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Historical Analysis of Resilience in Spanish Desalination Companies: Period 1980–2024

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Abstract: This article analyzes the evolution and resilience of the Spanish desalination industry in response to shifting market conditions and technological challenges. Initially focused on domestic projects, Spanish companies leveraged the AGUA Program (Actions for the Management and Use of Water; the acronym does not correspond exactly in English, as it is translated from Spanish) to build expertise, which later facilitated their successful international expansion as local demand declined. The industry has adapted to diverse international regulations and local conditions, demonstrating both flexibility and competitiveness. In recent years, there has been an increasing focus on integrating renewable energy into desalination processes to mitigate rising energy costs and address environmental concerns. This shift not only reduces CO_2 emissions but also stabilizes operational costs, underscoring the sector's ongoing innovation and adaptability.

Keywords: desalination industry; renewable; energy integration; water-energy nexus; seawater desalination; resilience strategies

1. Introduction

The group of Spanish desalination companies has gone through several phases, each characterized by clearly differentiated economic and industrial contexts. In fact, the current context is also marked by a shift in market demands, with greater emphasis on the use of green energy, particularly in Western markets. It should be noted that although we refer to the desalination market, there are actually multiple markets with distinct contexts, all sharing the common factor of relative water scarcity [1]. The objective of our study is to answer the following question: what strategies have these companies employed to adapt to the various challenges they have encountered?

Moreover, the reader may notice from the tone of this introduction that we are operating under an initial assumption. We are analyzing the Spanish companies in this sector with the assumption that there are, to some extent, homogeneous patterns within the group, which indeed is the case [2].

The approach of this work does not align with the typical business history case studies that are common in the field of economic history. Two aspects make this case particularly distinctive. First, it is important to emphasize that the desalination industry has a far greater future than past, making it a highly dynamic field. However, this does not diminish the importance of understanding its history and the factors that have shaped the current landscape. Second, the water treatment sector has been largely understudied within the broader context of economic history. For this reason, this work will feature fewer citations and references than is usual in a scientific article published in this journal. In other words, while there may be a temptation to force citations by including articles that tangentially address related topics, the truth is that there are only a limited number of citations that can be coherently and genuinely included.

In the last decade, a group of Spanish companies specializing in the construction and operation of desalination plants has positioned itself among the elite competitors in the

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global market. Industry rankings are often presented based on total installed capacity or by calculating contracted capacity for a given year. Typically, if we consider the top ten companies in these rankings, depending on the period, it is common to find that around four of them are Spanish. One of the key objectives of this study is to provide a detailed account of the trajectory these companies have followed to reach this position. Since the 1980s, these companies have faced numerous challenges; yet, as is characteristic of a success story, this business group has demonstrated remarkable resilience [1]. The challenges and resilience strategies of Spanish desalination companies are highlighted by Younos and Lee (2019) [1], Navarro (2018) [2], and Vera (2021) [3], providing essential context for understanding the historical trajectory of the industry and its remarkable ability to adapt and thrive in the global market.

2. Historical Overview of the Water Sector Prior to the AGUA Program (1980–2007)

The history of desalination extends much further back than is commonly believed. The earliest references date to Aristotle and Pliny the Elder, who conducted studies on desalination, and to Egyptian alchemists who used stills for distillation. Later, Roman legions utilized solar evaporation to obtain water during their campaigns in Africa, storing water in shallow basins and collecting the condensed liquid afterward. The Vikings also employed "fog-catching" techniques, using their ship sails to gather moisture from the atmosphere during sea voyages. This method is still in use today in some desert regions, including parts of the Andes mountain range.

In Spain, Arab scientific advancements in distillation and evaporation technologies, many of which involved the use of stills, were introduced through institutions like the University of Toledo [4]. Numerous references also exist to the production of water on ships between the 15th and 17th centuries using rudimentary stills powered by wood or coal. With the Industrial Revolution and the development of the steam engine, desalination by evaporation was introduced on ships in a more technological manner and eventually expanded to industrial applications and small desalination plants.

The use of membranes is relatively recent. In 1748, the French cleric and physicist Jean Antoine Nollet studied the passage of water through semipermeable membranes. Years later, Henri Dutrochet, a French physician, biologist, and physiologist, founded the cell theory and discovered the process of osmosis. However, none of these studies had practical applications and remained almost as laboratory curiosities until the 1960s, when researchers Sydney Loeb and Srinivasa Sourirajan developed the first flat Reverse Osmosis membranes made of cellulose acetate in California. This opened the way for the development of commercial membranes, which expanded on a large scale from the 1980s.

In Spain, the first land-based desalination plant was a small seawater desalination plant built in Lanzarote in 1964. This event marked the beginning of desalination development in the Canary Islands, which later extended to the Balearic Islands and eventually to the mainland. In the 1970s, several desalination plants were installed in the Canary Islands, initially for hotels and tourist areas, and then in the 1980s also for agriculture. These installations employed technologies such as Reverse Osmosis (for seawater and brackish water) and electrodialysis reversal (for brackish and wastewater). In the 1980s, potable water desalination plants began to be built on the mainland, both for seawater and brackish water, which progressively increased in size. In the provinces of Almería, Murcia, and Alicante, during the drought of the 1990s, around 300 small private desalination units (500–5000 m^3/day) were installed for agriculture [5]. At that time, agriculture relied heavily on water transfers, and with the drought, alternatives such as desalination were sought for the survival of the sector. Generally, these were plants desalinating brackish groundwater, although some seawater plants were installed in the Canary Islands. Most of these installations used Reverse Osmosis technology, although around 20 electrodialysis reversal plants were built in the Canary Islands, with capacities ranging from 1000 to 5000 m^3/day [5]. Farmers in southeastern Spain continued increasing desalination capacity until they built large-scale plants, such as those of the Irrigation Communities of Cuevas de Almanzora, Mazarrón, and Rambla Morales.

Between 2004 and 2011, the Spanish government, through the Ministry of Environment (now the Ministry for the Ecological Transition), developed the AGUA program to implement numerous desalination projects (around 25 plants with a capacity close to 700 Hm^3/year) along the Mediterranean coast to address the region's water deficit, as opposed to the water transfer policy promoted by previous governments. This led to a massive expansion of desalination, reaching the current installed capacity, estimated at around 5 million m^3 per day, which, if fully dedicated to drinking water production, could supply a population of 34 million people.

Currently, it is estimated that Spain has more than 770 desalination plants with capacities exceeding 100 m^3/day, of which more than 100 have capacities greater than 10,000 m^3/day (AEDyR, 2018). The largest seawater desalination plants in Spain are Torrevieja (240,000 m^3/day) and Águilas (210,000 m^3/day). Regarding brackish water desalination plants, notable examples include the El Atabal plant in Málaga (200,000 m^3/day) and the Abrera plant in Barcelona (200,000 m^3/day), the latter being the largest plant in the world using electrodialysis reversal technology. Today, most large desalination plants are in operation, though not at full capacity. Some facilities, like Águilas, have important agreements with farmers that ensure a high level of productivity (mainly for agriculture, benefiting the Irrigation Communities of Lorca, Pulpí, and Águilas). However, other plants, such as Muchamiel or Sagunto, are significantly underutilized [6]. Most small desalination plants built by Irrigation Communities or private farmers in the 1990s are no longer operational due to various reasons (lack of permits, brine management issues, etc.). However, in recent years, groups of agricultural entrepreneurs from Murcia and Almería have been planning the construction of several large private seawater desalination plants to reduce their reliance on water transfers.

In addition to seawater facilities, the increasing implementation of desalination membranes for the improvement of surface water (including large plants such as the Tajo, El Atabal, and Abrera drinking water treatment plants) and also for tertiary wastewater treatments (such as the Rincón de León wastewater treatment plant in Alicante or the Benidorm wastewater treatment plant) is noteworthy.

If we go back to 1980, desalination was a technology whose cost per cubic meter was substantially higher than it is today. Moreover, it is important to note that there are two major groups of desalination technologies: thermal and membrane-based. In recent decades, membrane plants have become increasingly prevalent because their energy efficiency is substantially higher. However, the further back we go in time, the more common thermal plants become. Thus, unlike in 2024, during the 1980s, desalination was a technology undergoing significant improvements.

At this point, it is important to differentiate between the global desalination sector and the specific characteristics of the group of Spanish companies dedicated to desalination. This section, therefore, focuses on the sector before the AGUA Program. We must understand that the launch of the AGUA Program marked a radical change for Spanish companies. In fact, one could say that before the AGUA Program, Spanish desalination companies did not represent a consolidated business sector.

Before the AGUA Program, this sector consisted of companies that represented diversification strategies for various construction companies. Many emerged as subsidiaries of larger business groups, such as Acciona Agua (part of the Acciona group) or Sadyt (part of Sacyr). In fact, at their inception, their function was predominantly that of construction companies undertaking water projects, among which desalination was just one of many services offered. Naturally, even after the AGUA Program, these companies continue to develop other types of infrastructure, but it is in the field of desalination where we can observe their greatest competitiveness and their presence in international markets.

Therefore, we can say that desalination in Spain before the AGUA Program had a moderate presence, allowing for the execution and operation of existing plants without leading to significant growth in the business sector we are studying.

However, it is important to note that water scarcity had already necessitated enough action to begin creating a group of companies. Generally, it is large public projects that generate demand in the water treatment sector.

A Technology Yet to Mature

Water desalination has emerged as an increasingly utilized solution to address potable water scarcity, particularly in arid and coastal regions. However, despite its apparent benefits, this technology continues to face several significant challenges that limit its widespread adoption. High energy consumption, operational costs, and the environmental impact of brine disposal are key factors indicating that desalination is a technology that still requires maturation. While efforts are underway to optimize these processes and mitigate their drawbacks, desalination remains a last resort rather than a comprehensive solution to the global water crisis.

Currently, technical advancements in desalination have stabilized to the extent that, in recent years, most sector proposals have focused on the integration of renewable energy sources. This shift aims to reduce indirect CO_2 emissions and decouple the energy consumption costs of desalination plants from fluctuating energy market prices. However, if we look back to the 1980s, we find a technology that had significant room for improvement. The degree of technological advancement can be measured by the energy consumption required to produce one cubic meter of desalinated water.

Due to energy considerations, thermal technologies have gradually been phased out in favor of membrane technologies. For readers less familiar with desalination, thermal technologies separate salt from water through an evaporation process, which typically requires more energy than membrane technologies. In contrast, membrane technologies force saltwater through membranes capable of generating a separation process between water and salt. The most widely used membrane technology is known as Reverse Osmosis. The reduction in energy consumption from the 1980s to the present in membrane technologies has been substantial, contributing to the exponential growth of Reverse Osmosis plants.

It is important to note that while we mentioned a reduction in energy consumption for desalination in the previous paragraph, we did not reference the economic implications of that energy consumption. This omission is significant. Given that energy prices fluctuate, an increase in energy costs could lead to higher operational costs for desalination plants. Since energy costs account for nearly half of the total expenses associated with desalination, rising energy prices would ultimately increase the cost of desalinated water.

Therefore, we can conclude that the period from the 1980s to the implementation of the AGUA Program is characterized by a reduction in product costs due to technological advancements, alongside a significant increase in total desalination capacity worldwide. During this period, desalination transitioned from being a novel and uncommon option to a widely implemented technology in countries where water scarcity and economic capacity coexist.

There are four key areas of improvement in which this technology is expected to continue progressing, and indeed, advancements are still being made in these areas today. Table 1 outlines these areas of improvement.

Table 1. The Four Areas of Improvement in Desalination.

	Description	Areas of Improvement
Energy Consumption	Desalination has higher energy consumption compared to other methods of water acquisition. Energy consumption has decreased over the past decades. Currently, between 3 and 4 kWh are required to produce one cubic meter of desalinated water.	- RO membranes are already approaching their thermodynamic limit, and it has been demonstrated that materials have a relatively insignificant impact on increasing energy efficiency [7]. It seems complicated to further reduce energy consumption, which, if possible, would be a considerable technological improvement. - Integration of renewable energies: utilize renewable energy sources, such as solar or wind power, to operate desalination plants, thereby reducing dependence on fossil fuels and minimizing the carbon footprint of the process. - Energy recovery: implement energy recovery techniques in the desalination process, such as pressure exchange technologies, to reuse energy and increase overall efficiency. Energy recovery systems are already used in nearly all RO desalination plants worldwide. However, the device itself can be improved to recover more pressure at low mixing rates - A significant reduction in energy consumption in Saudi Arabia's desalination processes, particularly in Reverse Osmosis (RO), has been achieved primarily through design optimization and improved technology. Over the past decade, Saudi Arabia has reduced the energy required for desalination by about 87%, a remarkable feat given the traditionally high energy demands of this process. This was accomplished through innovations in membrane technology and enhanced operational efficiency in RO systems [8]).
Costs	Costs range between $0.50 and $3 per cubic meter, depending on the type of water, year of construction, and plant size.	- Reduction of operational costs: invest in operational and maintenance improvements that reduce long-term costs, such as using more durable materials and optimizing filtration and pumping processes. - Economies of scale: increase the capacity of desalination plants and promote regional cooperation to leverage economies of scale and reduce unit costs of water production. - Financial innovation: develop financing models and subsidies that facilitate initial investment in desalination infrastructure, making the technology more accessible to developing countries. - New technologies create opportunities for improvement through AI and ML to optimize plant operations, which could reduce energy and chemical consumption.
Environmental Impact	Generation of brine that can harm marine ecosystems. Energy consumption may lead to CO_2 emissions.	- Sustainable brine management: develop more effective methods for brine management, such as dilution before discharge or the use of brine in other industries (e.g., mining) to reduce its environmental impact. - Development of green desalination: innovate in technologies that minimize environmental impact, such as solar thermal desalination, which could reduce the generation of harmful by-products. - Regulation and control: implement stricter regulations and monitoring systems to control brine discharge and protect marine ecosystems. - The CO_2 generated during the energy production process could be utilized in the RO system to mitigate environmental impact. [9]
Global Capacity	More than 16,000 plants in operation, producing less than 1% of total freshwater consumption.	- Capacity expansion: invest in the construction of new desalination plants in strategic regions, particularly in areas with chronic water scarcity, to increase desalination's contribution to the global potable water supply. - Optimization of existing infrastructure: modernize and enhance the efficiency of current desalination plants to maximize water production with the same resources. - Development of advanced technologies: encourage the research and development of new desalination technologies, such as electrodialysis or advanced membrane desalination, which could increase capacity and reduce costs in the future.

3. Current Challenges and Developments in the AGUA Program (2007–2011)

The AGUA Program (Actions for the Management and Utilization of Water) was a key initiative implemented in Spain in 2004 by the government of José Luis Rodríguez Zapatero in response to the growing water scarcity, particularly in the most arid regions of the country, such as the southeastern peninsula. This program marked a paradigm shift in water resource management in Spain, prioritizing sustainability and the optimization of water use over the traditional policy of large-scale water transfers, such as the controversial Ebro River transfer that had been promoted earlier.

One of the fundamental pillars of the AGUA Program was the promotion of desalination as a strategic solution to ensure the supply of potable water in coastal regions with the greatest water deficits. Prior to the program, desalination in Spain was an emerging and scarcely implemented technology, primarily focused on small plants serving isolated or tourist urban centers.

With the implementation of the AGUA Program, desalination experienced exponential growth. The government promoted the construction of new desalination plants along the entire Mediterranean coast, from Catalonia to Andalusia, with the goal of significantly increasing the production capacity of desalinated water. This effort resulted in the creation of infrastructures such as the Torrevieja desalination plant, one of the largest in Europe, capable of producing up to 80 cubic hectometers of water annually.

The AGUA Program also drove innovation in desalination technologies, fostering the development of more efficient and cost-effective techniques, and promoting research into the use of renewable energy sources to reduce the environmental impact of the desalination process. As a result of these policies, Spain became a global leader in desalination, ranking among the countries with the highest installed capacity, not only within Europe but also on a global scale.

During the years of the AGUA Program, there were no significant global changes in the desalination market or in its technological development. However, this program did transform the national landscape. The demand for desalination plants surged abruptly, and this demand was entirely met by domestic companies. This large-scale demand, concentrated over a few years, caused these small water treatment companies to grow substantially. The AGUA Program was also a primary driver of these companies' internationalization because, although they had expanded due to the Spanish market, it had become saturated. Once the AGUA Program's plants were built, the national market was considered exhausted, as the installed desalination capacity meant that no additional water would be required.

Many experts argue that the focus on desalination was disproportionate, a result of the "water war" that occurred at the political level. What was the water war? The Popular Party advocated for the importance of water transfers, particularly a potential transfer from the Ebro River, while the Socialist Party promoted desalination as the most suitable solution for addressing specific water scarcity issues.

The Socialist Party's commitment to desalination was so strong that they ended up constructing more plants than what seemed advisable from a technical perspective. This increased demand, which in turn led to greater competitiveness. Furthermore, given the government's association with desalination, strict environmental requirements were imposed. Any environmental damage caused by a desalination plant would have been used by the opposition as evidence of government failure. This resulted in higher environmental standards than those typically encountered by Spanish desalination companies abroad. However, this also enabled these companies to develop greater competitiveness due to the stringent demands. According to some industry executives, the demand environment in Spain was very challenging due to political and media scrutiny. This, in turn, better prepared these companies with the necessary expertise and know-how when they entered the international market.

3.1. Technological Refinement

The refinement of desalination technology over recent decades has resulted in substantial improvements in efficiency. The desalination plants constructed under Spain's AGUA Program were markedly advanced compared to earlier facilities, with the most significant change being the considerable reduction in energy consumption. These new plants were also designed to minimize negative externalities, provided it was cost-effective from a cost-benefit analysis perspective. Like any industrial or technological process, desalination technologies have continuously improved, although these advancements have predominantly focused on reducing energy consumption. However, while significant energy reductions were achieved in the initial decades, progress has since slowed and plateaued. The current trend within the industry appears to favor partially powering plants with renewable energy sources, rather than further reducing the energy demands of the desalination process.

Reverse Osmosis (RO) remains the most widely adopted desalination method globally. Traditionally, RO required substantial energy to generate the high pressure necessary to force water through semipermeable membranes, which retained the salts. One of the most significant advancements in this technology has been the development of low-pressure Reverse Osmosis, utilizing more efficient membranes that allow desalination to occur at lower pressures, significantly reducing both energy consumption and operational costs.

Another key advancement has been the implementation of energy recovery systems. In Reverse Osmosis plants, the pressure exerted during the process can be recovered and reused, decreasing the overall energy demand of the system. Devices such as pressure exchangers and turbochargers have played a pivotal role in enhancing energy efficiency in desalination.

The integration of renewable energy into desalination processes is also a rapidly advancing field. Notable progress has been made in utilizing solar and wind energy to power desalination plants. For example, solar thermal energy has been successfully applied in solar distillation systems, where the sun's heat vaporizes water, separating it from salts. This approach not only reduces reliance on fossil fuels but also lowers the carbon footprint of desalination plants.

A transformative advancement in the field is the development of nanotechnology membranes. These membranes, which incorporate nanoparticles or nanotubes, offer superior permeability and selectivity, enhancing desalination efficiency while further reducing energy requirements. Additionally, ongoing research on graphene membranes and other advanced materials holds the potential to revolutionize Reverse Osmosis in the near future.

Although less common, freeze desalination is an emerging technology that offers energy efficiency advantages in colder climates. This process involves freezing saline water, where the resulting ice is essentially pure water, leaving the salt behind during solidification. Freeze desalination requires less energy than thermal distillation and is particularly suited for regions with access to natural cold sources.

Finally, hybrid technologies, which combine different desalination methods, are gaining popularity. For example, combining Reverse Osmosis with membrane distillation enhances process efficiency and flexibility, adapting to varying conditions and types of saline water. These hybrid systems optimize resource use and allow for greater control over the quality of the produced water.

3.2. The Water War: The Spanish Case

Water is a scarce resource, and Spain is no exception in experiencing what some have called "the water war". However, this conflict is of particular interest due to its somewhat peculiar nature. In this case, a planned inter-basin water transfer, known as the Ebro Transfer, was never constructed. During the 1980s, 1990s, and early 21st century, the National Hydrological Plan (PHN) generated intense tensions between the autonomous communities of Aragon and Catalonia, on one side, and southeastern regions of Spain, such as Murcia and Valencia, on the other [10]. The plan proposed transferring water from the Ebro River to other areas of Spain, which sparked significant opposition in Aragon and Catalonia, where there were fears that such transfers would negatively impact the Ebro's ecosystem and local water needs. José Marco, President of the General Deputation of Aragon in 1997, stated: "We will not allow the Ebro's water, which is our lifeblood, to be taken from our land to serve interests outside our community". The opposition to the Ebro Transfer culminated in its repeal in 2004, following the election of José Luis Rodríguez Zapatero's government, which promoted an alternative policy based on desalination. The Popular Party in Spain favored the water transfer and largely opposed desalination, while the Socialist Party supported desalination. It is important to note that at that time, the country's political reality was much closer to bipartisanship than it is today. The conflict was so intense that slogans were created, with "water for everyone" as the pro-transfer slogan and "water forever" as the pro-desalination slogan.

This political polarization did not contribute to rational decision-making from a technical standpoint. In 2004, the Socialist Party won the election, significantly increasing the number of desalination plants in the country. However, it is also important to recall that the opposition (the Popular Party) was against desalination. This led to stricter control and oversight of desalination plants than of any other public works. Paradoxically, this increased the competitiveness of Spanish desalination companies, as they were forced to meet strict environmental, aesthetic, economic, and energy demands.

Proponents of the Ebro Transfer heavily criticized the desalination plants of the AGUA Program. Their main argument was the high energy consumption of these plants, which collectively would account for 1% of Spain's total energy consumption. It is not surprising, then, that from the outset, the primary focus of desalination development efforts has been on reducing its energy intensity. Although significant progress has been made, energy consumption remains relatively high [11].

Today, controversies and territorial disputes persist, although the transfer currently at the center of the debate is the Tajo–Segura Transfer. The Tajo–Segura Transfer is an aqueduct built in 1979 to carry water from the Tajo River basin to the arid regions of southeastern Spain, such as Murcia, Alicante, and Almería. This transfer has been a constant source of conflict between the water-receiving communities and those in the source basin, particularly Castilla-La Mancha, which argues that the transfer significantly reduces its own water resources. José Bono, then President of Castilla-La Mancha, stated in 2004: "The Tajo–Segura Transfer is a bleeding scar, a historical injustice that must be reviewed to ensure that water stays where it is needed". Over the years, the transfer has been the subject of multiple debates and regulatory modifications and remains a highly controversial issue in Spanish politics.

4. International Expansion or Decline: 2006–2019

The AGUA Program was like a wave that came and went. When it receded (metaphorically speaking), it left behind an industrial sector that previously did not exist and no longer had opportunities to generate revenue in Spain, as all the necessary plants had already been constructed [12] At this point, Spanish desalination companies began seeking opportunities in other countries [13] The degree of success these companies achieved was substantial, largely due to the experience and competitiveness they had developed in the Spanish market.

The internationalization of Spanish desalination companies following the AGUA Program is a well-documented phenomenon, with various data and examples highlighting how these companies began expanding their global presence during this period.

Starting in 2006, Spanish desalination companies began securing significant contracts abroad, particularly in water-scarce regions such as the Middle East, North Africa, and Latin America. The effects of the AGUA Program were already evident, and the exhaustion of the domestic market in Spain was a clear reality; companies had to internationalize or face extinction. The Spanish company Acciona Agua became a global leader in desalination. Acciona began its international expansion with projects in Algeria, the United Arab Emirates, and Australia. In 2007, it won a contract to build the Adelaide desalination plant in Australia, one of the largest in the world at the time, with a capacity of 300,000 m^3/day.

Another Spanish company, Tedagua, a subsidiary of ACS, also began to gain ground internationally. In 2007, Tedagua was awarded the construction and operation of the Barka II desalination plant in Oman, with a capacity of 120,000 m^3/day.

In 2006, the Spanish company Abengoa started its expansion into the international desalination market, winning contracts in regions such as North Africa and the Middle East. In 2009, Abengoa secured a major contract to build the Beni Saf desalination plant in Algeria, with a capacity of 200,000 m^3/day. Sacyr Vallehermoso, through its subsidiary Sadyt, also began operating internationally in desalination projects. In 2007, Sadyt was selected to develop a desalination plant in Israel, demonstrating the ability of Spanish companies to compete in highly competitive markets.

By 2006, Spanish companies accounted for approximately 20% of the world's installed desalination capacity, establishing themselves as leaders in Reverse Osmosis technology, according to data from the Spanish Desalination and Reuse Association (AEDyR). From 2006 onwards, it is estimated that Spanish companies participated in the construction of more than 50% of the new desalination plants in the Middle East and North Africa.

The Spanish government, through the Spanish Institute for Foreign Trade (ICEX), began actively supporting the internationalization of its water sector companies, including those specializing in desalination, by promoting Spanish technology in strategic markets. These data and examples illustrate how, starting in 2006, Spanish desalination companies not only began to compete internationally but also established themselves as global leaders in the industry, contributing to addressing water challenges in various parts of the world.

5. The Imperative of Energy Sustainability: Challenges and Prospects for 2022–2024

As mentioned earlier, the Spanish desalination sector is an international leader, with numerous companies among the world's top performers. This strength is not solely due to large constructors and operators but also includes suppliers, engineering firms, consultancies, small and medium-sized enterprises, entrepreneurs, public companies, and research centers.

In Spain, there are numerous research centers and universities that are internationally recognized for their research on desalination. Generally, research trends in this sector are focused on energy efficiency and reducing the carbon footprint [6,13], minimizing the environmental impacts of desalination, and improving equipment (membranes) and facilities. In summary, these research efforts are typically applied and more focused on cost and impact reduction than on developing new processes or technologies.

In the field of energy efficiency and CO_2 footprint reduction, there is a growing emphasis on research and the implementation of renewable energy sources. These sources are used both to produce the electricity needed for desalination and to attempt direct integration with desalination systems. However, the expansion of renewable energy for desalination faces several challenges, such as the high concentrations of power required in certain locations (large desalination plants), the technical or economic infeasibility of energy storage (since desalination plants must operate continuously to remain viable), or the fact that the location of the desalination plant does not always coincide with the best site for renewable energy production. This latter issue has been resolved in some countries, such as Spain and Australia, by supplying the necessary renewable energy equivalently from parks located hundreds of kilometers away from the desalination plant, thereby offsetting their emissions.

In earlier sections, we mentioned that the energy consumption of desalination has decreased over the decades. However, does this mean that the cost of desalination has decreased at the same rate? No, and it is important to note that academics highlighted this fact years before it became a reality. It is crucial to understand that the economic cost associated with energy consumption is not the same as the energy consumption itself. The key difference here is that the economic cost linked to energy consumption depends on the price of energy, which can fluctuate. This reality has always been present, but it seems that until what is theoretically certain becomes a fact, it is not approached with the same seriousness.

In 2022, a conflict erupted between Russia and Ukraine, leading to numerous consequences, one of which was a significant increase in energy prices. This resulted in a substantial rise in the economic cost of desalination, given that nearly half of its cost is attributed to energy consumption. Since then, the desalination sector has begun to exhibit a new trend in projects, with growing demand for the use of renewable energy sources in desalination plants.

The integration of renewable energy into desalination offers three key advantages:

- It reduces CO_2 emissions, aligning with the environmental goals of many countries.

- It stabilizes the cost of water by reducing variability, as the portion of energy supplied by renewable sources is linked to a fixed investment cost that does not fluctuate.
- It decreases dependence on external energy sources, as imported energy is subject to a range of variables largely beyond the control of any single country.

Significant advancements have been made in desalination technologies. Reverse Osmosis, the most widely used process, now consumes less energy and, consequently, emits less CO_2 compared to thermal processes. This improvement is the result of several decades of enhanced energy efficiency in the technologies employed. Since 1970, the energy consumption of Reverse Osmosis plants has been reduced tenfold. However, challenges remain, particularly in protecting membranes from salt damage, as well as in further improving the cost-effectiveness and energy efficiency of the process. Most market leaders maintain active research and development (R&D) departments dedicated to this field.

Despite these tangible improvements, Reverse Osmosis desalination remains energy-intensive, which explains the gradual development of its integration with low-carbon energy sources, primarily renewable energies, whose implementation costs have significantly decreased in recent years, and even nuclear energy.

Solar energy is considered to have the greatest potential as a long-term renewable energy source for sustainable desalination [14,15]. There are two main types of solar-powered desalination: Concentrated Solar Power (CSP) and Photovoltaic (PV). CSP generates direct heat and is generally used to evaporate water in thermal desalination. PV uses solar panels to produce electricity, which powers pumps for Reverse Osmosis. For example, the Al Khafji plant in Saudi Arabia produces 60,000 m^3 of desalinated water each day using Reverse Osmosis powered by photovoltaic panels.

A study published in the International Journal of Economic and Management Sciences highlights the potential of solar desalination, showing that a Reverse Osmosis plant powered by photovoltaics can produce water at a cost of $1.213/$m^3$, while the current cost of producing desalinated water using energy from a fossil fuel-based power plant varies considerably, ranging between USD 1.118 and USD 1.555.

The record production cost of 1.75 cents per kWh for the Sakaka project in Saudi Arabia demonstrates that renewable energy can compete broadly with fossil fuels in financial terms.

At this stage, most large-scale desalination projects powered by renewable energy utilize wind power. Wind-powered desalination is particularly suitable for coastal and island communities due to the proximity of the energy source, water supply, and the user population. Wind energy is employed in the Canary Islands of Gran Canaria and Fuerteventura in Spain, where climatic conditions are especially favorable. In Australia, the Perth plant is powered by electricity from the 80 MW Emu Downs wind farm. Each year, this wind farm supplies 270 gigawatt-hours (GWh) to the grid, exceeding the 180 GWh per year requirement of the desalination plant.

Wave energy is more challenging to harness. In Australia, an innovative project was launched in 2014 to produce drinking water and electricity from the ocean. Cape Verde is also on the verge of launching a wave-powered desalination project.

Desalination plants can also be coupled with nuclear generators, and the ongoing installation of three nuclear plants in the United Arab Emirates' grid opens the possibility of coupling them with desalination facilities. Thus, solar and wind coupling has highly promising potential [16,17].

However, currently, only 1% of desalination plants use renewable energy. The Global Clean Water Alliance, founded by the International Desalination Association, has set a goal for at least 20% of new desalination plants to operate on renewable energy between 2020 and 2025. In Australia, all new desalination plants are required to operate on renewable energy.

Nevertheless, obstacles remain. The first is the issue of intermittency, meaning the mismatch between energy supply and demand due to the dependence of production on weather conditions. This is particularly problematic for solar (PV) and wind-powered desalination.

Energy storage is becoming essential for the uninterrupted and reliable operation of desalination plants, yet batteries remain an expensive option that is not always a suitable solution [18] Several approaches can be considered to address the intermittency problem: coupling solar and wind energy wherever possible, supplemented by a grid connection (with more green electricity); and thermal storage, as found in concentrated solar power (CSP) plants that can store heat to continue operating for several hours even without sunlight.

"Currently, most thermal storage systems have an efficiency between 8% and 16%. It is expected that in 10 or 20 years, technical improvements will increase efficiency by 15–25%", according to the World Bank (2019). Another alternative is to increase water storage capacity. Water towers can also be built to store excess water produced during the day and release it at night [13].

6. Conclusions

In the introduction, we posed the question of how Spanish desalination companies have adapted to the multiple changes in the sector. We have observed a business sector with strong resilience, from which we can highlight the following key adaptations to the evolving context:

1. Initial phase. Spanish desalination companies began by undertaking various projects, such as desalination plants, wastewater treatment plants, and brackish water treatment plants. Given the size of the market, these companies initially maintained a small structure with limited staff, and their focus was primarily on the domestic market.
2. Efficient response to the opportunity presented by the AGUA Program. Spanish companies successfully constructed and operated the plants under this program, gaining significant experience and expertise in the process [19].
3. Internationalization. Perhaps the greatest display of resilience occurred when local demand was exhausted. By then, these companies had grown considerably and faced the choice of either internationalizing or dismantling a significant part of their structure. Spanish desalination companies embarked on a successful process of internationalization.
4. Adaptation to the varying conditions of each country. Resilience did not end with internationalization. Desalination plants are not a product that can be manufactured in the home country and exported; rather, they are facilities built on-site, where they must be adapted to local laws and conditions. Spanish desalination companies showed a strong capacity to adapt to the requirements of each tender, allowing them to win contracts against larger, but less flexible, competitors.
5. The most recent demonstration of resilience has been seen in how the sector's companies have adapted to new trends in renewable energy. This change is mainly driven by environmental considerations, but it also brings other benefits. For instance, it allows for more predictable energy supply costs by reducing dependence on the energy market.

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