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Addressing Desalination's Carbon Footprint: The Israeli Experience

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Abstract: Given the extraordinary proliferation of seawater desalination plants, Israel's transition to become a country that almost exclusively relies on desalination for municipal water supply is instructive as a case study, especially given concerns about the technology's prodigious carbon footprint. This article offers a detailed description of the country's desal experience with a focus on the associated energy requirements, environmental policies and perspectives of decision makers. Israel's desalination plants are arguably the most energy-efficient in the world. The present consensus among government engineers, however, is that meaningful improvements in energy efficiency are unlikely in the foreseeable future. Official evaluations of increased introduction of solar-driven reverse osmosis (RO) processes concluded that mitigation of greenhouse gases will have to be attained in industries other than the water sector. The article details myriad environmental benefits that desalination has brought the country. However, it argues that given the imperative of stabilizing atmospheric concentration of carbon, and the modest renewable energy supply to Israel's national grid to date, public policy can no longer offer the water industry a path of least resistance. Present plans envision a significant expansion of Israel's desal infrastructure, requiring a far higher commitment to renewable energy supply and regulations phasing down present energy demands.

Keywords: desalination; Israel; climate change; mitigation; policy; environment

1. Introduction

As climate change [1] and burgeoning population [2] exacerbates scarcity for residents living in water-stressed regions around the world, desalination increasingly emerges as a critical technology [3]. A 2015 survey by the International Desalination Association reported that 18,426 desal plants already produce more than 86.9 cubic meters each day for over 300 million people [4] in 150 countries [5]. In recent years, more and more large desalination facilities are being built. This trend is not without environmental consequences. While actual energy consumption depends on seawater concentrations of boron and salts, along with the distances of feed and brine piping lines, desalination's carbon footprint invariably is prodigious. Already desalination is responsible for 0.4% of the world's electricity consumption [6], given existing trends, desalination production could easily double internationally within six years [1] with associated global emissions reaching 400 million tons of carbon equivalents per year [7].

The present energy calculus is fairly clear: desalinating 1000 cubic meters of water (one million liters) per day consumes the rough equivalent of 10,000 tons of oil per year. The resulting greenhouse gas emissions raise questions about the sustainability of a technology that, otherwise, holds enormous environmental benefits [8]. The carbon footprint for seawater of reverse osmosis (RO) desalination has been calculated between 0.4–6.7 kg CO_2eq/m^3 [9]. This means that desalinating 1000 cubic meters of seawater could potentially release as much as 6.7 tons of CO_2. With heroic global efforts underway to keep global warming below 2 °C [10], the cumulative carbon footprint of seawater desalination facilities can no longer be ignored.

Israel's experience, therefore, is particularly germane when considering an environmental strategy for the world's future desalination development. Since its inception, Israel has always been defined as a water-stressed country [11]. Located on the Eastern Mediterranean, despite its remarkable climatic diversity, some 93 percent of the country is defined as drylands [12], with a third of the country receiving less than 100 mm of rainfall annually [13]. Recently, scarcity has grown worse, as renewable water resources in Israel appear to be diminishing [14] due to climate change [15]. Born of the country's acute hydrological exigencies, Israel's innovative approaches to water management are widely recognized [16]. Although many mistakes have been made in the accompanying trial and error process, an adaptive management process made corrections, and for the most part, the country's water resource management strategies are considered to be sustainable [17].

For over five decades, Israeli researchers have been world leaders in developing desalination technologies [16]. For many years desalination advocates in Israel argued that a desal infrastructure was necessary. However, economic interests in the bureaucracy resisted and exploited occasional rainy years to justify putting off the inevitable. Fifteen years ago, the government was finally convinced that the time had arrived to become operational. Since 2005, the country has increasingly come to rely on desalinated water for its domestic water supply [18]. Specifically, five large-scale desalination plants have begun to transform seawater into potable water, utilizing RO, a process where clean water is filtered out and salts accumulate in the brine when they pass through a membrane under high pressure [19]. Water managers see desalination as a cost-effective solution to the country's perennial historic shortages, some even "quietly declaring the end of water scarcity" [20]. The magnitude of the change cannot be overstated: today, some 75 percent of the country's household drinking water comes from desalination [21].

However, this transition brought with it a meaningful increase in energy demand. All told, Israel's water supply consumes almost 10% of national electricity production, with desalination constituting about 4 to 5% of the energy demand [22]. While this may be lower than the country's air conditioners, it is significant enough to raise questions about the sustainability of the country's desal revolution.

With of the opening of its first major desalination facility in Ashkelon in 2005, Israel embarked on a new strategic orientation and took a leap of faith [23]. A country that had always relied on massive water conveyance from the relatively rainy Galilee in the north to the densely populated center and desiccated southern Negev drylands suddenly was drinking water that originated in the sea. It was the dramatic drop in the cost of desalination that created a new feasibility to allow for this transformation [24]. Presently, the five major RO desalination plants produce roughly 582 million cubic meters (mcm) of extremely high-quality every year, water at a price that rarely exceeds 60 cents for 1000 L, meeting most the country's domestic needs [25].

In a country that frequently suffers from myopia in planning, several years ago Israel's Water Authority promulgated an impressive long-term blueprint that sets out the country's water management strategy from 2010 to 2050 [26]. Officially, the plan only describes desalination plants as "a complementary source for the natural sources of water", alongside enhanced efficiency measures and reallocation of water from agriculture to domestic use [26]. In fact, expanded utilization of seawater constitutes the very heart of the hydrological future envisioned.

Even though Israel has expanded its desal capacity dramatically, it is not enough: The country's population is growing at a rate of 2% per year while standards of living rise even more rapidly [27]. To meet anticipated demand, the National Water Masterplan projects that between the years 2020 to 2050, annual desalination production will need to grow from 750 mcm/year to approximately 1600 mcm/year.

Although not formally framed that way, Israel's transition to total reliance on desalination can be seen as a climate change adaptation measure. Yet, paradoxically, the decision flies in the face of Israel's climate change mitigation efforts, especially given the commitments made in the country's Intended Nationally Determined Contribution (INDC), submitted to the, United Nations Framework Convention on Climate Change prior to the Paris climate conference in 2015. In this action plan, the country pledged to reduce capita greenhouse gas emissions by 26% by the year 2030 [28]. The blueprint makes a vague commitment to addressing the issues involving energy consumption that are associated with its water industry, stating: "Coordination in the development of infrastructures, between the water sector and the energy sector will be increased." [26]. Unfortunately, the document is conspicuously short on specifics.

This in no way means that increasing the energy conservation and reducing the greenhouse gas emissions associated with desalination are "non-issues" in Israel. Indeed, their significance will only increase. By 2010, seawater reverse osmosis (SWRO) desalination plants in Israel were already consuming an average of 1030 million kWh per year [29]. By 2020, energy demand from Israel's desal sector is likely to double to 1961 million kWh per year [29], close to 3.7% of present electricity production.

This article presents the country's experience and present thinking about the so-called water-energy nexus, evaluating measures that might be taken to reduce the carbon footprint of Israel's water production system. It opens with a brief review of the Israeli desalination network and the associated environmental impacts. Chief among these is the contribution of desalinated water production to the country's aggregate greenhouse gas emissions. Alternative strategies for reducing the desalination's greenhouse gas emissions are considered. The article concludes that while modest additional reductions in energy consumption in the desalination process through engineering innovations may yet be attained, a truly sustainable domestic water supply system will only be achieved when desalination comes to rely on renewable energy sources.

2. The Environmental Impacts of Israel's New Desalination Era

Desalination is the process of producing potable water from sea or brackish water by removing salts. Different forms have long been recognized, and desalination was already utilized by ancient Romans. When Thomas Jefferson served as the American Secretary of State, in 1790 he began requiring U.S. military ships to bring a basic thermal desalinization "apparatus" for distilling water, to ensure a water supply given the vicissitudes of the sea. The technology took a quantum leap forward during World War II, when thermal processes (evaporation and distillation) were developed for military purposes. By the 1960s, the first commercial thermal desalination plants were producing relatively small quantities of potable water. A decade later, two technologies, reverse osmosis (RO) and electrodialysis, became commercially available. Today, RO has emerged as the predominant technology for desalination, providing about 60% of global installed capacity. Thermal desalination accounts for an additional 35% [30].

In terms of design, all five recently constructed Israeli large-scale desalination plants conform to the reverse osmosis process: after water is pumped from the sea, a pretreatment stage removes suspended solids and other debris, the pH of the feedwater is adjusted and a chemical inhibitor is added to protect the RO membrane. Subsequently, the pressure in the pumping system is increased sufficiently to allow for the seawater to be pushed though the RO system. As the water goes through the membranes, the solvent (almost pure H_2O) passes through the membranes, while the solute containing the salts and other substances is separated out as brine, which is then returned to the sea. The purified water goes through additional treatment in order to remove boron residues and restore some of the minerals removed as part of a stabilization process, before being sent out to a national water grid as drinking water [31].

Judged by most criteria, Israel's large-scale desalination facilities are an unqualified success. The low operational expense in Israeli desalination plants constitute a model of how cost-effective desalinated water production can be. For instance, the new Sorek desalination plant (Rishon Lezion, Israel) produces 627,000,000 L of fresh water at a price of 58 cents per cubic meter (1000 L) of water [32]. Israel's low desal prices are the result of an impressive litany of technological improvements in production efficiency and the relatively low cost of energy (8 cents/kWh) paid by desalination plants in Israel [24]. Initially, cost savings came from advanced energy recovery systems and highly efficient pumps. Recent innovation at the new Sorek plant involve utilization of 16 inch diameter pressure tubes in lieu of the conventional 8-inch, a move that contributes to 200 percent reduction in the costs of piping.

The Israeli facilities are also holding up nicely over time. With meticulous maintenance, desalination membranes in Israeli plants have proven to be impressively durable, replaced at a much lower rate than was originally predicted [33]. While the tenders that set forth Israeli desal plants' specifications guaranteed operations for a period of 27 years, the facilities will probably last far longer. For instance, during the facility's 12 years of operation, only 60% of the original membranes have had to be replaced at the Ashkelon desalination plant (Ashkelon, Israel), the country's oldest desal facility on the Mediterranean.

Israel's shift to desalinated water brings unquestionable environmental benefits: The country recycles close to 90% of its sewage. Ensuring low concentrations of salt in municipal water is critical to preventing damage to agricultural yields and soil composition. (Typically, during the wastewater recycling process, salinity increases due to evaporative processes. The result of chronic high salinity in irrigated waters has led to calls to reconsider the sustainability of comprehensive effluent recycling [34]). With exceedingly low levels of salinity, desalination offers a better municipal source of water for reuse. Continuous measurements in many of Israel's main municipal sewage treatment plants show that from 2007 onwards, salinity in treated effluents has been considerably reduced. Although still in the early stages, new research suggests that since the advent of a desalinated municipal water supply, the concentration of salt in leaves of crops that rely on effluent irrigation has begun to drop [25].

This is not to say that the world of desalination in Israel is entirely utopian. While the facilities, generally run by Israeli-international consortia, are managed well, there are exceptions. For instance, the Ashdod desalination facility on the southern Mediterranean coast has encountered so many managerial problems that Israel's State Comptroller began a formal investigation into management improprieties [35]. From an environmental perspective as well, from the outset there have also been concerns.

To begin with, Israel's coastline is modest—only 185 km long. The government's decision to establish a Mediterranean Sea desalination network in 2002 was greeted with apprehension in some quarters about the dangers posed to the integrity of the shoreline. With military and industrial installations already occupying large swaths of Israeli beaches, civic and green leaders feared that public spaces, bathing and scenic areas would be supplanted or compromised by the new water production facilities.

It seems, however, that Israel's coastal zone management system has evolved over the years and that such worries were unfounded [36,37]. While the jury is still out, the regional and national planning commissions appear to have been both conscientious and clever in their efforts to avoid the sprawl of additional infrastructure on Israel's coastline. Empirically, it is impossible to point to the loss of any public shoreline due to desalination production. In some cases, the new plants are neatly embedded into existing industrial areas, such as in the Ashekelon or in the Hadera plant. Both are sited in the heart of power plant complexes. In other cases, seawater is delivered inland through a subterranean pipe, with production set far back from the water line. Nearby, unwitting bathers enjoy the scenic sea and sand, blissfully unaware of massive water manufacturing taking place only a kilometer or two away.

Pollution of the Mediterranean waters, however, constitutes a more formidable conundrum. Feedwater delivered to Israel's desalination plants is typically pumped at a depth of 9 m, a full kilometer from the shoreline [21]. Nonetheless, substantial concentrations of contaminated seawater from land-based sewage (including discharges into streams that flow into the sea) reach such distances and pose a hazard, which leads to intermittent plant closures [38]. Moreover, the proximity of seawater inlets to infrastructures, such as oil terminals and ports, has led to closures out of prudency, when oil is released into the Mediterranean [39]. Pretreatment of water can address many of the water quality problems found in "open intake systems" that draw water from the ocean. However, there are limits.

Ultimately, sewage discharges from Israeli wastewater plants are relatively rare and tend to involve extreme storm events or occasional snafus and mechanical mishaps.

In the Palestinian Gaza Strip however, it is poor sanitation and exceedingly inadequate sewage infrastructure (along with insufficient energy to power the wastewater treatment processes) that is responsible for a chronic pollution source that fouls seawater. This has proven to pose a significant challenge for the Ashkelon desalination facility, located near Israel's southern border. Given the de facto state of war along this border region, the political dynamics complicate the most feasible solutions. Reportedly, poor marine water quality, contaminated with Gazan sewage, has forced multiple closures of the Ashkelon plant until currents and dilution sufficiently improve water quality [40].

There are two separate waste streams produced by desalination plants: the brine reject separated during the production process and that associated with the cleaning solutions. Since desalination's inception in Israel, the fate of these discharges in the Mediterranean has been the cause of environmental anxiety [23]. This is due to the variety of chemicals added to seawater during the desalination process, all of which eventually are discharged into the sea. In particular, magnesium, boron, sulfate as well as trace quantities of heavy metals are utilized to prevent corrosion and disrepair of the desalination plant. In excessive concentrations, they have the potential to negatively affect sensitive components in the marine environment [41]. While not considered exceptionally toxic, given the massive flows leaving desal plants, the quantities of the chemicals released are substantial. Ultimately, the brine delivers foreign substances to a sea, where in the case of the Mediterranean, the self-purification capabilities are extremely limited [42].

Typically, chemicals are used during five separate stages of the RO desalination process: first, iron, aluminum salts and polymers are used as coagulants during the pretreatment stage to clean the seawater prior to purification. Biocides, such as chlorine, and neutralizers, such as sodium sulfite, are then added. In Israel, due to environmental regulations, ferric sulfate is used as a flocculation agent in the pre-treatment stages of desalination. Subsequently, a range of antiscalants is utilized to prevent fouling in the membranes. These include iron-hydroxides and polyphosphonates, polyphosphates, polyacrylic acid and polymaleic acid. The antiscalants are a relatively stable group of chemicals, with low biodegradation rates and long residence times in coastal waters. This, in and of itself, reduces but does not eliminate the potential for environmental damage. For instance, polyphosphates are easily hydrolyzed, becoming orthophosphate, a major nutrient for primary producers. (This explains the eutrophication observed near outlets of desalination plants in the Arabian Gulf [43]). Israeli desalination facilities limit their use of antiscalants to polyphosphonates as due to environmental concerns. The fourth stage, when chemicals are utilized, involves reverse osmosis cleaning solutions, including detergents as well as both acidic and alkaline solutions. Finally, after the water is purified, lime ($CaCO_3$) is added to adjust the hardness and provide important nutrients for plants, in the event that the water is utilized for agriculture. Trace amounts of sulfates are often utilized to expedite the dissolving process. Containing twice the salinity of seawater, brines are typically piped far into the sea before being released. (The solid wastes produced during removal of the solids in the backwashes prior to this stage constitute a separate, environmental management challenge [39]). In addition to the chemicals released into the ocean, as the brine from several Israeli desalination plants is mixed with the cooling waters from adjacent electricity plants, the temperature of the discharged brine is typically higher than that of receiving waters [44].

The marine environments along Israel's Mediterranean coast into which the five large desal plants discharge brine reject are monitored regularly by the Israel Oceanic and Limnologic Institute, a government research agency. The parameters and frequencies of the ongoing monitoring are set by the Ministry of Environmental Protection in the desalination's plants' operating permit. Initial monitoring at the brine outfall in the Mediterranean identified several environmental impacts. None of them involved catastrophic eutrophication or significantly toxic outcomes that were feared. However, ecological effects were measurable. For instance, when desalination first was introduced into Israel's Mediterranean coastline, a rise in concentrations of nutrients was measured at the outfall. Presumably, this was the cause of the drop in phytoplankton densities at the Ashkelon plant's outflow site. Temperature and salinity were also higher in the immediate area of discharge, while turbidity increased from the suspended particulates in the brine [44].

Although limited in their range, the findings were significant enough to trigger the intervention of Israel's Ministry of Environmental Protection. The Ministry required reduction both in the inputs of iron (in the form of iron hydroxide) and the quantities discharged from the facility. The Ministry also stipulated that brine be released continuously instead of the pulsed "backwash", which had been the practice and was considered more harmful to receiving waters [44]. Subsequent research of marine environments near other plants found that iron-hydroxide and polyphosphonates were inducing modest physiological and compositional changes in the microbial communities, raising concern about the cumulative destabilizing impact of desalination facilities on aquatic food webs [45].

Even though the brine is now pumped further out to sea than was original required (typically 2 km or more) concerns about the effects on marine life from contamination remain. Effluent density tends to be higher than that in the receiving seawater, so a plume from wastewater can settle on the ocean floor, changing environmental conditions adversely for sensitive marine organisms [41]. A variety of measures can mitigate such impacts. Selecting an appropriate sub-tidal marine environment, with persistent turbulent flow as the discharge site, for example, can reduce risks of ecological damage [46].

Like any industrial process, source reduction constitutes an important objective. There is room for decreasing the quantities of antiscalants and the chemicals used during other stages of the desalination process. Israel's government sponsors a range of research efforts to find alternative substances that are both environmentally friendlier and effective at lower quantities [47,48]. Microfiltration and ultrafiltration during pretreatment of source water has also been suggested as a way to cut back on chemical usage [3]. Future technological developments are likely to produce reverse osmosis membranes that are more resistant to fouling, obviating the need for constant chemical treatments.

Ultimately, the ecological damage caused by brines and desalination chemicals discharged into the Mediterranean appears to be extremely local in its dimensions and modest in magnitude. Moreover, the marine pollution experts at the Ministry of Environmental Protection observe that desalination actually cleans massive quantities of seawater, which it then releases, so some of the impact from brine discharges may not be negative at all [39]. Twenty years after the first studies about marine impacts from desalination were initiated, this remains an area where longitudinal, comparative research should be pursued [49]. As technology improves, presumably even these effects will attenuate over time, and research designed to lower brine discharges will likely contribute to reducing the dimensions of the outflow. The same cannot be said, however, about the environmental impacts associated with energy production. As global alarm over greenhouse gas emissions heightens, apprehension about the copious electricity required to drive the desalination process also intensifies [31].

3. Desalination's Energy Demands

At the top of the list of the environmental downsides associated with the global proliferation of desalination is the accompanying carbon footprint. Israel is a case in point. Israeli desalination plants all utilize reverse osmosis as opposed to the more energy-intensive thermal distillation desal processes, where seawater evaporates and then condenses. Nonetheless, in the RO process, substantial energy is required to pressurize water sufficiently to pass through semipermeable membranes. That means that the amount of energy utilized in an RO facility is ultimately dependent on the concentration of salt in the feedwater. Plants where feedwater comes from brackish groundwater, whose salinity is lower than seawater, use less energy than those where feedwater comes from the sea [29].

For most of the country's history, much of Israel's irrigation and drinking water came from Lake Kinneret (the Sea of Galilee) via a national water carrier [50]. Prodigious amounts of energy are needed to pump water up from the lowest freshwater lake on the planet (200 m below sea level) to a height of 151 m in the Galilee hills. From there the water is piped throughout the country via gravitational flow. When first built, providing the requisite 100 megawatts/h of electricity annually was a daunting task for the nascent country [51]. Today it still takes between 0.4 to 1.0 kWh to pump a cubic meter of water from Lake Kinneret to consumers across Israel. Yet, this is relatively modest when compared to the desal alternative: a cubic meter of water produced by a desalination plant consumes between 3.0–3.5 kWh of energy [52].

As Israel begins to consider its climate change mitigation responsibilities, reducing desalination's carbon footprint should constitute a central policy objective. That means that policy interventions need to reduce greenhouse gas emissions that are both directly and indirectly caused by the desalination process and the related water delivery [53].

It is important to understand this challenge within the general context of the dramatic decrease in energy consumption that has already transpired as a result of technological advances in the desalination process. This progress has been driven by improved, high-permeability membranes, installation of energy recovery devices, and the use of more efficient pumps [3]. As a result, the energy costs associated with operation of Israeli desalination plants have already fallen by some 300 percent [31]. Further reductions in energy consumption appear to be more elusive.

There are four essential stages that take place during the reverse osmosis process, all of which require energy. These include:

- Intake and pretreatment of the seawater prior to its being purified
- Pressurizing of the electric pumping system to a level (800 to 1000 psi) that enables seawater to be pushed through a membrane
- Separating brine from the water
- Stabilizing the purified water following treatment [29]

Together, the pre- and post-treatment of the water is associated with only 13% of desalination plants' energy demands, with water intake from the sea requiring an additional 7%. It is the RO desalination process itself that consumes the lion's share of the plant's electricity [41].

To understand the potential and limitations for reducing the energy in the desalination process, it is instructive to consider the experience of Israel's oldest and newest large-scale desalination facilities. The 7-hectare Ashkelon Desalination Plant is located roughly 2 km south of this southern coastal city, alongside the coal-based, Rothenberg Power Station [29] V.I.D. Desalination Company Ltd. (Ashkelon, Israel), a consortium of Israeli and French companies, designed and built the project, which went on line in 2005. It continues to operate the plant today under a BOT (Build Operate Transfer) agreement with the Israeli government [54] but the general assumption is that given Ashkelon's high performance, the contract with the consortium will be extended.

High energy efficiency was among the more notable engineering innovations in the Ashkelon plant, contributing to what was, at the time, phenomenally inexpensive water production. Significant energy recovery and recycling were built into the desalination process. Specifically, the plant contains a Three-Center Design that includes a pumping center, a membrane center and an energy recovery center. The pumping center uses 3 + 1 High-Pressure Pumps to transfer seawater to all 16 RO Banks. The capacity of each pump amounts to 5.5 MW. The energy recovery system collects pressurized brine from the 16 reverse osmosis banks, transferring the energy to the seawater and pumps as part of the same common feed ring [55]. The design of the pressure center utilizes the "horizontal centrifugal axially split high-pressure pumps, with an optimized size in order to achieve optimal efficiency. The pressure center offers an economy of scale and simplified erection, which allows feed pressure to the RO trains to be increased or decreased. This means that all RO trains remain operational during periods of reduced production, thereby reducing system recovery without increasing the total feed to the plant" [56].

The Ashkelon facility is powered by an on-site, 80 MW natural gas-fueled combined cycle turbine, but is also connected to the national grid to provide redundancy. (Excess electricity generated at the desal plant is sold back to the grid or to private customers [29]) At the time of construction, most of Israel's electricity came from coal-fired plants. Accordingly, the high efficiency of the combined cycle turbines, along with natural gas's lower CO_2 equivalent emissions relative to coal, and reduced transmission losses gave the Ashkelon plant a relatively clean energy profile by local standards. Nonetheless, the facility still had considerable energy requirements: 55 MW in electricity demands, comparable to the energy requirement of an Israeli city of 45,000 people [31]. Like other major desalination plants (e.g., Hadera, Soreq) energy costs are roughly 35% of the total selling price of the desalinated water [57].

The Sorek plant, Israel's newest major facility, was built in 2013. It is considered Israel's (and one of the world's) largest desal facility, with a daily capacity of 624,000 m^3 (or 26 thousand m^3/h) and an annual production level of 150 million m^3 of water. Today the facility supplies Israel with roughly 20% of the country's municipal water demand. In its operations, the plant also utilizes the pressure center approach that was first introduced in Ashkelon a decade earlier. Here as well, the reverse osmosis process consumes 67% of the energy used in the facility [56]. Notwithstanding over a decade of intensive research, it generally has the same engineering specifications as the Ashkelon plant. This suggests that desalination efficiency may be reaching the limits.

Where are reductions in energy utilization during the desalination process likely to be found in the future? Israeli government officials assume that membranes will continue to become more efficient, "tougher against bio films" with better permeability and longevity. (Revolutionary new technologies, such as low energy systems that collect water from the atmosphere, are generally dismissed as ideas that will not scale up to commercial dimensions for the foreseeable future [33]).

Should such improvements eventually be developed, regulators assume that they will immediately be reflected in lower operational expenses, and lower prices submitted by contenders in future desalination tenders. With the price for desalinated water set in long, multi-year contracts between desal companies and the government, the consortia presently running desalination plants in Israel in fact have ample motivation to reduce their energy consumption and consequently greenhouse gas emissions. By cutting energy costs, corporate profits increase. Indeed, that is why operators tend to prefer that their desalination plants become independent power producers and build a cogeneration facility: it saves them money.

The problem is that the laws of thermodynamics establish a minimum amount for the energy that will always be required for removing salts from seawater. This reaches approximately 1 kWh/m^3 of water. Already, modern reverse osmosis processes have begun to approach this theoretical thermodynamic minimum [29]. A recent assessment of the potential for future additional reduction in desalination's energy demands in Science by Elimelech and Philips outlines underlying physical limitations that need to temper optimism about likely improvements in energy efficiency from the reverse osmosis process. Membrane permeability ultimately determines the magnitude of the overpressure required for generating water fluxes. Regardless of how permeable a membrane is, the applied pressure cannot be reduced below the osmotic pressure of the concentrate: "highly permeable membranes may help reduce capital costs by reducing the membrane area needed, but they will not reduce energy consumption. The energy consumption is set by the need to bring the feed volume to a pressure equal to the osmotic pressure of the concentrate." [3].

In the original tenders for private-public partnerships in establishing new desalination plants, general energy efficiency standards were written into the operational conditions required. However, excellence in energy conservation, per se, has never been a central criterion for selecting a given bid for building a desalination plant. After initial quantum leaps in improving desalination's energy efficiency, during recent years, additional progress has been relatively slow. Israeli water managers have always seen a basic level of 3.5 kilowatts per cubic meter (1000 L) of water as something of a technological ceiling [33]. This is unfortunate as they can probably do better: an RO plant located in southern California has shown even lower energy consumptions of only 3.1 kWh per m^3 of water [58] with many experts arguing that seawater desalination with energy consumption levels as low as 2 kWh/m^3 are eminently feasible [59]. Recent research shows that two-stage, batch-like processes and processes with increased staging could offer energy savings as high as 15% over present one-stage reverse osmosis seawater operations [60]. Indeed, there are many suggestions for innovative approaches to desalination that could reduce energy requirements dramatically [61,62].

The importance of monitoring the energy efficiency of desal plants will increase as they get older. Notwithstanding the impressive longevity of desal plants, over time, overall efficiency naturally decreases. As membranes grow older, there is more fouling and scaling so that the amount of energy required to push seawater through increasingly soiled membranes is bound to rise. Standards can and should be set in this regard. Yet, rather than increasing efficiency, they will simply ensure that plants' energy consumption stay in place. In short, while there are differences in technological strategies for future desalination facilities in Israel, none are expected to break the 3.2 Wh/m^3 barrier in the foreseeable future [33].

4. Desalination and Clean Electricity

Strategies to diminish desalination's carbon footprint can either reduce the amount of electricity utilized by facilities or change the energy source that supplies the electricity. As described above, improvements in desalination efficiency are likely to become increasingly incremental. Even though desalination's energy efficiency has improved dramatically, most experts believe that it is unlikely that plants in the future will be significantly more efficient than those being built today. Hence, it is worth considering technologies and policies that could greenify the electricity supply powering desalination processes.

For the years following the introduction of major desal plants, independent, natural gas-based combined-cycle turbines for power generation Independent Power Producers (IPPs) were an important part of strategic thinking at Israel's Water Authority. These power plants allow for the simultaneous efficient on-site production of electricity with high-quality water. That is because until recently, Israel's electricity was largely dependent on coal. With coal combustion's massive carbon footprint [63], almost any combined-cycle facility, fueled by natural gas, improved the overall carbon footprint of a polluting electricity production system [58]. In general, combined-cycle energy production is increasingly popular around the world, demonstrating high energy-conversion efficiency (65–85%) relative to the low efficiency of open-cycle, coal-based power generation (38–42%) and even the more efficient electricity plants run on natural gas [64]. Overall, however, in addition to the economic dividends, the environmental benefits are substantial. These advantages include reduced transmission losses, the reduction of specific energy and CO_2 emissions by reutilizing low-grade waste heat in the desalination process, as well as a drop in cooling water demand [65].

Three of Israel's five major desal facilities have been granted licenses to construct and operate cogeneration facilities on site. The Sorek plant, for example, is the most recent facility to establish an on-site gas-fueled turbine. However, the fact that only 60% of the desalination plants had this option built into their contract suggests that it was a relatively low regulatory priority—on which the Water Authority did not insist. For instance, the Hadera desalination facility is located on land owned by the Electric Company. Therefore, the operators agreed to purchase their electricity directly from the national electricity utility [33].

With the discovery of significant natural gas deposits in the Mediterranean in recent years, the predominant use of coal by Israel's power plants has begun to decline. Local electricity supply has increasingly come to rely on natural gas as its primary fuel source. (At present, only 36 percent of local electricity utilizes imported coal [64]). This neutralizes much of the energy conservation "bonus" associated with utilizing on-site, combined-cycle turbines in desal plants, albeit transmission losses are still reduced by having a contiguous electricity source. At all five of Israel's desalination facilities, specific energy levels are converging around 3.3 kWh/m^3. This means that the environmental benefit sought in the past by opting for cogeneration rather than relying on grid-supplied energy is likely to decline as the respective carbon footprints of centrally and independently generated electricity converge.

Therefore, climate change mitigation interventions need to focus on ensuring a transition in desal plants' electricity source from fossil fuels to renewables. While not unprecedented, this approach is still relatively rare. Today only 1% of the world's desalinated water is produced using renewable energy sources [65]. There are many compelling reasons that advocates offer for setting concrete renewable targets for desal facilities. Some commentators caution that when water relies on fossil fuel-supplied energy, it leaves water prices hostage to the vicissitudes of the world's capricious energy market [66]. Furthermore, desalination based on conventional energy sources increases a country's dependence on fuels supplied by less-than-virtuous governments [67]. In Israel, where intermittent military conflicts are the norm, central power plants are increasingly targeted by hostile neighbors' missiles. Smaller, more modular solar facilities, presumably, would be less vulnerable as the energy-producing component in Israel's water delivery system.

There are many countries, especially in remote or developing regions, that remain far away from available energy grids, where powering with independent solar or wind energy plants already makes sense economically. Presumably the price of expanding the electricity grid in the short-run to power desal plan with conventional electricity would be far higher than establishing cogenerating renewable power sources at present. The same may be true of older desalination facilities that are less energy efficient than new RO plants [68]. With the costs of renewable energy declining dramatically [69], when full-cost, environmental accounting is applied, building renewable energy facilities as part of new desalination plants makes economic sense everywhere.

One country that has begun to internalize the new economic and environmental dynamics is Australia. In 2007, rapid population growth along with a perennially dry climate and inadequate water reserves compelled the city of Perth to expand its water supply. Conscientious municipal leaders decided to aspire for carbon neutrality in this effort, offsetting the new desalination plant's energy consumption by relying on 100% renewable electricity [70], The Perth Seawater Desalination Plant is the largest in the world outside of the Middle East, with a daily capacity of 144 mega liters. It provides 17% of the water needs for the city's 1.6 million residents [70]. The electricity that runs the plant comes from the Emu Downs Wind Farm, located a full 200 km north of the city. The farm's 48 wind turbines generate 83 megawatts of electricity per day or 272 giga-watt-hours (GWhr) per year—fully covering all of Perth's desalination 180 GWhr annual energy demands. [71] Similar wind-generated desalination operations can be found at De Planier in France, Therasia in Island Greece and CREST in the UK [65].

Could this model be one that Israel might emulate? Any positive answer contains certain caveats. Desalination plants in Israel operate within an energy system that is essentially a monopoly overseen by the Israel Electric Company (IEC). A symbolic number of homes have installed photovoltaic panels on their roofs, and then sell the electricity generated at a relatively lucrative feed-in tariff rate to the utility. However, the IEC still controls over 95% of the electricity generated. In the absence of any meaningful regulatory signal or incentive program to induce a transition to renewable energy, it has chosen the path of least resistance, leaving Israel a country with almost exclusively non-renewable electricity. While the government has a long history of ambitious decisions and promises to international bodies pledging different renewable energy levels, none of these targets have ever been met. At present, only 2.6 percent of Israel's electricity comes from renewable sources, almost of all these solar [29].

Were Israel to follow the Australian example, wind energy would be an illogical renewable choice. Thus far, Israel has not embraced wind power, due to the large amount of land required along with protestations by environmental advocates involving migrating birds, landscape aesthetics and exposures to infrasound. The minimal electricity produced from wind also reflects the general sluggishness of a country that has never prioritized renewables for electricity. (Israel has, however, required a passive solar system on the roofs of all new buildings for heating hot water since the 1970s, a regulation that revolutionized the way households heated their water across the country [72]). In opting to prefer solar electricity as the renewable of choice for its desalination network, Israel would hardly be unique. Solar photovoltaic-generated electricity supplies 43% of the desalination plants receiving renewable energy at present, with wind energy reaching only 27% [73].

Adopting a solar strategy for Israel's desalination plants has visceral appeal, but would surely encounter many practical obstacles. To begin with, photovoltaic plants also require massive amounts of space: one study calculates that assuming a specific energy consumption of 8 kWh, in order to produce a single cubic meter of water (1000 L) a day, an area of up to 28 square meters is required [65]. Even though energy efficiency in Israel desal plants is twice as high, the amount of land required to enjoy the desired economies of scale still appears to be excessive. Israel's coastal plain contains the highest-demand real estate in the country with no zoning provisions at present for a major thermal–solar plant. In other words, the shadow price of lands makes the effective cost of the electricity prohibitively high.

Offshore wind and solar farms are not seen as a compelling alternative in Israel, despite the proof of concept that can be found in countries such as Denmark and the UK [74]. The technology is eminently feasible in shallow waters. However, in Israel's territorial sea, the continental shelf drops quickly, even along the southern sections, reaching depths of 100 m, less than 10 km from the shorelines [39]. Generating electricity in the sea, therefore, comes at a great expense and with some uncertainty. Yet, it may eventually emerge as an engineering possibility.

Finally, desalination plants typically run 24 h a day. Until there are low-cost solutions to the problem of storing solar energy, solar-powered desalination plants would still need to receive conventional electricity during nocturnal shifts.

Israel's Ministry of Environment is not uninterested in the sustainability of desalination [75]. Without an excessive sense of urgency, it does seek opportunities to meet commitments made pursuant to the United National Framework Convention on Climate Change's Paris Agreement, where the country pledged to reach 17% renewables in its electricity supply by 2030 [76]. Unfortunately, beyond its ability to lobby within inter-ministerial task forces, the ministry's formal authorities are limited to areas involving marine water quality or indirectly by setting air quality standards. While the Ministry may not be able to impose a command and control, design standard for desalination plants' electricity sources, it does have authority to promulgate a simple carbon tax that could produce the desired results. Unfortunately, historically, Israel's environmental ministry tends to acquiesce to the generally complacent spirit of the Israeli government towards climate change mitigation [29]. When the Ministry does try to push beyond these limits, it often is overruled by more powerful economic interests or rival ministries.

Technology may yet come to the rescue: for over 50 years there has been talk about large-scale, solar-driven, RO desalination [77]. In addition, there has been "talk" in Israel of the potential for wave-driven desal plants [39]. Already a decade ago, three types of solar desalination had been demonstrated locally: photovoltaic-powered reverse osmosis (PV-RO) solar thermal-powered RO, and hybrid solar desalination [78]. Pilot facilities elsewhere have shown promise. These are found in areas as diverse as Chile, where membrane separation technology is powered by an array of solar panels [79], to northern Australia, where a solar-powered system was developed to service remote communities [80]. Proof of concept exists. However, these have been of modest dimensions and never scaled up to significant levels. Recently, construction of the world's largest solar-powered desal facility apparently is underway in Saudi Arabia. The plant will contain a 15 megawatt solar array using polycrystalline solar cells [81]. There are no final price tags reported yet, which would allow for assessing the feasibility of the approach. However, the plant has already generated considerable interest. Science celebrity Bill Nye even declared that this approach could be the "key to our future" [82].

Another solution, promoted by Israel's civil society, involves utilizing enhanced desalination technologies such as thermal-based desalination combined with solar thermal energy or waste heat from existing power generation [83]. The assumption is that limited land resources and high population densities will preclude large-scale solar or wind power installations for the foreseeable future. Nonetheless, at present, prodigious heat produced by Israel's major electricity plants is not utilized at all. This energy could be tapped for thermal desalination processes in adjacent desal plants [84]. Waste-heat recovery would require a change in perspective among policy makers, who would need to integrate energy planning and water planning better [85].

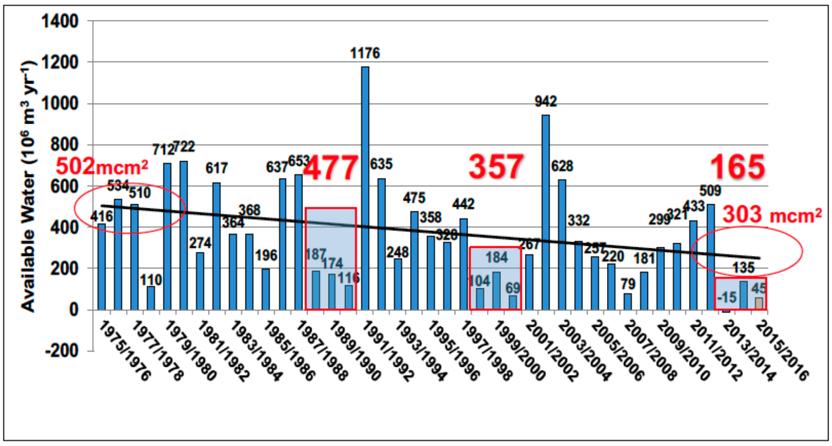
Naturally, a role for solar energy in supplying desalination plants' electricity has been discussed by Israeli decision makers. Yet, in the absence of any immediate breakthrough in solar energy efficiency, local regulators tend to be dismissive of a meaningful role for renewable energy in designing desalination facilities. The amount of space required is simply deemed to be too vast for a country with modest land resources to begin with, especially in the densely populated coastal plain. For instance, at the newly opened Sorek desalination plant, the rooftops are entirely covered in photovoltaic panels. However, the total amount of energy generated is hardly enough to provide lighting for the plant, and generation falls woefully short of the electricity required to power the reverse osmosis process. Moreover, with no cost-effective storage solution for solar energy available at present, the problem remains of providing energy at night for 24/7 production.

Nongovernment Organizations (NGOs) in the region have highlighted the opportunity for peacemaking by relying on transboundary cooperation to deliver renewable energy for desalination. The development of a regional water-energy grid with Jordan—where Israel provides the desalination water and Jordan provides the solar energy—is actively promoted by organizations such as regional environmental advocates, Ecopeace. In addition, indeed, in its most recent promotional presentations, seeking funding for a new desalination port in its port city of Aqaba, Jordan's Ministry of Water writes that a solar IPP "could be one of the ways of reducing the project energy costs" [86].

During the run-up to the Paris Climate Summit in 2015, an Israeli government task force sought to coordinate a strategy that would take advantage of opportunities for greenhouse gas reductions. Desalination was considered closely, given its high present and even higher future electricity demand. The consensus among the officials and civil service professionals was that in light of present technological constraints and anticipated technological developments, greenhouse gas emission reductions would have to be found elsewhere. After a fairly thorough evaluation, the committee became resigned to desalination actually increasing its contribution to the country's future aggregate carbon footprint. Only in the event of a significant technological breakthrough would the Water Authority favor revisiting the issue [33].

5. Discussion: Nuances and Paradoxes

The more one considers the interface between water supply and greenhouse gas mitigation, the more decisions appear complex and paradoxes emerge. For example, although this article focuses on desalination within the context of climate change mitigation policies, the issue of climate change adaptation is also highly germane. That is because of the profound shifts in Israel's rainfall patterns, and reduction in precipitation, especially in the northern Galilee region [2]. During the 31 years between 1975 and 2016, annual precipitation declined in the Kinneret Lake's watershed by some 50 million cubic meters on average (roughly 10%) while extractions increased by 150 million cubic meters. Figure 1 shows the steady drop in flow into Israel's only freshwater lake, the Kinneret, as a result of the new rainfall patterns.



Source: Israel Hydrological Service

Figure 1. Water availability in Kinneret Lake 1975–2016.

During August 2017, the lowest inflow into the lake in one hundred years of recorded, hydrological history was measured [87].

Israel's new desalination capacity relieves the lake of its historic role as a national reservoir [88]. However, its significance as a tourist venue and spiritual site cannot be overestimated and will only increase. Projections anticipating major drops in the lake's level worry water managers who are already planning to take the necessary measures to preserve the resource. In the national masterplan, designed to provide water until the year 2050, the government is evaluating four possible sites on the northern Mediterranean shoreline to place a desalination plant. Much of its production would go to replenishing the lost rainfall and inflow reaching the Kinneret. The notion of desalinizing water to deliver to the lake to maintain a minimal level for fisheries, tourism, etc. may seem fantastical to the lay public. However, many water managers believe it to be inevitable.

Plans for establishing a sixth desal plant on the northern coast may become essential to ensure that Israel is able to honor its commitment to Jordan under their peace agreement, which stipulates a yearly transfer of 50 million cubic meters of fresh water. Moreover, under a new water swap arrangement, Jordan is supposed to desalinize water from the Red Sea near its southern border and transfer 40 million cubic meters to Israel; in return, Israel has agreed to transfer the same amount to Jordan in the north, to help ameliorate the acute shortages that Jordanian cities increasingly face [86]. Implementation will require additional water transfers to Jordan from the Kinneret, something that may be ecologically harmful, given projected water levels in the lake.

Environmentalists also are beginning to realize that the new desal reality requires news ways of thinking about local resources. Israel has relatively significant quantities of brackish water in its aquifers in its southern Negev region [89]. Because the salt content is so much lower here than in seawater (between 2 to 5 parts per thousand or roughly a tenth of the 38 ppt in the Mediterranean) the brackish groundwater can be converted to drinking water for a fraction of the price of desalinating seawater (1 shekel/cubic meter or 40% of seawater plants). Israel has several small facilities that are expected to expand to increase threefold between 2010 and 2020 [90]. Along its border with Israel, Jordan also has prodigious groundwater resources, which could be pumped and desalinized. It might be argued that the potential for transboundary cooperation in developing brackish water desalination projects exists. However, it is worth remembering that recharge in these desert regions is minimal. In Israel, official estimates are only 32 million cubic meters/year [91]. So "mining" this resource and desalinating these brackish aquifers is hardly a panacea as it is essentially unsustainable, and should only be seen as a temporary measure until other sources become feasible.

As the population swells and open spaces give way to residential development, the Mediterranean shoreline for many becomes increasingly sacrosanct. That is why for over eight years, Israel's Water Authority has been unable to finalize the site for a desalination facility on the northern coastline of Israel, even though its primary objective is environmental! One solution is to move the plant further inland, leaving beach areas intact.

Such a solution involves another paradox: the further a desalination facility is moved away from the sea to preserve the coastline, the greater the potential risk of a leak in the piping (or sabotage) which could cause salination of underlying aquifers. Distancing desal plants from the sea also means increasing the quantities of energy required to pump the water inland—and subsequently back into the sea when discharging the brine. For instance, the Sorek desalination plant requires transporting water a distance of 3.5 km. This raises the costs of production and the carbon footprint of the plant. To some extent this can be avoided by thoughtful planning: the Sorek facility is sited in a dell, below sea level, with the supply pipes dug along a gradual incline so that the seawater arrives by gravitational force. However, with energy to power extraction and return of seawater already comprising 20% of total energy consumption, environmental considerations are not unequivocal.

Moreover, the optimal outfall for the anticipated facility in western Galilee may need to reach as far as 4 km out to sea, twice the 2 km that is the default distance for sea discharge at the desalination plants along Israel's southern and central shores. The reason for the greater distance involves the sensitivity of this section of the Mediterranean continental shelf. The proposed engineering solution literally involves drilling through the shelf so that the pipe can reach the required distance before releasing the brine. However, there will undoubtedly be consequences—economic and ecological—for such specifications.

A related question, salient for future Israeli water management strategy, involves the full price of desalination relative to the alternative expense of pumping water from the Galilee's Lake Kinneret (Sea of Galilee) through the national water carrier. In the past, the Director of the Water Authority posited that were the full expense of transporting water from the Galilee to the center and south of Israel to be quantified, desalination would not be significantly more expensive than conventional water from the Kinneret Lake [92].

Although Israel's Water Authority has an internal study underway to offer a more precise calculation, it acknowledges that the results will not be clear cut and ultimately of limited value [33]. That is because the quality of the water is so different. For example, the high-salinity levels (350 mg/L chlorine) in water drawn from the Kinneret Lake become magnified during wastewater reuse and may have a detrimental long-term effect on soil composition. Israel recycles roughly 90% of its wastewater today [34]. Accordingly, desalination helps address the major concern about the long-term environmental impacts of using effluents for agricultural irrigation. The high levels of salinity that remain in Kinneret water, even after sewage is treated at tertiary levels, pose a threat to the long-term viability of local agriculture, particularly in arid regions where there is relatively little washing and leaching of salts from soil surfaces. When desalinated water is utilized and then treated at a sewage treatment plant, as mentioned, effluent salinity levels are relatively low, even following evaporation during storage at warm temperatures. In short, reused effluents, produced after recycling desalinated water, contain far lower salinity levels than more saline natural sources. This constitutes an enormous benefit.

Because of this disparity, it is difficult to put a number on the actual advantage provided to irrigation when desalinated water comes around a second time. Then there are the matters of seasonable availability and reliability, which are also difficult to quantify. While most people consider the two sources of water interchangeable, a thoughtful analysis quickly reaches the conclusion that actually it is a case of "comparing apples with oranges".

The chemical composition of the brine discharged into the sea is yet another paradox. The Ministry of Environment has recently begun requiring that iron be removed from any discharged brine into the Mediterranean. Because antiscalants prolong the life and improve the efficiency of desalination facilities, they are critical to reducing plants' carbon footprint. However, at the same time, there are concerns about the long-term effect of discharging considerable quantities of iron into the sea, even as no evidence of egregious damage yet exists. The new regulatory requirements are an example of the ministry's application of the precautionary principle in the brave new world of desalination. This may be a case where such a precautionary position is justified. Surely, when considering the global picture and the 240 km^3 of brine rejection expected to soon reach the world's oceans each year [65], concerns about the cumulative impact of discharges—both regional and global—make sense. However, it also means that plants need to introduce flocculation technology to increase the size of the sediments so that they can be removed.

Twice a year, desalination facilities submit reports about their performance and results of the environmental monitoring required by a range of government agencies, including Israel's Ministry of Environmental Protection. Thus far, no data have been reported which explicitly or implicitly suggest a need to fundamentally change present desalination processes. The Ministry of Environmental Protection has never objected to desalination, as it was well aware of its critical role in ameliorating pervasive water shortages. It also was well aware of significant environmental benefits, such as freeing up fresh water for river rehabilitation and long-term dividends in soil integrity due to the aforementioned drop in the salinity of recycled effluents. Nonetheless, the Ministry does intervene and exert a modicum of oversight. Israel's Water Authority is open about the fact that the environmental ministry’s demands make their life more difficult. If Israel’s Water Authority, a government agency, feels that environmental regulation makes its life more difficult, the corporations running desalination plants must feel the regulatory burden even more acutely. That said, Israel’s overall policies are decidedly “pro-desal”.

That is why Israeli water managers consider the situation in California with bemusement. The need for massive desalination for California has been written on the wall for some time. Like Israel, the state has a rapidly growing population, experiences droughts with increasing frequency and has a substantial agricultural demand for water [93]. Yet, construction of the Carlsbad desalination plant to supply water for the city of San Diego was delayed for years due to virulent protests by environmentalists [94] before finally going operational in 2016 [95]. Some 15 other proposed major desalination projects face similar opposition [96]. Recent studies show that much of California’s present and future groundwater depletion could be prevented by establishing a desal infrastructure [97]. The state has promulgated new rules designed to address environmental concerns: closely regulating sub-surface intake system, imposing salinity limits on brine discharges and requiring extensive monitoring on marine ecosystems [98]. However, California’s powerful and vociferous environmental community remains uncomfortable with the technology, leaving the general public confused and fundamentally ignorant about the associated issues and dilemmas [99].

Based on Israel’s experience, the environmental benefits of desalination should not be understated. They include freeing up water for stream rehabilitation initiatives, reducing scale in the drinking water, reducing the salts in recycled wastewater and providing water for neighboring countries that are even more parched than Israel. Another of the less-appreciated bonuses of desalination is that it increases the ability of farmers to plan ahead.

Until Israel developed a reliable desalination capacity, the capricious weather patterns of its Mediterranean climate made life for the country’s agricultural community extremely precarious. Water allocations could be cancelled with little warning when the country’s winter rains disappointed and were below average, desiccating orchards and sabotaging long-term agricultural projects. For farmers, the results could be devastating. Now, agricultural operations are able to plan three years ahead, and receive long-term allocation commitments from the government, which knows that it will always have a steady supply of desalinated water [33]. This allows farmers to make more economically rational decisions and financial commitments to more optimal crop strategies. Israeli industry also can invest in infrastructure that requires set quantities of water without concerns that allotments might be lowered due to drought conditions.

Desalination also addresses one of Israel’s major security concerns: ensuring sufficient water reserves in the event of a protracted conflict. For the first time in history, “overcapacity” in water production allows the country to embark on a long-term program of recharging its depleted aquifers. These subsurface reservoirs may one day provide emergency sources of water in the event that there are military attacks or terrorist sabotage that disable desalination facilities and require the rebuilding of infrastructure. The whole notion of redundancy assumes that when parallel sources of water exist, it is unlikely that they will both be damaged simultaneously. Because Israel’s water system is based on a national grid, the new sources allow Israel to be more flexible in implementing a policy of adaptive management. However, all of these advantages come with a price tag in terms of the country’s carbon footprint.

Finally, there has been discussion in the international literature about the possibility of making desalination facilities net “negative” carbon emitters through carbon sequestration. The idea relies on the potential utilization of the magnesium content in seawater [100]. The amount of energy required to break down the magnesium chloride into magnesium hydroxide in seawater is modest [101]. This would allow absorption of the carbon dioxide generated in on-site cogeneration plants. Given Israel’s extensive desalination infrastructure, the country offers an opportunity to serve as a “laboratory” for assessing the potential capacity of the Mediterranean Sea as a carbon sink to absorb desalination-related emissions.

6. Conclusions

As dryland countries facing water scarcity begin to consider a potential role for desalination in their hydrological portfolio, climate change must be considered in developing the associated energy strategy. Even though Israel's desal plants are arguably the most efficient in the world, they make an ever-increasing contribution to the country's carbon footprint. This in no way means that environmental advocates need to disqualify desalination as a water supply strategy. In many situations, the myriad ecological and environmental benefits that desalination provides are compelling. Nonetheless, it should also be recognized that at present, it is plausible that the limits to the energy efficiency improvements that can be attained in desalination processes are rapidly being approached.

Ensuring a supply of clean energy, therefore, appears to be essential for attaining carbon neutrality in the planet's ongoing desalination revolution. Indeed, this is an approach that is already being implemented in countries such as Australia and Saudi Arabia. Israel's experience suggests that in a world characterizing by burgeoning populations, improved standards of living and aggravated water scarcity, low-cost RO desalination constitutes an extremely valuable, technological development. However, it must be embraced fully cognizant of the environmental consequences of its high energy demands and the investment required to address them. It is worth remembering that some forty years ago, a technology-forcing regulation in Israel set the young nation on a new, sustainable route for heating water that transformed passive solar technology worldwide. Given the present imperative of stabilizing atmospheric global carbon levels, it is time to phase in tougher electricity regulations for the country's desal plants and induce Israel's innovative water industry to renew its commitment to renewable energy.

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