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Desalination and agriculture

Technologies, trends and recommendations to combat water scarcity in the EU and beyond

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1 Aim of the document

The aim of this report is to provide an overview of desalination technologies and their potential for responding to water scarcity in agriculture, a problem which is expected to exacerbate over the coming years under future climate change ([1]). The report focuses on the European Union – though it looks at experiences from all over the world – and has several key objectives:

- Review the fundamental principles, established technologies, emerging innovations, advantages, and limitations of thermal and membrane-based desalination processes.
- Summarise the regulatory framework, policies, and incentives related to desalination at the European Union level.
- Highlight case studies from Europe and globally where desalination plays a role in agriculture.
- Analyse future trends, sustainability considerations, and recommendations to support increased adoption of renewable energy powered desalination aligned with European environmental regulations.
- Serve as an introductory resource to enable stakeholders to critically assess opportunities and challenges associated with employing desalination to increase the availability of freshwater for agricultural uses in the EU.

The scope of this report is limited to desalination for agricultural irrigation. This is a deliberate limitation: other uses of desalinated water, such as drinking water supply and industrial applications, are relevant but are not covered, and the findings should not be extended to them.

([1]) https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002567

2 Introduction

Overall, the aim is to summarise existing literature to provide a balanced synthesis of the technical, economic, policy, and environmental dimensions of desalination technologies and their applications. The report strives to consolidate perspectives that can inform strategies for utilising desalination in a sustainable way of integrated water management. In doing so, the report also looks at best practices and new approaches outside the European Union, aiming to support evidence-based decision-making regarding sustainable desalination development aligned with economic viability and environmental protection goals.

Climate change is imposing severe and escalating pressures on freshwater resources across Europe, with significant implications for all activities including the agricultural sector. Rising temperatures, shifting rainfall patterns, glacial melt, and more frequent extreme weather events such as droughts and floods have already impacted crop yields, livestock production, and farmer livelihoods across the region (Cammalleri et al. 2020; Spinoni et al. 2020). Prolonged droughts have long been causing widespread agricultural losses and over EUR 100 billion in economic damages globally (Tsegai et al. 2022), affecting Southern Europe particularly strongly, while climate change is also driving significant agroclimatic shifts towards warmer and drier conditions in parts of Central Europe (Schewe et al., 2014; Trnka et al., 2011).

Projections indicate the agricultural impacts of climate change will intensify in the coming decades. Increased drought frequency, severity and geographic extent is expected across most of Europe, with the most acute risks in southern regions (Samaniego et al. 2018). Under medium and high emission scenarios, droughts that currently occur every 100 years could happen every 10-30 years on average in southern Europe by the 2070s. Such intensification threatens severe, widespread consequences for European agriculture, potentially endangering regional and global food security (Webber et al. 2018, IPCC, 2022).

Adapting European agriculture to increased climate variability and water scarcity is critical. Improved water use efficiency, shifts to less water-intensive crops, enhanced irrigation infrastructure, drought early warning systems, insurance programmes and other farm supports are all important adaptation strategies (Iglesias et al. 2007, IPCC, 2022). Moreover, agriculture in water stressed regions would benefit from a hierarchically structured**,** multi-pronged strategy to adapt to climate change, first by promoting crop diversification and shifts to less water-intensive varieties, second by scaling up the safe reuse of treated wastewater as a primary non-conventional source, third by improving conveyance and on-farm irrigation efficiency, and as a complementary option in coastal areas, by considering desalination (FAO, 2012; JRC, 2021). In this context, a portfolio of non-conventional water sources have emerged as a potential solutions to address water scarcity in agriculture. Wastewater reuse is increasingly applied to reduce dependence on rainfall while enabling nutrient recycling, whereas

desalination of seawater and brackish groundwater remains particularly relevant in water-scarce coastal and arid inland regions (Jones et al., 2019; Qadir et al., 2020). Expanding these non-conventional water sources, especially where conventional resources are unavailable or unsuitable, can help reduce agriculture's dependence on rainfall, although high costs, energy requirements and environmental impacts continue to constrain the large-scale deployment of desalination technologies (Ghaffour et al., 2013).

This report synthesises the state of the art and outlook for desalination technologies, economics, environmental and sustainability considerations. The analysis is consistent with the objectives of EU water and environmental legislation; however, under the EU Sustainable Finance Taxonomy, desalination can qualify as a sustainable economic activity only if specific technical screening and DNSH criteria are met. The report is a literature-based synthesis drawing on peer-reviewed studies, EU policy documents and institutional reports; it does not present original empirical research.

3 Overview of desalination

3.1 Definition and principles of desalination

Desalination refers to processes that remove dissolved salts and other minerals from saline water to produce freshwater suitable for human consumption, agriculture, and industrial uses. It enables the utilisation of brackish groundwater and seawater resources that would otherwise be unsuitable for many human purposes due to their high content of total dissolved solids (TDS). Desalination has become an increasingly important water supply option as populations grow, climate change threatens surface water resources, and some coastal aquifers experience saline intrusion. The principal aim of desalination is to separate the water molecules from the dissolved ionic solids, producing potable water with a TDS concentration below recommended guideline value (around 500 mg/L), while concentrating the salts and minerals to generate a hypersaline brine stream (Greenlee et al., 2009).

The key physical-chemical principles that desalination processes rely on are distillation and membrane separation. Distillation mimics the natural water cycle, using thermal energy input to induce a phase change from liquid to vapor, then condensing the purified water vapor to a liquid distillate while the salts remain in the residual brine. Multiple effects or stages are utilised to improve energy efficiency by recycling latent heat. Membrane separation processes use semi-permeable membranes that allow the passage of water molecules but block dissolved ions. By applying hydraulic pressure to the saline feed, the water permeates through the membrane while salts are retained, generating a desalted product water permeate and a concentrated brine reject (Elimelech and Phillip, 2011). Both distillation and membrane technologies produce freshwater flows equivalent to 35-60% of the intake saline water flow, with the remainder being discharged brine concentrate (Lattemann and Höpner, 2008).

3.2 Desalination technologies

The main thermal distillation technologies employed for desalination include multi-stage flash distillation (MSF), multi-effect distillation (MED), and mechanical vapor compression (MVC). Among these technologies, MSF distillation accounts for the largest share of installed thermal global desalination capacity, takes place in a series of chambers with successively lower temperatures and pressures. Saline feed water entering each stage chamber flashes to steam when the pressure drops causes boiling at lower temperatures, while heat exchangers condense pure water vapor from the steam. Recycling this latent heat of condensation improves thermal efficiency. MED distillation also utilises multiple effects or stages but uses the heat from condensation of water vapor generated

in one stage to pre-heat the feed water for the next stage. This cascade arrangement further improves energy efficiency. MVC distillation compresses water vapor using a mechanical compressor instead of sequential stages heated by steam, reducing energy input needs (Chafidz et al., 2019).

Reverse osmosis (RO) has surpassed thermal processes to become the most widely used desalination technology globally, especially for smaller-scale installations. RO uses semi-permeable membranes that allow the passage of water molecules but block dissolved salts when sufficient hydraulic pressure is applied to the saline feed. Typical RO systems use arrays of spiral-wound membranes or hollow-fiber membrane modules. Energy is needed to generate the required transmembrane pressure, which exceeds the naturally occurring osmotic pressure, to desalt the feed water (Greenlee et al., 2009).

Electrodialysis (ED) and electrodialysis reversal (EDR) use an electric potential applied across ion-exchange membranes to draw positively and negatively charged ions through selective membranes. This leaves desalinated water behind as the diluate product ([2]). ED and EDR have found niche applications for brackish water desalination but have limited large-scale usage compared to RO.

Emerging membrane technologies include forward osmosis and membrane distillation (MD), which utilises low-grade heat to evaporate water across a hydrophobic microporous membrane. Hybrid thermal-membrane desalination processes that combine principles of distillation and membrane separation are an active area of research and development.

([2]) The term *diluate* specifically refers to the solution that has been desalinated in electrodialysis processes, where dissolved ions are removed by an applied electric potential across ion-exchange membranes. This term is frequently used in technical and engineering literature on membrane processes, as highlighted in the work of Elimelech & Phillip (2011) in *The future of seawater desalination: Energy, technology, and the environment* (Science, 333(6043), 712-717), and Strathmann (2010) in *Electrodialysis, a mature technology with a multitude of new applications* (Desalination, 264(3), 268-288).

4 Regulatory and policy framework

4.1 European Union regulations and policies

The European Union has established several water, environmental, and energy legislations and policies that are relevant to desalination projects, although they do not specifically target desalination technology.

The EU Water Framework Directive (2000/60/EC) provides an overarching framework for integrated and sustainable water management in Europe. It established ambitious goals for all water bodies to reach “good status” both qualitatively and quantitatively by 2015 – with the possibility of extending deadlines up to 2027 under specific conditions and exemptions set out in the Directive (European Commission, 2000). The WFD lists desalination as one of the "supplementary measures" that can be adopted by Member States to achieve the environmental and ecological objectives of the directive (Article 11(4) and Annex VI, Part B). This indicates desalination is considered a potential drinking water supply option within the EU water policy landscape. However, the WFD also emphasises that water pricing policies should provide adequate incentives for users to use water resources efficiently and enable recovery of the costs of water services (Article 9). This has implications for the economics of desalination projects if water prices reflect the full costs of supply.

The Marine Strategy Framework Directive (2008/56/CE) provides an overarching framework to protect and conserve the health of our coasts, seas and ocean. Its aim is to achieve a good environmental status of the EU's marine waters and sustainably protect the resource base upon which marine-related economic and social activities depend. This Directive requires Member States to develop national marine strategies with the objective of achieving, or maintaining where already achieved, Good Environmental Status (GES) of marine waters by 2020. These marine strategies comprise regular assessments of the marine environment, the setting of environmental objectives and targets, the establishment of monitoring programmes, and the implementation of measures to improve the state of marine waters. This framework has clear implications for desalination projects, which must be designed and operated in a way that does not adversely affect marine ecosystems.

The recast Drinking Water Directive (EU) 2020/2184 concerns access to and the quality of water intended for human consumption, with the aim of protecting human health through the application of water quality standards. The parametric values and guideline requirements apply to all water intended for human consumption, regardless of its source, and therefore also to desalinated water. While desalination processes remove most chemical contaminants of concern, the finished water still requires adequate disinfection to control microbial risks (WHO, 2011).

The Environmental Impact Assessment (EIA) Directive (2011/92/EU) as amended by Directive 2014/52/EU specifies categories of public and private projects that require a formal environmental impact assessment (EIA) before development consent can be granted (European Parliament & Council, 2011, 2014). The projects are categorised based on capacity thresholds. For example, groundwater abstraction projects, dams, and inter-basin water transfer schemes are listed but desalination projects are not specifically included. Desalination plants may require an EIA depending on the proposed intake volume and capacity.

At the broader EU policy level, directives like the Renewable Energy Directive (2009/28/EC) and amending Directive EU/2023/2413 aim to promote renewable energy usage and reduce greenhouse gas emissions (European Parliament & Council, 2009). The European Green Deal further commits the EU to carbon neutrality by 2050 (European Commission, 2019). This high-level policy landscape provides impetus for desalination projects to transition from conventional fossil fuel energy sources toward renewable energy, in order to align with the EU's sustainability goals.

While the cited EU policies focus primarily on drinking water and environmental protection, irrigation is another significant water use that can benefit from desalination. The EU Strategy on Adaptation to Climate Change mentions that ensuring that freshwater is available in a sustainable manner is fundamental for climate resilience as water underpins many sectors of the economy and access to drinking water is a basis human need. This Commission calls to sharply reduce water use and improve water efficiency (European Commission, 2021).

In addition, in the Water Resilience Strategy, the Commission has recognised the importance of the water hierarchy and the Water Efficiency First principle. Increasing supply by using seawater to replace freshwater can be part of the solution,, if done sustainably, in particular in regions severely affected by water scarcity and once the water efficiency is prioritised. The Commission will support innovation to mitigate the environmental impacts of brine disposal and increase the recycling and reuse of energy and minerals from the brine in the industry sector.

Regulation (EU) 2020/741 establishes minimum requirements for the safe reuse of treated urban wastewater for agricultural irrigation across the EU. Its purposes include addressing water scarcity and promoting the circular economy (Art. 1(2)). Recital 9 of the Regulation states that the reuse of properly treated wastewater is considered to have a lower environmental impact than alternative water supply methods such as water transfers or desalination (European Parliament and Council, 2020).

The regulation on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) provides support for investments in water savings and sustainable irrigation to enhance water use efficiency in agriculture

(Regulation EU No 1305/2013). This can include modernisation of existing irrigation systems and construction of new sustainable irrigation facilities.

Although not explicitly mentioning desalination, this EU policy framework provides potential financial support for the adoption of efficient irrigation technologies, such as desalination-fed irrigation systems. Integrating desalination into sustainable irrigation practices could help European farmers address increasing water scarcity exacerbated by climate change.

The recent enforcement of the EU Nature Restoration Law (NRL) in August 2024 is expected to have a significant impact on various sectors, including desalination, with a particular focus on sustainability and environmental regulations.

In addition to the broader EU regulatory framework on water, environment and energy, the EU Sustainable Finance Taxonomy represents a particularly relevant reference for assessing the sustainability of desalination investments. Under the EU Taxonomy framework, desalination-related investments may qualify as environmentally sustainable only if they comply with the general requirements of Regulation (EU) 2020/852, notably the demonstration of a substantial contribution to climate change adaptation (Article 11) and compliance with the "Do No Significant Harm" principle (Article 17). In practice, desalination may be assessed under the economic activity "Construction, extension and operation of water collection, treatment and supply systems" listed in Annex II of Commission Delegated Regulation (EU) 2021/2139, as amended by Regulation (EU) 2023/2485, and is therefore subject to the applicable technical screening and DNSH criteria.

While the Taxonomy does not explicitly prescribe a water hierarchy, its application could be expected to be consistent with broader EU water policy principles, including integrated water management and the efficiency-first approach, as reflected in the Water Framework Directive and related policy guidance. Moreover, the DNSH requirements imply careful management of environmental impacts associated with seawater intake and brine discharge, in line with EU marine environmental legislation. As a result, desalination cannot be considered automatically Taxonomy-aligned; rather, only projects combining high energy efficiency, low-carbon energy sourcing and robust environmental safeguards are likely to meet the Taxonomy's eligibility conditions.

In line with the broader EU regulatory framework, which already promotes water efficiency and the use of renewable energy, the EU Nature Restoration Law (NRL) is expected to influence desalination, particularly through stricter environmental standards. As the law targets marine and coastal ecosystem restoration, desalination plants will likely face increased scrutiny regarding their brine discharge and water intake systems, which can harm marine life. The NRL's emphasis on biodiversity protection may push desalination operations to adopt more eco-friendly technologies and reduce their environmental footprint. Additionally, the NRL aligns with the EU's climate goals, encouraging a shift

toward renewable energy to power desalination, reducing carbon emissions in line with broader sustainability objectives.

Conclusively, EU regulations handle subjects concerning the quality of drinking water, environmental safeguarding, and water management. However, they do not specify particular technical guidelines, incentives, or policies that are directed towards desalination technology or irrigation. The EU's strong focus on sustainability, renewable energy, and water efficiency fosters a supportive environment for the development of sustainable desalination.

4.2 Incentives and government support for desalination

To expand freshwater supply capacity, some European and Mediterranean countries have provided financial incentives and policy support to spur development of seawater desalination projects (WWF, 2007).

In most cases, these interventions have focused on conventional have supported plants connected to electricity grids powered by fossil fuels rather than renewable energy alternatives (ProDes, 2010). In fact, whether a desalination facility uses fossil fuels or renewables depends primarily on the energy mix of the grid to which it is connected. Reverse osmosis membranes, moreover, typically require continuous operation to avoid scaling, fouling, and corrosion, which raises technical challenges for relying solely on variable renewable energy sources (Shahzad et al., 2019) Recent studies show, however, that the integration of hybrid renewable systems (e.g. solar PV, wind), combined with energy storage solutions and advanced grid management, can support stable operation while significantly increasing the renewable share (Caldera et al., 2016;). While achieving 100% renewable desalination remains complex, particularly at large scale, such approaches are making very high renewable penetration increasingly conceivable.

For example, Spain has promoted large-scale reverse osmosis desalination plants through subsidies, preferential electricity tariffs, and public-private partnerships to subsidise capital investment costs (Hernández, 2020). Under its AGUA Program started in 2004, up to 25% of the initial investment costs of desalination plants were covered by government subsidies, and plants were provided 15-year power purchase agreements at rates 25-45% below market electricity prices (Dolnicar & Schäfer, 2009). As of 2020, Spain had over 60 large desalination plants in operation, mostly using energy from fossil fuels, encouraged by these incentives (Hernández, 2020).

The subsidised electricity rates for conventional desalination plants give them a significant cost advantage compared to renewable energy-powered desalination projects, which creates an uneven playing field (ProDes, 2010). Removing electricity subsidies or imposing taxes on fossil fuel use by desalination plants could help account for negative externalities like air pollution and greenhouse gas

emissions. This could improve the relative cost competitiveness of renewable desalination alternatives (ProDes, 2010).

Policy instruments like feed-in tariffs, capital investment subsidies, and renewable quotas have been implemented for renewable energy in some European countries but are not broadly targeted at desalination projects specifically (ProDes, 2010). Setting minimum quotas for renewable energy use for new desalination plants over a certain capacity is one potential measure proposed to incentivise renewables (ProDes, 2010). Investment subsidies to offset the high upfront capital costs of renewable desalination systems could also be implemented.

EUR Cyprus provides an example of integrating renewable energy research with desalination technology, as well as recent policy incentives specifically for desalination. The PROTEAS Facility, the largest research infrastructure in Cyprus, is devoted to research, development and testing of Renewable Energy Sources with emphasis on Concentrating Solar Thermal (CST), Thermal Energy Storage (TES) and thermal Desalination of Sea Water (DSW) ([3]).

The first major experiment at PROTEAS concerns the co-generation of electricity and desalinated water from Concentrated Solar Panels (CSP). Specifically, the experimental plant consists of a heliostat central-receiver system for solar harvesting, thermal energy storage in molten salts, followed by a Rankine cycle for electricity production and a Multiple-Effect Distillation (MED) unit for seawater desalination. (WEFEMED, 2024) Additionally, the Water Development Department has launched a grant scheme for small desalination units with applications open until September 2026, supporting the installation of desalination units with a daily capacity of up to 1 500 m^3 by private entities, including hotels and tourist facilities, as well as by municipalities and communities for irrigation purposes (Cyprusmail, 2025). In Cyprus, all large-scale desalination plants operate under Build, Own, Operate, Transfer (BOOT) contracts, where private companies use their own financing capacity to develop infrastructure through public-private partnerships (Global Water Partnership, 2018).

Cyprus relies on seawater desalination for a large part of its drinking water supply, with reverse osmosis providing more than 95% of the total desalination capacity in the country and at present, 5 large desalination plants supply drinking water to municipalities, while approximately 24 smaller desalination units are used by other sectors (Xevgenos et al., 2021).

In Malta, the most water scarce country in Europe and in the top ten in the world (Hartfiel et al., 2020), desalination has been a critical water source since the 1980s. Multi-stage flash distillation of seawater was introduced in the 1960s, while the 1980s saw the introduction of reverse osmosis technology on a commercial scale – at that time the Ghar Lapsi Plant was the largest in the Mediterranean (Sapiano, 2017). In 2022, reverse osmosis plants produced 22.8

([3]) https://energy.cyi.ac.cy/facilities/proteas/

million m^3 of water, accounting for 64% of the total potable water blend, while groundwater accounted for approximately 36%" (Water Services Corporation, 2023). Financial incentives to support desalination and water management projects in Malta are integrated into the broader framework of national research and innovation (R&I) strategies. The Energy and Water Agency, in collaboration with the Malta Council for Science and Technology (MCST), developed the National Strategy for Research and Innovation in Energy and Water 2021-2030, which focuses on efficient solutions in energy and water, desalination and water treatment processes, and renewable solutions for islands. During the first year, half a million euro was allocated to encourage R&I activities in these areas (Energy and Water Agency, 2020).

4.3 Policy and economic considerations

The regulatory requirements and policy landscape for desalination projects have economic impacts that affect the feasibility and competitiveness of desalination.

Imposing more stringent regulations on the discharge of brine concentrate from desalination plants is expected to increase costs but provide environmental benefits from reduced marine ecological impacts (Lattemann and Höpner, 2008). Appropriate policies aim to balance these costs and benefits. For example, the EU's Urban Wastewater Treatment Directive set standards for wastewater treatment across Europe that increased costs for municipalities but yielded downstream water quality improvements with socioeconomic benefits. The revised Directive, which entered into force in January 2025, is expected to bring financial benefits of approximately EUR 6.6 billion per year by 2040, far outweighing estimated implementation costs (European Commission, 2024).

Government subsidies, preferential electricity tariffs, and public-private partnerships to support conventional fossil fuel desalination can negatively affect renewable desalination economics by improving the cost competitiveness of non-renewable plants. Removing such subsidies and preferential policies could lead to higher, but more equitable, water costs from conventional desalination. The PESETA IV project (2020), carried out by the European Commission's Joint Research Centre, quantified the socioeconomic impacts of climate change, including water scarcity. The study estimated current annual losses from drought in the EU at approximately EUR 9 billion, with projections that these could more than double as a share of GDP by end of century under high warming scenarios (JRC, 2020). Water scarcity impacts are particularly severe in southern Europe, where regional drought losses could reach 0.3% of GDP, with agriculture potentially losing up to 10-15% of sector economic output (Cammalleri et al., 2020). Many European countries currently underprice water from conventional surface and groundwater sources, which makes desalination seem expensive in comparison (OECD, 2023). Moreover, Moore (2018) emphasised that aligning water pricing with true costs, including externalities like environmental degradation and ecosystem service losses, would make alternative water sources like desalination more competitive, particularly as traditional freshwater sources become scarcer and more expensive to exploitThe EU Water Framework Directive's requirement for water pricing policies to account for the full costs of water services could improve the relative cost competitiveness of seawater desalination compared to traditional freshwater sources like rivers and lakes.

Higher energy costs are also a key factor affecting desalination economics. Renewable energy technologies like solar and wind power have seen rapidly declining costs in recent years (IRENA, 2020), which improves the economic viability of coupling them with desalination. However, intermittent power supply from renewables requires desalination systems capable of flexible operation, adding complexity and costs.

Desalination can provide significant social and economic benefits. Socially, it could contribute to enhance water supply by increasing availability, particularly in arid regions, and can support urban and industrial growth, driving economic development. Desalination is of specific interest in locations where alternatives are high cost or where the risk of supply failure is high and to serve sectors that require high quality of water such as high-value industry, commerce, and tourism. It also could contribute to drought and climate resilience by offering a stable water source independent of rainfall, which is crucial during prolonged droughts or emergencies particularly when implemented as part of integrated water management and under the efficiency-first principle. These social and economic benefits need, however, to be weighed against important environmental considerations, which are addressed in the following paragraph.

Environmentally, desalination entails significant impacts; however, when it substitutes groundwater over-extraction or diversions from stressed surface waters, it can indirectly help protect freshwater ecosystems by easing pressure on aquifers, rivers, and lakes. Evidence from Israel shows that the expansion of SWRO capacity has reduced withdrawals from the Sea of Galilee, from 513 million m^3 annually in 2001-2002 to just 25 million m^3 in 2018-2019- thereby contributing to the protection of freshwater habitats in the basin (Israel Water Authority; Fanack Water, 2022). Strategic guidance from the World Bank also frames desalination as a targeted option to close supply demand gaps in water-scarce settings, thereby potentially reducing ecological externalities associated with unsustainable abstraction (World Bank, 2019).

Despite the benefits, there are many environmental concerns related to the desalination facilities as:

- Water intake structures can affect marine ecosystem and lead to permanent alteration of hydrographical conditions
- chemicals are commonly used in the treatment phases and are discharged with the brines.
- Brine discharges can harm marine life and seafloor ecosystems in the area where they are released, due to their high salinity and dissolved minerals. Brine discharge will also lead to a local increase of the salinity and temperature of seawater
- Desalination entails high energy consumption, leading to significant greenhouse gas emissions and high costs.

Desalination is therefore an area with significant innovation potential to improve the sustainability of desalination facilities in particular to reduce the energy consumption and improve the brine disposal, through sustainable practices and technological innovations.

Desalination also poses challenges in terms of locations particularly in densely populated coastal areas, where the expense of transporting water adds to the complexity.

In summary, while EU regulations provide standards for drinking water quality, emission limits, and environmental protection, they do not establish fully harmonised technical norms for desalination at EU level. However, the adoption of the EU Sustainable Finance Taxonomy (Climate Delegated Regulation, 2021 and amendments) has introduced, for the first time, technical screening criteria that are directly relevant to desalination projects under the activity *"Construction and operation of water collection, treatment and supply systems."* These criteria, covering energy efficiency thresholds, renewable electricity sourcing, and environmental safeguards for brine discharge and marine ecosystems, create a *de facto* benchmark for projects seeking to qualify as sustainable investments. It is important to note, however, that the Taxonomy functions as a financial classification framework rather than a binding operational regulation for all desalination plants However, some national-level policies still favour conventional fossil fuel based desalination, presenting obstacles for renewable energy alternatives to compete on costs. Broader trends toward renewable energy pricing parity and water pricing reforms account for full costs could enable wider uptake of renewable desalination. Studies such as PESETA III and IV have underscored that integrating desalination into climate resilience strategies can provide long-term economic and environmental benefits, particularly in water-scarce regions of Europe.

Table 1 - Comparative analysis of desalination technologies: key characteristics, benefits, and limitations

Technology	Key points	Advantages	Disadvantages
Multi-Stage Flash Distillation (MSF)	Utilises a series of chambers with successively lower temperatures and pressures. Accounts for the majority of the global desalination capacity.	High salt rejection rates, reliable operation. Economically viable for large-scale applications.	High energy consumption. Requires corrosion-resistant materials.
Multi-Effect Distillation (MED)	Uses the heat from condensation in one stage to pre-heat the feed water for the next stage. Cascade arrangement improves energy efficiency.	Lower energy consumption than MSF. High purity of product water.	Less scalable for smaller operations. Requires corrosion-resistant materials.

Technology	Key points	Advantages	Disadvantages
Mechanical Vapor Compression (MVC)	Compresses water vapor using a mechanical compressor. Does not rely on sequential stages heated by steam.	Lower energy consumption than both MSF and MED. Can be used for small to medium scale operations.	High operating costs due to wear and tear on mechanical parts. Lower throughput compared to MSF and MED.
Reverse Osmosis (RO)	Uses semi-permeable membranes allowing water passage but blocking salts. Most widely used desalination technology globally.	Lower energy consumption than thermal processes. Scalable for a variety of applications, from home use to industrial scale.	Membranes can be fouled by biological material, scale, or particles. High pressure required for operation can lead to energy-intensive processes.
Electrodialysis (ED) and Electrodialysis Reversal (EDR)	Utilise electric potential across ion-exchange membranes to draw ions through membranes. Primarily used for brackish water desalination.	Lower energy consumption compared to RO for brackish water. High ion rejection rates.	Not suitable for seawater desalination due to high salinity. Membranes can be fouled by biological material, scale, or particles.
Emerging Membrane Technologies (Forward Osmosis, Membrane Distillation, Hybrid Processes)	Utilise innovative methods like low-grade heat evaporation or a combination of distillation and membrane separation. Currently under investigation and development.	Potential for lower energy consumption and higher efficiency. May offer improved flexibility and scalability.	Still in developmental stages, not yet commercially proven. Potential challenges and limitations are not fully understood.

5 Use of desalination in agriculture

5.1 Issues of water scarcity in agriculture

Agriculture accounts for approximately 70% of global freshwater withdrawals, making it heavily dependent on reliable water resources (WWAP, 2012). However, climate change, drought, overexploitation of groundwater, and contamination have caused water scarcity in many agricultural regions worldwide. Insufficient or unstable water availability can lead to reduced crop yields, loss of farm income, and threats to food security.

The impacts are most acute in semi-arid and arid regions where water resources are already scarce, as well as coastal areas where excessive pumping has caused groundwater depletion and seawater intrusion into aquifers Prusty & Farooq, 2020). Seawater intrusion and use of brackish groundwater for irrigation exacerbates soil salinisation over time, lowering soil productivity and sustainable agricultural output (Pitman and Läuchli, 2002).

Recent prolonged droughts in Europe have had severe consequences for agriculture and water resources. In the Po Valley region of northern Italy, below-average rainfall since late 2021 has led to critically low levels of surface water in lakes and rivers as well as decreasing groundwater reserves. Rice cultivation has been particularly affected, with an estimated 30-40% reduction in production (Coldiretti, 2022; European Commission Joint Research Centre, 2022). In southern Spain, reservoirs in Andalusia fell to critically low levels after months of drought, prompting emergency irrigation restrictions. Olive groves and other crops have experienced moisture stress and yield declines (AEMET, 2022). Seawater intrusion and use of brackish groundwater for irrigation exacerbates soil salinisation over time, lowering soil productivity and sustainable agricultural output (Pitman and Läuchli, 2002). The economic impacts on the agricultural sector in these regions have been in the billions of euros ([4]). With climate models projecting increased frequency and severity of drought in coming decades, enhancing the resilience and sustainability of water resources for agriculture is crucial. Desalination and water reuse present potential alternative supply options, though energy requirements and brine management remain challenges to scale-up. A mix of technological solutions and improved water use efficiency will be needed to address growing agricultural water scarcity.

([4]) https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf

5.2 Potential of desalination for agricultural irrigation

Reverse osmosis (RO) has emerged as the most widely used and suitable desalination technology for providing alternative water sources for irrigation, due to its modularity, declining costs, and reliability compared to thermal distillation processes (Ghaffour et al., 2015; Jones et al., 2019)). RO membranes reliably remove salts and minerals from brackish groundwater and seawater to generate freshwater flows that can supplement limited surface and groundwater sources. However, desalinated water is low in essential minerals such as calcium, magnesium, and sulfur- ions that are beneficial for plant growth and soil structure (Yermiyahu et al., 2007; Avni et al., 2013).

While this represents a significant limitation for agricultural use, the mineral deficit can be managed through established practices such as fertigation (injecting nutrients via the irrigation system), blending with mineral-rich water sources, soil amendments, and careful crop selection. In water-scarce regions, the reliability of desalinated supply often outweighs these drawbacks, particularly for high-value crops where precise nutrient management is already standard practice (Martínez-Alvarez et al., 2018). Desalinated water also has very low buffering capacity and is highly corrosive, which can negatively impact soils, plant growth, and irrigation equipment when directly applied for irrigation (Qadir et al., 2020) ([5]).

Therefore, blending desalinated water with other water sources or targeted remineralisation is generally necessary to adjust the ionic composition and reduce corrosivity prior to irrigation usage. Boron is a further constraint. Most crops are sensitive to concentrations above 0.75 mg/l in irrigation water, and RO removes boron only partially (about 60%), which in Murcia limits the direct use of desalinated water for irrigation (Post et al., 2021). The high energy demand and capital costs of operating RO desalination pose additional constraints on scalability for agricultural applications.

Transitioning to renewable energy sources such as solar or wind can significantly reduce the carbon footprint of desalination; however, the intermittent nature of these sources poses operational challenges. Reverse osmosis membranes typically require continuous operation to prevent fouling and maintain performance, as intermittent operation can lead to reduced membrane permeability and accelerated degradation (Freire-Gormaly & Bilton, 2019; Mito et al., 2019). This means that renewables alone cannot guarantee uninterrupted power supply for 24/7 operation. To address this constraint, desalination facilities

([5]) This mineral deficit represents a key disadvantage for agricultural use, as post-treatment (remineralisation or nutrient supplementation) is required to make the water suitable for crops, which substantially increases costs. For drinking water, remineralisation is also necessary to meet health standards and improve taste, but the lower per-liter consumption and higher willingness to pay make the economic burden more acceptable compared to large-scale irrigation.

can integrate energy storage systems – such as battery banks or thermal storage – or maintain grid connectivity as backup (Ghaithan et al., 2019; Pistocchi et al., 2020). While neither solution entirely eliminates the environmental footprint – battery production carries its own lifecycle impact, and grid backup may still rely partly on fossil fuels – both strategies substantially reduce greenhouse gas emissions compared to fully fossil-fuel-dependent operations. In this context, incremental improvements represent meaningful progress toward sustainability, even if a zero-carbon outcome remains elusive.

5.3 Economic impact of desalination usage in agriculture

The high capital and operational costs of seawater and brackish water desalination plants impose economic constraints on their feasibility for providing irrigation water, except for high-value greenhouse and cash crops (FAO, 2012). For staple crops the constraint is stricter: producing 1 kg of rice or wheat requires about 1 m³ of water, so even a EUR 1 per m³ increase in water cost would make them too expensive (Post et al., 2021, p. 23).

Government subsidies, blending with other water sources, and in some cases sharing infrastructure and distribution networks with municipal water utilities , have enabled limited use of desalinated water for irrigation. Moreover, combining urban and agricultural supply can improve the economics of desalination: water is primarily directed to households and industry during the year, while surplus capacity in summer months can be allocated to irrigation, thereby smoothing demand profiles and balancing costs across multiple user. Planning shared infrastructure between municipal and agricultural sectors can leverage the presence of local stakeholders willing to invest, reducing the marginal cost of producing desalinated water for irrigation (Zolghadr-Asli et al., 2024).

However widespread adoption still faces challenges particularly regarding cost-competitiveness and the optimisation of supply across different uses. Combining end-uses, urban supply year-round and agricultural irrigation during peak summer months, can help balance demand over the year and improve overall cost-effectiveness of desalination infrastructure.

Estimates of the costs for desalinated water for irrigation range from EUR 0.50 to EUR 2 per m^3 depending on the energy sources utilised, the existence of subsidies, and scale of the desalination plant (Karagiannis and Soldatos, 2008). Cost estimations are highly variable, as there are many factors that come into play; more recent studies confirm that costs remain within this range or even higher, with desalination costs reaching up to EUR 1.66 per m^3 (Areosa et al., 2024).

For comparison, surface irrigation water is often subsidised and priced to farmers between EUR 0.05 to EUR 0.35 per m^3, while reclaimed wastewater may range from EUR 0.02 to EUR 0.83 per m^3 (Areosa et al., 2024; Hurtado and Berbel, 2024), making it significantly cheaper and competitive with conventional sources.

The higher costs of desalinated water make cost-competitiveness difficult without subsidies except for high profit-margin crops, whereas reclaimed water – particularly when combined with nutrient management – shows a substantially higher benefit-cost ratio and thus greater potential for agricultural use, with a lower environmental impact. In the longer term, the levelised costs of renewable electricity from solar and wind are becoming cost-competitive with fossil fuels, which could significantly reduce desalination costs (IRENA, 2020). However, intermittent power supply from renewables requires storage or flexible operation, adding complexities. Gains in RO membrane performance and energy recovery continue to reduce energy needs and costs as well. Nevertheless, widespread feasibility studies on the in-field impacts of desalinated irrigation water on soil quality, crop yields, farm incomes, and food prices remain limited. Further research and experience are needed to provide clarity on the economic viability and potential of desalination technology to sustainably expand agricultural water supply.

As climate change exacerbates droughts and water scarcity in arid and semi-arid agricultural regions worldwide, desalination of brackish groundwater and seawater has emerged as a potential sustainable alternative freshwater resource to supplement irrigation water supplies. Reverse osmosis (RO) is the most widely applied membrane-based technology, with two main applications: seawater reverse osmosis (SWRO) for high-salinity seawater, and brackish water reverse osmosis (BWRO) for lower-salinity inland aquifers. While both rely on semi-permeable membranes and high pressure to remove dissolved salts, SWRO requires significantly higher energy inputs and entails greater challenges in managing brine discharges to the marine environment, whereas BWRO operates at lower pressure and has smaller energy and ecological footprints but can impact inland groundwater balances and soil salinity.

While desalination technologies like RO have been available for decades, major advances in membrane materials and pre-treatment methods coupled with declining costs have enabled larger-scale adoption for agriculture in select arid countries (FAO, 2006, Martínez-Alvarez et al., 2016).

However, the high capital and operational expenditures of desalination remain a constraint, In principle, the price of water should recover investment and operational costs, but in practice this is rarely the case in agriculture, where water tariffs are often subsidised for farmers. As a result, government support mechanisms such as subsidies, off-take guarantees, and cost-sharing with urban supplies have been necessary to facilitate agricultural applications Martínez-Alvarez et al., 2019; Terrero and Zarzo, 2023). The following chapter provides an overview of case studies where desalination has been incorporated into

agricultural water systems, with a focus on Israel and Saudi Arabia as global leaders. The potential benefits in increasing irrigation reliability, cultivating higher-value crops, and reducing pressure on overexploited aquifers are weighed against challenges like intermittent operation from renewable energy sources, remineralisation requirements, and impacts on long-term soil quality.

5.4 Selected case studies

While adoption is still geographically limited, desalination shows promise as one option to ensure availability of freshwater, especially in water-scarce coastal regions susceptible to seawater intrusion. However, further field studies directly comparing yields, soil responses, and farm economics using desalinated water versus conventional irrigation sources over the long term are critically needed. Such field studies should also consider trade-offs of irrigation with desalinated seawater for the climate and the coastal environment. The case studies summarised provide insights into present applications but also highlight unresolved questions regarding the sustainability, crop productivity response, and cost-competitiveness of desalination-based irrigation compared with both traditional freshwater irrigation and reuse alternatives. Case studies around the world.

5.4.1 Israel

Israel has emerged as a global leader in leveraging large-scale desalination to bolster irrigation water security. With recurring multi-year droughts and declining freshwater availability from the Sea of Galilee, Israel has rapidly expanded seawater reverse osmosis (SWRO) desalination capacity since the early 2000s (Tal, 2006). As of 2022, Israel's five major desalination plants produced over 600 million m^3 per year of freshwater, meeting approximately 50% of total national water consumption 85% of total national municipal and industrial demand. While most desalinated water is directed to municipal use, the integration of desalination into the national water grid has indirectly supported agriculture by freeing up other water sources, including treated wastewater, for irrigation (Raveh and Ben-Gal, 2018)

The typical cost paid by Israeli farms for desalinated water was approximately EUR 0.50 per m^3 when first introduced in the early 2000s, significantly higher compared to water from conventional sources which was heavily subsidised at EUR/m^3 0.05-0.35. However, thanks to technological improvements in desalination and economies of scale, the cost of desalinated water in Israel has dropped to EUR/m^3 0.30-0.40 in recent years, with the new Sorek B plant, setting a new global benchmark (Israel Water Authority, 2022). This makes it much more competitive compared to historically subsidised sources, while remaining slightly more expensive. Access to desalinated water at competitive prices has enabled thriving intensive agriculture in Israel’s arid areas such as the Arava Valley (Lew et al. 2020). The Negev desert in Israel’s arid south has particularly benefited from access to desalinated brackish groundwater and reclaimed wastewater. The Dan Region wastewater recycling plant, the largest in the Middle East, treats approximately 140 million m^3 per year of wastewater from the Tel Aviv metropolitan area and supplies reclaimed effluent suitable for unrestricted agricultural irrigation to farms in the Western Negev, where more than 60% of

agriculture relies on this water source (Mekorot, 2023). The Arava Valley, located further south, relies primarily on brackish groundwater desalination and local wastewater recycling for its agricultural water supply, enabling intensive, high-yield agriculture with valuable export crops like dates, tomatoes, and peppers to thrive in the harsh arid conditions (Lew et al., 2020). The Sorek B (officially named Sorek 2 – Be'er Miriam) plant represents a significant milestone in Israel's pursuit of large-scale desalination to address water scarcity challenges. The facility became operational in early 2025 and is now actively supplying water to Israel's national grid, making it the largest desalination plant in Israel and one of the largest in the world, with an annual output of 200 million m³ (670 000 m³/day) (IDE Technologies, 2025). The plant has achieved a record-low contracted water price of approximately USD 0.41 per m^3 (equivalent to approximately EUR/m³ 0.38), setting a new global benchmark for seawater desalination costs (Israel Water Authority, 2022; IDE Technologies, 2025).

Sorek 2 – Be'er Miriam incorporates several groundbreaking innovations. It is the world's first steam-driven seawater reverse osmosis (SWRO) plant, featuring state-of-the-art capabilities that optimise energy utilisation and minimise environmental impact. The facility employs advanced 16-inch diameter membrane elements in vertical configuration, high-efficiency pumps, sophisticated energy recovery devices, and on-site chemical production to reduce dependency on external supplies. Notably, the plant operates with its own independent power station, enabling autonomous operation unaffected by fluctuations in the electric grid (IDE Technologies, 2025).

A key sustainability feature is the plant's integrated carbon capture system, which recycles CO_2 from the independent power station into the remineralisation process. This innovative approach reduces the facility's specific carbon footprint by 30%, resulting in savings of approximately 120 000 tonnes of CO_2 emissions annually. These advancements have earned Sorek 2 – Be'er Miriam a nomination for the 2025 Global Water Award for Desalination Plant of the Year (IDRA, 2025).

The integration of Sorek 2 into Israel's broader desalination network – alongside the Ashkelon, Palmachim, Hadera, Sorek (I), and Ashdod plants – brings the total national SWRO capacity to approximately 750-800 million m^3 per year, supplying over 85% of Israel's municipal and industrial water demand. While desalinated seawater is primarily allocated to municipal and industrial use, its availability indirectly supports agricultural irrigation by reducing pressure on conventional freshwater sources and enabling greater allocation of treated wastewater to farming (Raveh and Ben-Gal, 2018; Kramer et al., 2022).

5.4.2 Morocco

Morocco represents a significant case study as it hosts the world's largest seawater desalination plant specifically designed for combined drinking water and agricultural irrigation purposes. The Chtouka-Agadir desalination plant, located in the Souss-Massa region of southern Morocco, became operational in 2022 and represents an innovative public-private partnership (PPP) model for agricultural water supply (Ministère de l'Agriculture du Maroc, 2022).

The Chtouka plain is characterised by high-value greenhouse horticulture, producing approximately 65% of Morocco's fruit and vegetable exports destined primarily for European markets. Since the early 2000s, the region has experienced increasing pressure on water resources, with groundwater extraction exceeding the aquifer's renewable potential and causing a continuous decline in water table levels estimated at a deficit of approximately 90 million m³ per year, threatening agricultural sustainability (Ministère de l'Agriculture du Maroc, 2020).

The desalination plant has an initial production capacity of 275 000 m³/day, with 150 000 m³/day allocated to drinking water supply for Greater Agadir (population 2.3 million) and 125 000 m³/day dedicated to irrigation of 15 000 hectares benefiting approximately 1 500 farms. The facility is designed to expand to 400 000 m³/day at full capacity, with production shared equally between drinking water and irrigation (Ministère de l'Agriculture du Maroc, 2022). The plant employs seawater reverse osmosis technology and is increasingly powered by renewable energy sources (wind and solar).

The total project cost amounts to approximately 4.48 billion Moroccan dirhams (approximately EUR 400 million), financed through a public-private partnership between the Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests (MAPMDREF) and the National Office of Electricity and Drinking Water (ONEE), with private sector participation for a 30-year concession period including construction, operation, and maintenance (Ministère de l'Agriculture du Maroc, 2020).

The Moroccan government has implemented complementary governance measures to ensure sustainable aquifer management, including: a groundwater protection decree establishing extraction quotas to limit groundwater pumping; and mandatory commitments from farmers cultivating high-value crops to use 3 600-4 000 m³ of desalinated water per hectare per year (Ministère de l'Agriculture du Maroc, 2020). This integrated approach combining desalination supply with demand-side groundwater management provides a model for addressing agricultural water scarcity in semi-arid coastal regions.

The project is estimated to prevent economic losses of approximately 9 billion dirhams in agricultural value-added and 3 billion dirhams in capital by 2035, while preserving over 1 million jobs annually in the agricultural sector (Ministère de

l'Agriculture du Maroc, 2022). Morocco has announced plans to expand its national desalination capacity to 1.7 billion m³ annually by 2030 through construction of additional plants, several of which will include agricultural irrigation components (ONEE, 2024).

5.4.3 Saudi Arabia

Saudi Arabia is the world's largest producer of desalinated seawater, with a daily production capacity exceeding 16 million m^3 (MEWA, 2025). The Kingdom operates over 40 desalination plants along the Red Sea and Arabian Gulf coasts, with approximately 69% of national production managed by the Saline Water Conversion Corporation (SWCC) and the remainder by private sector operators (MEWA, 2024). While the country historically relied on multi-stage flash (MSF) thermal distillation technology powered by fossil fuels, Saudi Arabia is increasingly transitioning to more energy-efficient seawater reverse osmosis (SWRO) systems, achieving a nearly 50% reduction in energy consumption for desalination and the world's lowest production costs (MEWA, 2025).

Agriculture accounts for approximately 88% of total water withdrawals in Saudi Arabia (FAO AQUASTAT, 2008). However, this water is sourced almost entirely from non-renewable groundwater aquifers, not from desalination. According to FAO AQUASTAT (2008), 97% of irrigated agriculture relies on groundwater, while desalinated water is allocated primarily for municipal and industrial uses, supplying approximately 60% of urban water (MEWA National Water Strategy, 2018). The heavy reliance on desalination for municipal supply imposes a significant economic burden on the Saudi economy due to relatively high production and transmission costs, particularly for pumping water from coastal plants to inland cities (MEWA, 2018).

Saudi Arabia achieved wheat self-sufficiency during the 1980s and 1990s through extensive irrigation from fossil groundwater aquifers. However, recognising that groundwater withdrawals substantially exceeded natural recharge and that agriculture based entirely on groundwater was unsustainable, the Saudi government enacted a policy change in 2008 to phase out wheat cultivation (FAO, 2016). Domestic wheat production was completely terminated by 2016 to preserve depleting water reserves (FAO GIEWS, 2022). The Kingdom now imports the majority of its wheat requirements, though limited domestic production was reintroduced in 2018 with a quota of up to 1.5 million tonnes annually to reduce import dependence (FAO GIEWS, 2022). Despite phasing out wheat, the agricultural sector continues to account for the largest share of water consumption, with fodder crops alone constituting 67% of agricultural water demand (MEWA, 2018).

The Saudi National Water Strategy 2030 aims to reduce non-renewable groundwater use by 90% by 2035 and cut water production costs by 50% (MEWA, 2025). The strategy has already achieved savings of 8 billion m^3 of non-

renewable agricultural water annually and increased renewable water use by over 1 billion m^3 through initiatives including the construction of 1 000 dams (MEWA, 2025). By 2030, the Ministry of Environment, Water and Agriculture targets meeting 90% of the Kingdom's water needs through desalination and 10% through ground and surface water sources.

Saudi Arabia’s capacity to invest extensively in desalination is supported by its abundant petroleum resources. According to the US Energy Information Administration (EIA, 2024), Saudi Arabia holds approximately 267 billion barrels of proven oil reserves – approximately 15% of the global total and the second largest in the world after Venezuela. The Kingdom maintains crude oil production capacity of approximately 12 million barrels per day and was the world's third-largest crude oil producer and top crude oil exporter in 2023 (US EIA, 2024). This petroleum wealth provides relatively low-cost energy to power large-scale desalination. This differential in energy costs contributes to Saudi Arabia’s ability to produce desalinated water at price points that would be difficult to achieve in the EU context. However, the Kingdom is increasingly investing in renewable energy-powered desalination facilities to reduce carbon emissions and further lower production costs, including the world’s largest solar-powered desalination plant at Al-Khafji (MEWA, 2025).

5.5 Case studies in Europe

Europe, particularly the Mediterranean regions, is increasingly reliant on desalination, specifically reverse osmosis desalination, as a key water source for agricultural irrigation. This approach is critical in these regions due to the arid and semi-arid climate, recurrent droughts, and the growing demand for water due to population growth and agricultural intensification.Countries like Spain, Greece, and Cyprus have implemented desalination technologies to supplement irrigation water, primarily for the growth high-value horticultural crops such as fruits, vegetables, and grapes.

Spain, for instance, has one of the world's most extensive seawater desalination capabilities and accounts for approximately three-quarters of the European Union's total desalination capacity (The Blue Economy Observatory, 2024). Major facilities including the Torrevieja, Alicante I and Valdelentisco plants employ reverse osmosis technology. Following the implementation of the AGUA Programme in 2004, the Spanish Government designed the construction of 21 high-volume desalination plants with a total capacity of 1 063 hm^3/year, of which 46% was planned to be devoted to agriculture (Zarzo et al., 2013; Martínez-Álvarez et al., 2016). This desalinated water is channelled to irrigation districts in the southeastern Murcia and Almería regions, which predominantly produce fruit, vegetables, and grapes for export to European markets. Studies suggest that during drought periods, when surface water resources are strained, desalinated seawater can constitute between 50-80% of the total agricultural irrigation supply in these regions (Martínez-Alvarez et al., 2016). In Murcia, desalination was the only reliable water source for agriculture during the 2015-2018 drought, when inter-basin transfers fell to 142-188 million m^3/year (Post et al., 2021, p. 26). However, the actual uptake of desalinated water by farmers has been limited due to its higher cost compared to conventional sources, resulting in some desalination plants operating below capacity in recent years (Martínez-Álvarez et al., 2016, 2017).

In the Greek islands and coastal regions, water scarcity has prompted the development of small-scale desalination plants, particularly on the Aegean Islands where water has traditionally been transported by ship at high cost (Chartzoulakis et al., 2001; Mentis et al., 2016). On the island of Crete, groundwater constitutes the major water source, covering more than 95% of water uses, with agricultural irrigation accounting for approximately 84.5% of total consumption (Chartzoulakis et al., 2001). While the potential for wastewater recycling and reuse in Crete is relatively high, preliminary estimates suggest that implementation of such plans could lead to water savings of up to 5% of total irrigation water (Chartzoulakis et al., 2010).

Similarly, on the Island of Cyprus, where seasonal droughts are a common occurrence, desalination has become an important component of the national water supply strategy. However, challenges remain regarding the long-term

agronomic effects of irrigating with desalinated seawater, including concerns about boron toxicity to sensitive crops and potential impacts on soil physical properties due to the low calcium and magnesium content of desalinated water (Martínez-Álvarez et al., 2016). These concerns require careful attention to post-treatment remineralisation, appropriate blending with conventional water sources, and selection of tolerant crop varieties.As Mediterranean Europe continues to grapple with challenges presented by climate change and population growth, desalination is expected to play an increasingly important role in maintaining the region's food security. It provides a promising solution to water scarcity in these areas, but it is crucial that its implementation is carried out with a careful consideration of its environmental implications and sustainability.

6 Future perspectives and recommendations

6.1 Future trends in desalination

Several key technological, sustainability, and systems integration trends are anticipated to shape the advancement of desalination globally and in Europe in the coming decades:

Transition to renewable energy supplies: Conventional desalination powered by fossil fuel combustion will shift towards renewable energy sources like solar photovoltaics, concentrated solar thermal, onshore and offshore wind, wave energy, and geothermal heat. However, effectively managing the intermittency and variability from solar, wind, and wave sources will require integrating cost-optimal hybrid renewable systems, buffers, and storage along with advanced power electronics, controls, and flexible operation capabilities tailored to desalination processes (IRENA, 2021).

- Intermittency challenge: to overcome the intermittency challenge, incorporating energy storage solutions, such as batteries and accumulators, becomes crucial. These storage systems serve as a means to store excess electricity generated during periods of surplus and utilise it when production falls short of demand. The implementation of energy storage systems can reduce reliance on the instantaneous availability of renewable sources, enhancing the stability and reliability of power supply for desalination processes. These storage systems can be seamlessly integrated with advanced power electronics, controls, and flexible operational capabilities, as highlighted in the IRENA report. Furthermore, combining batteries, accumulators, and other energy storage systems with state-of-the-art desalination technologies can create efficient and cost-effective hybrid systems. This approach ensures a continuous supply of fresh water without complete dependence on the immediate availability of renewable sources.Advanced membrane materials: membranes are a critical component determining the energy efficiency, water recovery, and process economics of reverse osmosis, electrodialysis, and emerging technologies like forward osmosis and membrane distillation. Next generation nanostructured, biomimetic, and graphene-based membrane materials offer potential for substantial gains in permeability while maintaining high salt rejection (Subramani & Jacangelo, 2015). Membranes incorporating nanoparticles, carbon nanotubes, or graphene show promise as innovative desalination technologies with superior performance in terms of water permeability and salt rejection, though only nanocomposite membranes have been commercialised while others remain under fundamental developmental stages (Subramani & Jacangelo, 2015).

- Hybridisation and process intensification: combining the principles of distillation, membrane separation, freezing, microbial desalination, and other techniques into integrated hybrid processes allows synergies for overall energy and water recovery optimisation (Droli et al, 2017). However, the complexity increases capital costs. Process intensification via innovative equipment design, integration, waste heat utilisation, and brine recycling also provide major efficiency gains but requires overcoming scaling challenges.
- Smaller, modular systems: factory manufactured, standardised, containerised desalination systems with capacities between 100 to 5 000 m^3/day offer advantages of modular scaling, rapid installation, and decentralised operation for on-demand needs (IRENA, 2012). But modular designs lose out on the economies of scale of large centralised facilities.
- Increased water reuse with desalination: as climate change is becoming a major issue and environmental regulations tighten, directly treating wastewater effluent or blending it with seawater for desalination will become increasingly common as a planned indirect potable water reuse solution, despite public perceptions (Panagopoulos & Haralambous, 2020). However, health and social acceptance concerns remain for direct potable water reuse.
- Improved brine management: with stricter discharge regulations, brine management technologies and strategies will transition from simple dilution and disposal to recovery of salts, minerals, and metals along with volume minimisation approaching zero liquid discharge (Morillo et al., 2014, Panagopoulos, 2021). However, scaling control during brine concentration remains a persistent challenge.

6.2 Key findings from EU-funded projects

The European Union has long recognised the strategic importance of desalination research and has funded numerous collaborative projects in this domain. Beginning in the early 2000s, EU programmes have provided critical support for innovative desalination technologies, integration approaches with renewable energy supplies, systems optimisation, pilot demonstrations, and policy development. These projects have catalysed cross-border coordination between partners from universities, research institutes, technology developers, and water utilities across European member states.

Key lessons learned based on outcomes of these EU-funded efforts include:

- Renewable energy supplies like solar and wind can be coupled with desalination but require careful management of intermittency through storage or hybrid configurations (ProDes, MEDESOL, MEDIRAS).
- Membrane distillation (MD) technology shows promise for distributed desalination in the 0.1-50 m^3/day capacity range, particularly when driven by low-grade solar thermal heat (MEDESOL, MEDIRAS, MEloDIZER).
- Microbial desalination cells can simultaneously treat wastewater and generate bioelectricity for desalination, though challenges remain with scaling and biofouling (MIDES).
- Circular economy approaches to brine management can recover valuable minerals while reducing environmental impact (ZERO BRINE, SEA4VALUE).
- Concentrated solar power can effectively drive thermal desalination with waste heat utilisation achieving significant CO_2 reductions (MATS, DESOLINATION).

It should be noted that the majority of EU-funded desalination projects listed in Table 2 focus on desalination technology development in general, rather than specifically on agricultural irrigation applications. Most projects target municipal drinking water supply, industrial water use, or remote community water provision.

Projects with explicit agricultural focus are rare:

- AQUASOL (2025-2028) is the only Horizon Europe project explicitly targeting “Water Desalination in Agriculture and Wastewater Recycling”;
- ADIRA (2003-2008) included irrigation among its objectives for rural Mediterranean communities.

This gap reflects the economic challenges of agricultural desalination where costs remain significantly higher than conventional irrigation water and the fact that agricultural water management falls largely under Member State jurisdiction, with countries like Spain developing national programmes (e.g., AGUA Programme)

rather than relying on EU-funded research. Despite this limited agricultural focus, these projects remain relevant because they develop enabling technologies energy-efficient membranes, renewable energy integration, cost-effective brine management, that are prerequisites for economically viable agricultural desalination.

Table 2 – List of EU-funded desalination projects

Project	Period	Programme	Focus	Key outcomes
ProDes	2008-2010	IEE	Market development for RE-desalination in Southern Europe	RE-desalination roadmap; training courses; 14 EU partners
MEDESOL	2006-2009	FP6	Solar-powered membrane distillation with compound parabolic concentrators	Multi-stage MD systems for 0.5–50 m^3/day capacity
MEDINA	2006-2009	FP6	Integrated membrane-based desalination	Water recovery up to 95%; brine minimisation strategies
MEDIRAS	2008-2012	FP7	Cost-effective solar-driven MD systems for remote areas	Demo sites in Gran Canaria, Tuscany, Tunisia (up to 5 m^3/day)
NAWADES	2012-2017	FP7	Nanotechnological applications in water desalination	Combined UF+RO membranes; nanoparticle coatings
MIDES	2016-2020	H2020	Microbial desalination cells for low-energy drinking water	World's largest MDC demonstrator; demo sites in Spain, Chile, Tunisia
ZERO BRINE	2017-2021	H2020	Circular economy recovery of water and minerals from industrial brines	Demo at Rotterdam Port; recovery of Mg, NaCl, $CaCO_3$
SEA4VALUE	2020-2024	H2020	Multi-mineral brine mining from desalination plants	Recovery of Mg, B, Sc, Ga, Li, V, In, Mo, Rb; mobile lab in Tenerife
WATER-MINING	2020-2024	H2020	Next-generation water-smart management with resource recovery	Integration of wastewater reuse and desalination
DESOLINATION	2021-2025	H2020	CSP coupled with forward osmosis desalination	Demo at King Saud University, Riyadh; target LCOW <€0.9/m^3

Project	Period	Programme	Focus	Key outcomes
Sol2H2O	2022-2025	Horizon Europe	Solar-driven water production with zero liquid discharge	Circular economy framework for solar desalination
MEloDIZER	2023-2027	Horizon Europe	Sustainable membrane distillation for industrial water reuse	High-performance MD membranes; 90–100% renewable energy
AQUASOL	2025-2028	Horizon Europe	RE-powered desalination for agriculture and wastewater recycling	Graphene-based membranes; energy management systems
ADIRA	2003-2008	MEDA-Water	Autonomous RE-powered desalination for rural areas including irrigation	10 demo units in Jordan, Morocco, Turkey, Cyprus (ADIRA Handbook, 2008)

6.3 Recommendations for promoting desalination in Europe

These recommendations originate from several key studies and reports, as cited below, and are designed to promote the increased adoption of desalination while aligning with European environmental sustainability goals. The following specific policy, economic, collaboration, and research measures are recommended:

- Develop regional or national level desalination master plans considering available alternative water supply options, environmental factors, and sustainability objectives to guide suitable desalination capacity expansion and site selection (ProDes, 2010).
- Establish dedicated public R&D funding programmes at EU and national levels focused on pilot and demonstration projects to de-risk and facilitate commercialisation of innovative desalination technologies integrated with renewable energy supplies (ProDes, 2010, MEDINA, 2011).
- Implement preferential feed-in tariffs and priority grid access for electricity generated by renewable powered desalination facilities (ProDes, 2010).
- Provide investment tax credits, soft loans, and capital investment subsidies specifically for sustainable desalination projects, while removing embedded electricity subsidies for conventional desalination (ProDes, 2010).
- Develop European level technical codes and standards specific for desalination plants considering energy efficiency, material selection, corrosion prevention, brine management, environmental impact assessment, and other factors tailored to desalination (MEDINA, 2010).
- Reform urban and agricultural water pricing to reflect the full economic cost of freshwater supplies, allowing comparison to desalination costs on an equitable basis (ProDes, 2010)Enhance R&D funding within Horizon Europe dedicated to sustainable desalination innovations, including circular economy approaches for resource recovery from desalination brine and wastewater (WATER MINING, 2020).
- Implement more stringent regulations on brine disposal, while funding pilot projects on brine volume minimisation, recovery, and zero liquid discharge systems (Altaee et al., 2022).
- Strengthen coordination, knowledge sharing, advocacy, and harmonisation of policies through the European Desalination Society (EDS) and support establishment of dedicated working groups for renewable energy-powered desalination (ProDes, 2010).

- Conduct comprehensive analysis of seawater characteristics at potential desalination sites in European regional seas to inform site selection and technology choices (ProDes, 2010; MEDINA, 2010).

The combination of supportive policies, targeted funding programmes, strong sustainability regulations, and collaborative innovation networks can enable desalination to increase future water supply security in Europe in a sustainable manner.

7 Conclusions

As climate change impacts intensify in Europe and globally, increasing pressures on freshwater resources have increased interest in desalination as a complementary option for enhancing water supply, especially in coastal areas. Seawater desalination and brackish water desalination provide alternative water sources that can supplement constrained conventional supplies. However, desalination has high capital and operational costs and must be pursued sustainably.

This report has provided an overview of established and emerging desalination technologies, regulatory considerations, case studies, future trends, and recommendations focused on the EU context. Thermal distillation processes including multi-stage flash and multi-effect distillation along with membrane-based reverse osmosis have clear advantages and limitations that determine suitable applications. Hybrid membrane-thermal approaches are an active area of innovation. Regulatory frameworks at the EU level related to water quality, environmental protection, and sustainability provide boundaries within which desalination systems must align. Case studies in water scarce regions like Israel, Morocco, Saudi Arabia, Spain, and Cyprus reveal existing uses for irrigation and drinking water.

Looking ahead, coupling desalination with renewable energy supplies, concentrating brine streams, and recovering resources will be critical for sustainable expansion. Supportive policies, targeted R&D funding, water pricing reforms, and collaboration networks can enable increased appropriate adoption of desalination in Europe. .

At the same time, it should be noted that, even under a no-change scenario – that is a scenario where there are no further technological and legal developments in the coming years – desalination is likely to become a more attractive option for agricultural use, in spite of its relatively high operational costs. This is because, in a Europe where droughts are projected to become more frequent and intense, there is a high risk that agricultural output will decrease; the opportunity costs will thus also change, making desalinated water relatively more competitive.

In conclusion, desalination forms an essential component of diversified, resilient water supply portfolios moving forward, but must be pursued in a sustainable manner consistent with circular economy principles and in the context of an integrated water management with the efficiency first principle.

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