.

According to Luigi Leva, to understand the importance of the pervaporation in the European landscape it is important to frame temporally its developments. As stated, "*pervaporation has a long important history. The process was discovered in 1917 and reached commercial application in 1983 with polymeric membranes, while ceramic membranes reached the market in 1999-2000. Today, Pervaporation is a mature and interesting technology, and the plants today are at industrial scale. In general, the pervaporation market is a small market, its expansion will require the acquisition of existing companies and then the transformation of their processes to pervaporation. There are around 200 pervaporation plants worldwide with Italy being the country with the highest number of pervaporation plants. It is a consequence of the historical, strong attention of the Italian industry and research endeavor to the implementation of processes with a better energy balance*".

Moving on the main applications of pervaporation, Deltamem's Managing Director states that "*today, pervaporation is industrially used most exclusively for the solvent dehydration – solvents that form azeotropic mixtures with water and therefore, their further purification with distillation is impossible. Pervaporation is therefore used to save energy and avoid the use of a third component to remove water. The most common solvents are ethanol and isopropanol, which represent ca. 80% of the solvent volume for which pervaporation is utilized. The industrial sectors where pervaporation is actually applied are the pharmaceutical and fine chemicals where the recovery of organic solvents is taking place. Although these industries prefer to use fresh solvents and purchase it rather than purifiying and recovering, they sell the exhausted solvents to companies that are actually specialised in the recovery of exhausted solvents and their further use as lower-value products, i.e., diluents. These companies that actually recovery the solvents are the ones*

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that use pervaporation plants. The biggest plant for solvents regeneration in EU is located in Italy, Itelyum, which is an example of companies that could implement pervaporation for solvent recovery, purification and recycling. Essentially, there are two types of pervaporation approaches:

(i) Pervaporation where the feed is liquid, the organic solvent to be purified is liquid while the water to be removed is vaporized.

(ii) Vapor permeation, where all the components of the mixture are in the vapor phase – this is suitable where solid impurities are present in the mixture or when the mixture to be separated is already available in the vapor phase – such as at the exit of a distillation column. In this case, energy is saved because the distilled vapor is not condensed and sent to a further purification step/stage but fed directly into the pervaporation system. This is the so-called hybrid process or plant and it is energetically advantageous".

In addition to focusing on the main applications and type of processes of pervaporation, Luigi Leva also gave his thoughts on other potential and emerging applications of this technology. "*A future potential application for pervaporation is in the field of bioethanol and biofuel. Ethanol has to be very dried to be mixed with gasoline, thus, ensuring mixability, high heat of combustion and preventing corrosion of the engine due to high water content. At the moment, the state-of-art technology for ethanol dehydration as biofuel application is based on molecular sieves, that come after distillation. Distillation affords ethanol with a purity of 92-93% V/V and then the passage on molecular sieves affords a purity of 99.1-99.5 % V/V. Although this technology is not efficient from an energetical point of view is applied for very large volume – it is indeed applied for the biorefinery, being biorefinery a sector that treats large volume of organic liquid and it is difficult to replace the current technologies with alternatives"*.

Then, the interview focused on the main advantages and disadvantages of the mainly used membrane materials, namely polymeric and ceramic. According to Luigi Leva there are four main differences between polymeric and ceramic membranes for pervaporation. "*The first difference is the compatibility of the membrane material with the complexity and composition of the mixture to be separated. For instance, an isopropanol mixture containing 50% V/V of water content is not suitable for a ceramic membrane. Ceramic membranes, commercially available today and based on zeolites, are not compatible with mixtures that have a water content higher than 20% V/V. Polymeric membranes, like those developed by Deltamem, are instead compatible with mixtures that have a water content very high, up to 80-90% V/V. Therefore, they are compatible with industrial plants that treat solvents with a quite high water content. One application here is the purification of aqueous solutions for the production of biopolymers".*

An other difference is the Temperature. "While ceramic membranes work up to 130 °C, the polymeric go up to 95-103°C. This is an advantage for the ceramic membranes since they enable the reaching high flow rate of the feeding water and therefore having more compact plants".

The third difference is the membrane performance and selectivity per m2 giving the same operational temperature. "Ceramic membranes are more selective towards water and purify higher amount of water".

Finally, the last important difference concerns to the costs. "Ceramic membranes have higher costs than polymeric membranes and this could be an obstacle to their commercial diffusion".

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Moving the interview on the customers needs aspect, he said that for one of the main end-user of pervaporation, the pharmaceutical industry, "*the companies require solvents with very high purity, meaning a very low water content-0.5% V/V, as well as free of other impurities. Although the volume of solvents to be purified are low, pharmaceutical industry is very keen on adopting sustainable technology, reducing carbon footprint*".

Considering the main market barriers, Luigi Leva said that "*at the moment the price of energy is still low and recovery process are not so yet convenient even if in Europe there is however higher attention. This represents a relevant market barrier as the companies still prefer to burn the exhausted solvents and recover the energy and heat rather than purify the solvent. The main "competitor" in this regard is the incinerator. In this context the policy policymakers could have a key role in regulating and pushing for more sustainable strategies. However, the main barrier in implementing pervaporation is the CAPEX required to install a pervaporation plant. An other barrier is the bias of the end-users who think of membranes as something that often requires replacement or in general more often than a distillation plant - a distillation column has to be replaced after 10 years of operation*".

Despite there are some barriers to entry for this type of technology, it has several advantages compared with alternative solutions like classic distillation. According to the stakeholder, "*Pervaporation is more sustainable than extractive distillation and also more safe, since thus not require the use of a third, in same cases toxic, components. While a distillation plant requires constant assistance, pervaporation does not and therefore has a competitive advantages compared to distillation. Installing a pervaporation plant does not require further workers and/or operators for that from the company. The pervaporation plants can operate in continuous on purifying the same solvent mixture or operating as batch, i.e., being multi-purpose plants and therefore versatile to be switched among different solvents to be dehydrated without changing the membrane. In terms of sustainability, pervaporation used 1/5 of the energy required by distillations and an even higher energy saving can be achieved if waste heat can be used for pervaporation. Pervaporation allows a purity of 99.9% to be achieved for organic solvents, but it only enables the removal of water not of other purities*".

3.5 SWOT Analysis

A **SWOT analysis** has been performed for each of **MEASURED**'s business case to respectively identify the strengths, weaknesses, opportunities, and threats of the project that might guide the future exploitation of the technologies, new potential and minimise the associated risks.

The analyses are the result of workshops and interviews with **MEASURED** partners and are presented below for each of the business case.

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3.5.1 SWOT Analysis for MEASURED’ Carbon Molecular Sieve Membranes in Gas Separation Technology Line

Carbon molecular sieve membranes (CMSM) developed in **MEASURED** project have applicability in gas separation processes.

Compared to current technologies that are based on polymeric and palladium (Pd) membranes, CMSM have significant **strengths**: higher flexibility and versatility for a broader range of applications and gaseous mixture to be separated. CMSMs enable operational processes at higher temperatures and pressure while ensuring higher selectivity towards the gas molecules. The higher permeability and ability to withstand higher pressures allow the purification of higher volumes of gases in shorter time, i.e., at higher flow rate, compared for example to polymeric membranes, and the production of purified gases with an outcome pressure already suitable for grid requirements. This aspect has a direct effect on reducing the costs related to the process and the gas production and it is an outstanding strength in for example methane (CH4) purification and separation, and its flowing in the gas grid. CMSM advantages make them applicable in the production of renewable methane and can be in fact integrated into power-to-methane processes.

CMSM have higher resistance to chemicals and to high temperatures than polymeric membranes, thereby, the membrane units have longer lifetime. The longer lifetime of CMSM membrane and the lower costs of its support and module might have an advantage on reducing the costs of the process.

CMSM have lower price and a less impactful end-of-life option than Pd-based membranes. The possibility of separating gaseous mixtures containing more than two gases by a modular system with sequential arrangement of membrane units is one of the strengths of **MEASURED**’s outcomes. Indeed, a technical solution is provided to separate in a single process carbon dioxide (CO2) and hydrogen (H2) from CH4, and to subsequently separate CO2 from H2.

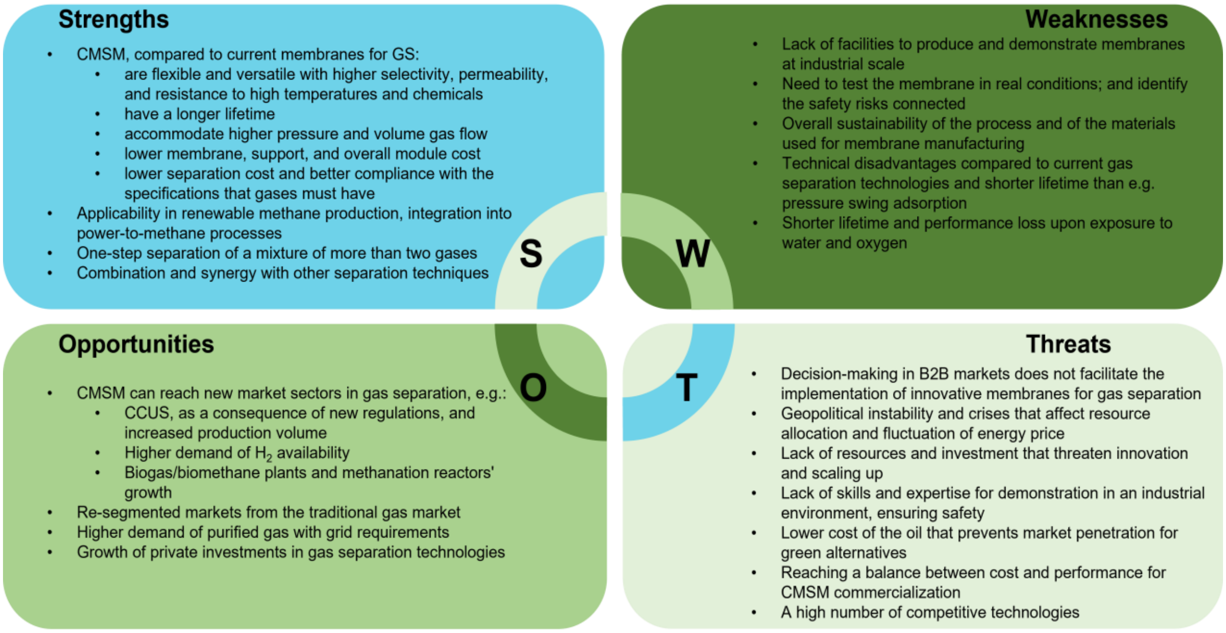

Figure 22: SWOT Analysis for Gas Separation

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Yet – the lack of facilities to demonstrate the project advances and membrane production at an industrial scale is one the **weaknesses**.

To ensure business development, the membranes should also be tested in real conditions, while the risk related to the processes should be identified to guarantee suitable training of the operators and thereby enable risks mitigation measures to be taken.

The overall sustainability of the gas separation process by using CMSM membranes should also be assessed alongside the sustainability of the membrane unit. At the end-of-life, once it cannot be regenerated any longer, the carbon molecular sieve layer is usually removed by pyrolysis and the as-obtained, clean support a new layer of carbon molecular sieve is deposited. Their lifetime is usually shorter when gas mixtures to be separated contain oxygen and moisture.

Although, CMSMs have a longer lifetime than for instance polymeric membranes, membrane-based facilities for gas separation usually guarantee a shorter lifetime than currently available technologies, one example is pressure swing adsorption.

New **opportunities** have been identified for CMSM in gas separation due to changes in regulations, new market trends and demand, as well as the advancement of innovative technologies.

Specifically, CMSMs have opportunities in the market sector related to carbon capture use and storage (CCUS). The forecasted increased production volume of CO2 and the regulations into action aiming to reduce and eventually reach net-zero carbon emission create business opportunities for new technologies that enable CO2 separation, as indeed CMSM.

Another opportunity is represented by the H2 production market, which is also expected to significantly increase over the coming years: The higher production volume requires new technologies and higher availability of processes for hydrogen purification.

The production of biogas and biomethane is also expanding and CMSMs have also the opportunity to be implemented in the reactors for methanation. An opportunity that is also fostered by the increasing demand for purified gas matching the requirements of the grids.

It is evident that the gas separation sectors are expanding and growing, and the related technology can advance also as a consequence of the current growth of private investments in these business opportunities.

The achievement of the market potential and opportunities for CMSMs can be threatened by several factors. The implementation of new gas separation technologies, as CMSM-based, can be hampered by the decision-making process in B2B markets, which is one of the **threats**.

Unpredictable crises and political instability might also threaten the resources and investment allocation and availability to develop, implement, and scale up these new technologies as well as cause fluctuations in energy costs that also influence the development road.

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3.5.2 SWOT Analysis for MEASURED' Ceramic Membranes in Pervaporation Technology Line

The HyBSI membranes developed in the **MEASURED** project have applicability in pervaporation processes.

These ceramic-based membranes have several **strengths** compared to the currently utilized membranes that are usually polymeric in this separation technology. Their composition enables stability at higher temperatures and operability under harsher conditions, ensuring versatility for different processes. Their ceramic nature also guarantees a longer service lifetime and one of **MEASURED**'s goals is to develop membranes which surface can be regenerated. These membrane characteristics, together with the higher energy efficiency of the process and their higher separation capacity positively impact the operational costs of the process. Their larger surface area allows higher volumes to be separated with an additional cost reduction.

The combination of pervaporation as a technology for separation with for example distillation or absorption can be a complementary strategy to afford for instance dehydrated ethanol with higher purity in a minor number of separation iterations.

To ensure business development and large-scale production, another strength of the **MEASURED** project is the activities performed to assess quality control of the process, evaluate the actual cost reduction, and verify the recyclability of the materials used for membrane manufacturing.

The internal factors to the project might however represent **weaknesses** for the business development: the lack of facilities to produce and demonstrate membrane at an industrial scale is one of them, as well as the need to test the membrane performance in real conditions. Thereby, there is the need to identify the potential risks and mitigation strategies that might arise from a large-scale process that operates in real conditions.

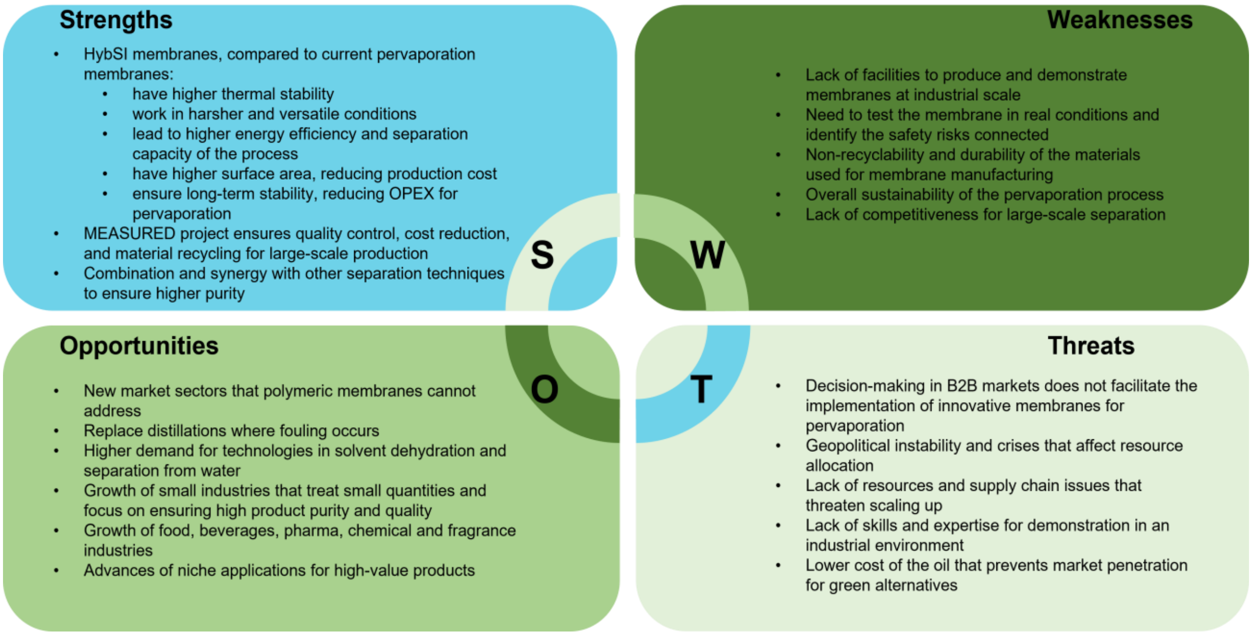

Figure 23: SWOT Analysis for Pervaporation

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Business **opportunities** might be fostered by external factors: HyBSI ceramic membranes might address new market sectors where polymeric membranes do not match the process requirements, as well as replace the distillation process where fouling problems affect the quality of the final product and the efficiency of the process.

Pervaporation is a suitable separation technology when relatively low quantities of liquid and volatile organic solvent, usually of high value should be purified and/or dehydrated and collected in high purity. Hence, business opportunities might be fostered by the increasing demand for technologies, e.g., the green and biobased solvent sector, that require product dehydration and by the growth of industries such as food, beverages, pharma, chemicals, and fragrances, and in general all the niche application that produce high-value products in a relatively small amount.

As for membranes for gas separation processes, the implementation of pervaporation, and the new membranes developed in the **MEASURED** project, external **threats** might hamper the business opportunities that have been identified.

Decision-making in B2B markets might not easily facilitate the introduction of new technologies and/or the replacement of traditional processes with new ones. The development and implementation, as well as the scale-up of **MEASURED** technology in pervaporation, can also be slowed down by external crises and geopolitical instability that affect resource allocation and availability.

Political and economic scenarios also determine the price of fossil versus renewable resources, which has a direct effect on the potential for market penetration of new products and alternative technologies. To reach business maturity and technology readiness, the developed membranes should be produced and demonstrated at an industrial scale, and their performance tested and evaluated in real conditions. The lack of facilities and capacity to execute such activities, and to identify the potential risks and mitigation strategies that might arise from a large-scale process that operates in real conditions, is also an identified threat to business development.

3.5.3 SWOT Analysis for MEASURED’ PVDF Membrnaes in Membrane Distillation Technology Line

The last SWOT analysis is presented for the membrane distillation (MD) business case. MD sustains several **strengths** compared to current, competitive separation technologies such as distillation and reverse osmosis. MD-based processes are more efficient in terms of resources and energy, in fact, MD operates at lower temperatures than distillation, while compared to reverse osmosis yields products, i.e. water from desalinization, in higher purity in a lower number of separation steps, reducing the actual amount of waste that is generated after the process and that requires disposal or further treatment.

Thus, MD should lead to a reduction of the operational costs of the processes. another strength is indeed the possibility of combining MD with the current separation processes to afford in a sequential process a higher purity product in a lower number of steps and operational time.

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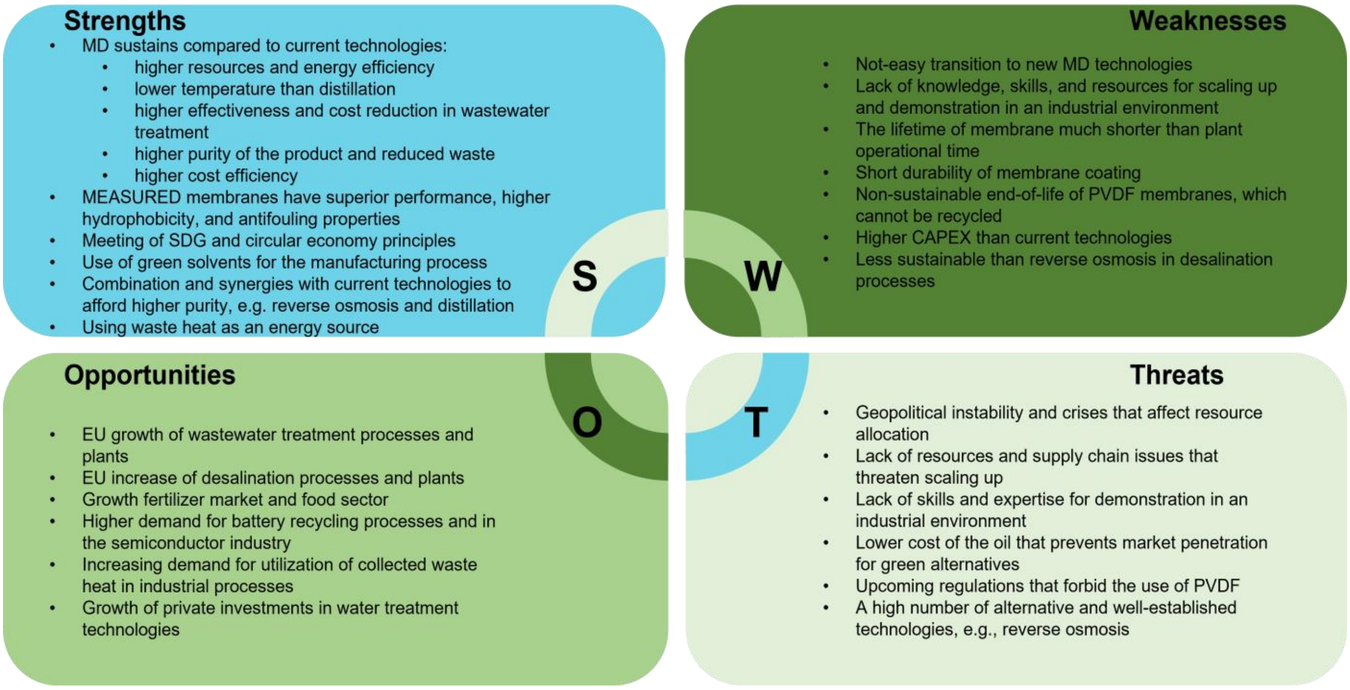

Figure 24: SWOT Analysis for Membrane Distillation

Membranes developed in the **MEASURED** project have also strengths compared to currently available membranes, they have superior performance and a more hydrophobic surface area that prevents fouling from occurring, hence, ensuring a longer service lifetime.

MD has the potential to reduce the material required and the emission of carbon dioxide related to separation processes. Although it requires more energy than current technologies, one of its strengths is the possibility of being implemented in processes and plants where there is a recovery and need for utilization of waste heat. Moreover, having higher applicability in water purification MD is a technology that meets and contributes to the sustainable development goals (SDG), above all goal n. 6: Ensure availability and sustainable management of water and sanitation for all.

Despite its strengths, **weaknesses** have been identified for the implementation and transition to MD technologies. Currently, MD is less sustainable than distillation and reverse osmosis, especially in desalinization, and has higher capital costs.

Although – as stated above – the combination of these technologies might have a better outcome in terms of both product quality and efficiency of the process. The shorter lifetime of the membrane than the plant's operational time has also been identified as a weakness, therefore, replacements of the membrane should occur several times during the service life of the plant. Another pitfall is related to the material currently utilized for the manufacturing of the membranes: PVDF is a not recyclable polymer and therefore does not enable circularity of the process.

Potential business **opportunities** for MD are fostered by new market trends, sector growth, and changes in regulations. At the EU level, there is a growth in technology demand for wastewater treatment and desalinization to afford and guarantee clean water availability.

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Besides regulations and research activities funded and supported by EU programs, significant growth has also been observed in private investments in technologies for wastewater treatment creating new business opportunities.

Moreover, new market sectors are expanding, such as battery recycling and the semiconductor industry, that require technologies for their wastewater purification and MD has been identified as a suitable candidate for this opportunity.

The feasibility of penetrating the market and meeting such business opportunities might be prevented by external **threats**. The development and implementation, as well as the scale-up of MD can also be slowed down by external crises and geopolitical instability that affect resource allocation and availability.

Political and economic scenarios also determine the price of fossil versus renewable resources, which has a direct effect on the potential for market penetration. To reach business maturity and technology readiness, the developed membranes should be produced and demonstrated at an industrial scale.

Moreover, MD competes with a high number of well-established technologies that are applicable to analogous separation processes. Upcoming regulations that forbid the use of PVDF as a material is also a very likely threat to business development of MD.

4 MEASURED INNOVATION ECOSYSTEM

This chapter is dedicated to meticulously scrutinizing and mapping the **innovation ecosystem** that surrounds the solutions developed within **MEASURED project**, specifically in the domain of membrane technology for Pervaporation (PV), Gas Separation (GS), and Membrane Distillation (MD).

The aim of the analysis is to provide a comprehensive understanding of the innovation dynamics and contextual framework within which these technologies operate and to form the basis for the identification of the major stakeholders in this landscape, who will be thoroughly examined in the subsequent chapter (5).

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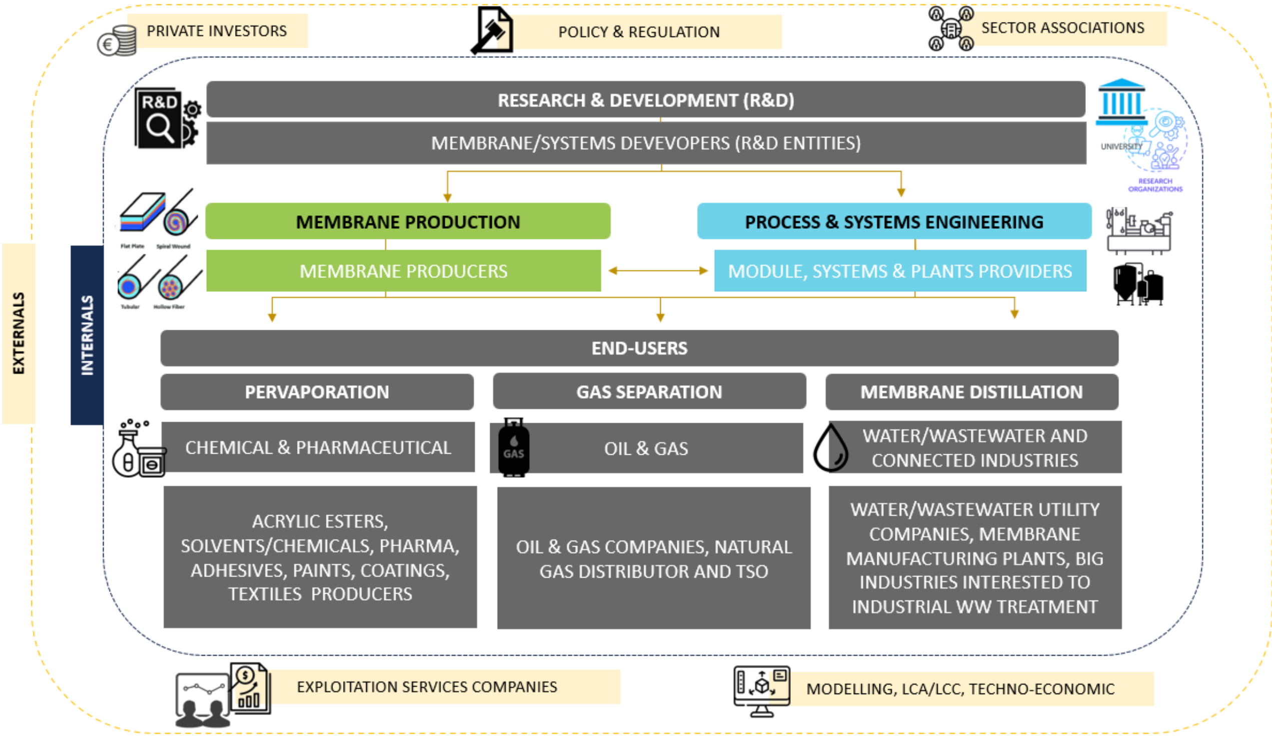

Figure 25: MEASURED Innovation Ecosystem

The examination of the innovation ecosystem is structured around **two fundamental pillars**:

the *financial perspective* and the *technological/innovation perspective*. This dual approach enables a nuanced exploration of critical aspects that shape the innovation ecosystem and consequently, the market.

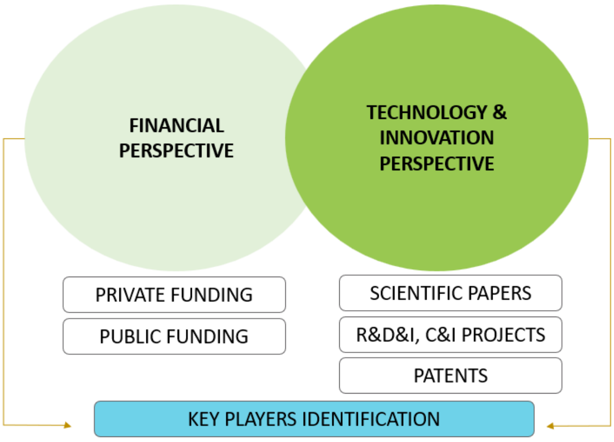

Figure 26: PNO's Innovation Ecosystem Analysis Pillars

Financial Perspective: This facet delineates the primary investment streams, encompassing both public and private funding. We delve into the intricacies of financial support mechanisms, encompassing grants, venture capital, and other key resources that underpin the development and commercialization of these technologies.

Technological/Innovation Perspective: Here, we identified pivotal trends emanating from an array of sources. The sources include scientific papers, closed and ongoing research and development projects, innovative commercial initiatives, strategic collaborations, and patenting activities. This multifaceted perspective provides an overview of the technological trajectory and innovation trends relevant to **MEASURED** project.

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By synthesizing the insights gleaned from this two-perspective analysis, we strengthen the market outlook, providing stakeholders with a deep understanding of the financial dynamics and technology landscape facing the pervaporation, gas separation and membrane distillation market.

4.1 The Financial Perspective

A funding analysis is important to understand where financial resources are coming from and how they are being allocated, if there is enough financial support related to a technology in a specific sector segment, and to understand if this technology is attracting potential investors and stakeholders.

This analysis highlights the trends in funding for membrane technology across the three business cases of the project, indicating a consistent increment in both private and public funding.

4.1.1 Private Funding

A comprehensive **two-step analysis of private funding** at European level was undertaken to provide a detailed overview of investment trends in the membrane technology sector. The analysis pursued two distinct objectives: *first*, to outline the general trend of private investments in membrane technology (all sectors), and *secondly*, to conduct a a detailed survey of the investments in the three sectors of interest for this project - gas separation, pervaporation, and membrane distillation. This analysis encompasses the period from January 2014 to December 2023 and is concentrated on specific investment operations, namely Venture Capital (VC), Merger & Acquisition (M&A), Private Equity (PE), and Initial Public Offering (IPO). While, less pertinent categories were excluded.

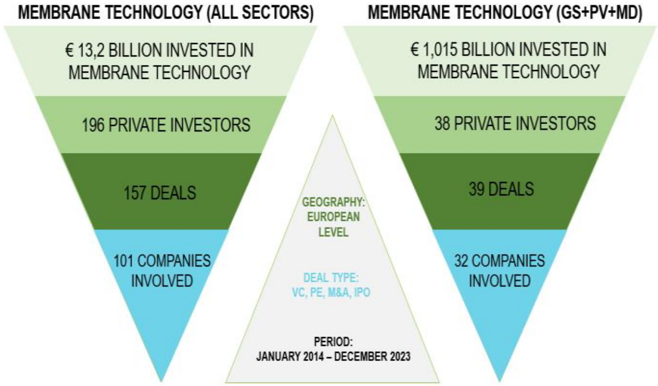

Figure 27: Two-Step Private Funding Analysis. Key Results in Membrane Technology Sector, at General Level and Insight on Gas Separation, Pervaporation and Membrane Distillation

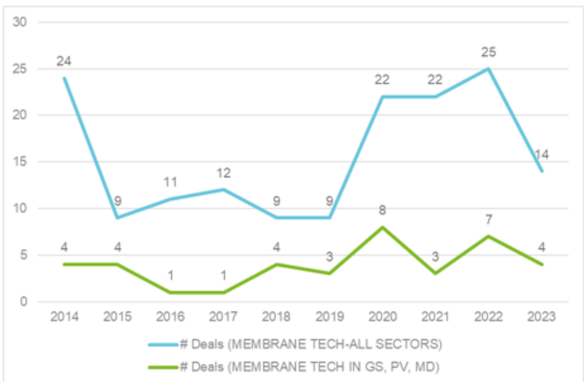

Figure 28: Number of Deals in Membrane Technology Sector, at General Level and Insight on Gas Separation, Pervaporation and Membrane Distillation

At a European scale, the membrane technology sector has been a magnet for substantial private investments over the past decade, engaging numerous primarily small and medium-sized enterprises, including startups. Notably, an aggregate of over €13 billion has been invested in 157 operations, led by 196 private investors. Of this, **€1 billion has been invested in companies operating in the gas separation, pervaporation, and membrane distillation sectors, distributed across 39 operations facilitated by 38 private investors**. Impressively, **32% of the companies engaged in private funding operations within the last decade are situated within**

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the three MEASURED sectors. Moreover, whether examining the trajectory of private funding deals within the membrane sector broadly or within the three sectors of prime interest for **MEASURED**, a consistent pattern emerges. The overall **trend reveals a notable increase in the number of operations**, particularly noticeable from 2019 onwards, reaching **peaks in 2020** and **2022**. Particularly, the last five years have witnessed a significant surge in private investments within the membrane technology sector. In fact, during this recent timeframe, 59% of all operations were recorded when considering the sector as a whole. Furthermore, when **focusing on the three applications of primary interest (GS, PV, MD)**, an impressive **64% of private funding deals occurred within this same last five-year period**.

Within the pivotal domains of gas separation, pervaporation, and membrane distillation, a discerning observation reveals that an impressive **72% of private funding activities over the past decade pertained to venture capital investments**. Specifically, this accounts for 28 out of the total 39 operations. Additionally, 21% of the operations involved Merger & Acquisition activities, constituting 8 out of the 39 recorded (see figure below). **The abundance of venture capital investment across the three sectors indicates that there is significant investor interest in supporting and funding new businesses and startups. This suggests that the sectors are considered promising and the technology innovative, with important opportunities for growth and technological development. However, a high flow of venture capital investment can lead to increased competition within the industry and can also stimulate merger and acquisition activity, with companies seeking to consolidate their position in the market and this is evidenced by good portion of M&A transactions already closed**. Diving deeper into the realm of venture capital, we find that of the 28 operations, 16 were attributed to companies specializing in gas separation, 9 in pervaporation, and 7 in membrane distillation. It's noteworthy to mention that these figures do not sum up to the total, as certain companies operate in more than one application sector.

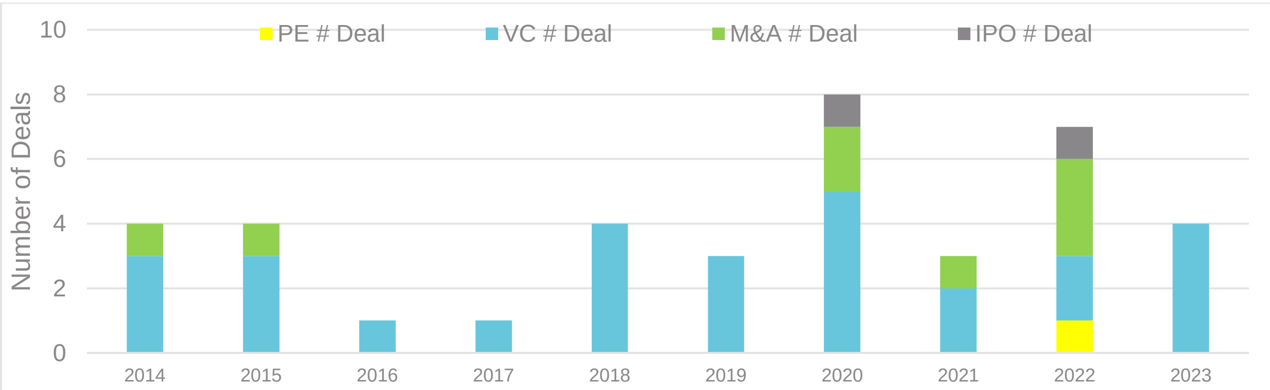

Figure 29: Number of Deals by Type in the last Decade in Membrane Technology Sector for GS, PV, MD Applications

With a single operation, the **IPO** attributed to **GVS** represents almost 50% of the total private funding in value for the three sectors, while the **private equity** fund received from **Borsig** (a company that operates on both gas separation and pervaporation) represents approximately 22% of the total capital financed in the three sectors. The remaining part of capital is distributed between Venture Capital and M&A operations. As previously mentioned, **gas separation represents the main sector in terms of number of venture capital deals but also in terms of capital raised**. **In particular, over 90% of the capital invested through venture capital funds in gas separation concerns**

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companies operating in the hydrogen purification segment. **H2Site** (€23.5 million), **Hydrogen Mem-Tech** (€17.34 million) and **Unisieve** (€9.21 million).

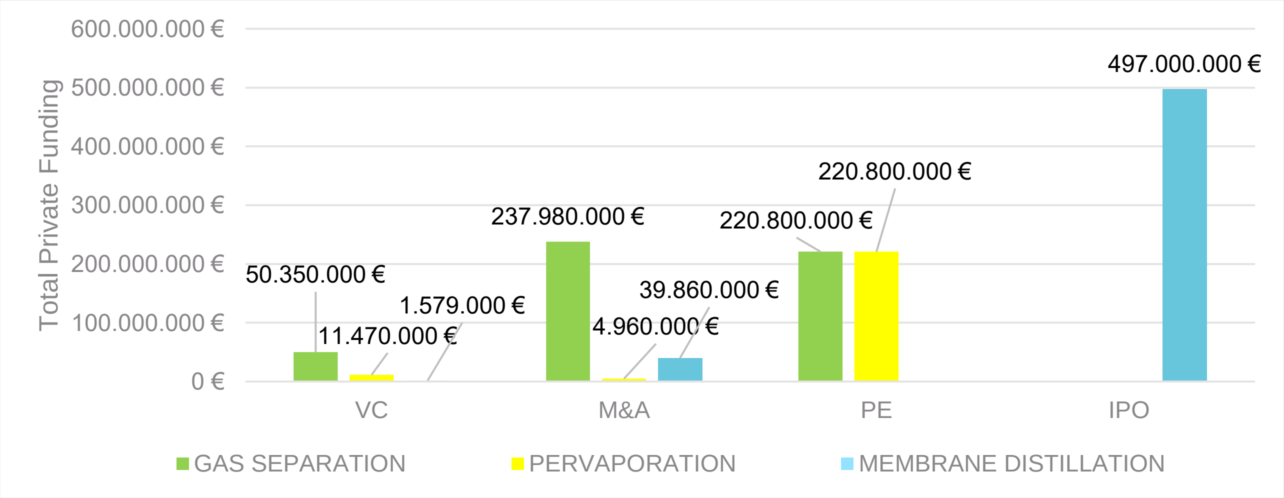

Figure 30: Private Funding Raised by Type of Deal and Sector

In general, **32 companies** were identified from the analysis of private investments **within the 3 sectors of interest**. 15 out of 32 operate in the gas separation, 12 out of 32 in pervaporation and 10 in membrane distillation sector, respectively. Only 6 companies operate in more than one sector. While, geographically they are located in central and south Europe: 6 companies have their headquarters in the Netherlands, 5 in Germany and 4 in Spain.

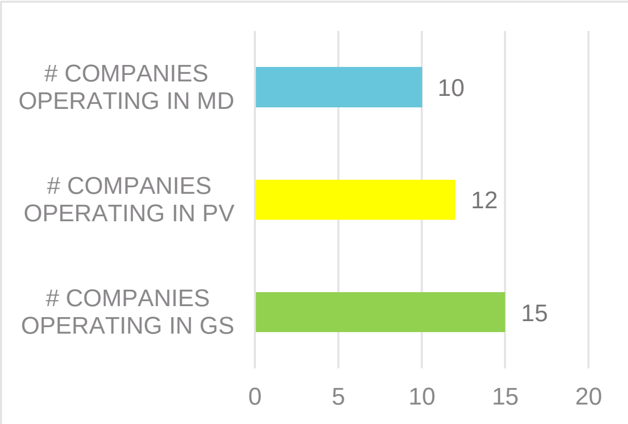

Figure 31: 32 Companies emerged from Private Funding Analysis. Map by Country's HQ and Sector Application

4.1.2 Public Funding

Public funding refers to financial support by public institutions in Research, Development, and Innovation (R&D&I) projects and in this report refers to fund projects centred on membrane technology for gas separation, pervaporation, and membrane distillation. These projects have been granted within various programs at both European and national levels.

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The following diagram provides an overview of European public funding, categorizing programs based on Technology Readiness Level (TRL) and development phase. In this analysis we used PNO's intelligence tools able to examine all the programs mapped below. Horizon 2020 and Horizon Europe, which funded **MEASURED** Project, emerged as leading EU programmes for membrane technology.

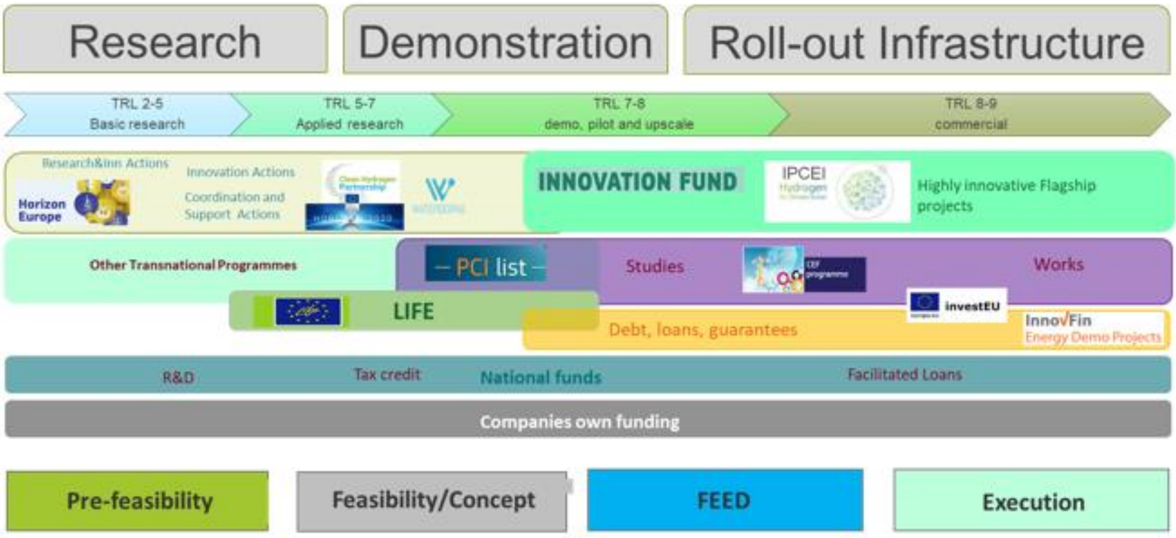

Figure 32: EU funding map sketch showing different schemes compared to TRL (Technology Readiness Levels) and stage of development.

Since 2014, an impressive €162 million has been allocated to 73 R&D&I projects dedicated to advancing membrane technology for gas separation, pervaporation, and membrane distillation. Notably, €38.2 million has been directed towards pervaporation projects, €59.7 million towards membrane distillation, and €76.5 million towards gas separation initiatives.

A significant majority, over 88%, of this public funding stems from European funds and programs. **The remaining 12% accounts for national funding programs**: Norwegian public funding contributes with 3%, while the Dutch accounts for 2%; the remaining 7% is distributed across the action of Belgium, Czech Republic, France, Germany, Italy, Switzerland, and the United Kingdom.

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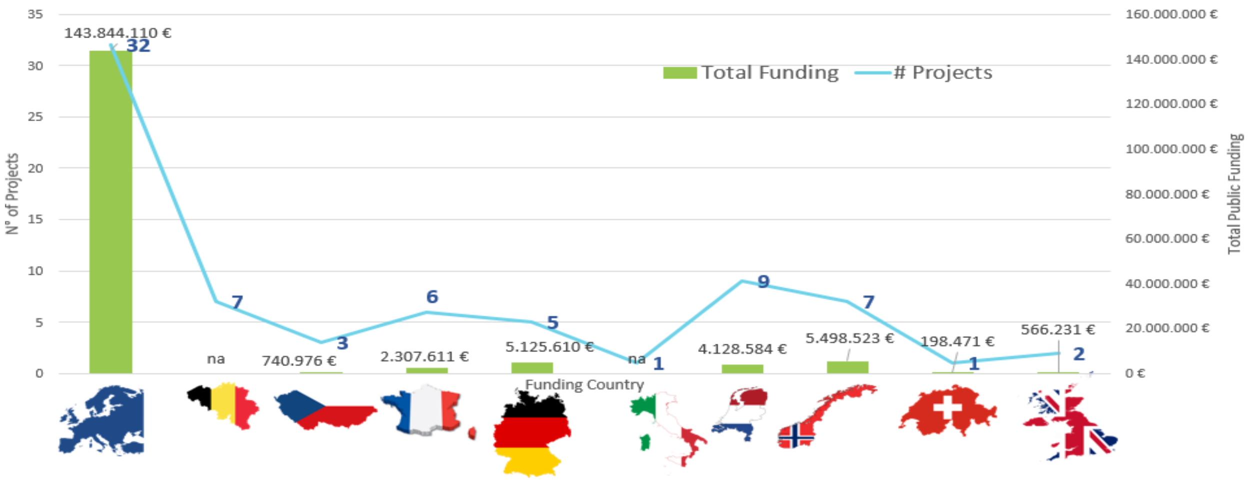

Figure 33: Public Funding in R&D&I Projects related to MEASURED Thematical Areas by Funding Country

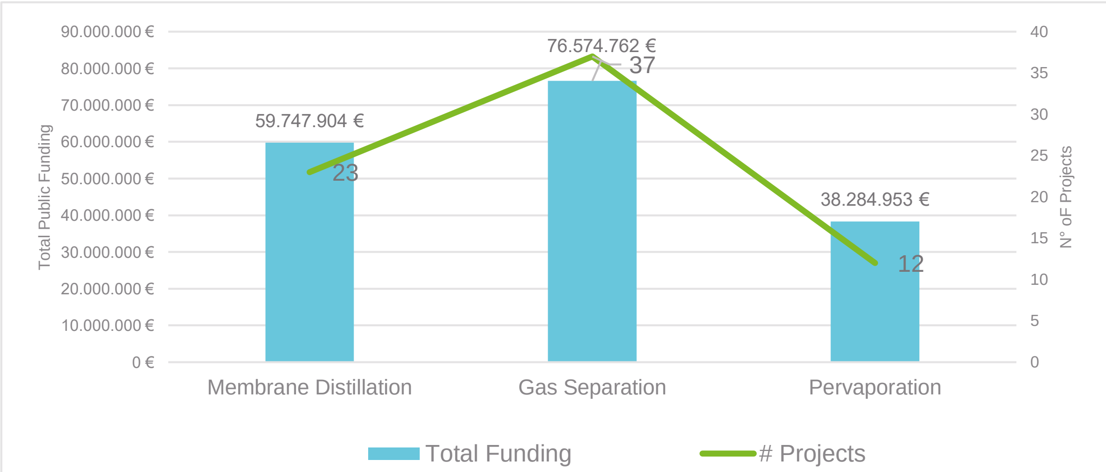

Figure 34: Public Funding per in R&D&I Projects by Sector

4.2 The Technology and Innovation Perspective

4.2.1 Innovation Benchmark and Used Tools

To gain a comprehensive view of the technological and innovation landscape around **MEASURED** project and assess the positioning of **MEASURED** technologies in the R&D landscape, we have undertaken an extensive analysis drawing from various sources. These sources include:

- Scientific papers;
- Ongoing and completed research and development projects;
- Innovative commercial projects and collaborative initiatives,
- Patenting activities.

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The focus of the analysis was on the development and production of membrane technologies (and related modules and systems) that are applicable to gas separation, pervaporation, and membrane distillation, excluding other possible applications. Notably, we refrained from imposing restrictions on the materials and supports considered, thus, to ensure a holist understanding of innovative trends in these sectors. This multifaceted approach discloses the intricate technological trajectory and the prevailing innovation trends that are relevant to the **MEASURED** project.

Our analysis started by gathering data from the initial benchmark provided by project's partners during the proposal and grant agreement phases. Subsequently, we adopted a mixed approach that combines the utilization of PNO intelligence tools with extensive searches of secondary public sources through desktop analysis.

4.2.2 Scientific Papers

Despite the several decades of research and development history, membrane technology stands as a distinctly modern innovation that finds widespread and new applications across various sectors. In fact, the membrane sector is overall characterized by continuous improvements and advancements respect to the state-of-the-art. Notably, within the application domains akin to those encompassed by **MEASURED**, membrane technology is gaining prominence as a compelling alternative to existing technologies and processes.

This progress is for instance demonstrated by the prolific number of scientific publications at the European level over the past decade. Since 2014, a **constant publications trend and extensive body of work composed by about 2500 publications has emerged**, encompassing the realms of gas separation, pervaporation, and membrane distillation. To delineate further, **1582 papers are focused on membrane applications in gas separation, 543 are focused on membrane distillation, and 369 are specifically addressing pervaporation**.

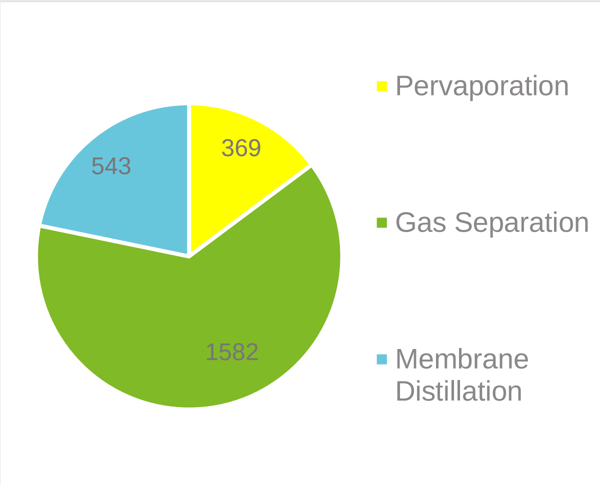

Figure 35: Number of Scientific Papers on Membrane Technology in GS, PV, MD in the Last Decade in Europe

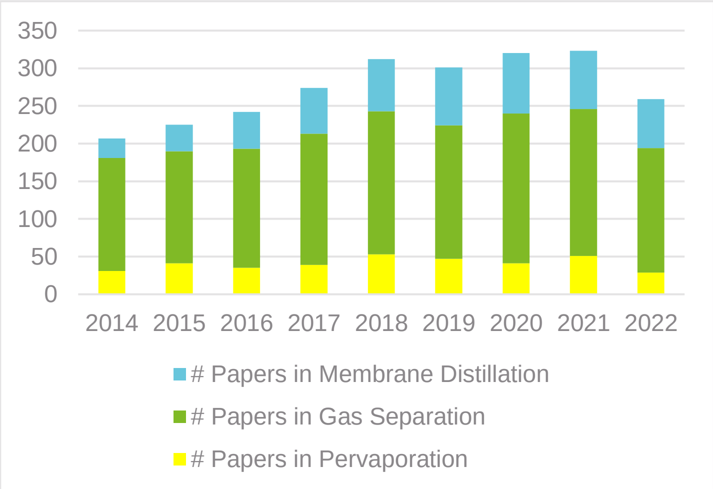

Figure 36: Scientific Papers Trend by Year and Sector

The detailed examination presented in the heatmaps below uncovers both <u>shared and distinctive areas of focus within each sector</u>. Across all three sectors, scientific publications prominently center on critical disciplines including **materials science**, **process engineering**, and **chemical engineering**, as well as processes, such as **permeation**.

Pervaporation Insights: Within pervaporation, scholarly discourse predominantly focuses on key themes, notably polymers, solvent dehydration (with emphasis on ethanol and butanol), and the intricacies of the distillation process.

Membrane Distillation Insights: The membrane distillation output is significantly concentrated on topics like membrane fouling and wetting, alongside pertinent subjects related to waste management. Noteworthy applications span from desalination, reverse osmosis, and to broader wastewater treatment processes.

Gas Separation Insights: Turning attention to gas separation, the discourse primarily revolves around selectivity and permeance, examined through a rigorous technical and performance-oriented lens. Notably, polymers emerge as a preeminent membrane material type. Additionally, the reactor is approached as a holistic system that encompasses the membrane. Hydrogen and methane are the primary gases of focus.

32 Aqueous solution	29 Biochemistry	36 Butanol	219 Chemical engineering	166 Chemistry
50 Chromatography	33 Dehydration	27 Desalination	52 Distillation	38 Engineering
25 Ethanol	191 Materials science	284 Membrane	31 Membrane technology	41 Methanol
58 Organic chemistry	105 Permeation	336 Pervaporation	43 Polymer	43 Process engineering

Figure 37: Scientific Papers Heatmap (Pervaporation) by Key Topic

158 Biochemistry	129 Catalysis	836 Chemical engineering	559 Chemistry	129 Chromatography
122 Composite material	170 Engineering	128 Environmental science	592 Gas separation	250 Hydrogen
945 Materials science	1,062 Membrane	117 Membrane reactor	272 Methane	132 Nanotechnology
196 Organic chemistry	157 Permeance	303 Permeation	318 Polymer	233 Selectivity

Figure 38: Scientific Papers Heatmap (Gas Separation) by Key Topic

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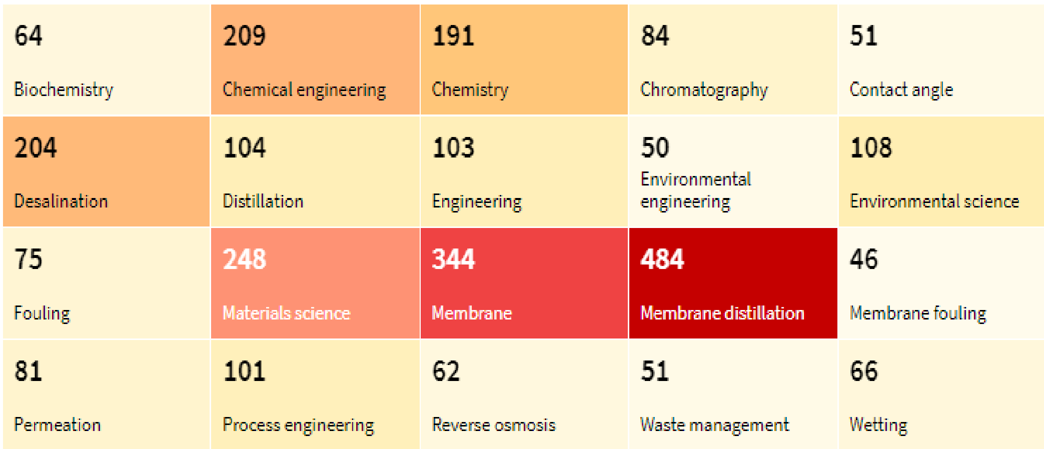

Figure 39: Scientific Papers Heatmap (Membrane Distillation) by Key Topic

The ca. 2500 scientific publications since 2014 come from 123 European stakeholders of which the 85% constitutes universities. The 29% of the total identified scientific publishers work in at least two out of three sectors, while 13 organisations work in all three sectors. This demonstrates a high proximity and interconnection between these sectors compared to membrane technology.

Considerations have to be done regarding the connection between number of papers by each sector and the country of publishers. Notably, The 37% of total papers identified on membrane distillation business case come from organisations sited in Italy and Spain, and this could be connected to the numerous presence of desalination plants in the southern Mediterranean. The 66% of total papers identified on gas separation sector come from organisations sited in the United Kingdom, Germany, Netherlands, France and Italy. This could be connected to the high number of oil & gas companies and other enterprises interested to treat the gas mixtures in these countries. Finally, concerning the pervaporation business case, the 54% of total papers identified come from entities located in United Kingdom, Belgium, Netherlands, France and Germany, probably because in these places there is the highest and consolidated presence of chemical and pharmaceutical industries.

4.2.3 R&D&I Projects

The comprehensive analysis of European public funding has unveiled a total of **73 significant Research, Development, and Innovation (R&D&I) projects** in the last decade. These projects exhibit varying concentrations across the sectors of interest. Specifically, **37 projects**, which constitute a substantial 50% of the total, are dedicated to advancements in the **gas separation membrane technology**. This result indicates the significant R&D effort on enhancing gas separation membrane processes within the European landscape. Furthermore, **membrane distillation** emerges as a pivotal focus, with **23 projects** (equivalent to 31% of the

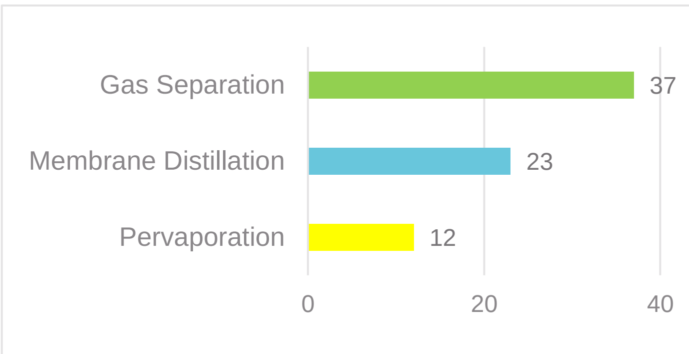

Figure 40: Number of R&D&I Projects Identified by Sector

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identified total) devoted to its advancement. This data underscores growing interest and investment in this cutting-edge membrane technology. although it is represented by a slightly lower number, **pervaporation** accounts for **12 projects**: a number that corresponds to a notable 19% of the total identified initiatives and that indicates a significant drive towards innovation and development in this specialized field.

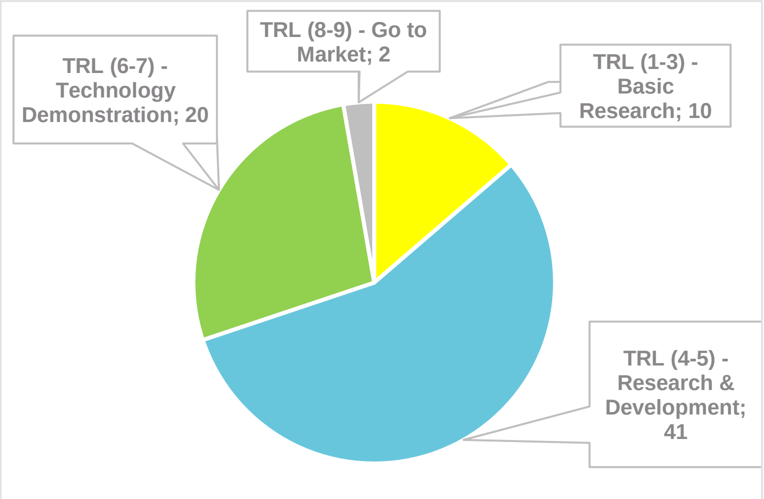

Figure 41: R&D&I Projects by TRL

Among the identified R&D&I projects, a notable **70% is associated with technologies in the early to mid-stages of development, with Technology Readiness Levels (TRL) ranging between 1 and 5**. Specifically, 10 projects are primarily focused on fundamental research, while additional 41 projects are situated in the crucial research and development phase. The remaining 30% of projects showcase a higher degree of maturity, having TRL level higher than 5. These projects have successfully demonstrated membrane technology and related systems already, within industrial settings. However, only two projects are classified as poised for market entry, representing a promising but still evolving landscape. The coexistence of numerous projects with a moderate overall TRL suggests that membrane technology is swiftly emerging as a viable solution within these sectors. Yet, time and a continued effort are still required for its widespread scalability and a successful commercialization.

Upon scrutinizing the membrane technologies employed in the identified R&D&I projects and comparing them across the three sectors of interest, a distinct pattern emerges. **Polymeric membranes** are currently, the most prevalent in the market, they **take the lead in project utilization, featuring prominently in 26 out of the 73 projects**. These membranes find application across all three business cases, with a key and prevalent application within the domain of membrane distillation. **Palladium membranes are following and exclusively employed in gas separation processes**. This category represents the second most explored membrane technology after polymeric variants, featuring in 10 projects. Moreover, in the sphere of gas separation, 8 projects delve into the development of hybrid or mixed matrix membranes. **Ceramic membranes**, on the other hand, are **primarily utilized in pervaporation processes**, showcasing their specialized application within this sector. Lastly, it is noteworthy that only 3 projects, including the **MEASURED** project, are currently focused on carbon membranes, indicating that this niche area has a promising potential.

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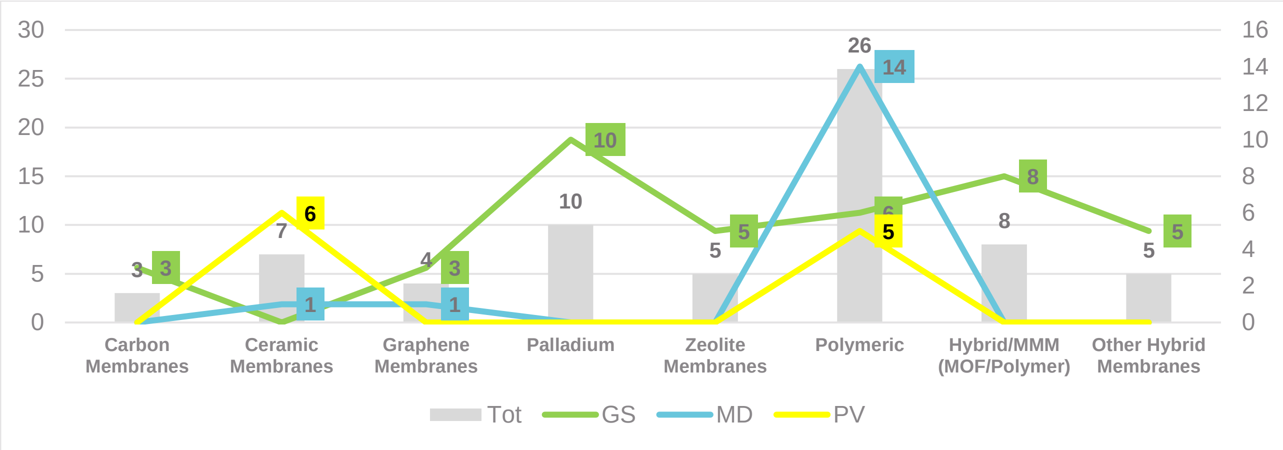

Figure 42: Number of R&D&I Projects by Type of Membrane for each Sector

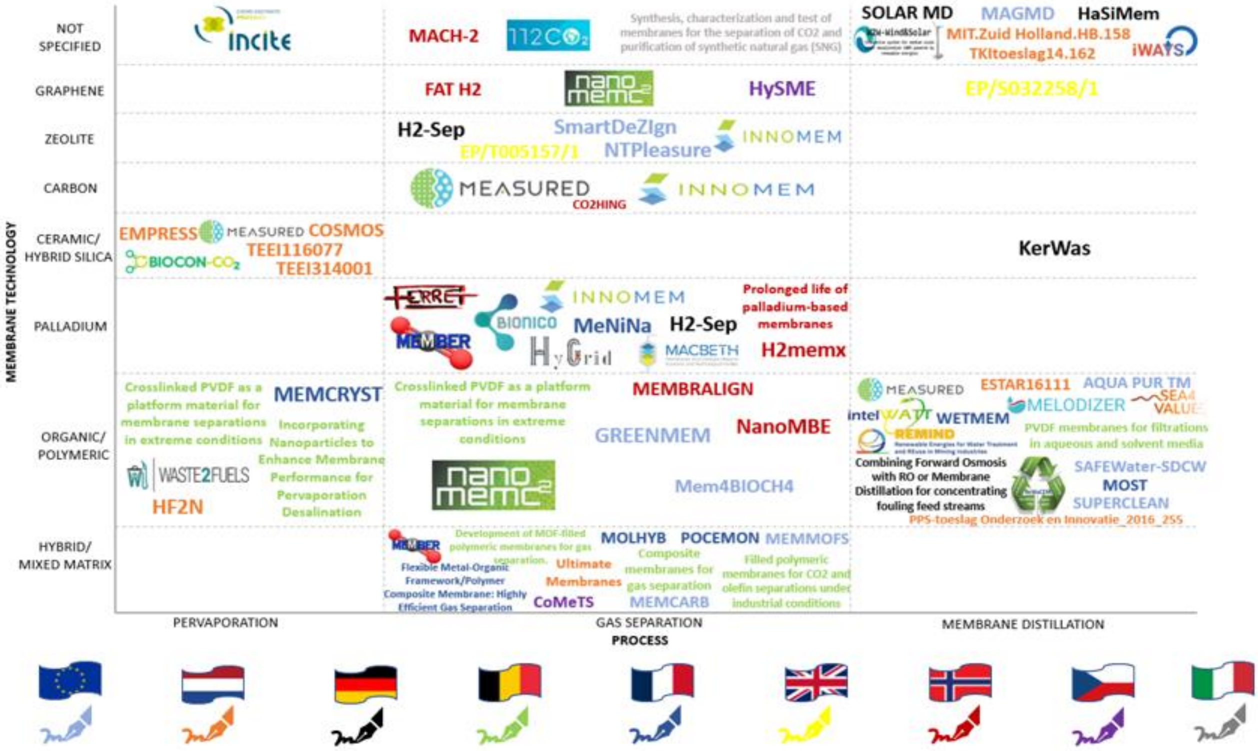

Figure 43:R&D&I Project Map by Type of Membrane and Sector

By screening the main application fields within the identified research, development and demonstration projects on membrane technologies, it emerges that:

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- In the case of **membrane distillation**, the predominant application lies in the realms of desalination and the treatment of industrial and/or urban wastewater. These projects are strategically aligned to address critical challenges in water management and environmental sustainability.
- In the realm of **pervaporation**, the projects primarily target the separation of solvents and alcohols. This application showcases a concerted effort to enhance efficiency and sustainability in chemical processing and related industries.
- In the domain of **gas separation**, a substantial portion of the identified projects is dedicated to the separation of gaseous mixture as CO_2/CH_4, CO_2/H_2, and CO_2/N_2. These projects are integral to vital processes such as hydrogen purification, natural gas sweetening, and biogas upgrading. On a broader perspective, it signifies a concerted drive towards advancing clean energy solutions.

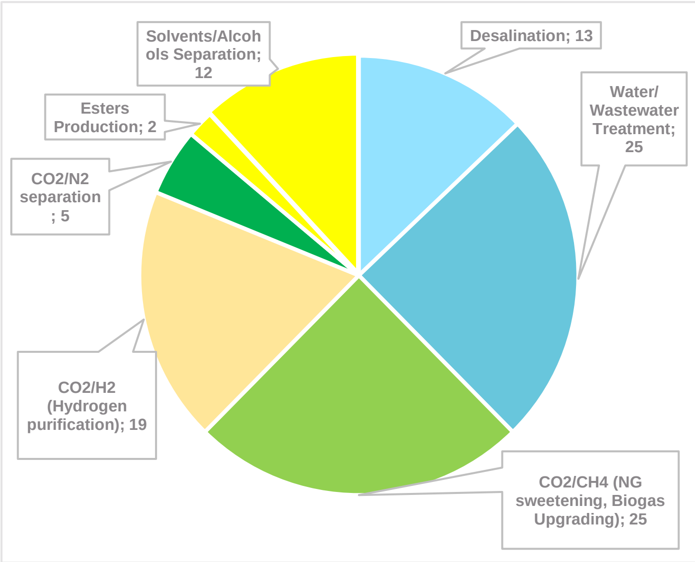

Figure 44: R&D&I Projects by Application

The extensive analysis of 73 R&D&I projects has brought to light a collective of 127 stakeholders, of which 80 from projects concerning membrane distillation, 49 those on gas separation, 21 for pervaporation and 11 are transversal to all three value chains. Several stakeholders are in the Netherlands (31), Spain (18), Germany (17), Italy (16) and France (9). A significant number of membrane and system developers emerged as well as membrane producers and potential end users of the different systems developed in **MEASURED**. **The 65% of the total stakeholders emerged belong to industrial projects**, while the remain percentage refers to R&D entities (universities and research centres), with also 4 sector associations to close the circle.

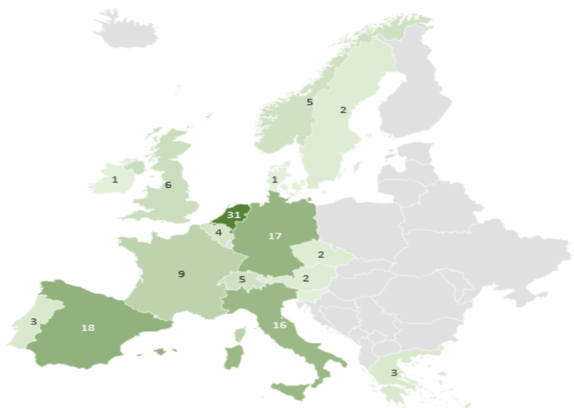

Figure 46: R&D&I Projects Participants by HQ Country

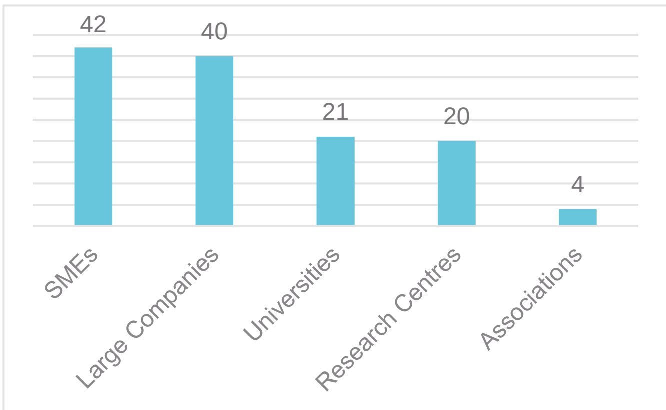

Figure 45: R&D&I Projects Participants by Type of Organisation

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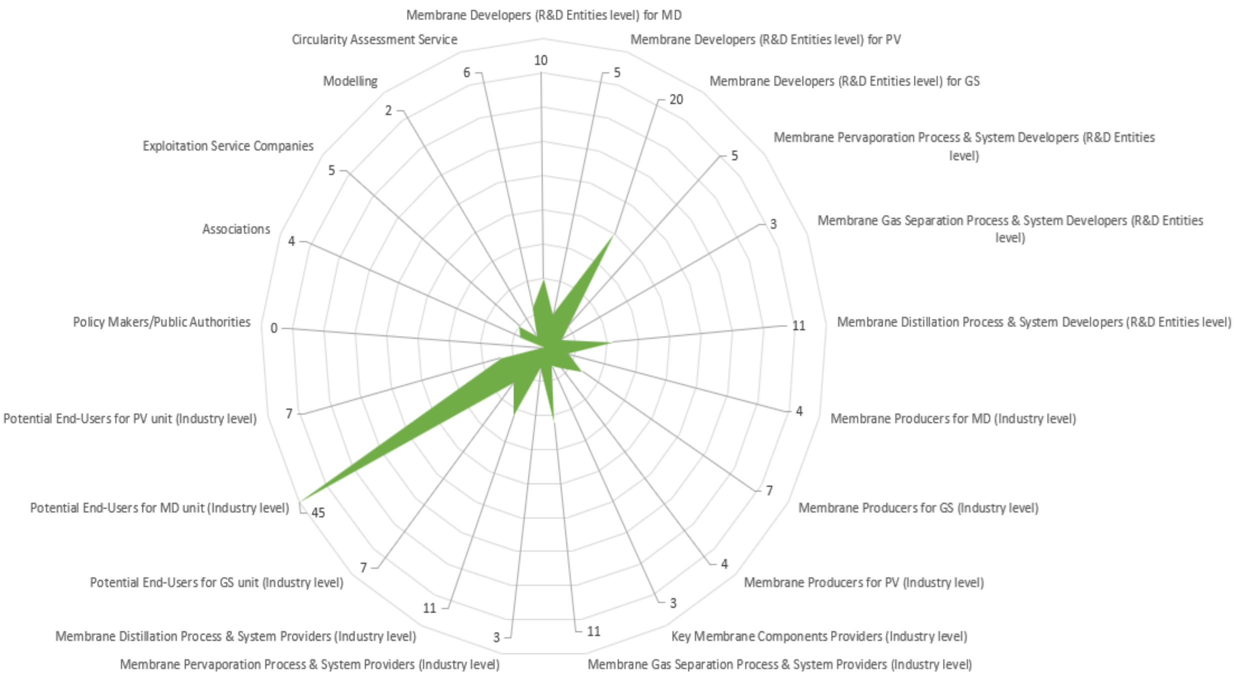

Figure 47: R&D&I Projects Participants by Role in the Value Chain

Notably, **43% of these entities have participated in more than one project and the 27% participated in more than two projects**, illustrating a **robust culture of collaboration and expertise within the European landscape of research, development, and innovation in membrane technology for these three sectors and, therefore, a well-established network of proficient partners, which will be analysed in the next chapter, at the forefront of advancements in this domain**.

4.2.4 C&I Projects

C&I projects refer to strategic collaborations and commercial partnerships specifically geared towards the development of technologies poised for scaling and commercialization. Notably, these initiatives are privately financed by the involved stakeholders, distinct from projects funded by public institutions.

A total of **6 C&I projects** have been identified, with two dedicated to each sector of interest. These initiatives represent a concerted effort to bring forth market-ready technologies in their respective domains.

From these 6 projects, **12 stakeholders are emerged**. Remarkably, **seven of these entities are based in Germany, while three have headquarter in the Netherlands**. This distribution highlights the active involvement of key players from these regions in advancing membrane technology solutions and it also confirms what emerged from the analysis of the R&D&I projects.

It is noteworthy that **seven of the identified stakeholders have, not only contributed to C&I projects but, also actively participate or have been involved in R&D&I projects**. This data indicates a synergistic approach, where stakeholders engage across a spectrum of research, development, and commercialization projects.

Specifically, for the gas separation sector the commercial projects investigate the use of **polymeric membranes in natural gas treatment and hydrogen purification**. In the case of membrane distillation, the projects are focused on **membrane module scale-up for wastewater treatment**. Finally, considering the Pervaporation sector, one project investigates the use of **ceramic membranes for organic acids dehydration** while the other project develops **polymeric membranes for ethanol dehydration**. The figure below provide an overview of the 6 C&I projects mapped according to the membrane technologies and the related application.

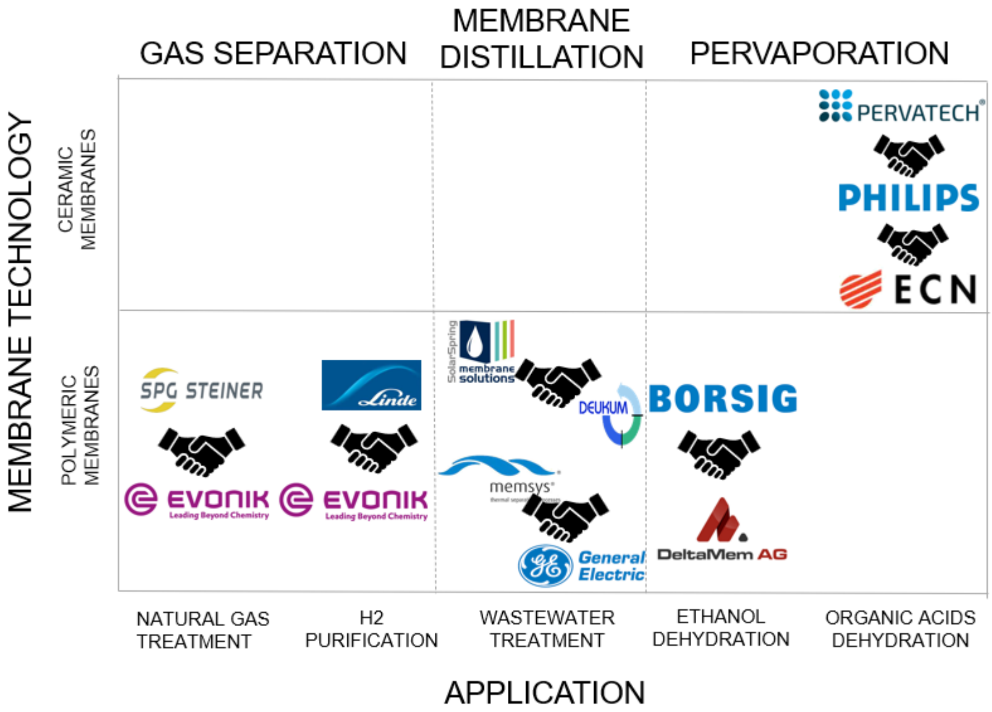

Figure 48: C&I Projects Map by Membrane Technology and Application

4.2.5 Patenting and IP Benchmark

To complete the innovation & technology mapping and benchmarking, a patent analysis has been carried out to integrate the papers and projects investigation. Consistently, the focus of the patents intelligence is on the application of membrane technology in the three sectors of interest.

The analysis has been carried on through PNO's specific intelligence tools, on a database of tens of millions of patents from a global portfolio. The queries funnel has been used in order to better address the research and to identify the most relevant patents for **MEASURED**'s sectors. The analysis started from about 3 million of documents at global level related to the membrane technology at large scale and without time limits and application sectors, then this sample has been limited to just over 1000 narrowing the focus on the application of membranes in the three sectors

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of interest, targeting the patents applicant at European scale, by grouping the patents documents by family, retaining early priority dates from 2014, and identifying a set of relevant CPCs as shown in the table below.

Table 5: Relevant CPC for the Patents Analysis based on Membrane Technology in GS, PV, MD

CPC Categories	CPC Descprition
B01D	Separation
B01D2311	Details relating to membrane separation process operations and control
B01D2313	Details relating to membrane modules or apparatus
B01D2325/027	Details relating to properties of membranes-nanoporous membranes
B01D2325/38	Details relating to properties of membranes-Hydrophobic membranes
B01D53/228	Separation of gases or vapours; Recovering vapours of volatile solvents from gases characterised by specific membranes
B01D61/36	Pervaporation; Membrane distillation; Liquid permeation
B01D61/362	Pervaporation
B01D61/3621	Separation process comprising multiple pervaporation steps
B01D61/364	Processes of separation using semi-permeable membranes in Membrane distillation
B01D61/3641	Processes of separation Comprising multiple membrane distillation steps
B01D63	Apparatus in general for separation processes using semi-permeable membranes
B01D67	Processes specially adapted for manufacturing semi-permeable membranes for separation processes or apparatus
B01D69/04	Semi-permeable membranes for separation processes-Tubular membranes
B01J19/1893	Membrane reactors
B01J19/2475	Membrane reactors
B01J2219/00907	Chemical, physical or physico-chemical processes in general; Their relevant apparatus-using membranes
B01J2219/2423	Separation means, e.g. membrane inside the reactor
B01J2219/2475	Separation means, e.g. membrane inside the reactor
B01J35/065	Catalysts, in general, characterised by their form or physical properties-membranes
B01J8/009	Membranes, e.g. feeding or removing reactants or products to or from the catalyst bed through a membrane
C01B2203/0405	Integrated processes for the production of hydrogen or synthesis gas; purification by membrane separation
C01B2203/0445	Integrated processes for the production of hydrogen or synthesis gas by selective methanation
C01B2203/1241	Integrated processes for the production of hydrogen or synthesis gas-natural gas or methane
C01B2210	Purification or separation of specific gases
C01B3	Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures containing it
C02F1/00	Treatment of water, waste water, or sewage
C02F1/447	Treatment of water, waste water, or sewage by membrane distillation (distillation and evaporation without the use of membranes
C02F1/448	Treatment of water, waste water, or sewage by pervaporation
C07C45/786	Preparation of compounds by membrane separation process, e.g. pervaporation, perstraction, reverse osmosis
Y02P20/156	Technologies relating to chemical industry-Methane [CH4]
Y10S48/05	Diffusion membrane for gas reaction or separation
Y10S55	Gas separation
Y10S95	Gas separation: processes

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After examining all patents obtained from the final sample, **112 relevant patents belonging to stakeholders with HQ or other subsidiaries in Europe were selected** and analysed subsequently. By distributing the most relevant patents according to the publication date, a general trend emerges that is growing and consistent with what emerged from the analysis of the projects and scientific publications.

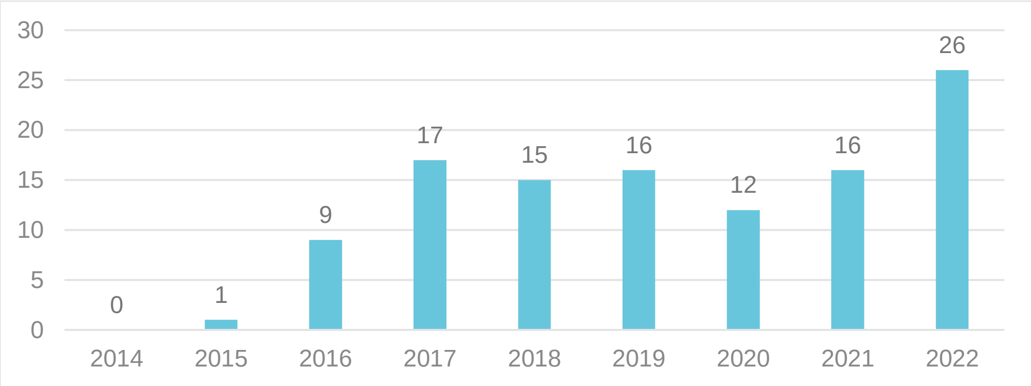

Figure 49: Most Relevant Patents on Membrane Technology in GS, PV, MD by Publication Date

Consistent with the analyses of scientific publications and projects, the analysis of the most relevant patents also shows that **gas separation is the sector with the highest number of patents**. Notably, of the 112 patents selected, **74 concern gas separation, while 21 pervaporation and 18 membrane distillation**.

These 112 patents come from an heterogeneous corpus of **63 stakeholders**, 26 large companies, 14 small and medium enterprises, 14 universities and 9 research centres. **France and Germany represent the countries with high number of identified applicants, both with 12 applicants**.

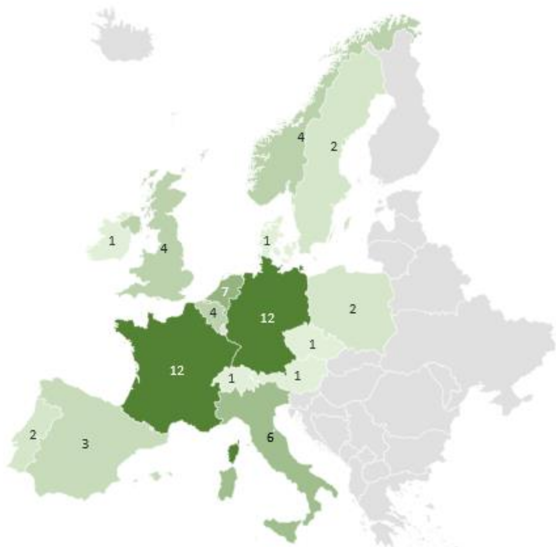

Figure 51: Map of Patents Applicants by Country

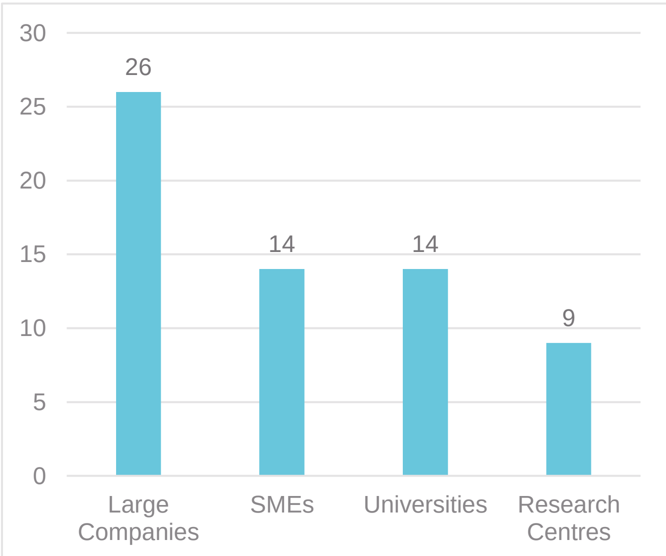

Figure 50: Patents Applicants by Type of Organisation

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Polymeric membranes represent the most considered technology with 56% of the selected patents, especially used for the membrane distillation and for gases separation in specific segments like natural gas treatment, biogas upgrading and hydrogen purification. However, it is important to notes that **new types of membranes are emerging, like carbon and zeolite based membranes**, where 30 and 20 patents have been identified respectively.

An in-depth analysis of the selected patents reveals that in the case of carbon membranes, these types of membranes are mainly applied to three type of gas separation processes: natural gas treatment, biogas upgrading and hydrogen purification. In particular, 18 out of 30 patents refer to CO or CO_2/CH_4 separation, 7 to H_2/CO_2 separation and 5 to H_2/CH_4 separation. Regarding Zeolite membranes, these are mainly used for solvents dehydration but, in 8 out of 20 patents, these membranes are used also for gas separation, in particular CO or CO_2/CH_4 separation. The same applications have been observed also in the selected patents referred to ceramic or hybrid silica membranes. Finally, all the identified patents on PVDF membranes consider membrane distillation or water filtration as application field.

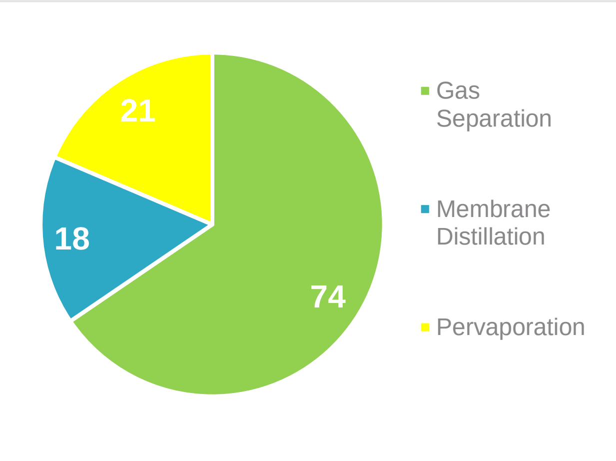

Figure 54: Relevant Selected Patents by Sector

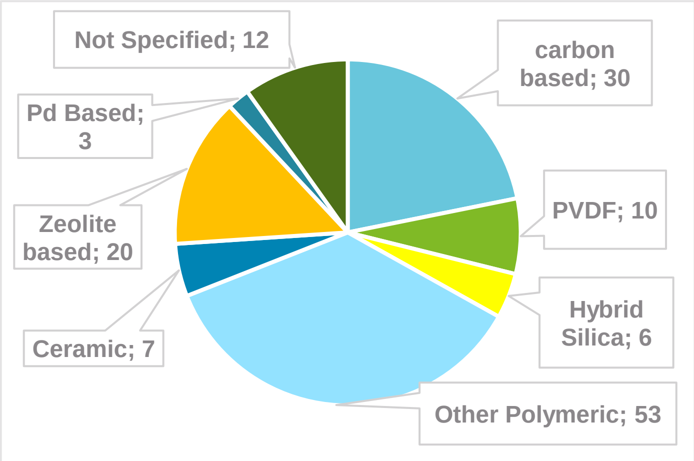

Figure 53: Relevant Selected Patents by Membrane Type

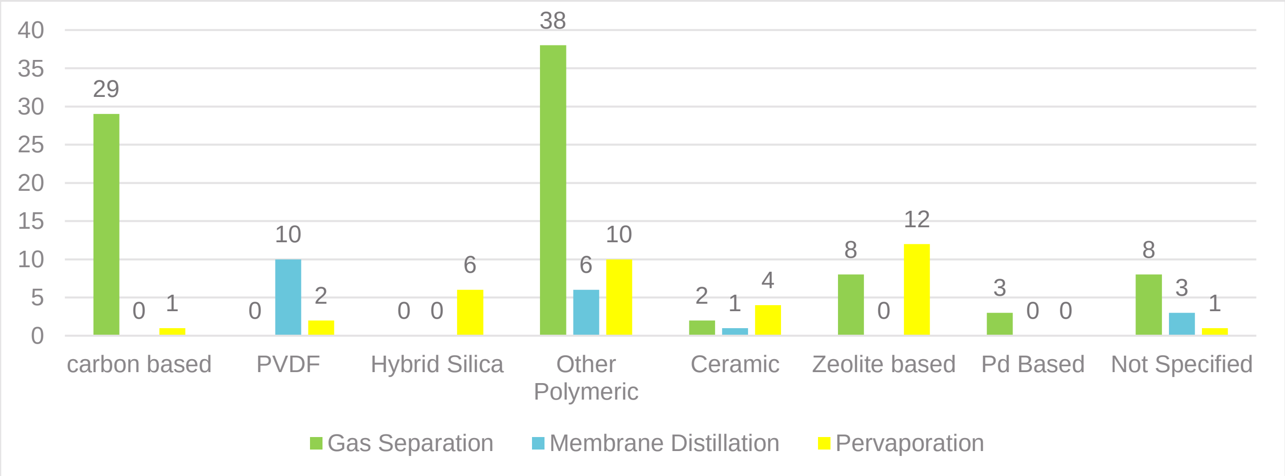

Figure 52: Relevant Patents by Type of Membrane and Sector

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Upon comprehensive examination of the most pertinent patents, a noteworthy observation emerges. out of the selected patents, **67 (constituting 60% of the total) are currently undergoing the application phase, while 45 have already been granted**. This data provides valuable insight into the dynamic landscape of the sectors of interest. The general high proportion of patents in the application phase indicates a fervent dedication to advancing membrane technology, a vigorous commitment to ongoing research and development initiatives within these sectors and that the technology is positioned in an early stage of innovation. Furthermore, Focusing on the type of membranes, we observe that in more extreme cases, such as for palladium membranes, carbon membranes and ceramic membranes, the percentage of patents in the application phase even rises to 67%, 68% and 72% respectively. However, the number of patents granted is already significant which represents an encouraging milestone and tell that the technology is moving rapidly towards an acceleration phase. It implies that membrane technology is progressively gaining validation and adhering to the established industry standards. This is already observable regarding the polymeric membranes, where the percentage of granted patents is higher than other types of membranes.

It's worth considering how this distribution is correlated with private funding trends. The prevalence of patents in the application phase reflects a surge in venture capital investments, signifying a collective belief in the potential of these technologies.

Figure 55: Correlation between Private Investments and Innovation (Patents) (Source: GlobalData)

5 KEY STAKEHOLDERS ANALYSIS AND CLUSTERING

The primary objective of this chapter is to provide a detailed insight of the key stakeholders identified through in-depth market outlook and innovation analysis in the field of membrane technology. The focus will be on the three areas of interest in the **MEASURED** project: gas separation, pervaporation, and membrane distillation.

On one hand, we will assess the positioning of these stakeholders along the various stages of the value chains, taking into account their involvement in projects, scientific publications, and patents.

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Gender equality will also be considered to ensure an inclusive and diversified perspective. A holistic view will be offered, intertwining innovation capabilities and investment capacity. On the other hand, a detailed examination of potential competitors and end-users will be conducted based on the project's outcomes.

The mapping and clustering of stakeholders is fundamental for effective management of relationships with all the players who populate the membrane technology landscape in gas separation, membrane distillation and pervaporation, and allows to adopt a more targeted and appropriate engagement strategy for each group of actors.

5.1 Overview and Insights

A total of **541 stakeholders** have been identified in the field of membrane technology for gas separation, pervaporation and membrane distillation.

266 out of 541 are integrated in the membrane distillation value chain, 260 in gas separation and 119 in pervaporation. Many stakeholders have interests and can be positioned in more than one value chain according to their business activities.

Three different value chains for each sector of interest have been realised and are illustrated below. Each value chain includes the R&D entities involved in the development and engineering of membrane technology and/or systems, membrane producers, systems/plants providers (including engineering, procurement and construction (EPC) companies, potential end-users and horizontal stakeholders (leading private investors, sectors associations and clusters, exploitation services companies and entities specialised in LCA/LCC, modelling and techno-economic analysis.

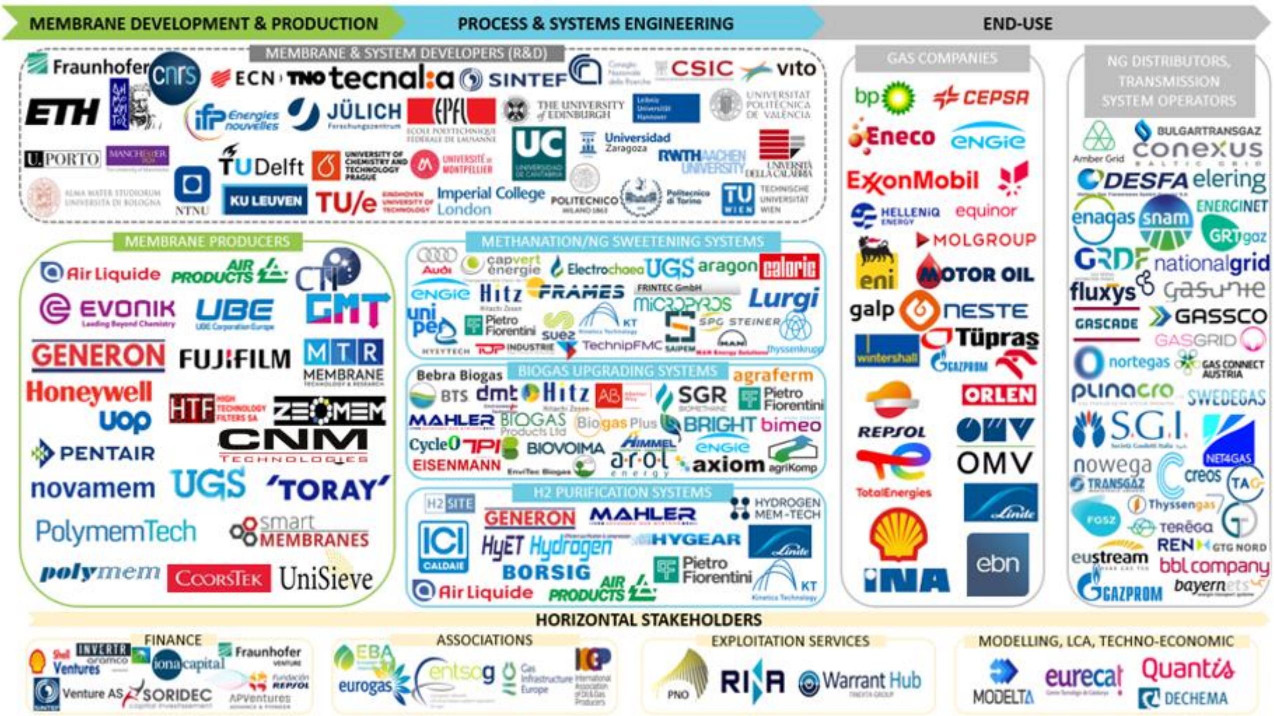

Figure 56: Gas Separation Value Chain

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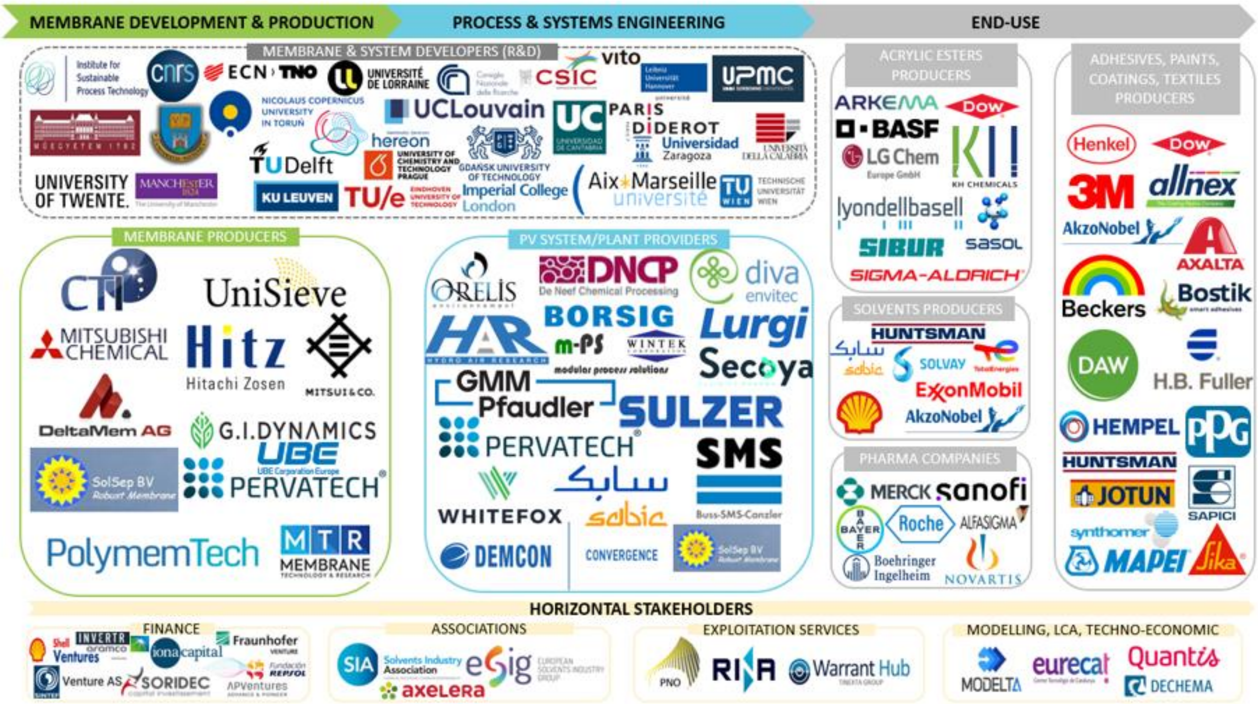

Figure 57: Pervaporation Value Chain

Figure 58: Membrane Distillation Value Chain

As can be seen, the innovation ecosystem in the field of membranes for gas separation, pervaporation and membrane distillation includes many players. Some stakeholders positioned in

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the different value chains, and illustrated above, come from market report and secondary sources analysis (284 out of 541 stakeholders), others stand out distinctively for their capacity for innovation which, in part, derives from their centrality in participation in funded public projects, the number of scientific publications released, the patents filed and the private funding received from investors such as venture capital (257 out of 541 stakeholders). Independently from the perspectives observed (market outlook or innovation) many key players at different steps of the value chains emerge. The total number of key players by their specific role in the three different value chains is illustrated in the following radar.

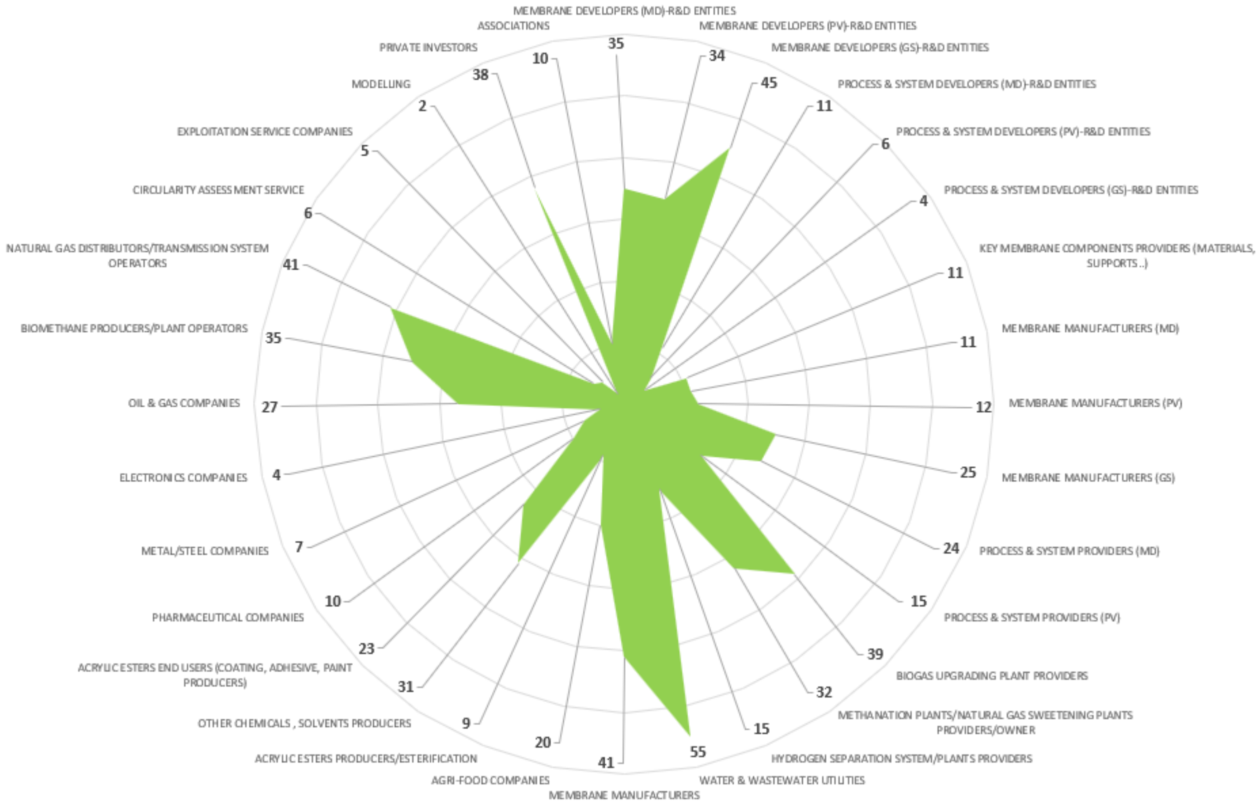

Figure 59: Value Chain Positioning Radar of Total Key Players in the Membrane Technology Landscape for GS, PV, MD

On one hand, **52% of the stakeholders have been derived from comprehensive market reports and other secondary sources pertaining to the project Outcomes**. However, **the remaining 48% holds significant value, as it has been discerningly identified through focused analyses central to the innovation process, that encompasses papers, R&D&I/C&I projects, patent portfolios, and substantial private investments**. It Is therefore appropriate to highlight those stakeholders who stand out within the different Innovation perspectives.

Among the organizations with the highest number of scientific publications on membrane technology for the three sectors of interest we find those illustrated in the figure below in which the top 5 organizations for scientific articles published by sector are highlighted.

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It is interesting to note that for example there are organizations such as **KU Leuven** that are in the top 5 position for number of papers in all three sectors. Others, like the project partner **CNR**, emerge in top 5 position in two of the three sectors, namely gas separation and membrane distillation.

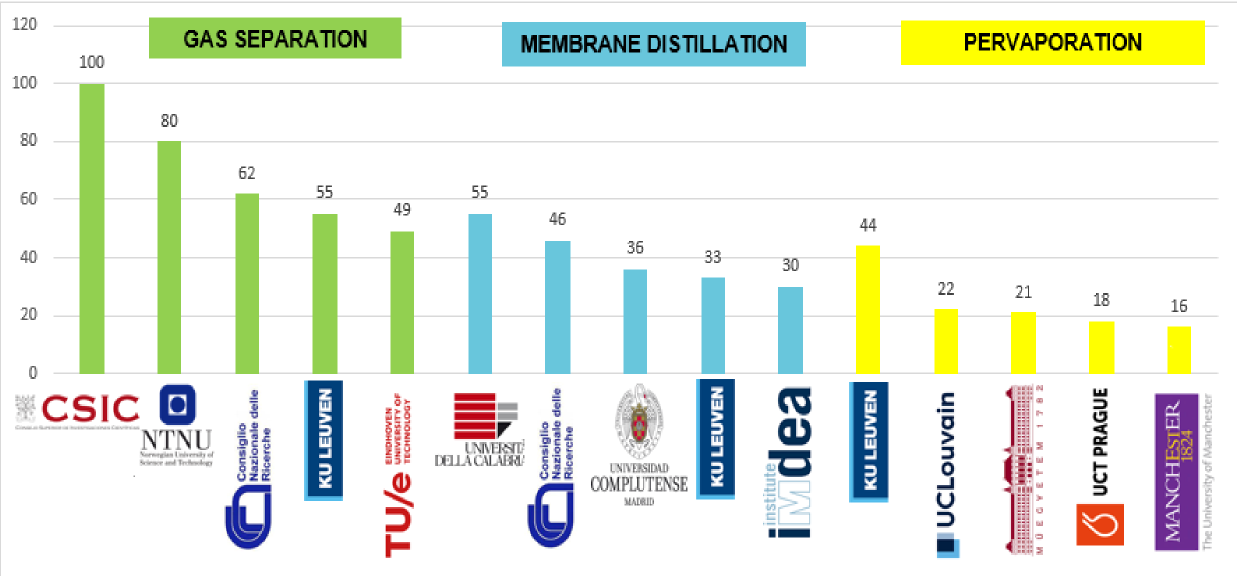

Figure 60: TOP 5 R&D&I Entities by Number of Scientific Publication on Membrane Technology per Sector

By focusing instead on public R&D&I projects financed by institutional investors, **over 30 stakeholders play a key role in research, development and innovation at a European level in membrane technology for gas separation, pervaporation and membrane distillation**. These are those key players who have the **highest number of participation in R&D&I projects** in the area of interest of the **MEASURED** project and are the key nodes of R&D&I projects collaboration network which is investigated to the end of this chapter. **KU Leuven**, which also emerged as a top organization in terms of paper publications, stands out as the organization with the highest number of funded public projects (10), followed by two large research centres, **Fraunhofer** and **Tecnalia** with 9 project participations. The company with the highest number of projects is **SolarSpring** (7) which operates in the field of membrane distillation.

It is important to highlight that **9 out of 34 top project participants are also partners of MEASURED project**, testifying to the innovativeness and centrality of **MEASURED** in the panorama of membrane technology for gas separation, pervaporation and membrane distillation. The top key players by highest number of R&D&I projects participations are mapped in the figure below.

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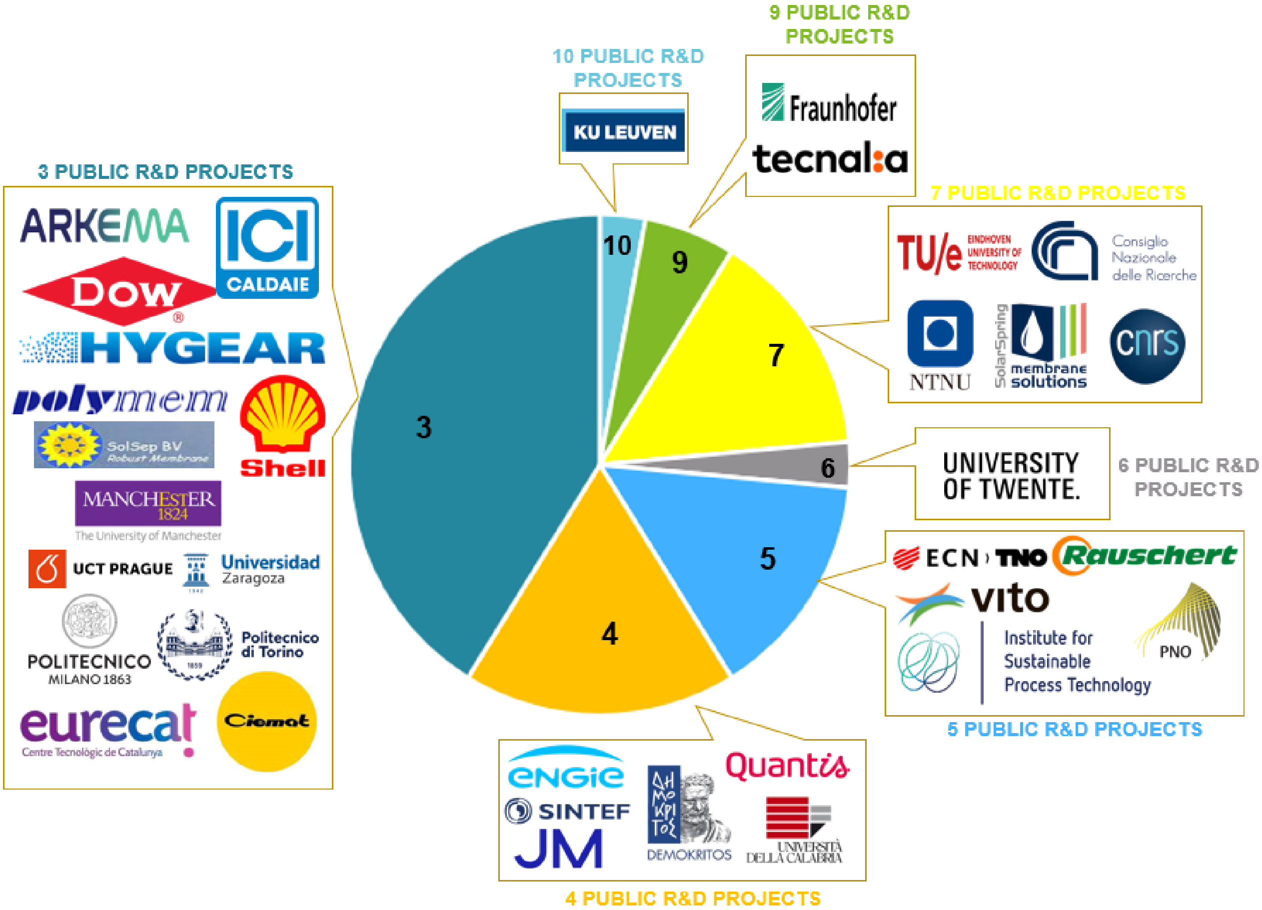

Figure 61: Stakeholders with Higher Number of R&D Projects Participations

From the patent perspective, however, 63 stakeholders emerge in Europe, of which **22 have filed more than one relevant patent** with priority dates since 2014 and 41 only one patent. 28 of the 63 applicants also participated in at least one of the 73 R&D&I funded projects, while 17 also published scientific articles.

Air liquide, **Honeywell UOP** and **Fujifilm** emerge as the top three gas separation patent applicants, with 13, 11 and 5 relevant drinks respectively. While Air Liquide has also filed some patents on carbon membranes for gas separation, Honeywell and Fujifilm focus exclusively on polymeric membranes. In the field of pervaporation, **Mitsubishi** has deposited 3 relevant patents mainly focused on zeolite membranes, while another two concern the application of zeolite or carbon-based membranes for gas separation. **Vito** is positioned as one of the most interesting patent applicants for both pervaporation and membrane distillation, with 6 patents in total focused on a various type of membranes (PVDF, polymeric in general, hybrid silica, ceramic and zeolite). Finally, regarding membrane distillation, **Abengoa** has filed two patents on PVDF membranes, while other players have only one patent in their portfolio.

The top patent applicants (more than one relevant patent identified) emerged from the analysis have been mapped in the figure below.

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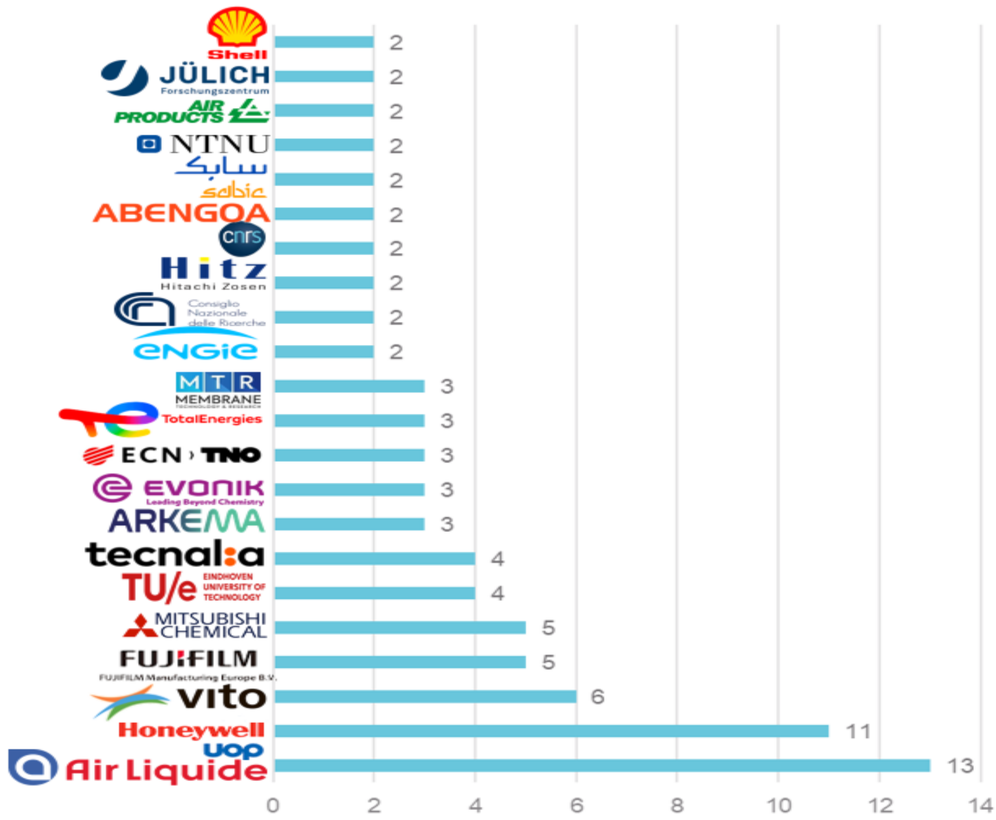

Figure 62: Patents Applicants with more than one Relevant Selected Patents on Membrane Technology for GS, PV, MD

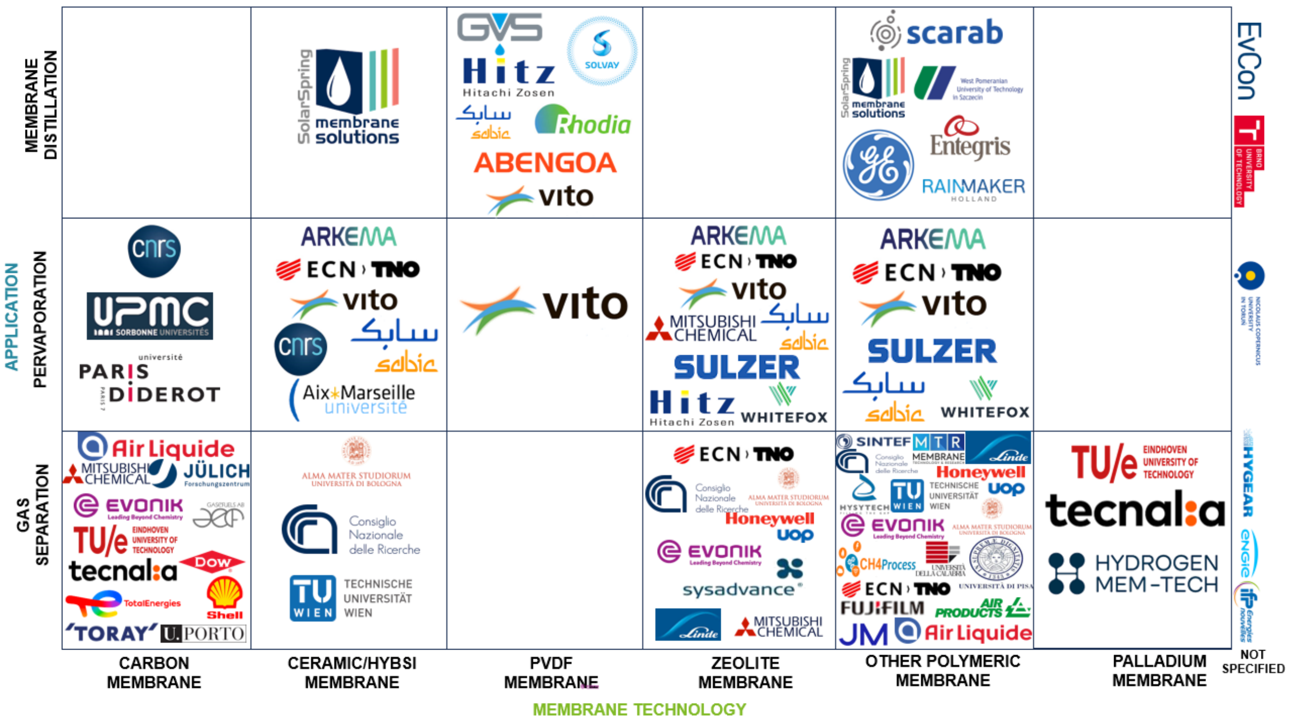

Figure 63: Patents Applicants by Type of Membrane and Application Sector

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To complete the insight into the most innovative and active key players identified in the scientific papers, projects and patents, an overview of the European stakeholders is offered in terms of private funding. **A total of 32 companies and 38 private investors emerged** from this analysis. 12 companies are involved in pervaporation process, 10 operating membrane distillation and 11 in gas separation sector. In addition, **15 out of 32 companies that have received or invested private funding also participate in R&D&I projects, 3 in C&I projects and 7 have patented technologies relating to the MEASURED sectors**.

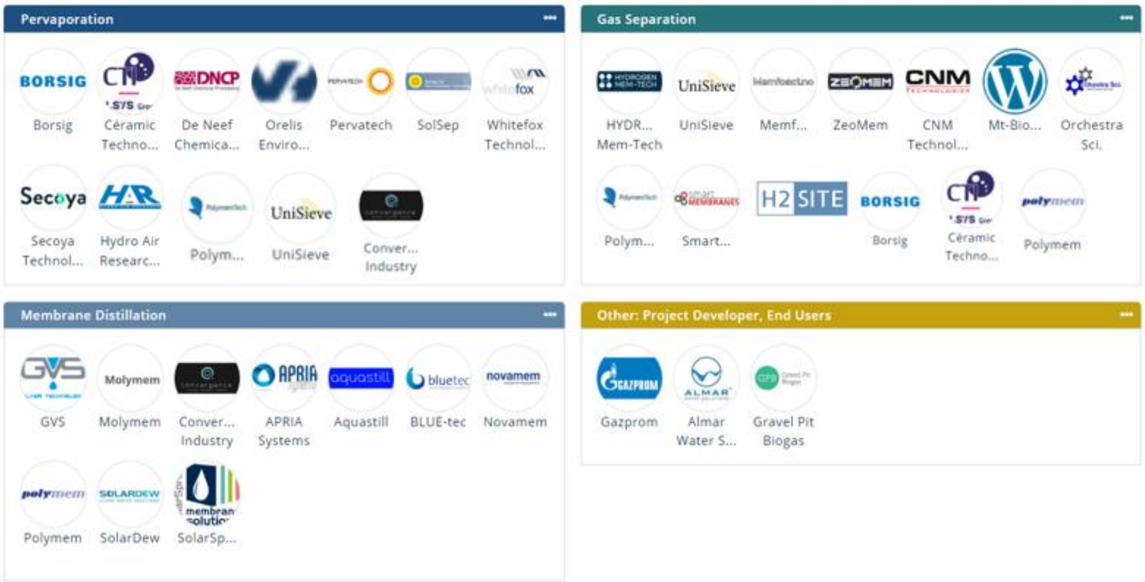

Figure 64: Key Companies emerged from Private Funding Analysis by Sector

Figure 65: Key Stakeholders form Private Funding Analysis and Comparison with Other Analyses

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In the gas separation sector, certain emerging companies such as Unisieve, Hydrogen Mem-Tech, and H2Site have successfully secured substantial capital from venture capital funds. In contrast, companies concentrated on the other two sectors of interest received comparatively lower amounts of funding. Notably, within the realm of VC investments, some funds engaged in multiple deals, contributing to the overall investment landscape, like **EIT, Fraunhofer Venture, Repsol Foundacion** and **Soridec**.

Figure 66: Key Stakeholders by Type of Private Funding

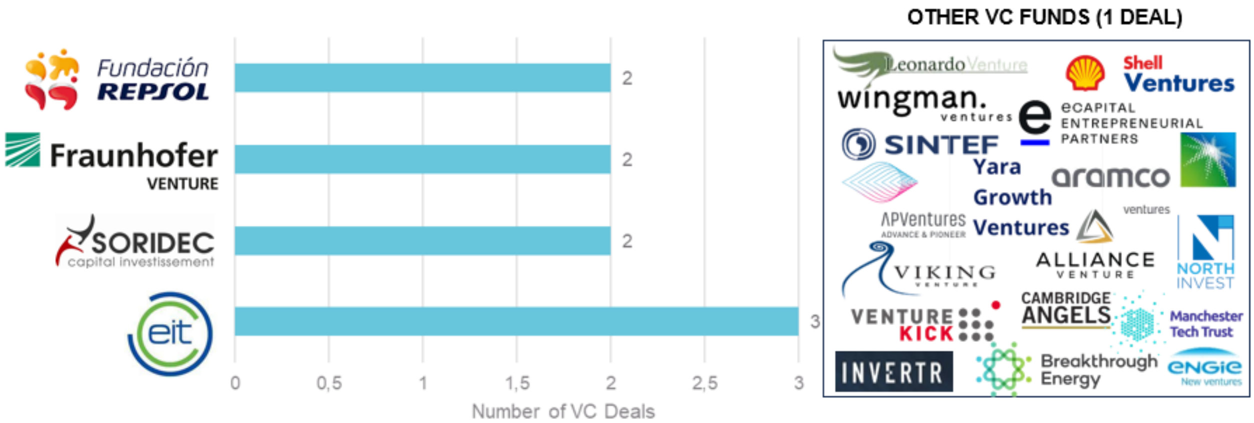

Figure 67: Top VC Investors by Number of Deals in **MEASURED**'s Membrane Technology for GS, PV, MD

5.2 Competitors and End-Users Landscape

After presenting a general overview of the stakeholders of the MEASURED innovation ecosystem, we delve deeper and map the competitors on the one hand and the potential end-users of the project's outcomes on the other.

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Since **MEASURED**'s Outcomes concern both membranes and the related separation systems, from the point of view of competitors the focus is both on membrane manufacturers and on providers of systems applicable to the three sectors of interest. From the point of view of end users, instead, a direct overview of potential customers of systems including membranes is offered.

5.2.1 Competitors insight

Over 40 membrane manufacturers with HQ in Europe or companies outside Europe but with at least one operational headquarters in Europe have been identified, of which **25 in the field of membranes for natural gas separation**, **12 related to pervaporation and 11 to membrane distillation**.

While in the case of natural gas separation there is an equal relationship between SMEs and large companies, in the case of pervaporation SMEs prevail while, on the contrary, in membrane distillation large companies are greater than SMEs.

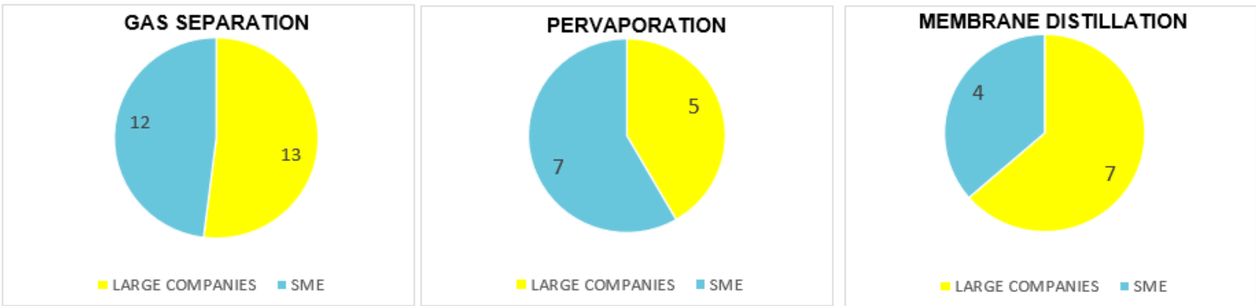

Figure 68: Membrane Manufacturers by Type in the Gas Separation, Pervaporation and Membrane Distillation

In all three sectors of interest, **Germany is the first country in terms of the number of competitors identified**.

Figure 69: Membrane Manufacturers by Country in the Gas Separation (left), Pervaporation (central) and Membrane Distillation (right)

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Almost all membrane manufacturers for gas separation mapped above are exclusively focused on polymeric membranes applied to natural gas sweetening, biogas upgrading and hydrogen purification. However, some companies such as **Air Liquide, Evonik, UBE, UGS, Air Products** and **Generon** also market polymer membranes for **other types of gas separation such as nitrogen generation or helium production**.

In the case of **membrane distillation**, most of mapped membrane producers are involved in the **PVDF membranes**, while considering the **pervaporation** membranes some players focus on **polymeric** and someone on **ceramic** or **zeolites**.

Moving on to **membrane-based system providers**, a total of **over 65 players** have been identified of which **32** constitute a large set including both **natural gas sweetening systems providers** and **providers/owners of methanation plants**, **15 provide pervaporation systems** and **24 provide membrane distillation systems**.

While in the case of natural gas separation or pervaporation there is a equal ratio between large companies and SMEs, **in the case of membrane distillation most of MD system providers are SMEs**.

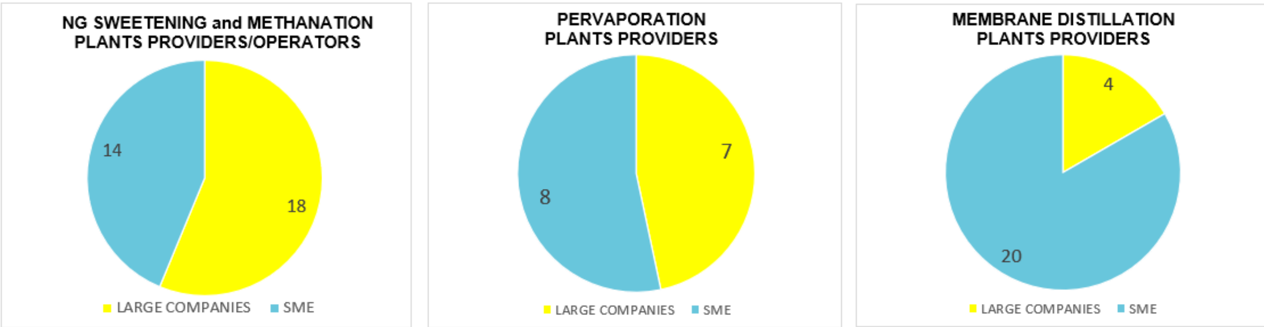

Figure 70: System Providers by Type in Natural Gas Separation, Pervaporation and Membrane Distillation

In the sector of gas separation, the 90% of NG sweeting/methanation systems providers is located three EU countries (Germany, France and Italy). Pervaporation systems providers, instead, are based mainly in Netherlands and Germany. Finally, in the case of membrane distillation, the systems providers are mainly distributed in Spain, Germany and Netherlands.

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Figure 71: System Providers in Natural Gas Separation (left), Pervaporation (central) and Membrane Distillation (right)

5.2.2 End-Users Insight

A total of 288 potential end-users for the membrane-based systems developed in **MEASURED** have been meticulously selected. Among these, 24% were pinpointed through comprehensive analyses focused on R&D&I/C&I projects, patents, and private funding. The remaining 76% were sourced from reputable secondary public sources via rigorous desktop research.

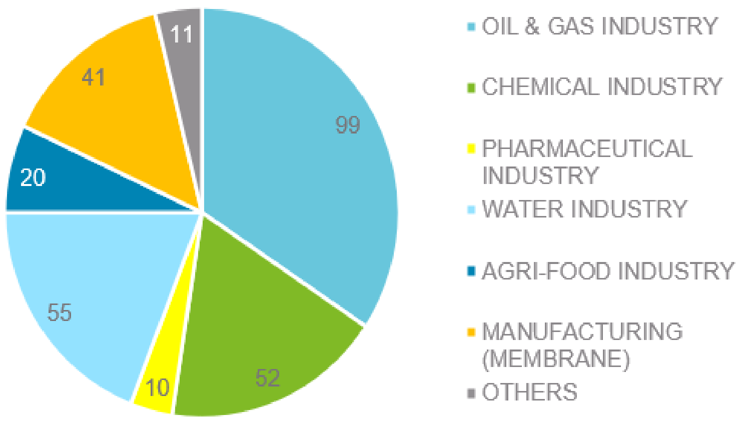

Figure 72: Industrial Classification of the Total Selected End-Users of the Membrane-based Systems developed in MEASURED project

Notably, within the oil & gas, chemical, pharmaceutical, and agrifood industries, a meticulous selection process was undertaken. This involved prioritizing companies that demonstrated a notable inclination towards or direct utilization of membrane technology and, in second moment, enlarging the set of potential customers choosing among those with the highest revenue generation in these industries.

The 52% of the total selected end users operate in the oil & gas sectors (including natural gas producers, biomethane producers and gas distributors) **and in the chemical sector** (where 9 produce acrylic esters while others are producers of other chemicals, solvents and users of acrilyc

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esters such as producers of coatings, adhesives and paints). Another **19%** of selected end-users operates in the **water industry**.

The 20% of the total selected end-users is located in Germany. Considering the first 6 countries, the 66% of the total end-users operate in the European countries with highest gross domestic product (GDP): Germany, Netherlands, Italy, United Kingdom, Spain and France.

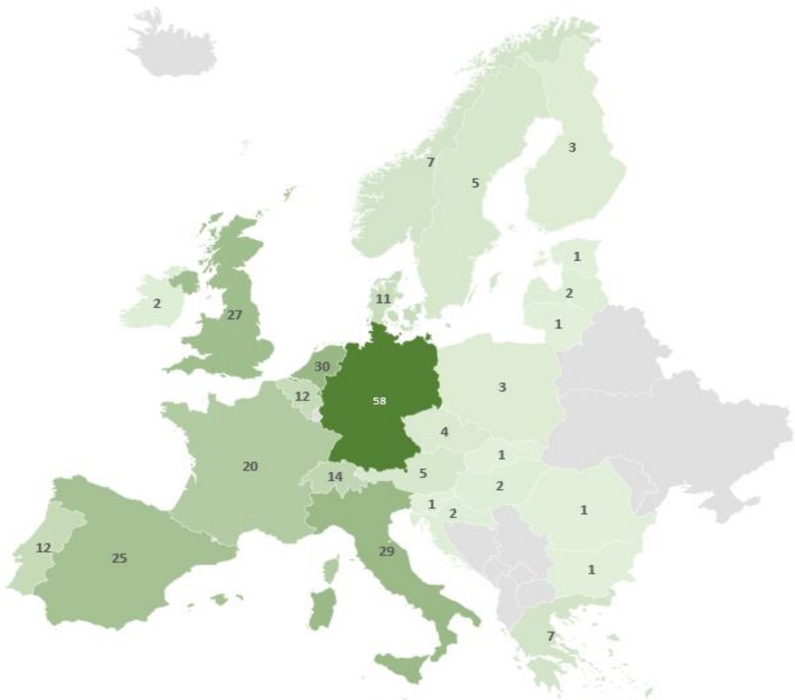

Figure 73: Selected End-Users by Country

The developed membrane distillation systems could be sold to all potential end users included in the pie and in the Figure 74, while the gas separation and pervaporation systems would primarily be targeted at oil and gas companies and chemical and pharmaceutical sectors, respectively.

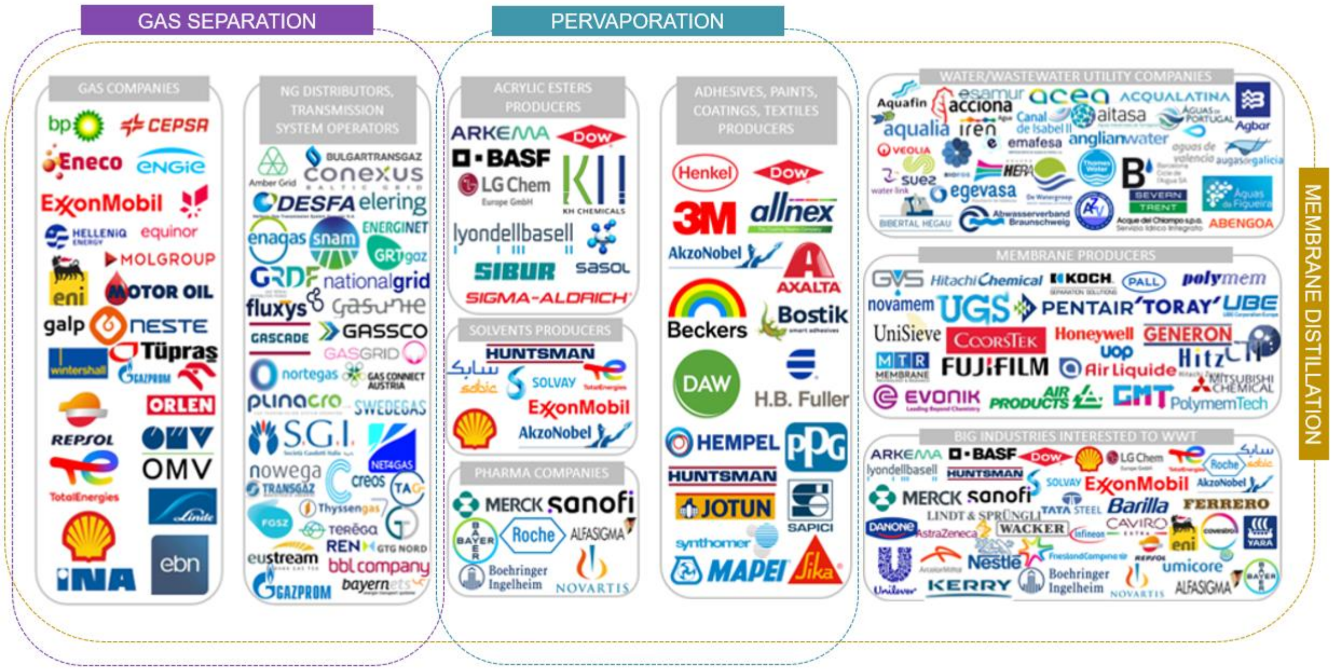

Figure 74: Overview of Potential End-Users by Sector

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5.3 Projects Collaboration Network

In Europe, research, development and innovation on membrane technology are characterized by strong cooperation between academic and industrial partners. This collaboration is based on numerous project consortia focused on this technology and which are financed at the same time by both European and national programmes.

The collaboration between different key players is so intense that the three sectors of interest of the **MEASURED** project end up intertwining and merging among them thanks to the centrality and know-how of some stakeholders on these prominent issues. **70 European stakeholders, 13% of all identified actors, collaborate with each other within R&D&I projects and create a very dense network of project collaborations** which is illustrated below.

In the map of the R&D&I project collaboration network, the academic partners are indicated by the blue (research centres) and green (universities) circles, while the industrial partners are indicated by the purple circles. The numbers inside the circles indicate the number of R&D&I project participation, while the grey connecting lines represent the connection between one partner and another, which means that they have collaborated in at least one project, but if the line becomes more marked then these partners have collaborated with each other more than once.

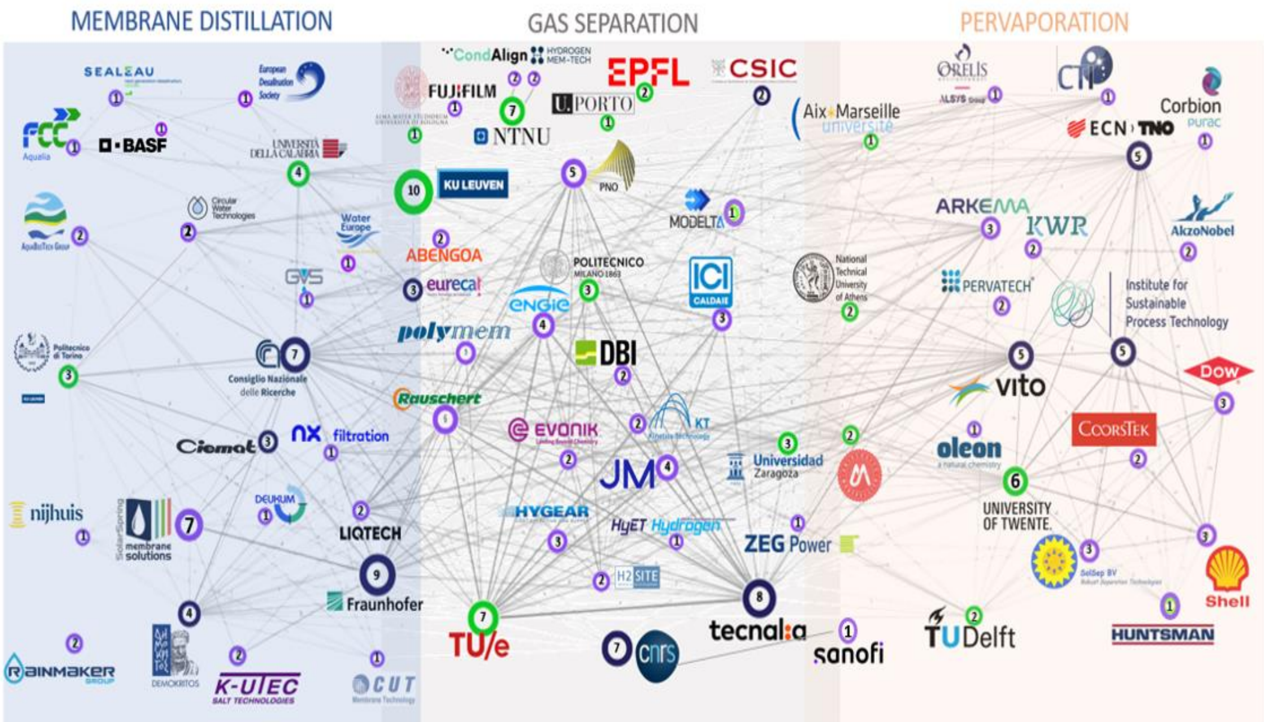

Figure 75: R&D&I Projects Collaboration Network Map

One of the most relevant aspects that can be observed from the map concerns the importance and centrality of some partners, so-called **network nodes**, on which the entire collaboration network is based. Thanks to their high expertise on many of the applications of membrane technology, these **academic institutes act as a link between projects focused on membrane distillation, those**

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on gas separation and pervaporation, literally acting as a bridge between one sector and another and allowing their unification and fusion. **The main nodes of the network are mainly made up of academic partners** such as **CNR, fraunhofer, KU Leuven, TU/e, Tecnalia, TNO, ISPT, CNRS** and **Vito**, **which is consistent with the fact that the membrane technology is still in the experimental phase and development**.

However, the presence of both large companies and many SMEs and/or startups characterized by a high number of project participations indicates the propensity for the scalability of the technology up to the prospect of future widespread commercial diffusion. The large industries with the most participations present in the network are **Engie, Arkema, Dow, Shell** and **PNO**, while some SMEs stand out for their high involvement such as **SolarSpring, Polymem, Hygear, Solsep, ICI Caldaie, Pervatech, Liqtech, Rainmaker, Hydrogen Mem- tech** and **H2Site**. **Other companies**, like **GVS**, **have recently entered the network and probably as many will follow the same path and expand the entire network of collaborations**.

5.4 Innovators from MEASURED Ecosystem

After completing the analyses described above, in this paragraph is suggested a selection of the top 55 stakeholders from the **MEASURED** ecosystem.

5.4.1 Innovation Criteria

The following criteria were taken into consideration to select and map the top stakeholders of **MEASURED** ecosystem:

A. The organisations emerged from many analyses (R&D&I projects+C&I projects+Patents +Private Funding): **SolarSpring**.
B. The organisation emerged both in C&I and R&D&I projects which have some relevant patent in their portfolio or received venture capital funding: **Evonik, TNO, Pervatech, Deltamem, Borsig, Linde, Philips Ceramics, Deukum**.
C. R&D entities emerged as top by number of scientific papers in all three sector of interest: **KU Leuven**.
D. Other R&D entities with more than 3 R&D&I projects participation which have also published scientific papers and relevant patents: **CNR, TU/e, Vito, University of Calabria, CNRS, Tecnalia, NTNU, University of Twente**.
E. R&D entities having Corporate ventures for membrane technology: **Fraunhofer, Sintef**.
F. Companies raising more than € 1 Mln in VC funding: **Secoya Technologies, Hydrogen Mem-Tech, Unisieve, H2Site**.
G. Large companies with relevant patents on carbon membranes for gas separation, ceramic membranes for pervaporation or PVDF membranes for membrane distillation: **Air Liquide, Mitsubishi Chemical, Dow, Arkema, Sabic, Shell, Total, GVS, Abengoa, Hitachi Zosen, Sulzer**.
H. Other relevant companies (among membrane producers, system/plant providers or end-users) positioned in the R&D&I projects collaboration network: **Polymem, Condalign, Rainmaker, hyet Hydrogen, Hygear, Johnson Matthey, Sanofi, KT-Kinetics, ICI Caldaie,**

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Solsep, Akzo Nobel, Huntsmann, Fujifilm, BASF, CTI, Orelis, Circular Water Technologies.

I. Other system providers received VC funds: **Whitefox, Blue-tec, Aquastill.**

5.4.2 PNO's Innovators Quadrant – Vision and Innovation Potential (VIP©)

As a wrap-up of this ecosystem's analysis, the top-55s have been choosen to populate **PNO's innovators quadrant (Vision and Innovation Potential-VIP©)**. The VIP© is a 4-quadrants matrix defined in the last 10 years. It is built in such a way to:

1) Spot noticeable companies working on a particular technology topic.
2) Evidence those key – smaller/emerging - players with a very specific knowledge on the analysis subject matter.

The analysis is qualitative but based on a quantitative weighted measurement of a mixed scoreboard. More in detail.

- **Innovation Vision and Specific Knowledge** (x-axis) – take into account both the R&D capacity in the field (including funding and IP) and a specific Affinity Index which weights the proximity to the specific project technology at the centre of the analysis

- **Investing Capacity** (y-axis) – considers the capacity and structure to invest (e.g. turnover), considering the nature of the organisation.

The organisations with growing investing capacity are positioned from the bottom to the top. Going from the left to the right instead, the organisations with increased specific domain/market knowledge and innovation capacity can be found.

Therefore, the upper quadrants define in one hand the companies interested to buy the technologies while on the other side those organisations most likely to be market incumbents/leaders. Instead, the lower quadrants show to the left the market followers and R&D experts and to the right relevant expert, technology providers or "visionaries", with most specific knowledge with respect to the analysed topic.

For the **MEASURED** case, the VIP identifies the "position" of an organisation with respect to membrane technology with applications for gas separation, pervaporation and membrane distillation.

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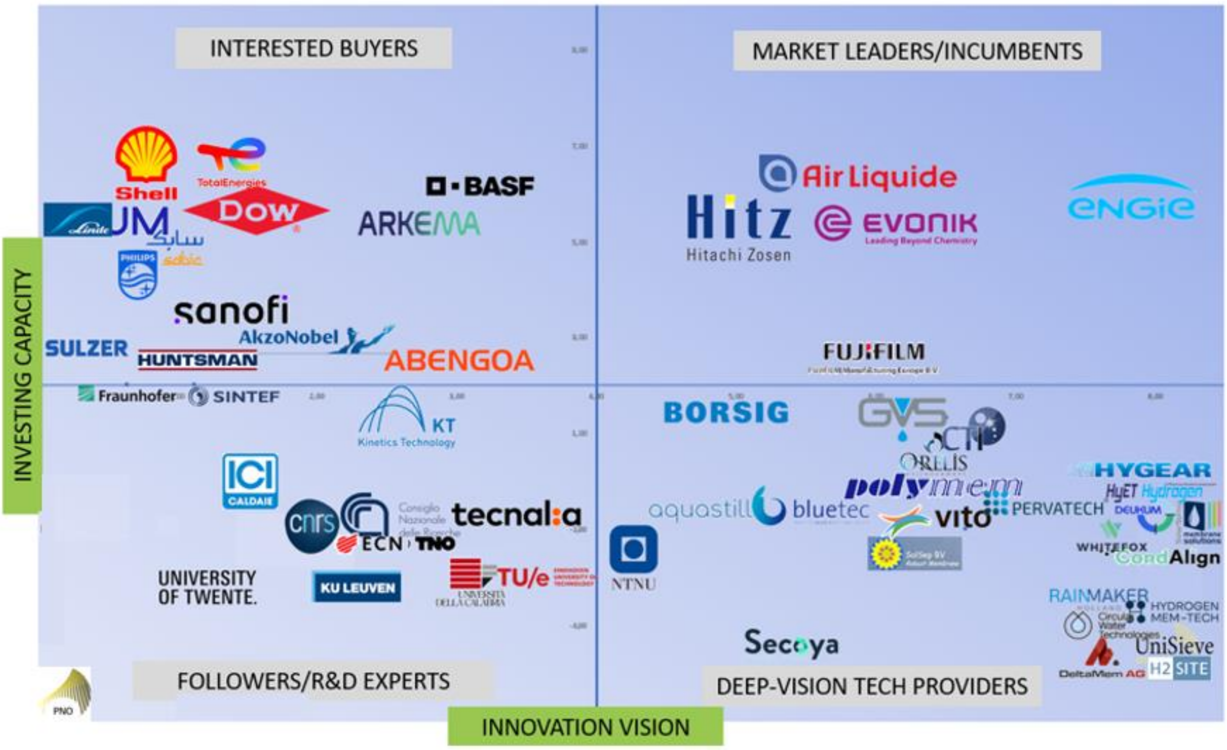

Figure 76: MEASURED VIP Quadrant

<u>The key headlines from the map are as follows</u>:

- Large companies in the chemical sector such as **BASF, DOW, AKZONOBEL, ARKEMA, HUNTSMANN**, pharmaceuticals such as **SANOFI**, water such as **ABENGOA**, oil & gas such as **SHELL, TOTAL, LINDE**, characterized by strong financial capacity are looking for innovative solutions in the field of membrane technology to improve their operations and sustainability. All these companies have been collaborating and innovating in this technological sector for some time now. Some of them, such as **ARKEMA**, are already testing or are in the process of testing innovative solutions in their systems, therefore it is likely to find them positioned among the market leaders in the future when the technology will find wide commercial diffusion. Therefore, some of these players may seek partnerships with the innovative technology providers in the lower right to exploit new ideas and solutions or also in the upper left quadrant like **SULZER** which is the biggest technology provider of pervaporation solutions in Europe.

- Established companies, such as **AIR LIQUIDE, EVONIK** and **ENGIE** currently dominate the market and have a good balance between investment and innovation. Such organizations have a large customer base and are able to influence the market. **AIR LIQUIDE**, which has R&D facilities in USA on membrane technology, began to focus on polymeric membranes but, in recent years, it is expanding its portfolio more than anyone with patents relating to carbon membranes for gas separation. **EVONIK** is following AIR LIQUIDE but with less emphasis at moment. **ENGIE** already owns and operates methanation plants where it has

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been testing membranes for a few years. **HITACHI-ZOSEN** is one of the biggest providers of methanation equipment and systems in Euorope.

- R&D experts with limited financial resources but have a solid knowledge base are clustered together and form the solid basis for future research and development collaborations in the membrane sector at European level (**CNR, TECNALIA, CNRS, TNO, KU LEUVEN, UNICAL, NTNU, UNI TWENTE**). These players are expert in all the three sector of interest for **MEASURED** and often collaborate at the same R&D&I projects on membrane technology.

- Some organizations like **KT-KINETICS** are slowly opening up to membrane innovation and future implementation. The company has also a technology R&D park in Italy where tests membrane for gas separation.

- Important research centres, such as **FRAUNHOFER** and **SINTEF**, position themselves as intermediaries between technology buyers and R&D experts since they represent two important research centres at European level equipped with corporate ventures that invest in startups in the world of membranes.

- Numerous start-ups and emerging companies with a very strong propensity for innovation and limited financial resources populate the lower right part of the quadrant. Some of the most innovative emerging companies such as **H2SITE, HYDROGEN MEM-TECH, UNISIEVE, SOLARSPRING** have attracted the interest of private capital investors (venture capital).

- Companies specializing in the research and development of advanced technologies, such as **POLYMEM, CTI, PERVATECH** and **ORELIS**, with high growth potential. These, together with **BORSIG,** and **GVS** could have great growth potential if they manage to transform their innovative ideas into successful products or services, and could follow the market leaders in the future.

5.5 Gender Perspective

A workforce's gender distribution analysis for the key stakeholders of the **MEASURED** ecosystem has been carried out in order to give an insight on the gender perspective for different type of stakeholders.

Starting from the analysis of the status quo on the gender of employees of different organizations it helps us to better understand which types of organizations will have to invest more time and resources to promote equity and inclusion, improve diversity and corporate reputation and image, and respond to regulatory changes.

In the case of **MEASURED**, the gender analysis is based on the **55% of the actors positioned in the VIP quadrant, therefore 30 key players have been selected of which 10 large companies, 10 small/medium size companies, 7 research centres and 3 universities**. For each player the

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gender analysis takes into account the **total workforce gender composition** and those related to **management and leadership positions**. The gender data have been collected from the gender equality plan of the organisations, except for the SME where their website in the team's part has been considered.

Analysing the entire sample of organisations it emerged that at **the general level of the workforce the average of male is 68% and that of females is 32%. Shifting the horizon of analysis to the positions held at management and leadership level, however, on average 74% are held by male and only 26% by women**.

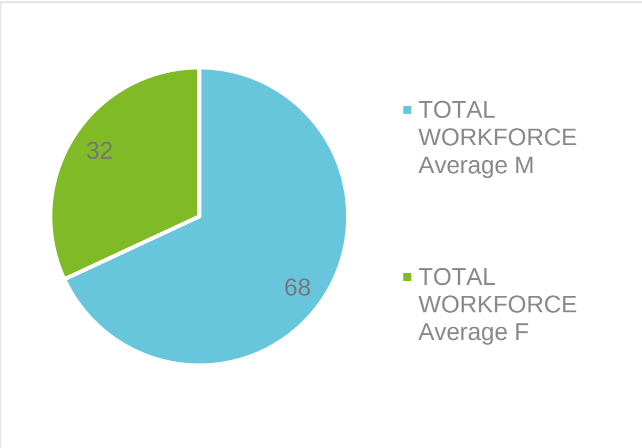

Figure 77: Average of Male and Female for the General Workforce in the MEASURED Stakeholders' Sample

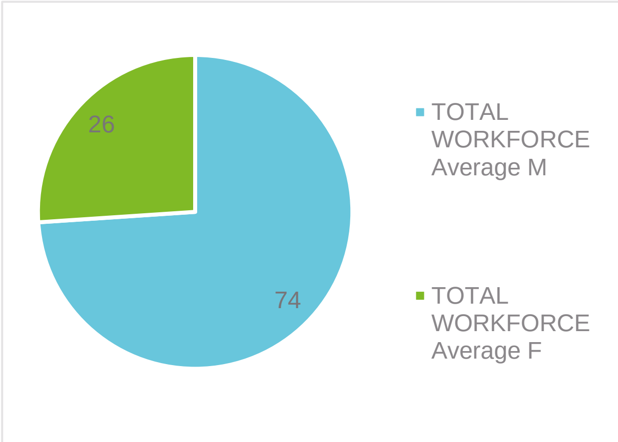

Figure 78: Average of Male and Female for the Workforce employed at Management and Leadership Level in the MEASURED Stakeholders' Sample

Noteworthy distinctions, however, are observed when we analyse the actors separately by type of organization. What emerges is that within **large companies**, the average of male **is 71% and 29% of women**. Gender distribution becomes more equal within **SMEs**, where **31% of the workforce is made up of women**. **The greatest equality, however, is observed within research centres, where on average 37% of the workforce is based on women**.

However, if at a general workforce level the average of women is higher in SMEs than in large companies, **at a managerial and leadership level** the opposite happens and that is that **the average of women in SMEs is still very low, around 22%, while 78% are male. Within universities the gender distribution in management positions is about 1:4 in favor of men**.

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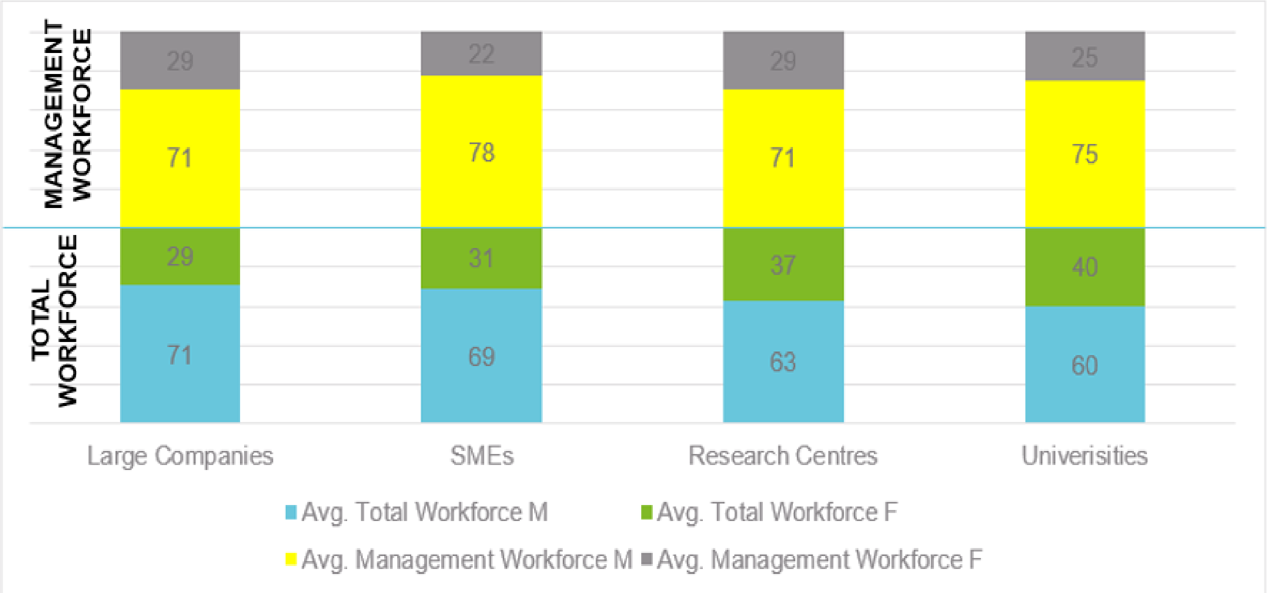

Figure 79: Total Workforce and Management Workforce by Average of Male and Female in the Four Type of Organisations in the MEASURED Stakeholders' Sample

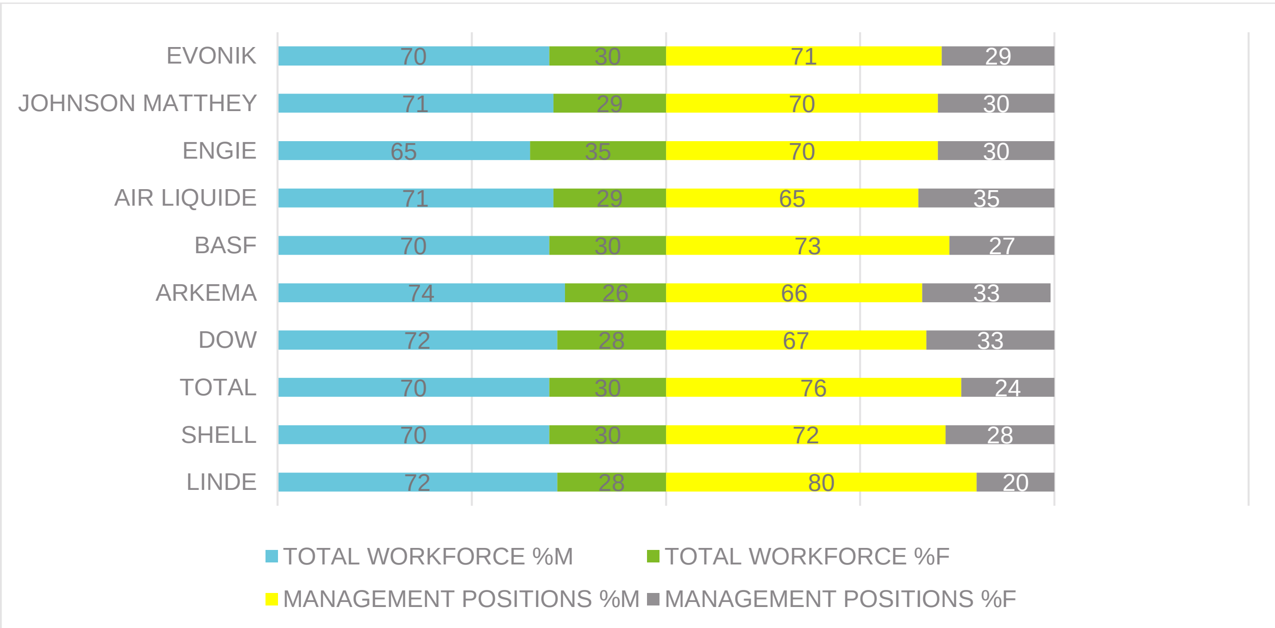

Figure 80: Total Workforce and Management Workforce by Average of Male and Female in the Large Companies of the Sample Analysed

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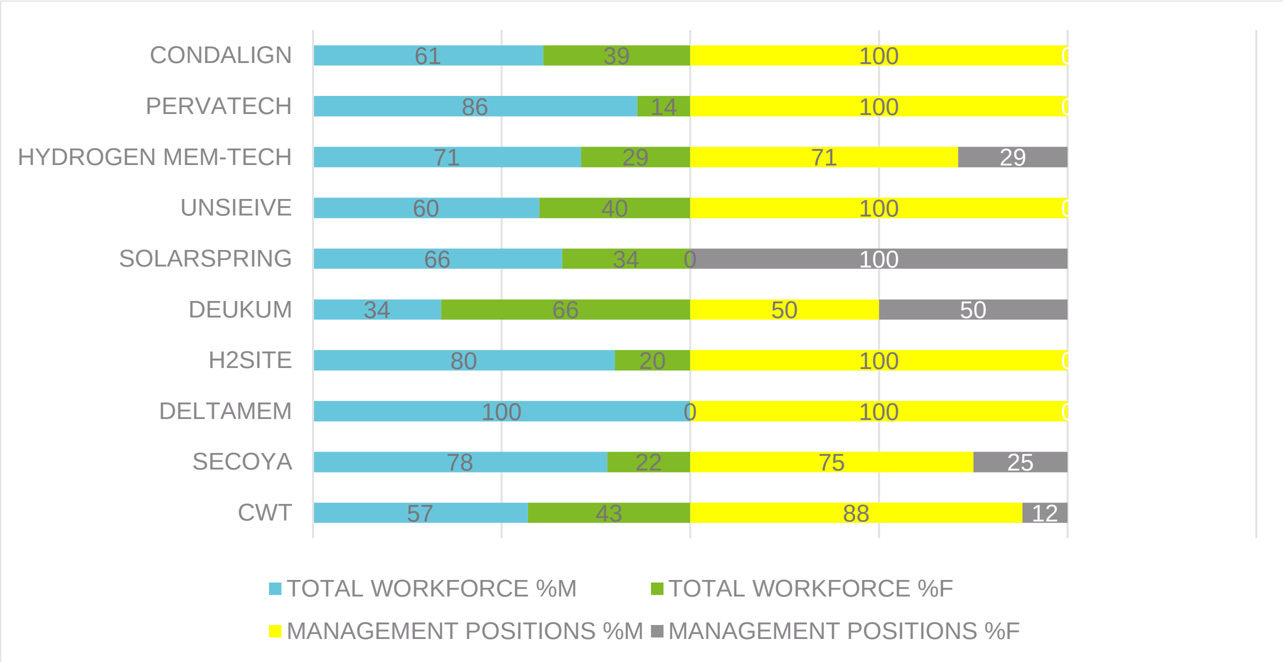

Figure 81: Total Workforce and Management Workforce by Average of Male and Female in the SMEs of the Sample Analysed

Figure 82: Total Workforce and Management Workforce by Average of Male and Female in the Research Centres of the Sample Analysed

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6 CONCLUSIONS

Several interesting insights emerged from the analyses previously conducted and shown in the previous chapters.

Membrane technology, although it has been introduced on the market for several decades and has been constantly improved and strengthened thanks to continuous investments in research and development over the last decade, still represents a niche segment in many end applications, mainly in due to the high competition with numerous conventional technological solutions such as distillation or PSA which still strongly dominate the markets where separation and purification technologies of substances are highly requested.

However, the economic and environmental benefits that membrane technology offers compared to conventional technologies place it in a position of competitive advantage for the foreseeable future in numerous application segments such as gas separation, pervaporation and membrane distillation. In these sectors of interest for **MEASURED** project, membrane technology has already been used for some time, mainly through the exploitation of polymeric membranes. However, the market today requires more technically and economically advantageous solutions that carbon membranes for gas separation, ceramic membranes for pervaporation and PVDF membranes for membrane distillation offer or are about to offer in the medium-short term. What current and potential customers of membrane solutions strongly require is a right balance between economic and environmental sustainability of membrane technology, guaranteeing high performance as well as a lower use of energy in the processes, indicating OPEX and CAPEX as the most critical aspects to consider for the purposes of a potential investment in this technology. The MEASURED' technologies are well positioned to answer these market needs.

Numerous players at European level and beyond are moving to develop and bring to the market more modern and advanced membrane solutions similar to those developed in **MEASURED**. In this context, public and private financing is playing a fundamental role to speed up and increase efforts on the development of these innovative solutions. The presence of numerous small and medium-sized enterprises but also as many large companies in the production of membrane indicates a strong and growing interest in this technology and many of them are collaborating with numerous organizations expert in R&D and potential end-users, forming a huge co-development network while many actors also they are also privately investing significant resources in the market deployment of these technologies as indicated by a strong growing trend in patenting activities related to intellectual property and private investments such as venture capital and merger and acquisitions operations.

Some players, compared to the multitude of identified stakeholders in the sectors of interest, already hold the role of market leaders in the sector while others with a deep vision of innovation are following the revolutionary wave through important investments in carbon, ceramic and PVDF membranes, contributing to strengthen the presence of relevant players on the market.

The strong interest shown in this types of membranes for their respective application markets, the numerous prospects and revenue opportunities will help incentivize additional players to enter the market in the future, helping to strengthen the momentum of the sector and its consolidation.

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8 ANNEX

In the Annex section the list of relevant selected projects and patents is shown.

Table 6: R&D&I Funded Projects in Gas Separation, Pervaporation and Membrane Distillation

Projects Acronym	Projects Title	Start year	End Year	Funding Country	Project funding	Funding Programmes
FERRET	A Flexible natural gas membrane Reformer for m-CHP applications	2014	2017		1.730.663 €	FP7
MEMBER	Advanced membranes and membrane assisted processes for pre- and post-combustion CO2 capture	2018	2022		7.918.901 €	H2020
BIONICO	Biogas membrane reformer for decentralized hydrogen production	2015	2019		3.147.640 €	H2020
BIOCONCO2	Biotechnological processes based on microbial platforms for the conversion of CO2 from iron steel industry into commodities for chemicals and plastics	2018	2022		6.999.886 €	H2020
CO2Hing	Carbon membranes for CO2 removal from high pressure natural gas in subsea processing	2017	2020		1.197.874 €	RCN
****	Combination of forward osmosis with reverse osmosis or membrane distillation to concentrate highly rotting liquid feed streams. Adaptation and further development of membrane distillation for use in hybrid plants with forward osmosis	2016	2018		96.850 €	BMBF
ESTAR16111	Combining Forward Osmosis with RO or Membrane Distillation for concentrating fouling feed streams	2016	n. a		137.425 €	RVO
****	Composite membranes for gas separation	2014	2019		0 €	FRIS
****	Crosslinked PVDF as a platform material for membrane separations in extreme conditions	2022	n. a		0 €	FRIS
AQUA PUR TM	Development and market penetration of an innovative water purification technology for industrial applications	2018	2018		50.000 €	H2020
****	Development of MOF-filled polymeric membranes for gas separation.	2019	n. a		0 €	FRIS
SEA4VALUE	Development of radical innovations to recover minerals and metals from seawater desalination brines	2020	2024		6.995.736 €	H2020
SolarMD	Development of solar powered membrane distillation systems for resource-efficient desalination in remote areas	2014	2016		195.336 €	BMBF
GREENMEM	Disruptive green membrane for sustainable chemical and energy industries	2020	2022		2.395.618 €	H2020
H2MemX	Enabling ultrathin Pd based membranes through surface chemistry diagnostics and control	2018	2022		865.173 €	RCN
TEEI314001	Energy efficient valorisation of Components from Process Stream	2014	n. a		795.240 €	RVO

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Ultimate Membranes	Energy-efficient membranes for carbon capture by crystal engineering of two-dimensional nanoporous materials	2019	2024		1.875.000 €	H2020
EMPRESS	Energy-savings using Membranes for higher Process and Reaction Efficiency through Selective Separation	2014	n. a		991.929 €	RVO
Enhanced-MUMs	Enhanced multi-Functional Membranes for Water Treatment and Desalination	2018	2020		168.277 €	H2020
POCEMON	Enhancing polymer Crystallinity in mixed Matrix Membranes by Incorporating Metal-Organic Framework Nanosheets for an Efficient CO2 Capture	2019	2021		431.457 €	ANR
****	Filled polymeric membranes for CO2 and olefin separations under industrial conditions	2017	2020		0 €	FRIS
HyGrid	Flexible Hybrid separation system for H2 recovery from NG Grids	2016	2021		2.527.710 €	H2020
****	Flexible metal-organic framework/polymer composite membrane: highly efficient gas separation	2018	2019		198.471 €	SNCF
HF2N	High Flux 2D Nanosheet membranes	2018	n. a		74.178 €	RVO
MemMOFs	Hybrid membranes incorporating metal-organic frameworks	2015	2017		147.963 €	H2020
****	Incorporating Nanoparticles to Enhance Membrane Performance for Pervaporation Desalination	2016	2021		0 €	FRIS
INCITE	Innovative chemoenzymatic integrated processes	2019	2023		13.223.279 €	H2020
W2W - Wind and Solar	Innovative system for medium scale water desalination 100% powered by renewable energies	2017	2017		50.000 €	H2020
iWAYS	Innovative water recovery Solutions through recycling of heat, materials and water across multiple sectors	2020	2024		10.596.775 €	H2020
TKItoeslag14.162	Innovative Water Treatment: Application of airo technology	2014	n. a		154.850 €	RVO
VicInAqua	Integrated aquaculture based on sustainable water recirculating system for the Victoria Lake Basin	2016	2019		2.997.710 €	H2020
intelWATT	Intelligent Water Treatment Technologies for water preservation combined with simultaneous energy production and material recovery in energy intensive industries	2020	2024		10.308.277 €	H2020
MEMCRYST	Intensified and continuous membrane crystallization process: control of pharmaceutical active ingredients quality	2021	2025		579.328 €	ANR
112CO2	Low temperature catalytic methane decomposition for cox-free hydrogen production	2020	2024		3.585.178 €	H2020
MagMD	Magneto-responsive hydrophobic membrane and membrane distillation: insight into the real-time fouling and wetting mitigation mechanism	2023	2025		191.760 €	HORIZON EUROPE

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EP/S032258/1	Membrane distillation for sustainable desalination and water treatment	2019	2021		296.362 €	EPSRC
MEASURED	Membrane scale up for chemical industries	2023	2026		7.971.409 €	HORIZON EUROPE
MACH-2	Membrane-Assisted CO2 capture through liquefaction for clean H2 production	2019	2023		653.720 €	RCN
H2-Sep	Membrane-based H2 separation after H2 storage and transport in natural gas infrastructure. Synthesis and scaling of C-membranes, production of zeolite- and palladium-containing membranes	2022	2025		562.281 €	BMBF
MACBETH	Membranes And Catalysts Beyond Economic and Technological Hurdles	2019	2024		16.606.129 €	H2020
MembrAlign	Membranes with aligned nanostructures for CO2 separation	2018	2021		671.239 €	RCN
MeNiNA	Metallic nanoclusters embedded in Nitride Nanolaminates for efficient gas separation membranes	2018	2021		440.456 €	ANR
MOLHYB	Molecular Characterization of Hybrid Organic-Inorganic Membranes for Gas Separation under Harsh Conditions	2018	2022		154.980 €	ANR
FaT H2	Nanocomposite Facilitated Transport Membranes for H2 purification	2019	2022		801.896 €	RCN
NanoMBE	Nanocomposite membranes for CO2 separation containing bio-nanofiber and enzyme-like components.	2014	2019		881.562 €	RCN
NanoMEMC2	Nanomaterials Enhanced Membranes for Carbon Capture	2016	2019		4.990.815 €	H2020
CoMeTS	New composite membranes for targeted gas and vapour separations	2019	2021		228.485 €	GAČR
****	New Design Routes for Polymeric Composite Nanofiltration Membranes with High Performance	2016	2018		0 €	FRIS
HySME	New efficient membranes for effective H2 / CO2 separation	2017	2019		303.510 €	GAČR
WETMEM	New membranes and tools for a better understanding, modelling and control of pore wetting in membrane distillation for desalination	2014	2018		401.390 €	ANR
NTPleasure	Non-Thermal plasma Enabled catalysis-Separation system for upgrading biogas to methane	2018	2020		195.454 €	H2020
INNOMEM	Open Innovation Test Bed for nano-enabled Membranes	2020	2024		14.716.872 €	H2020
PPS-toeslag Onderzoek en Innovatie_2016 _255	Organic Pollutants Handling during Effective concentration of Unsaturated Salt-streams for re-use	2016	n. a		290.000 €	RVO
COSMOS	Organic solvent nanofiltration membranes on low-cost ceramic supports	2017	n. a		683.445 €	RVO

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EP/T005157/1	Origami-enabled Super Compaction of Membranes	2019	2021		269.869 €	EPSRC
\	Preparation and characterization of novel polymeric membranes with controlled embedding of additives for effective CO2 separation from gas mixtures	2015	2017		208.981 €	GAČR
\	Prolonged life of palladium-based membranes	2017	2021		427.059 €	RCN
\	PVDF membranes for filtrations in aqueous and solvent media	2014	2018		0 €	FRIS
REMIND	Renewable Energies for Water Treatment and reuse in Mining Industries	2018	2022		1.329.400 €	H2020
ReWaCEM	Resource recovery from industrial waste water by cutting edge membrane technologies	2016	2019		5.041.866 €	H2020
MEMCARB	Separation membranes for carbon dioxide removal from gas streams	2018	2019		150.000 €	H2020
SmartDeZIgn	Smart Design Tool of High Performing ZIF Membranes for Important CO2-Related Separations	2020	2022		153.085 €	H2020
MOST	Solar powered membrane-based processes and units for water desalination in tropical areas	2018	2021		300.000 €	ANR
TEEI116077	Solvent Tolerant Nanofiltration and Reverse Osmosis membranes (STNF) for the purification of industry	2016	n. a		976.517 €	RVO
SuperClean	Superhydrophobic membranes for clean water production	2023	2025		2.497.750 €	HORIZON EUROPE
MELODIZER	Sustainable membrane distillation for industrial water reuse and decentralised desalination approaching zero waste	2022	2026		7.007.470 €	HORIZON EUROPE
WASTE2FUELS	Sustainable production of next generation biofuels from waste streams	2016	2018		5.989.742 €	H2020
\	Synthesis, characterization and test of membranes for the separation of CO2 and purification of synthetic natural gas (SNG)	2014	n. a		NA	ENEA-MSE
KerWas	Thin-walled, wetted ceramic membranes and high volume-specific membrane area for nanofiltration and membrane distillation for the sustainable treatment of saline waters	2017	2020		2.446.176 €	BMBF
HaSiMem	Water recovery from heap seepage water on the basis of membrane distillation processes and coupling with crystallization	2021	2024		1.824.967 €	BMBF
MIT.Zuid Holland.HB.158	WW - separation of feed water and membrane	2017	na		25.000 €	RVO
Mem4BIOCH4	Implementation of novel ultra-permeable membranes for biomethane production	2023	2025		165.312,00 €	HORIZON EUROPE
SAFEWater-SDCW	A Disruptively Novel Approach to Clean and Safe Water Supply to Off-Grid Communities	2023	2025		1.539.105,00 €	HORIZON EUROPE

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Table 7: C&I Projects in Gas Separation, Pervaporation and Membrane Distillation

Commercial Projects	Business Case	Description
SPG Steiner/ Evonik Joint Project on gas separation membrane	Gas Separation	SPG Steiner GmbH expands its strategic cooperation agreement with Evonik, cooperating together focusing on the defossilization and plant efficiency of energy industries through Evonik's gas separation membrane technologies. The Evonik's polymer-based membranes considered are: PURAMEM® (to separate long-chain hydrocarbons from natural gas or nitrogen mixture), SEPURAN® (to separate CH_4, H_2 and N_2 from gas mixtures), DURAION® (electrolytic production of green hydrogen).
Linde/ Evonik Joint Project on gas separation membrane	Gas Separation	The Linde Group and Evonik Industries intensify gas separation collaboration enabling Linde to offer a complete gas separation and purification portfolio. They have announced intensified collaboration in membrane-based gas separation within the framework of the groundbreaking ceremony for the expansion of Evonik's membrane production facility held in Schörfling,Austria. Evonik's polymer-based membrane technology will be used in the gas separation and purification plants of Linde's Engineering Division.
SolarSpring/ Deukum Joint Project on membrane distillation	Membrane Distillation	SolarSpring Announces Partnership for Membrane Distillation Module Production. After 12 months of joint development, SolarSpring GmbH, the subsidiary of Clean Industry Solutions Holding Europe AB and a pioneer in the field of membrane distillation, is officially announcing a cooperation with the company DEUKUM GmbH for the purpose of a specialized upscaled component production. The cooperation will lead to a significant reduction in production costs and the new production facility will have an initial capacity of 10,000 m² of module surface per year with further expansion potential. The cooperation agreement between DEUKUM GmbH and SolarSpring GmbH is the results of a one-year period of intense research and development on the optimization of flat plate membrane distillation module production methods and materials research. The outcome is a highly specialized and cost-reduced production technique that is expected to fulfill the cost reduction target of 80% compared to the previous method and thus provide a highly competitive cost per unit. SolarSpring can hereby draw upon DEUKUM's multi-decade experience as a specialist in manufacturing flat sheet components, leading to the success of the joint development. From October 2022 onwards, SolarSpring will be setting up its new production line at a 500 m² facility in the close vicinity of the headquarters in Freiburg.
Borsig/ DeltaMem Joint Collaboration on pervaporation	Pervaporation	In 2019, BORSIG, together with DeltaMem, planned and built a unit for ethanol dehydration for an Asian customer from the pharmaceutical industry. The plant is designed for continuous drying of ethanol (initial water content of 10 wt%) down to a water content of 0.5 wt%. The pervaporation unit was delivered in September 2019. The heart of the BORSIG Pervaporation Unit are the high-performance PERVAPTM membranes from DeltaMem AG.
GE/ Memsys Joint Collaboration on Membrane Distillation	Membrane Distillation	GE partners with memsys to develop membrane distillation technology. GE will invest in testing the technology and in return receive an exclusive licence to use the technology in these applications. Germany and Singapore-based memsys has developed a multi-effect MD process in which conventional thermal process engineering has been transferred into an industrial design.
Pervatech/ Philips/ ECN Joint Collaboration on Pervaporation	Pervaporation	Pervatech, a leading membranes producer, and Philips Ceramics, Philips' global competence centre for technical ceramics, have announced their partnership by combining the superior ceramic substrates and knowledge from Philips Ceramics with the Pervatech membrane coating technology. As leading companies in pervaporation and ceramics, Pervatech and Philips are perfectly positioned to offer membranes to the industry for in situ dehydration of condensation reactions, enabling yield improvement and

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		efficiency of the process. They also provide solutions for the direct dehydration of organic acids such as acidic acid, propionic acid, butyric acid and other organic acids. The characteristic and high quality of the ceramic carriers enables users to reduce the number of coating steps, which is a prerequisite for diminishing production costs. By introducing the high quality Philips substrates, Pervatech can substantially reduce the production costs, because no repair of the raw substrates is required and several coating steps are eliminated.Guarantee for stable performance.

Table 8: Relevant Selected Patents in Gas Separation, Pervaporation and Membrane Distillation

Patent ID	Patent Title	Applicant
JP6909800B2	Method for producing (meth)acrylic esters	ARKEMA
JP2022511532A	METHOD FOR LOW HYDROGEN CONTENT SEPARATION FROM A NATURAL GAS MIXTURE	TECNALIA EINDHOVEN UNIVERSITY OF TECHNOLOGY
EP4046704A1	ADVANCED DOUBLE SKIN MEMBRANES FOR MEMBRANE REACTORS	TECNALIA EINDHOVEN UNIVERSITY OF TECHNOLOGY
EP3442695A1	DEVICE AND METHOD FOR COGENERATION OF METHANOL AND SYNTHETIC METHANE	ENGIE
EP3823739A1	SYSTEM FOR PURIFYING A GAS MIXTURE, AND ASSOCIATED PROCESS AND PLANT	ENGIE
US2022073457A1	METHOD FOR PURIFYING ALKYL HYDROPEROXIDE BY EXTRACTION WITH WATER AND SEPARATION OF THE AQUEOUS PHASE	ARKEMA
US2021046442A1	REACTOR AND PROCESS FOR THE HYDROGENATION OF CARBON DIOXIDE	TNO
EP3237370B1	METHOD AND APPARATUS FOR PURIFICATION OF DIMETHYL CARBONATE USING PERVAPORATION	TNO POSCO (POHANG IRON AND STEEL COMPANY) RIST (RESEARCH INSTITUTE OF INDUSTRIAL SCIENCE AND TECHNOLOGY)
US11517860B2	MEMBRANES CONTAINING POLYMERISED IONIC LIQUID FOR USE IN GAS SEPARATION	CONSIGLIO NAZIONALE DELLE RICERCHE UNIVERSITY OF CALABRIA FUJIFILM MANUFACTURING B.V. UNIVERSITA' DI PISA
WO2017013581A1	ALTERNATING POTENTIAL GAS SEPARATION PROCESS WITH CAPACITIVE MEMBRANES, AND RELEVANT PLANT	CONSIGLIO NAZIONALE DELLE RICERCHE ALMA MATER UNIVERSITA' DI BOLOGNA
US10981121B2	NEW MACROPOROUS POLYVINYLIDENE FLUORIDE (PVDF) MEMBRANES	GVS
US20160158702A1	DEVICE FOR MEMBRANE DISTILLATION	SCARAB DEVELOPMENT
EP3806982A1	MULTI-STAGE PSA PROCESS TO REMOVE CONTAMINANT GASES FROM RAW METHANE STREAMS	SYSADVANCE € SISTEMAS DE ENGENHARIA, S.A.
US11406932B2	TREATMENT BY MEMBRANE PERMEATION WITH ADJUSTMENT OF THE NUMBER OF MEMBRANES IMPLEMENTED ACCORDING TO THE PRESSURE OF THE FEED GAS STREAM	AIR LIQUIDE
US11219856B2	SYSTEM AND METHOD FOR TREATING A GASEOUS CURRENT BY MEMBRANE PERMEATION WITH ADJUSTMENT OF THE METHANE CONCENTRATION	AIR LIQUIDE
FR3063437B1	FACILITY AND METHOD FOR TREATMENT OF A FEED GAS STREAM COMPRISING METHANE AND CARBON DIOXIDE BY MEMBRANE PERMEATION	AIR LIQUIDE
EP3255127A1	METHOD OF PROCESSING A COAL SEAM GAS	LINDE
FR3079523B1	METHOD FOR POOLED PRODUCTION OF BIOMETHANE FOR INJECTION INTO THE NATURAL GAS NETWORK	IFPEN

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EP3626328A1	METHOD FOR SEPARATING A GAS MIXTURE BY PRESSURE SWING ADSORPTION	GREEN VISION (HYGEAR)
EP3356016A1	MEMBRANE CONTACTOR COMPRISING A COMPOSITE MEMBRANE OF A POROUS LAYER AND A NON-POROUS SELECTIVE POLYMER LAYER FOR CO2 SEPARATION FROM A MIXED GASEOUS FEED STREAM	NTNU
EP3953297A1	METHOD FOR SEPARATING HYDROGEN FROM GAS MIXTURES	TECHNISCHE UNIVERSITAET WIEN
US2022032237A1	CMS MEMBRANE, METHOD FOR THE PRODUCTION THEREOF AND USE THEREOF	FORSCHUNGSZENTRUM JUELICH
EP3328965B1	PROCESS FOR PREPARING A PARAFFIN PRODUCT	SHELL
WO2017068517A1	A CARBON MOLECULAR SIEVE MEMBRANE, METHOD OF PREPARATION AND USES THEREOF	UNIVERSITY OF PORTO
JP7090627B2	CARBON MOLECULAR SIEVE MEMBRANES FOR AGGRESSIVE GAS SEPARATIONS	SHELL
EP3393621B1	METHOD FOR PRODUCING BIOMETHANE BY PURIFYING BIOGAS FROM NON-HAZARDOUS WASTE STORAGE FACILITIES AND FACILITY FOR IMPLEMENTING THE METHOD	WAGA ENERGY
US10549244B2	HOLLOW FIBER CARBON MOLECULAR SIEVE MEMBRANES AND METHOD OF MANUFACTURING USING RADIAL-FLOW PYROLYSIS	AIR LIQUIDE
WO2022255877A1	CARBON MOLECULAR SIEVE MEMBRANE PREPARED FROM HYDROQUINONE AND THE METHOD OF MANUFACTURING	EINDHOVEN UNIVERSITY OF TECHNOLOGY
		TECNALIA
US9623380B2	Gas separation membrane	NTNU
US10010858B2	Apparatus and process for treating natural gas	JOHNSON MATTHEY
EP3787780B1	HYBRID POLYMER MEMBRANE	SINTEF
EP3679150B1	METHOD AND APPARATUS FOR IN SITU PRODUCT RECOVERY	VITO
MY171318A	Gas separation membranes with intermixed layers	FUJIFILM MANUFACTURING B.V
CN108124433B	Carbon-containing membrane for water and gas separation	FORSCHUNGSZENTRUM JUELICH
JP7142299B2	USE OF NANOPOROUS CARBON MEMBRANES FOR SEPARATING AQUEOUS/ORGANIC MIXTURES	UNIVERSITE PARIS DIDEROT
		CNRS
		UNIVERSITE PIERRE ET MARIE CURIE
EP3160909B1	Device for extraction of pollutants by multichannel tubular membrane	AIX-MARSEILLE UNIVERSITY
		CNRS
US2019001276A1	COMPOSITE CARBON MOLECULAR SIEVE MEMBRANES HAVING ANTI-SUBSTRUCTURE COLLAPSE PARTICLES LOADED IN A CORE THEREOF	AIR LIQUIDE
EP3624924A1	A METHOD FOR SEPARATING FLUIDIC WATER FROM IMPURE FLUIDS AND A FILTER THEREFORE	CNM TECHNOLOGIES
EP3037157B1	Carbon membrane, process for the manufacture of carbon membranes and use thereof	FRAUNHOFER
EP3628951A1	FLASH SEPERATOR FOR THE TREATMENT OF A FLUID MIXTURE CONTAINING LIQUEFIED METHANE AND CARBON DIOXIDE AND PLANT FOR PRODUCING LIQUEFIED BIOMETHANE OR NATURAL GAS COMPRISING SUCH A FLASH SEPERATOR	HYSYTECH
EP3860742A1	A DEVICE AND A PROCESS FOR SEPARATING METHANE FROM A GAS MIXTURE CONTAINING METHANE, CARBON DIOXIDE AND HYDROGEN SULFIDE	EVONIK
US2022112087A1	METHOD FOR THE PREPARATION OF A MOLECULAR SIEVE OF THE CHA-TYPE	UMICORE
WO2019048373A1	METHOD FOR PREPARATION OF A NOVEL ERI-MOLECULAR SIEVE	HALDOR TOPSOE
		POLYTECHNICAL UNIVERSITY VALENCIA
EP3883987B1	PROCESS FOR MANUFACTURING HEAT TREATED PVDF	SOLVAY
US11389764B2	PROCESS FOR TREATING A NATURAL GAS CONTAINING CARBON DIOXIDE	TOTAL
AU2019300356B2	Gas separation device	HYDROGEN MEM-TECH
WO2017140927A1	SET OF HOLLOW-FIBRE MEMBRANES AND USES THEREOF	ABENGOA

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EP4072715A1	CARBON MOLECULAR SIEVE MEMBRANE AND ITS USE IN SEPARATION PROCESSES	EINDHOVEN UNIVERSITY OF TECHNOLOGY TECNALIA
WO2019219131A3	PLATE MODULE FOR MEMBRANE DISTILLATION	SOLARSPRING
EP3801800A1	MULTISTAGE MEMBRANE DISTILLATION APPARATUS	EVCON
JP6728171B2	Membrane cartridge with integrated functions	VITO
US10421046B2	Method for making porous asymmetric membranes and associated membranes and separation modules	SABIC
WO2015140356A3	FILM-SUPPORTED POLYMERIC MEMBRANES AND METHODS OF MANUFACTURING	VITO
EP3562575A1	ISOTROPIC POROUS MEMBRANE AND METHOD OF PREPARING THE SAME	VITO
EP3488009B1	METHOD AND APPARATUS FOR PRODUCING SOLVENTS BY FERMENTATION	VITO
US2022062824A1	DEHYDRATION OF A MIXTURE CONTAINING A DIOL WITH HIGH WATER CONTENT USING OPTIMIZED PERVAPORATION PROCESS	SABIC
EP3195915A1	A SYSTEM FOR THE PURIFICATION OF AN ORGANIC SOLVENT AND A PROCESS FOR THE USE THEREOF	SULZER CHEMTECH
EP3094398A4	APPARATUS COMPRISING A MEMBRANE UNIT AND A WATER SCRUBBER UNIT FOR REMOVING CARBON DIOXIDE FROM A GAS	GASEFUELS
WO2022064159A1	BIOGAS TREATMENT METHOD - ASSOCIATED PLANT	CH4 PROCESS
EP4076709A1	A GAS SEPARATION ARTICLE, A METHOD FOR PRODUCING SAID GAS SEPARATION ARTICLE AND USE THEREOF	CONDALIGN AS
ES2807272T3	PROCESS FOR THE RECOVERY OF SODIUM SULFATE	RHODIA OPERATIONS
EP3280515A1	MEMBRANE DISTILLATION DEVICE WITH A HYBRID VAPOR COMPRESSION DRIVE AND ITS USE	GENERAL ELECTRIC
NL2022857B9	System and method for purification of water by membrane distillation	RAINMAKER HOLLAND BV
CN109070020B	HYDROPHOBIC POLYETHYLENE MEMBRANE FOR USE IN VENTING, DEGASSING, AND MEMBRANE DISTILLATION PROCESSES	ENTEGRIS
PL236552B1	Membrane for membrane distillation and method for modification of membranes for membrane distillation	WEST POLIMERANIAN UNIVERSITY OF TECHNOLOGY
PL425452A1	Method for obtaining and dehydration of acetone, butanol and ethanol from their water mixture, preferably from fermentation broth, through membrane distillation	NICOLAUS COPERNICUS UNIVERSITY IN TORUN
CZ32427U1	A membrane distillation module	BRNO UNIVERSITY OF TECHNOLOGY
US20200147551A1	POROUS MEMBRANE FOR MEMBRANE DISTILLATION, MEMBRANE MODULE, AND MEMBRANE DISTILLATION DEVICE	HITACHI CHEMICAL EUROPE
US20170036937A1	METHOD FOR TREATING AQUEOUS SALINE STREAMS	ABENGOA
EP3259304B1	SEPARATION OF LIGNIN AND SUGARS FROM BIOMASS PRE-TREATMENT LIQUORS	ECN (TNO)
EP3450565A1	METHOD AND APPARATUS FOR PRODUCING ESTERS OR AMIDES WITH IN SITU PRODUCT RECOVERY	VITO
US11007452B2	Process and system for dehydrating a byproduct stream in ethanol production	WHITEFOX TECHNOLOGIES
AU2018218250A1	Carbon molecular sieve membranes for aggressive gas separations	AIR LIQUIDE
US20170189859A1	ZEOLITE ENHANCED CARBON MOLECULAR SIEVE MEMBRANE	AIR LIQUIDE
US10183258B2	METALLOPOLYIMIDE PRECURSOR FIBERS FOR AGING-RESISTANT CARBON MOLECULAR SIEVE HOLLOW FIBER MEMBRANES WITH ENHANCED SELECTIVITY	AIR LIQUIDE
EA034642B1	PROCESS FOR SEPARATION OF GASES WITH REDUCED MAINTENANCE COSTS	EVONIK
US10315157B2	System and method for separating carbon dioxide from natural gas	MITSUBISHI CHEM
US20180369746A1	METHOD FOR SEPARATING CARBON DIOXIDE AND APPARATUS FOR SEPARATING CARBON DIOXIDE	MITSUBISHI CHEM
EP3966265A1	SYNTHESIS OF POROUS GRAPHITIC CARBON MEMBRANES	TOTAL
US20170247512A1	CARBON MOLECULAR SIEVE (CMS) HOLLOW FIBER MEMBRANES AND PREPARATION THEREOF FROM PRE-OXIDIZED POLYIMIDES	DOW CHEM
CN105983344B	PERVAPORATION AND VAPOR-PERMEATION SEPARATION METHOD OF GAS-LIQUID MIXTURES AND LIQUID MIXTURES BY ION EXCHANGED SAPO-34 MOLECULAR SIEVE MEMBRANE	TOTAL

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US20190299167A1	POROUS SUPPORT-ZEOLITE MEMBRANE COMPOSITE, AND METHOD FOR PRODUCING POROUS SUPPORT-ZEOLITE MEMBRANE COMPOSITE	MITSUBISHI CHEM
US20160376217A1	PURIFICATION OF (METH)ACRYLIC ESTERS BY MEMBRANE SEPARATION DEHYDRATION	ARKEMA
US20190091630A1	DEHYDRATION SYSTEM FOR AQUEOUS ORGANIC COMPOUNDS, OPERATION METHOD THEREFOR, AND DEHYDRATION METHOD	MITSUBISHI CHEM
US20170189862A1	ZEOLITE MEMBRANE, PRODUCTION METHOD THEREFOR, AND SEPARATION METHOD USING SAME	HITACHI ZOSEN
US10329229B2	Method for producing high-concentration alcohol	MITSUBISHI CHEM
US20180050309A1	HIGH SELECTIVITY COPOLYIMIDE MEMBRANES FOR SEPARATIONS	HONEYWELL UOP
US20180043298A1	DUAL LAYER-COATED MEMBRANES FOR GAS SEPARATIONS	HONEYWELL UOP
US20180333675A1	CO-CAST THIN FILM COMPOSITE FLAT SHEET MEMBRANES FOR GAS SEPARATIONS AND OLEFIN/PARAFFIN SEPARATIONS	HONEYWELL UOP
US20180050310A1	CHEMICALLY AND UV CROSS-LINKED HIGH SELECTIVITY POLYIMIDE MEMBRANES FOR GAS SEPARATIONS	HONEYWELL UOP
US20160303521A1	HIGH PERMEANCE MEMBRANES FOR GAS SEPARATIONS	HONEYWELL UOP
US9782730B2	1234YF- and 1234ZE-based polymeric membrane materials, membrane preparations and uses thereof	HONEYWELL UOP
US9751053B2	ASYMMETRIC INTEGRALLY-SKINNED FLAT SHEET MEMBRANES FOR H2 PURIFICATION AND NATURAL GAS UPGRADING	HONEYWELL UOP
US20160089627A1	POLYIMIDE BLEND MEMBRANES FOR GAS SEPARATIONS	HONEYWELL UOP
US20180133644A1	MULTIPLE MEMBRANE SEPARATION PROCESS USING GLASSY POLYMERIC MEMBRANE AND RUBBERY POLYMERIC MEMBRANE	HONEYWELL UOP
US20190381449A1	MULTI-STAGE MEMBRANE SYSTEMS WITH POLYMERIC AND MICROPOROUS ZEOLITIC INORGANIC MEMBRANES FOR GAS SEPARATIONS	HONEYWELL UOP
US10774273B2	Process and apparatus for recovering hydrogen from residue hydroprocessing	HONEYWELL UOP
US10569217B2	Production of biomethane using a high recovery module	AIR LIQUIDE
US20190321780A1	MULTI-STAGE MEMBRANE FOR N2 REJECTION	AIR LIQUIDE
US20170304769A1	METHOD FOR PURIFYING BIOGAS THROUGH MEMBRANES AT NEGATIVE TEMPERATURES	AIR LIQUIDE
US20160184770A1	POLYIMIDE MEMBRANE FOR H2S REMOVAL	AIR LIQUIDE
US10143961B2	Method and system for purification of natural gas using membranes	AIR LIQUIDE
US20160090910A1	Membrane Separation Of Carbon Dioxide From Natural Gas With Energy Recovery	AIR PRODUCTS
US20200088466A1	Helium Extraction from Natural Gas	AIR PRODUCTS
US20160144323B1	METHOD FOR PRODUCING POLYIMIDE MEMBRANES	EVONIK
US9975084B2	Fluid separation processes using membranes based on fluorinated and perfluorinated polymers	MTR
US9636632B2	Gas separation membranes based on fluorinated and perfluorinated polymers	MTR
WO2015137910A1	MEMBRANE-BASED GAS SEPARATION PROCESSES TO PRODUCE SYNTHESIS GAS WITH A HIGH CO CONTENT	MTR
US9808772B2	Gas separation membrane and gas separation membrane module	FUJIFILM MANUFACTURING B.V.
US20160256827A1	Spiral Wound Gas Separation Membrane Modules	FUJIFILM MANUFACTURING B.V.
EP3184558B1	COMPOSITION FOR FORMING POLYMERIC MEMBRANE, PROCESS FOR PRODUCING SAME, POLYMERIC MEMBRANE, SEPARATION MEMBRANE MODULE, AND ION EXCHANGE DEVICE	FUJIFILM MANUFACTURING B.V.
US20200171441A1	CARBON MEMBRANE FOR FLUID SEPARATION AND METHOD FOR MANUFACTURING THE SAME	TORAY

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