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Spain and Osmotic energy: From salinity gradients to dispatchable power

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Abstract:

This article argues that Spain has a window of opportunity to position itself in the osmotic energy industry, and that it should act before it closes. The argument rests on three pillars: first, osmotic energy can provide dispatchable power to the electricity system, a valuable complement to the variability of solar and wind; second, the value chain is anchored in European capabilities—membranes, water engineering and plant operations—in which Spain is globally competitive; and third, hybrid applications with desalination and industrial brines represent the most commercially promising niche, precisely where Spain's ecosystem of companies and technology centres can build a competitive advantage.

Keywords:

Osmotic energy, blue energy, salinity gradient, strategic autonomy, desalination, marine renewable energy.

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Introduction

Osmotic energy, also referred to as "blue energy" or salinity gradient energy, is a marine renewable technology that converts into electricity the energy released when water streams of differing salinity—typically freshwater and seawater—are allowed to mix. Unlike variable renewables, its resource can deliver a potentially highly stable generation profile, thus opening the door to dispatchable power for the electricity system, provided that sustained water flows and concentration gradients are available. Here, "dispatchable" should be understood as predictable and adjustable within operational margins, rather than as a full substitute for conventional firm capacity. Its global technical potential has been estimated[1] at over five thousand terawatt-hours per year (TWh/year), equivalent to 17% of global electricity demand in 2024[2].

The World Economic Forum included osmotic energy among its top ten emerging technologies in 2025. Beyond the resource itself, its strategic relevance lies in the fact that the value chain is anchored in European capabilities—membranes, water engineering, and plant operations—and that the most commercially promising use cases, namely hybrid applications combining desalination and industrial brines, may accelerate the pathway to commercial maturity.

Within this framework, Europe holds a technical potential of nearly 400 TWh/year[3], and Spain, by virtue of its world-leading position in desalination and the presence of estuaries and low-salinity streams along its coastline, has a window of opportunity to establish itself in this nascent industry.

What osmotic energy is and how it works

When freshwater mixes with saltwater, thermodynamic energy is released—the Gibbs free energy of mixing[4]. The salinity gradient between river water and seawater generates

[1] World Economic Forum, "How osmotic energy could generate 20% of global energy needs", September 2025. Available at: https://www.weforum.org/stories/2025/09/what-is-osmotic-energy-and-how-could-it-generate-one-fifth-of-the-world-s-energy-needs/ (accessed: 11 January 2026).
[2] Ember, Global Electricity Review 2025, April 2025. World electricity consumption reached 30,856 TWh in 2024. Available at: https://ember-energy.org/latest-insights/global-electricity-review-2025/ (accessed: 23 January 2026).
[3] IRENA, "Salinity gradient energy technology brief", June 2014. Available at: https://www.irena.org/media/Files/Publication/2014/Jun/Salinity_Energy_v4.pdf (accessed: 11 January 2026).
[4] United Nations, "Blue energy: Salinity gradient power in practice", GSDR 2015 Brief. Available at: https://sustainabledevelopment.un.org/content/documents/5734BlueEnergy.pdf (accessed: 7 January 2026).

an osmotic pressure equivalent to a 270-metre water column, comparable to a large hydraulic head[5].

Two technologies compete to capture this energy. Reverse Electrodialysis (RED) converts ion flow directly into electricity through stacks of ion-exchange membranes[6]; it operates at atmospheric pressure and performs best with moderate gradients, such as those found at river mouths. Pressure Retarded Osmosis (PRO) employs semipermeable membranes to pressurise water and drive a turbine; it is better suited to high gradients, such as those offered by desalination brines.

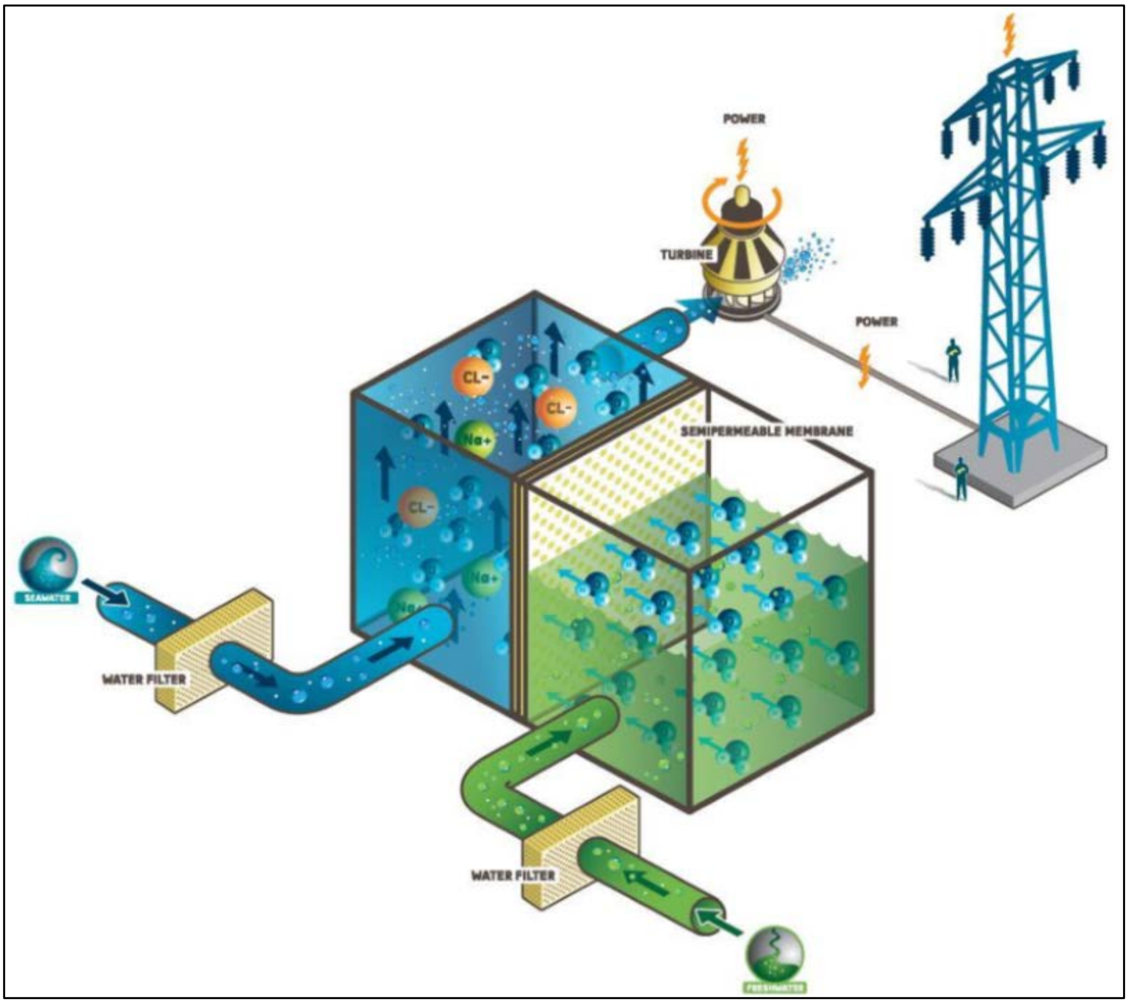

Figure-1: Simplified schematic of the PRO system
Source: Research Gate (www.researchgate.net/figure/Schematic-representation-of-the-PRO-process)

[5] Ocean Energy Europe, "Salinity Gradient". Available at: https://www.oceanenergy-europe.eu/ocean-energy/salinity-gradient/ (accessed: 19 December 2025).
[6] Ion-exchange membranes are polymeric structures that allow the selective passage of cations or anions. Cation-exchange membranes (CEMs) allow the passage of positive ions such as sodium (Na^+), while anion-exchange membranes (AEMs) allow the passage of negative ions such as chloride (Cl^-).

Membranes are the critical component. The threshold for commercial viability stands at 5 W/m² of power density; advances in two-dimensional nanomaterials[7] have demonstrated values exceeding 20 W/m² under laboratory conditions, although scaling up to industrial level remains a challenge.

To aid readability, four units are employed throughout this article: (1) TWh/year, to compare annual potential; (2) MW, for installed capacity; (3) W/m², a key indicator as it determines membrane surface area and CAPEX; and (4) kWh/m³ (or MJ/m³), for energy per volume of water processed. As a useful equivalence, 1 MJ ≈ 0.278 kWh.

Current state of the technology

The Statkraft prototype in Norway (2009) marked the beginning of the practical era of osmotic energy[8], yet it achieved only 1 W/m²—far below the commercial threshold of 5 W/m²—and the company abandoned the project in 2013[9].

A decade on, the landscape has changed considerably.

REDstack (Netherlands) has operated a 50-kW pilot plant in the Wadden Sea[10] since 2014, demonstrating continuous operation and exploring early-stage green hydrogen production[11].

SaltPower (Denmark) commissioned a 100-kW installation in 2023, fed by high-concentration industrial brines (approximately 16%)[12]; within the framework of its European project, the company has reported an estimate/target of 21 EUR/MWh for this niche—a figure that requires independent verification and evaluation at larger scale, but,

[7] The most widely studied two-dimensional nanomaterials for osmotic membranes include: graphene (single-atom-thick carbon sheets), MXenes (transition metal carbides or nitrides), and hexagonal boron nitride (a ceramic compound with a graphene-like structure).

[8] Power Technology, "Statkraft osmotic power plant". Available at: https://www.power-technology.com/projects/statkraft-osmotic/ (accessed: 19 December 2025).

[9] Statkraft, "Statkraft halts osmotic power investments", December 2013. Available at: https://www.statkraft.com/newsroom/news-and-stories/2013/Statkraft-halts-osmotic-power-investments/ (accessed: 20 December 2025).

[10] REDstack, "Our Heritage". Available at: https://www.redstack.nl/our-heritage/ (accessed: 4 January 2026).

[11] The Afsluitdijk, "Blue Energy". Available at: https://theafsluitdijk.com/projects/blue-energy/ (accessed: 10 January 2026).

[12] CORDIS, "Competitive and CO2 Free Energy from Osmotic Power-Large Scale Deployment", SaltPower project, Horizon2020. Available at: https://cordis.europa.eu/project/id/954045 (accessed: 4 January 2026).

if confirmed, would place the technology within competitive range[13] for high-salinity applications.

The first Asian project was inaugurated in Fukuoka (Japan) in August 2025: a hybrid system combining desalination brine with treated wastewater, with projected output of 880,000 kWh/year[14].

On the membrane front, Sweetch Energy (France) leads innovation with its INOD[15] technology, based on nanochannels fabricated from bio-based materials, with reported power densities of 20–25 W/m² under operationally representative conditions[16]. The company has secured funding from Électricité de France (EDF) and Compagnie Nationale du Rhône (CNR), and its demonstrator plant in the Rhône delta seeks to validate performance under real-world conditions as the basis for progressive industrial scale-up over the coming decade.

Technical challenges

Membrane fouling is the Achilles heel of the technology. Microbial colonisation and mineral scale precipitation[17] can reduce flux by 30% to 60%, cutting membrane lifespan to half of what was anticipated. Current research is exploring self-cleaning coatings[18], but the problem is far from solved.

Water pretreatment—filtration, chlorination, pH adjustment—accounts for 15% to 25% of operating costs and consumes energy that must be subtracted from net output. This is precisely where hybrid applications with desalination offer a structural advantage: the brine has already been pretreated, thereby eliminating a substantial portion of these costs and simplifying operations.

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[13] Note that 21 EUR/MWh = 0.021 EUR/kWh is just 20% of the average electricity price in the European Union.
[14] New Atlas, "Electricity through osmosis: Japan opens landmark osmotic power plant", August 2025. Available at: https://newatlas.com/energy/electricity-through-osmosis-japan-opens-worlds-second-osmotic/ (accessed: 11 January 2026).
[15] INOD: Ionic Nano Osmotic Diffusion, a technology patented by Sweetch Energy that employs nanochannels made from biologically derived materials.
[16] Sweetch Energy, "Pioneering osmotic power with INOD technology". Available at: https://www.sweetch.energy/company/ (accessed: 11 January 2026).
[17] Biofouling is the colonisation of surfaces by microorganisms that form biofilms, while scaling is the precipitation and accumulation of mineral salts on membranes.
[18] Nature, "Salinity gradient induced blue energy generation using two-dimensional membranes", npj 2D Materials and Applications, 2024. Available at: https://www.nature.com/articles/s41699-024-00486-5 (accessed: 7 January 2026).

Finally, a significant gap persists between theoretical potential and real-world performance. Maximum thermodynamic efficiency is approximately 91%, yet practical systems operate in the 30–40% range. Ion accumulation on membrane surfaces[19], reverse salt flux, and above all pumping consumption—which can absorb between 20% and 40% of gross output—constrain the net energy that can be harvested.

None of these obstacles is insurmountable, but they shape the roadmap: the first competitive projects will be those that minimise pretreatment and operate with high gradients.

Non-technological risks

Discussion of viability tends to focus on membranes and costs. Yet experience in marine renewables suggests that non-technological factors—permitting, environmental impact, social acceptance—can be equally or even more decisive than the learning curve[20]. Technical potential estimates rest on hydrological and salinity-gradient assumptions, but seldom incorporate ecological constraints or coastal spatial planning; the realisable potential ultimately depends on the ability to design projects that are compatible with ecosystem protection.

In environmental terms, the most attractive sites—estuaries, deltas and brackish mixing zones—coincide with areas of high ecological value, often designated under Natura 2000 or equivalent protection schemes[21]. The abstraction and return of water flows locally alter current velocities, salinity gradients and, to a lesser extent, temperature and turbidity. Such changes may affect transitional habitats, wetlands and fish migration routes, as well as interact with pre-existing pressures (pollution, eutrophication, dredging). To be viable, a project must demonstrate—through hydrodynamic modelling and baseline characterisation campaigns—that its impact is limited and reversible, and that its design

[19] Concentration polarisation is a phenomenon that occurs on membrane surfaces when ions accumulate or deplete locally, reducing the effective concentration gradient and thus the process efficiency.
[20] Ocean Energy Europe, Ocean Energy: Key Trends and Statistics 2023, March 2024. The report identifies delays in permitting and regulatory complexity as the main barriers to the deployment of ocean energies in the EU. Available at: https://www.oceanenergy-europe.eu/
[21] In the EU, more than 18% of the land surface and 9% of the seas are included in the Natura 2000 Network. Many European estuaries with osmotic potential—Rhine-Meuse, Rhône, Ebro, Tagus—host protected areas under the Habitats Directive (92/43/EEC) and Birds Directive (2009/147/EC).

incorporates mitigation measures: discharge diffusers, intake point selection, seasonal restrictions and flow control.

The permitting challenge is equally significant. Unlike other ocean technologies that operate in open waters, osmotic energy sits at the interface between energy, water, coastal, port and—on occasion—protected area jurisdictions.

In Spain, Royal Decree 962/2024[22] provides a framework for marine-based renewable installations; however, many osmotic projects will materialise as hybrids within water infrastructure (desalination plants, wastewater treatment works, salt-processing industries) or in estuarine zones, where discharge authorisations, water abstraction licences, occupation of the maritime-terrestrial public domain, grid connection and environmental impact assessment all converge. The practical consequence: the technology roadmap must include, from the earliest stages, a regulatory roadmap.

Social acceptance is the third vector. Coastal communities and sectors dependent on the estuary—artisanal fishing, aquaculture, tourism, conservation—demand guarantees of coexistence. Osmotic energy may benefit from two distinctive features: a limited visual footprint and the possibility of association with public services such as water supply or effluent[23] treatment. Hybrid configurations with desalination, in particular, turn a waste product (brine) into a visible co-benefit: reducing the net electricity consumption of water production whilst simultaneously lowering the salinity of the discharge. Communicating these co-benefits and establishing transparent monitoring mechanisms is decisive for building legitimacy.

From a project design perspective, strategies exist to reduce environmental and regulatory friction: prioritising already anthropised[24] industrial sites with existing intakes and outfalls; using available low-salinity streams (reclaimed water) instead of new river abstractions; adopting modular and reversible sizing, which facilitates pilots and learning; and committing to monitoring programmes with biological and hydrological indicators.

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[22] Spain's Royal Decree 962/2024, on 24 September, regulating the production of electricity from renewable sources in installations located at sea. Available at: https://www.boe.es (accessed: 4 January 2026).

[23] Effluents are the output streams from an industrial process or water treatment system. In the context of osmotic energy, they mainly refer to treated wastewater that can be used as a source of fresh water.

[24] Commonly used in ecology and land-use planning texts. From "anthropise" (OED), produced or modified by human activity.

Publishing operational data in open formats can accelerate both independent verification and institutional trust.

In sum, osmotic energy does not compete solely on W/m² or €/MWh: it also competes on the ability to deliver. The projects that advance first will be those that integrate, from the preliminary design stage, engineering, permitting, environmental assessment and public dialogue—just as has been learnt, not without difficulty, in offshore wind.

Osmotic energy in Spain

Spain possesses a unique combination of assets for this emerging sector: a desalination infrastructure unmatched in Europe and a business ecosystem with global experience in membrane technologies.

The country has over 765 desalination plants producing some 5 million m³/day, placing it among the top five worldwide in installed capacity. The Torrevieja plant (240,000 m³/day) is one of the largest in Europe. Companies such as Acciona Agua, Aqualia, Cadagua, Sacyr Agua and Tedagua lead the sector at global scale, with a presence in markets ranging from Saudi Arabia to Australia.

For the time being, the most advanced initiative is LIFE HYREWARD; the rest of the ecosystem has the requisite technical capabilities—membranes, process engineering, plant operations—but entry into this segment remains at an early stage. The space for industrial positioning is still open.

The reject brine[25] from these installations has concentrations of 60–80 g/L, approximately double that of seawater, which significantly increases the available mixing energy. Hybrid systems make it possible to recover part of the energy consumed in desalination whilst simultaneously diluting the brine prior to discharge, thereby reducing its environmental impact. This dual advantage—energetic and environmental—renders Spanish desalination plants natural platforms for pilot projects.

The LIFE HYREWARD project, led by Sacyr Agua together with REDstack and Pure Water Group, is Spain's most advanced initiative. With €2.2 million from the LIFE

[25] Reject brine is the high-salinity effluent (outflow stream) produced in desalination plants after the reverse osmosis process. It contains approximately twice the salt concentration of the original seawater.

programme (2021–2025), it has installed a pilot RED system at the Alicante desalination plant, which is already generating electricity[26]. A second phase in Alcudia (Mallorca) will use wastewater treatment effluent as the low-salinity source. Preliminary results point to recovery of up to 20% of the energy consumed in reverse osmosis[27].

The river-based potential is more modest, yet not negligible: the Ebro, with flows of 300–600 m³/s at its mouth, offers the best prospects, followed by the Miño and Guadalquivir. The conservative estimate for exclusively fluvial sources stands at around 500–1,000 MW of theoretical capacity—a medium-term complement, not the starting point.

The regulatory framework is supportive: Royal Decree 962/2024 governs renewable generation in marine installations, and the Roadmap for Ocean Energies (2021) sets a target of 40–60 MW by 2030[28].

The strategic dimension

From an energy security perspective, osmotic energy offers something in short supply within the renewable mix: predictable generation. In contrast to the variability of solar and wind, it can deliver a stable output profile provided a sustained salinity gradient exists. This capacity to supply high-availability power—at certain sites and in hybrid configurations—makes it a natural complement to electricity systems with high penetration of variable renewables, reducing storage requirements and contributing to grid stability[29].

Dependence on critical raw materials is minimal, a stark contrast with photovoltaics, where China controls over 90% of the module supply chain and 97% of wafer[30] production. Osmotic membranes can be manufactured using conventional polymers, cellulose fibres and bio-based materials, all of which are available in Europe.

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[26] Pure Water Group, "Blue Energy: The topic of the new LIFE HYREWARD project", 2021. Available at: https://purewatergroup.com/blue-energy-the-topic-of-the-new-life-hyreward-project-by-redstack-pure-water-group-and-sacyr-water/ (accessed: 3 January 2026).
[27] RO: Reverse Osmosis is the most widely used commercial desalination process.
[28] Ministry for the Ecological Transition and the Demographic Challenge, "Roadmap for the Development of Offshore Wind and Ocean Energies in Spain", December 2021.
[29] Earth.Org., "Osmotic power: The next wave of renewable energy". Available at: https://earth.org/osmotic-power-the-next-wave-of-renewable-energy/ (accessed: 3 January 2026).
[30] Wafers are thin sheets used as the base for manufacturing solar cells, cut from ingots of crystalline silicon.

European companies lead the development effort: Sweetch Energy (France), REDstack (Netherlands) and SaltPower (Denmark) are at the forefront of innovation, alongside membrane manufacturers from Germany and the Netherlands. The OE4EU[31] association, established in Brussels, promotes regulatory development at EU level. As for sites, those with the greatest potential are located in the Rhine-Meuse delta, the Rhône and the Norwegian fjords, although—as noted—the first commercial installations are opting for hybrid configurations with industrial brines rather than large-scale estuarine projects.

The European framework supports this opportunity. The Offshore Renewable Energy Strategy[32] (2020) sets targets of 1 GW of ocean energy by 2030 and 40 GW by 2050; the RED III Directive (2023) streamlines permitting for renewables[33]; and the NZIA Regulation includes ocean technologies among the strategic sectors whose scale-up is a priority[34].

Osmotic energy is thus positioned, together with tidal[35], wave[36] and ocean thermal[37] energy, within the scope of "ocean energies".

Compared with these, osmotic energy presents specific advantages. Offshore wind is more mature (19 GW in the EU) but variable; tidal is predictable but geographically limited; wave energy remains at demonstration stage with high costs. Osmotic energy stands out for its high-availability potential, its reduced visual footprint and its lower exposure to storms when sited in sheltered coastal environments or integrated into industrial installations.

In this context, Spain should prioritise a phased deployment centred on hybrid applications and operational validation.

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[31] OE4EU (Osmotic Energy for Europe) is an industrial association created in Brussels that brings together the main European companies in the sector (Sweetch Energy, REDstack, SaltPower, CNR) to promote the regulatory development of osmotic energy at Community level.
[32] European Commission, "An EU strategy on offshore renewable energy", COM (2020) 741 final, November 2020.
[33] Directive (EU) 2023/2413 of the European Parliament and of the Council, on 18 October 2023, amending Directive (EU) 2018/2001 (RED III).
[34] NZIA: Net-Zero Industry Act, European regulatory framework for the development of clean technologies.
[35] Tidal energy is a form of renewable energy that harnesses the rise and fall of tides to generate electricity using turbines and generators. Tidal power plants can be reversible, taking advantage of both the inflow of water at high tide and its outflow at low tide, as the turbines operate in both directions.
[36] Wave energy, also known as sea wave energy or wave power, is a form of renewable energy that harnesses the movement of ocean waves to produce electricity or other useful work (such as pumping or desalination). It uses the mechanical and kinetic energy of surface waves, which originates from wind blowing over the sea surface.
[37] OTEC: Ocean Thermal Energy Conversion, a technology that harnesses the temperature difference between warm surface waters and cold deep waters.

Conclusion: A window of opportunity

In fifteen years, osmotic energy has travelled from the laboratory to the first commercial installations. The Statkraft prototype (2009) barely reached 1 W/m²; today, several developers report densities of 20–25 W/m², and the SaltPower projects in Denmark and the hybrid system at Fukuoka, Japan, demonstrate that the technology can operate under real-world conditions. Whether these figures will hold at larger scale and over prolonged operation remains to be seen, but the trend is unequivocal.

Cost projections point to 100 EUR/MWh by 2030 in well-selected configurations, with learning rates of 15–20% per doubling of installed capacity—comparable to the early stages of photovoltaics[38]. In high-salinity niches, some estimates are even more optimistic. If confirmed, osmotic energy would enter competitive range with other dispatchable sources before the decade is out. The principal constraint remains membrane durability and the reduction of pretreatment and pumping costs.

For Europe, osmotic energy offers an uncommon combination: stable generation that complements the variability of solar and wind, minimal dependence on critical raw materials—in contrast to Asian concentration in photovoltaics and batteries—and a value chain in which European companies hold an early advantage before global dominances consolidate. This is the context in which the Spanish case should be read: not as an isolated wager, but as an opportunity to capture exportable industrial capabilities in a technology still at an early stage.

Spain has a concrete opportunity to participate in this development. Its leadership in desalination provides infrastructure, technical know-how and a business ecosystem with global reach. The most realistic pathway involves scaling up the results of LIFE HYREWARD towards demonstration plants, developing feasibility studies for the Ebro delta with integrated environmental assessment, and establishing guidelines for incorporating osmotic modules into new desalination plants or expansions of existing ones. In the medium term, a first commercial hybrid plant—perhaps linked to the expansion of Torrevieja—could position the country to export technology and expertise to

[38] Learning rate is an indicator that measures the percentage reduction in costs each time the cumulative installed capacity of a technology doubles. For solar photovoltaic energy, this rate has historically been 20-25%.

North Africa and the Middle East, markets where major desalination needs and blue energy potential coincide.

Sceptics have legitimate arguments: osmotic energy has spent decades in the promise phase, Statkraft failed once already, and investor capital may find more mature options in solar, wind or storage.

None of this is guaranteed. Osmotic energy remains a high-risk, long-term technological wager. But the bets placed before a technology has matured are precisely those that capture strategic value. Europe learnt this lesson—late and at considerable cost—with photovoltaics. Ocean energies are opening a new game; for Spain, the question is whether it wishes to play as a technology buyer or as an industrial actor. For a country with a maritime vocation, few opportunities fit better.

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