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Aspects of environmental impacts of seawater desalination: Cyprus as a case study

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ABSTRACT

Cyprus relies on seawater desalination for a large part of its drinking water supply, with reverse osmosis providing more than 95% of the total desalination capacity in the country. Nevertheless, the environmental impacts of desalination for the Cypriot environment remain poorly understood. Using a combination of mining existing governmental and corporate survey data and reports, this study explores the scale of desalination in Cyprus, the impacts on the coastal marine environment and its overall carbon footprint. Surveys of *Posidonia oceanica* seagrass meadows show strongly reduced density of shoots and leaf surface area, respectively. Analysis of the available data relating to the overall production of desalinated water and energy consumption reveals that 68.7 million m^3 of desalinated water were produced in Cyprus in 2017, resulting in the release of 160 ktons of CO_2 equivalent, representing around 2% of the total carbon emissions in Cyprus. The results are directly applicable for understanding the impacts of brine discharge on seagrass meadows, one of the most common types of Mediterranean seabed ecosystems and useful for providing guidance to decision makers as they are striving to achieve a zero-carbon economy. strategies for achieving greater sustainability in terms of reduced CO_2 emissions and less brine discharge are discussed.

Keywords: Cyprus; Brine; Carbon footprint; Desalination; *Posidonia oceanica*; Seagrass

1. Introduction

Cyprus is the easternmost and the third largest island in the Mediterranean, after Sicily and Sardinia, occupying an area of 9,251 km^2. The area of Cyprus studied in this paper is the southern part of the island, covering 5,800 km^2, which is under the effective control of the Government of the Republic of Cyprus. It has an intense Mediterranean climate with a typical seasonal variation in temperature and rainfall patterns. Freshwater availability depends almost entirely on rainfall, which is highly variable with frequent prolonged periods of drought. Cyprus ranks as the most water-stressed nation across Europe, having the highest water exploitation index [1].

Cyprus is characterized by an ultra-oligotrophic surrounding sea [2], and a warm-temperate climate, which is

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characterized by very hot summers and mild winters [3]. Based on projections of future changes in temperature and precipitation, Giannakopoulos et al. [1,4] showed the vulnerability of Cyprus to future climate change in two 30-y future periods. The warming, depending on the season, is in the range of 1.3°C–1.9°C for the 2021–2050 simulation and 3.6°C–5°C for the 2071–2100 simulation in this study. The shallow seabed around Cyprus is characterized by extensive seagrass meadows [5] of *P. oceanica* and *Cystoseira* forests as climax communities [6], with a mixture of rocky and sandy seabed. Close to industrialized areas, opportunistic seaweeds replace ecologically high value *Cystoseira* climax communities [7,8]. The total number of seaweed species and infraspecific taxa currently accepted is 313 [9]. Inshore marine life of Cyprus includes iconic species such as monk seals [10–12], green turtles and loggerhead turtles [13,14]. Cyprus has a number of alien and invasive species intruding in its waters, including the green seaweed *Caulerpa taxifolia* var. *distichophylla* [15], the holothurian *Synaptula reciprocans* [16], and most recently, the fish *Parupeneus forsskali*, *Torquigener flavimaculosus*, *Sargocentron rubrum*, and the lionfish *Pterois miles* [17], with many of these originating from the Indo-Pacific, having entered the Mediterranean via the Suez Canal as Lessepsian migrants.

Low and irregular rainfall, combined with drinking water consumption surge during summer, which is the tourism season in the island [18] resulted in Cyprus being a major user of desalination technology in order to support demand. These effects are further exacerbated by climate change. During the last 50 y rainfall has dropped 18%, from 560 mm in the period from 1901 to 1930, to 463 mm in the period from 1971 to 2000 [19]. According to the Ministry of Agriculture, Natural Resources and the Environment of the Republic of Cyprus [20], the island has almost 40% less water available compared with pre-1970 data estimations, with intense rainfall events becoming more erratic in recent years. At the same time, climate models predict a rise in the annual mean temperature, which further exacerbates the water scarcity problem in Cyprus [21]. Years of drought have led to the depletion of reservoir-stored surface water and the over-exploitation of aquifers, which are direct climate change effects especially for agriculture as the irrigation period elongated [22,23]. For instance, the drought in 2008 resulted in 100% reduction of water supply for irrigation/agricultural purposes and nowadays the water demand often exceeds the water supply. In these cases, part of the water demand for agriculture is not covered. Due to these circumstances, Cyprus has been a major user of seawater desalination since 1997 [21], but governmental investigations of environmental impacts have remained unpublished. The only (unpublished) documentations available are the original environmental impact assessments [24,25] and an internal report about dispersion of discharged brine [26]. At present, 5 large desalination plants are supplying drinking water to municipalities in Cyprus (Table 1), while approximately 24 smaller desalination units are used by other sectors (Table 2). Reverse osmosis (RO) is the main technology used in Cyprus. Nevertheless, this comes with undesirable environmental impacts, namely brine discharge into the marine environment from the desalination and CO_2 emissions from the electrical power generation required to drive the desalination process. This paper explores the scale of seawater desalination in Cyprus, its environmental impacts and potential remedies towards sustainability.

2. Methods

The methodology of this work included two main approaches: (a) analyzing the available desalination plant records with emphasis on data regarding their impacts, including brine discharge and CO_2 emissions, and (b) marine environmental surveys *in situ*. Data regarding the desalination plants and their operation were obtained by communicating with the relevant authorities in Cyprus (Department of Fisheries & Marine Research, Cyprus Government) with special reference to marine environmental impacts of the brine effluents generated by two desalination plants (Dhekelia and Larnaca) in Cyprus. In terms of the biological component, this study focused on identifying impacts of brine discharge on *P. oceanica*, both in terms of its density and cover as well as impacts on its morphology. *P. oceanica* was selected because it is a species known to be sensitive to environmental change and often used as a bioindicator [27]. *P. oceanica* also forms prairies, which constitute a priority habitat covered by the Directive 92/43/EEC on the conservation of natural habitats and wild fauna and flora. Over the last decade, following increased coastal urbanisation and industrialisation, many meadows have disappeared or have been altered. Given the extremely slow growth rate of this species (1–6 cm y^{-1}), such losses are virtually irreversible [28].

2.1. Data analysis of installed desalination capacity and relevant CO_2 emissions in Cyprus

The CO_2 emissions associated with the production of desalinated water were calculated as CO_2 equivalent per kWh of electricity consumed by combining data of the annual energy needed to produce electricity, both through conventional and renewable energy, and the carbon emissions from the electricity production sector. Reverse osmosis technology is used in desalination plants supplying drinking water in Cyprus. These plants consume only electricity (without direct input of thermal energy/steam). Combining the data then enabled to calculate the emissions in CO_2 equivalent per kWh of electricity consumed. It must be mentioned that in Cyprus all desalination plants used for drinking water supply are using reverse osmosis technology; thus consuming only electricity (without direct input of thermal energy/steam) to desalinate the water.

The water recovery factor [29] is calculated using the following formula:

$$\text{TDS}_{\text{brine}} = \text{TDS}_{\text{seawater}}\left(\frac{1}{1-R}\right) - \frac{R \cdot \text{TDS}_{\text{permeate}}}{100\left(1-R\right)} \quad (1)$$

This formula can be simplified as follows:

$$\text{TDS}_{\text{brine}} = \text{TDS}_{\text{seawater}}\left(\frac{1}{1-R}\right) \quad (2)$$

Table 1
List of large desalination plants in Cyprus

No	Plant name	Capacity (m^3/d)	Raw water	Districts served	Comment
1	Dhekelia	60,000	Seawater	Larnaca & Free Famagusta	Start-up in 1997 and then refurbished in 2007
2	Larnaca	60,000	Seawater	Nicosia & Larnaca	Start-up in 2001, refurbished in 2009 and then in 2012
3	Vassilikos	60,000	Seawater	Limassol & Choirokoitia Famagusta	Start-up in 2014
4	Episkopi (Limassol)	40,000	Seawater	Limassol	Start-up in 2012
5	Paphos	15,000	Seawater	Paphos	Start-up in 2020
Total:		235,000			

Source: Water Development Department [93].

Table 2
List of other desalination plants in Cyprus operated by private entities [94]

No.	Location	Project name	Output water (m^3/d)	Online date	User category
1	Bafra	Bafra Desalination	2,400	2010	Municipalities as drinking water
2	Bafra	Bafra	2,000	2007	Municipalities as drinking water
3	Vasilikos	Vasilikos	1,800	1999	Power stations
4	Dhekelia	Dhekelia	1,440	1982	Power stations
5	Nicosia	Nicosia	1,200	2001	Industry
6	Vasilikos	Vasilikos Power Plant	900	1985	Power stations
7	Paphos	Aristo	850	2009	Municipalities as drinking water
8	Dhekelia	Dhekelia	840	1992	Power stations
9	n.n.	Hotel	504	2008	Tourist facilities as drinking water
10	Dhekelia	Dhekelia	500	2001	Military purposes
11	n.n.	Hedra	500	2006	Municipalities as drinking water
12	Karavas, Kyrenia	Merit Aphrodite Hotel	490	2012	Tourist facilities as drinking water
13	Moni	Moni	360	1993	Power stations
14	Trikomo	Nuh'un Gemisi Hotel	350	2011	Tourist facilities as drinking water
15	Pera Chorio Nisou	Caramondani	325	2000	Municipalities as drinking water
16	Ayios Nikolaos	Ayios Nikolaos	300	1999	Military purposes
17	Nicosia	Lefkosa, Mersin	288	2006	Industry
18	Palm Beach	Palm Beach	150	2010	Industry
19	Larnaca	Larnaca port	150	2013	Municipalities as drinking water
20	Antiparos	Antiparos	53	2013	Municipalities as drinking water

The recovery factor (R) is then calculated from the following formula:

$$R = 1 - \frac{\text{TDS}_{\text{seawater}}}{\text{TDS}_{\text{brine}}} \quad (3)$$

Data for the electricity production in Cyprus were obtained from the websites of the authorities, namely the Transmission System Operator of Cyprus [30]; while missing data were completed through personal communication with the relevant authorities [31].

Data for the CO_2 emissions were obtained from the website of the United Nations Framework Convention on Climate Change [32]. The total greenhouse gas (GHG) emissions have been reported systematically by Cyprus since 2001, when the first inventory report was sent to the UNFCCC covering the period 1990–1997, being a non-Annex 1 country back then. The first inventory report of Cyprus as an Annex 1 country was in 2013. Cyprus as part of the Annex I to the UNFCCC [33] has the obligation to report its annual inventory submissions consisting of the national inventory report (NIR) and common reporting format (CRF). Within its NIR and CRF reports, Cyprus reports the emissions related to the stationary combustion energy industries (1.A.1), which corresponds to the electricity production sector for Cyprus. Detailed definitions for this sector and the rest of the activities reported under the UNFCCC have been reported elsewhere [34]. As in Cyprus, municipal drinking water is produced only by reverse osmosis units (which consume electricity and not thermal energy), the GHG emissions of the Cypriot desalination sector are estimated by determining: (i) the GHG emissions of the Cypriot electricity production sector (in kg CO_2 eq. per kWh) and (ii) the quantity of electricity needed for the desalination sector on an annual basis.

Data for the desalination capacity and the produced desalinated water per year were collected from the relevant authority, namely the Water Development Department (WDD). The main source of information was the WDD website, while missing data were completed through personal communication with the people in charge for providing information about desalination [35].

2.2. Marine environmental surveys

The outfall areas of two major desalination plants, Larnaca and Dhekelia, were surveyed by ship-based and scuba diving-based techniques. For assessing the state of *P. oceanica* seagrass meadows the protocol by Pergent was used [36]. Surveys are summarized in Table 3.

At the outfall of the Larnaca desalination plant, three permanent stations of dimensions 1 m × 1 m were installed; one right at the outflow of the brine, the second at 150 m distance and the third station, which is the reference station, at 2.5 km away. All stations are between 12 and 15 m depth.

The stations were placed at the edges of the *P. oceanica* meadow in a way that half of the station would be covered by *P. oceanica* in order to better allow the monitoring of the meadow's growth or loss through time, by taking annual pictures.

The sampling took place in 2008, 2010, 2011, 2015 and 2020 during the warmer months (June – November). Photographs of the permanent stations and video of the brine outfall (Fig. 1) were taken by scuba diving, along with visual observations such as depth, presence of epiphytes, fine matter, etc. and measurement of physico-chemical parameters such as temperature, conductivity, salinity and oxygen (Table S1). During 2008–2011, sampling included the measurement of shoot density, which is the most common means of description of *P. oceanica* community health for management purposes [36,37]. For better comparability, all measurements were taken at around 2–3 m inward from the permanent stations.

In 2008, the leaf surface area was also calculated by removing 30 *P. oceanica* shoots from each station. The *P. oceanica* leaves were detached from the rhizome according to Giraud's protocol [38,39]. 11 shoots were then separated according to their age (i.e., adult, intermediary (young) and juvenile leaves) and their length and width were measured along with the length of the petiole when it existed [36]. Finally the leaf area index, which corresponds to the surface area of the leaves per m^2, was calculated [40]. At the Dhekelia Desalination Plant outfall, only visual surveys were conducted for the years of 2008, 2012 and 2020 using scuba diving.

2.3. Statistical analyses

Comparisons of *P. oceanica* leaf surface area between the three locations were carried out using analysis of variance and subsequent pair-wise post-hoc comparisons with Tukey Contrasts comparisons of means. Repeated measures ANOVA was used to compare differences in shoot density between the three locations, to account for the lack of spatial independence between samples. All analyses and figures were carried out in R software (version 3.6).

Table 3
Marine environmental surveys of the outfall areas of the desalination plants in Larnaca and Dhekelia

Site	Date	Type of survey
Larnaca	September 2001	Macroscopic surveys
	July 2008	Macroscopic surveys
	September 2008	*Posidonia oceanica* sampling
	October 2008	*P. oceanica* sampling
	August 2009	Macroscopic surveys
	July 2010	*P. oceanica* – shoot density
	August 2011	*P. oceanica* – shoot density
	May 2012	Macroscopic surveys
	August 2015	*P. oceanica* sampling
	6 November 2020	*P. oceanica* – shoot density & macroscopic surveys
Dhekelia	July 2008	Macroscopic surveys
	March 2012	Macroscopic surveys
	5 November 2020	Macroscopic surveys

3. Results and discussion

3.1. Production and uses of desalinated water in Cyprus

In recent decades, water demand in Cyprus has always exceeded the available water supply. According to the latest data available from the Water Development Department (2017), water demand exceeded water supply by 40 million m^3, with desalination and water recycled from urban wastewater treatment plants contributing almost 40% of the total available water supply [29].

The drinking water sector is the main user of desalinated water in Cyprus. Therefore, the capacity of desalination plants in Cyprus has been designed in order to meet all urban residential water needs and to ensure water supply to households and firms independent of weather conditions. Table 1 presents the main desalination plants in Cyprus, providing information about the raw water used, their capacity, as well as the districts served per desalination plant. Fig. 2 presents the main uses of the water supplied in Cyprus and the share of desalinated water to the total drinking water supply for the period 2008–2018. This share varies from 13.8% (in 2013) to 72.9% (in 2018).

According to the Water Development Department, in 2016, the total desalinated water produced was approximately 69 million m^3 (Fig. 5). Given that seawater has a total dissolved solids content of approximately 42,000 ppm and assuming a TDS content in brine effluent of approximately 70,000 ppm, the water recovery factor [29] is calculated at 40%. As a result, the brine effluent generated from all desalination plants in Cyprus can be estimated at 103 million m^3 for 2016. Our work regarding the marine

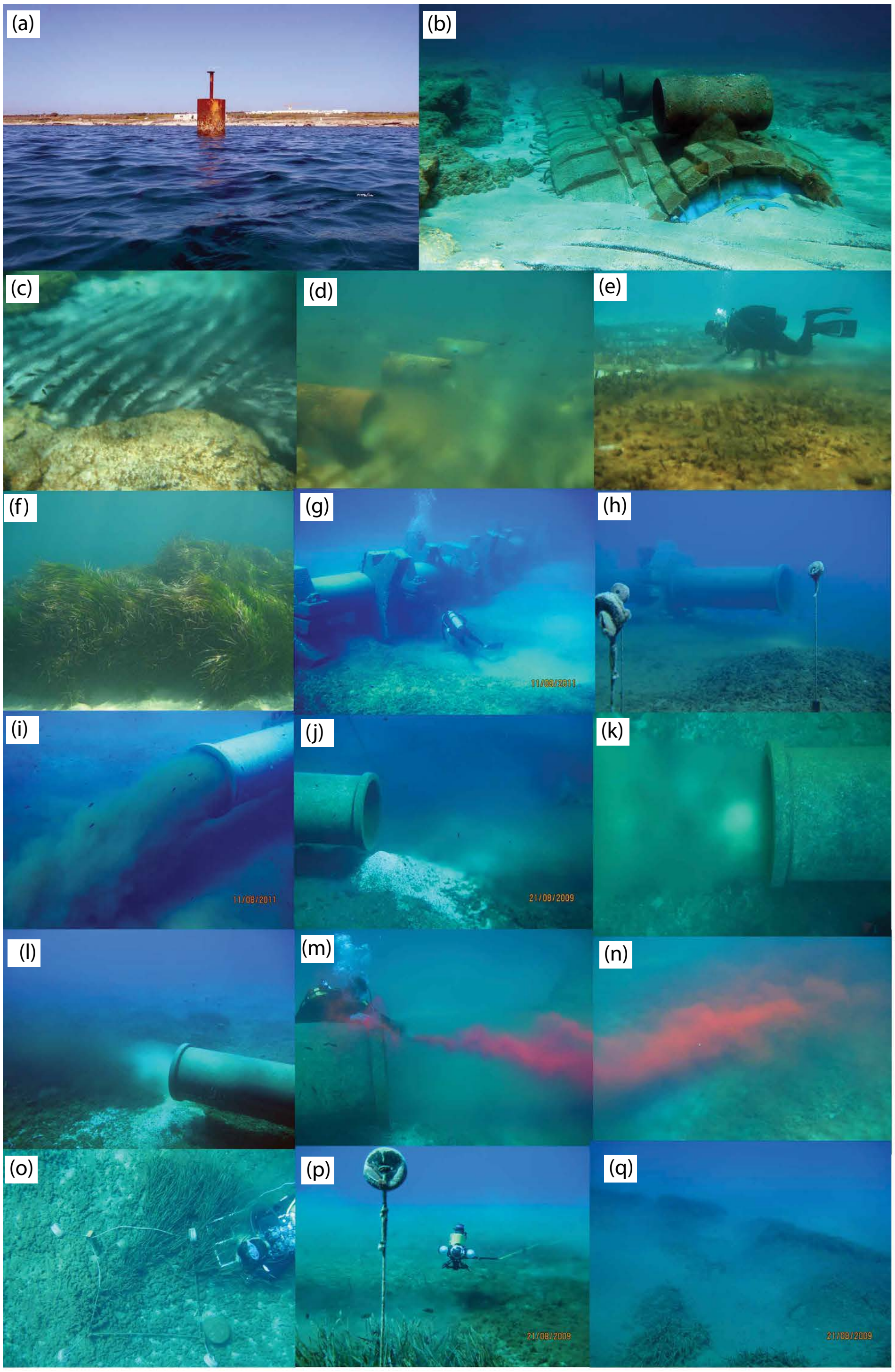

Fig. 1. *In situ* photographs of the desalination plant outfalls at Dhekelia and Larnaca. (a–f) Dhekelia. (a) Surface marker buoy of the outfall. (b) Overview of the outfall structure. The brine outfall pipe is covered by concrete padded-mats such as those used in the offshore oil and gas industry, with orthogonal, multidiffuser pipes standing above it. When this photo was taken, no brine was being discharged. (c) Due to the marked difference in density, the brine tends to sink into local depressions, causing turbid conditions. (d) The diffuser pipes discharging brine. (e) Diving survey of the vicinity of the diffuser pipes. Note the brine collecting near the seabed, visible by the turbid layer beneath the diver. (f) *Posidonia oceanica* meadow near the outfall pipe. (g–q) Larnaca. (g) Overall view of the outfall pipeline. (h–k) The brine outfall at different levels of plant operation: inactive (h), full operation (i), and intermediate levels (j–l). The outfall also contains insoluble solids, which precipitate at the outfall pipeline (j). In order to trace brine dispersion, a diver injected rhodamine, a fluorescent dye, into the outfall (m,n). *Posidonia* meadow health is monitored in long-term quadrats deployed on the seabed (o). Diving surveys are further supported by remotely operated vehicle (p). Near the outfall, brine impacts on seagrass are clearly visible (q).

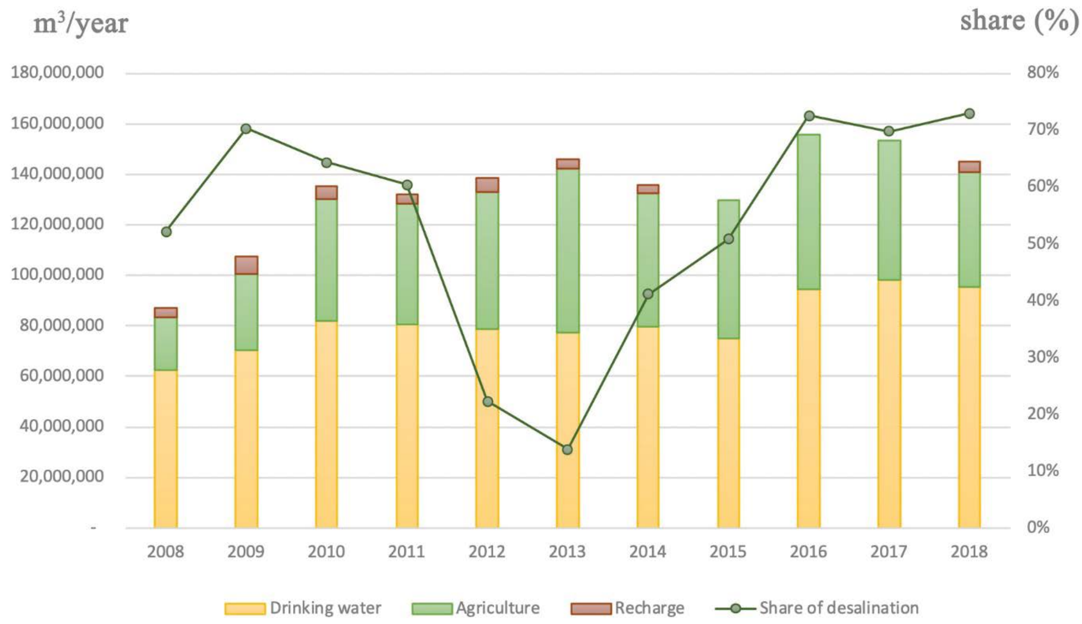

Fig. 2. Water supply by sector and year (2008–2018) [95]. The bars correspond to the left ordinate axis, while the share of desalinated water in total drinking water supply is read in the right ordinate axis.

environmental impacts focused on the desalination plants of Dhekelia and Larnaca. The desalination plant in Dhekelia started operation in 1997 with a total installed capacity of 40,000 m^3/d. Today, the desalination plant has a total installed capacity of 60,000 m^3/d. The desalination plant in Larnaca started operation in 1999 with a total installed capacity of 52,000 m^3/d. Today, the desalination plant has a total installed capacity of 60,000 m^3/d.

3.2. Greenhouse gas emissions generated from the Cypriot seawater desalination sector

The total GHG emissions have been recorded since 1990. The breakdown by sector is presented in Fig. 3. Historically, the energy sector is by far the largest contributor to the total national GHG emissions. According to the latest UNFCCC report, for 2017 the energy sector emitted 6,619 ktons CO_2 equivalent accounting for almost 74% of the total national GHG emissions in Cyprus (8,945 ktons CO_2 equivalent), followed by the Industrial Processes and Product Use sector with 1,270 ktons CO_2 equivalent (or ~14%), the waste sector with 562 ktons CO_2 equivalent (or ~6%) and agriculture with 495 ktons CO_2 equivalent (or ~5%). Within the energy sector, electricity production (Sector 1A1) comprises the largest contributor with 3,299 ktons CO_2 equivalent (~50%), followed by the transport sector with 2,094 ktons CO_2 equivalent (~32%) and the manufacturing sector with 660 ktons CO_2 equivalent (~10%). The methodology for converting the greenhouse gas emissions from the electricity production sector in Cyprus to CO_2 equivalent is in line with the IPPC guidelines (Tier 1: "Sectoral Approach") as discussed in detail elsewhere [33,41].

According to the Cypriot Transmission System Operator [42], in 2015, the total electricity consumption was 4,512,601 MWh with 4,127,876 MWh being produced by conventional energy sources. The total GHG emissions associated with electricity production in Cyprus and the total electricity production are presented in Fig. 4 for the period 1990–2018. Combining those two data series, the mean annual GHG emission factor for electricity production is calculated. As shown in Fig. 4, the GHG emission factor demonstrates a clear decreasing trend. This can be attributed to the penetration of renewable energy to the national energy mix, which has increased from almost 0% in 2010 to almost 9% in 2018.

Since 2001, two desalination plants (Dhekelia and Larnaca) have been continuously operating, with the other two (Limassol, Vasilikos) being added to the total desalination capacity since 2014 (Fig. 5). Three desalination plants (Paphos, Garilli, Moni) have been used only ad hoc, when additional capacity was needed between 2009 and 2011. For the estimation of the total electricity consumed by the desalination plants, the consumption of 4.5 kWh/m^3 of desalinated water produced published by the Water Development Department [43] for Dhekelia and Larnaca was initially used. The energy consumption data were unobtainable due to confidentiality issues, as this was considered market-sensitive data. The Water Development Department reports that, for 2011, the desalination plants in Dhekelia and Larnaca alone account for 2.2% and 1.7%, respectively (or ~4% collectively) of the total electricity consumption in Cyprus [43]. No further data have been published since then, despite the marked increase in the use of desalination in the country (constituting almost a doubling in capacity). In Fig. 6, the estimated energy use associated with the Dhekelia and Larnaca desalination plants is provided. Since the Vasilikos and Limassol plants are large-scale and more modern desalination plants, reduced energy consumption (in the order of 3.5 kWh/m^3) can be assumed. Further communication with the Water Development Department (Dr. Dinos Poullis) revealed that

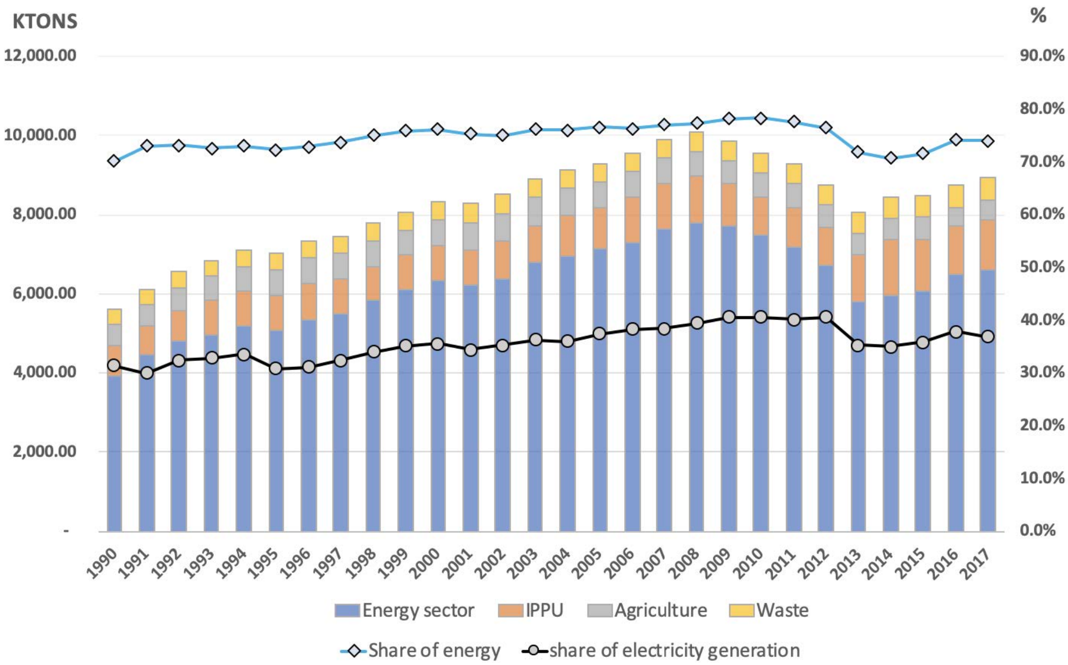

Fig. 3. Greenhouse gas emissions from all sectors in Cyprus (1990–2017) (bars read on left axis) and share of energy and electricity sectors (read on right axis) [33] IPPU: Industrial Processes and Product Use.

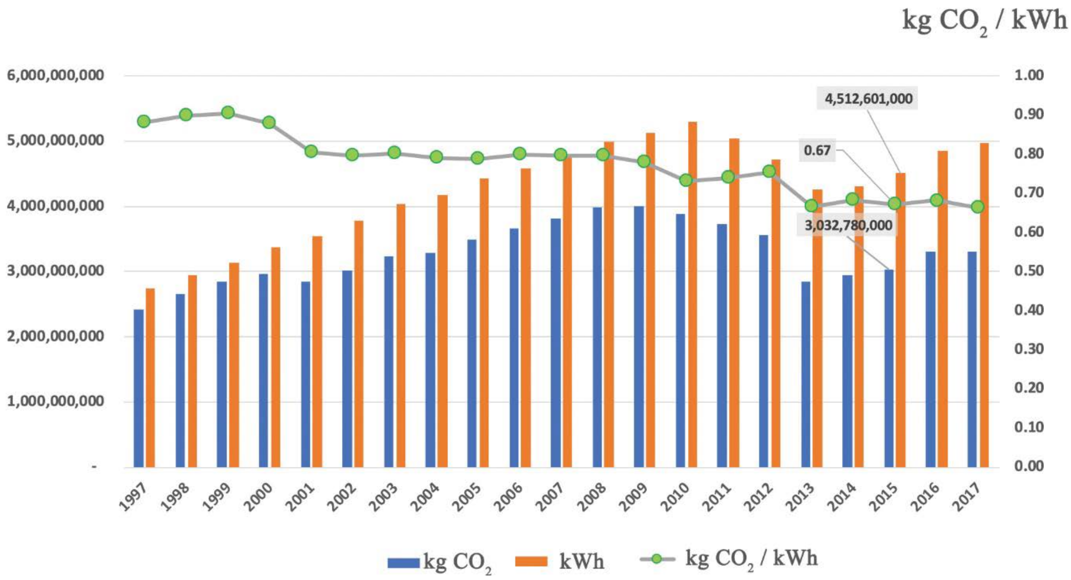

Fig. 4. Greenhouse gas emissions from the power sector in Cyprus (1997–2017) [33].

the total electricity consumption associated with the desalination sector in Cyprus for years 2015, 2016, 2017 and 2018 was 128.3, 239.4, 240.4 and 240.9 GWh, respectively, which results in an average electricity consumption of 3.5 kWh/m^3. As illustrated in Fig. 6, the total electricity production (including conventional and renewable energy production) for the same years was 4,513; 4,860; 4,974 and 5,026 GWh, respectively. As a result, the share of the desalination sector in the total electricity consumption was approximately 5%. Fig. 7 is a flowchart summarizing the energy sources and consumers in Cyprus including seawater desalination.

3.3. Marine environmental impact of desalination plants

Brine discharge from the Dhekelia and Larnaca desalination plants has resulted in alterations of the soft-bottom macrobenthic community composition in the vicinity of the brine outfalls. The main difference between the two

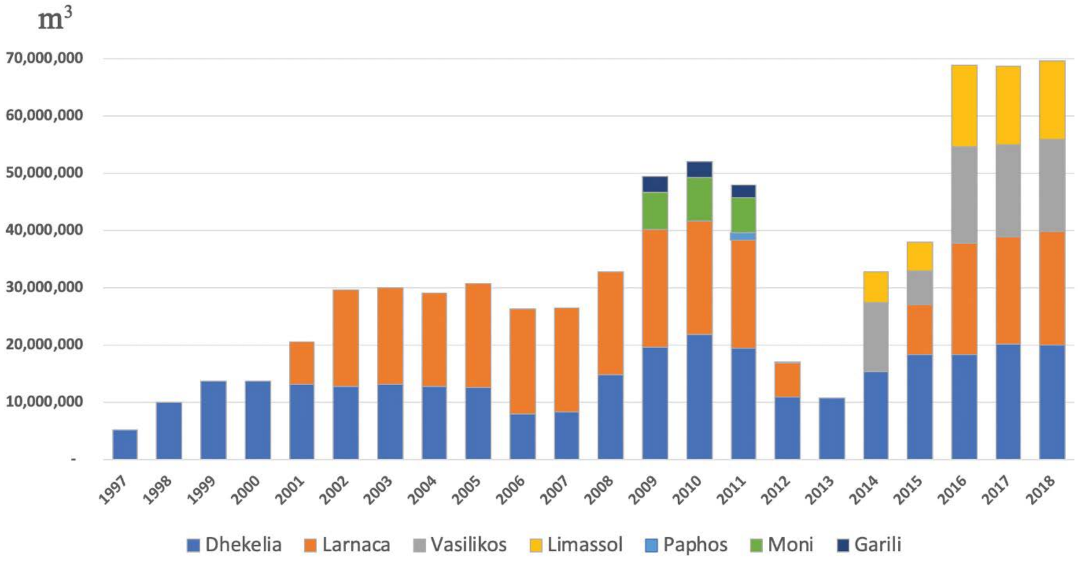

Fig. 5. Desalinated water produced per facility and year in Cyprus (1997–2018) [95].

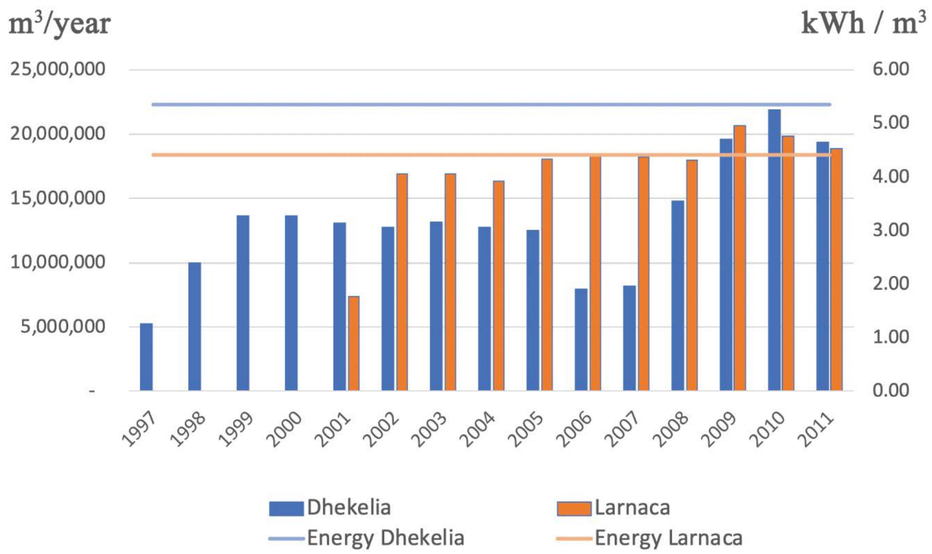

Fig. 6. Desalinated water production and energy consumption at the Dhekelia and Larnaca desalination plants, 1997–2011.

plant outfalls is that the one installed at Dhekelia is a multidiffuser while at Larnaca; there is only one outfall pipe. Also the depth between these two is different. The outfall at Dhekelia is around 4 m depth (Figs. 1a–f) while the Larnaca outfall is around 12–15 m deep (Figs. 1g–q).

Impact on *P. oceanica* communities and also individual plants were clearly detectable (Fig. 7). As confirmed by the surveys in November 2020, at both sites, *P. oceanica* beds showed die-offs in a range of tens of meters, downstream of the outfalls. Average shoot density (number of shoots/m^2, Fig. 8a) was 279.1 at the outfall (range: 0–475, SD: 135.3). At 150 m from the outfall, average shoot density was 415.5 (range: 176–700, SD: 130.6); control site: Average: 442.4 (range: 240–720, SD: 138.6). Repeated measures ANOVA identified significant differences between the sites (repeated measures ANOVA, d*f* = 2.71; *F*-ratio = 5.5, $P < 0.01$). The outfall site had significantly lower density of *P. oceanica* compared with both the 150 m site (Tukey's contrast estimate = 7.1, $P < 0.01$) and the control site (Tukey's contrast estimate = 11.8, $P < 0.001$; Fig. 7a). *Posidonia* shoot density varied temporarily between 2008 and 2020, but with no obvious upward or downward trend (Fig. 9). Average leaf area for adult *P. oceanica* (Fig. 7b) was 17.4 cm^2 at the outfall (range: 10.3–29.8, SD: 4.7). At 150 m from the outfall, average shoot density was 37.4 (range: 16.8–78.2, SD: 9.5); control site: Average: 40.2 cm^2 (range: 11.8–68.7, SD: 14.3). ANOVA identified significant differences between the sites (ANOVA, d*f* = 2,203; *F*-ratio = 48.2, $P < 0.0001$). The outfall site had significantly lower average leaf surface area of adult *P. oceanica* compared with both the 150 m location (Tukey's

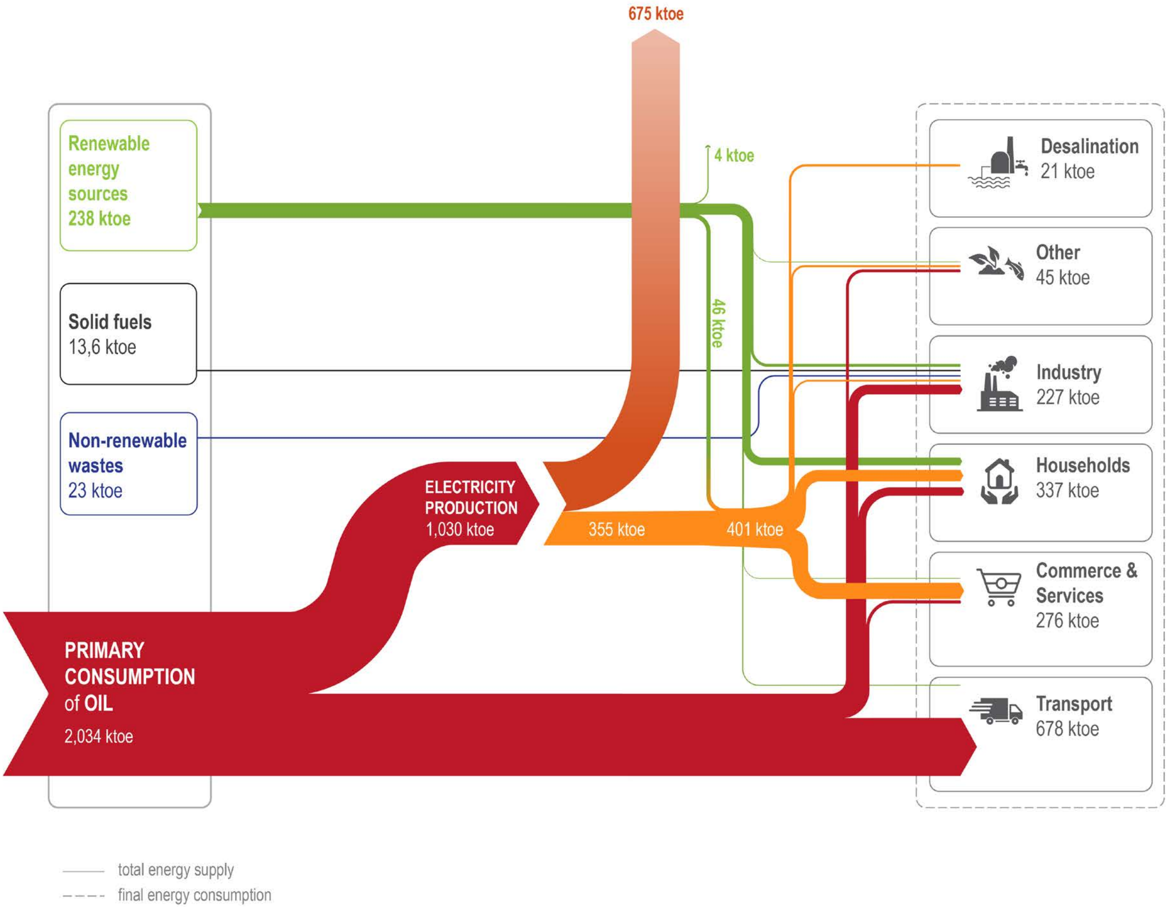

Fig. 7. Energy balance in Cyprus (data for 2018) illustrating the total available energy by fuel type and final end-consumers in Cyprus including seawater desalination. Data retrieved by Eurostat database (code: nrg_bal_c). According to Regulation (EC) No 1099/2008 on energy statistics "non-renewable wastes" are defined as industrial waste (non-renewable) and municipal waste which is of non-biological origin.

contrast estimate = 19.7, $P < 0.0001$) and the control site (Tukey's contrast estimate = 22.7, $P < 0.0001$; Fig. 7b).

With respect to young *P. oceanica*, average leaf area was 14.3 cm^2 at the outfall (range: 7.1–25.1, SD: 5.1; Fig. 7c). At 150 m from the outfall, average leaf area was 18.9 cm^2 (range: 6.2–49.3, SD: 8.6); control site: Average: 20.01 cm^2 (range: 7.7–57.4, SD: 9.6). ANOVA identified significant differences between the sites (ANOVA, $df = 2,203$; F-ratio = 8.99, $P < 0.001$). Young *P. oceanica* at the outfall site had significantly lower leaf surface area compared with both the 150 m location (Tukey's contrast estimate = 4.6, $P < 0.01$) and the control site (Tukey's contrast estimate = 5.7, $P < 0.001$). No differences in young *P. oceanica* leaf area were found between the control site and at 150 m distance (Tukey's contrast estimate = 1.1, $P > 0.05$; Fig. 7c).

As highlighted by several Spanish studies, *P. oceanica* is negatively impacted by increased salinity, which manifests itself in significant growth reduction and reduced shoot survival in tank-based experiments [44,45]. However, even though the conclusions are the same, the results of this study (reporting field surveys) are only of limited comparability to the aforementioned studies which report tank-based experiments to which the brine was added. In a shallow seagrass meadow and similar to the results of the present study, *P. oceanica* proved to be very sensitive to both high salinities and eutrophication caused by discharged brine [46]. In comparison with control plants, impacted plants not only had more epiphytes but also more nitrogen content in the leaves, concomitant with more necroses, less non-structural carbohydrates and reduced glutamine synthetase activity. However, the impacted meadow did not show any sign of large-scale decline. This may be due to its shallow location, resulting in fast dilution and dispersion of the brine plume combined with high incident irradiance. Also another study highlighted the sensitivity of *P. oceanica* to desalination brine [45] – while also providing guidance about salinity levels which should not be exceeded for ensuring healthy seagrass meadows in the proximity to outfalls. The same work also included recommendations for designing and placement of brine outfalls. At another site in Spain, no significant variations, which could be correlated to desalination brine, were observed [47]. A potential explanation for the lack of recorded impacts may be high natural variability, which is typical of such seabed systems in combination with the rapid dilution undergone by the hypersaline brine after exiting the discharge pipe.

An interesting aspect is the concentration of fish at the brine outfalls of the plants surveyed here, which is reminiscent of observations from Australia [48] and hitherto unreported for the Mediterranean. Even though only qualitative photographic surveys were conducted, they reveal the main fauna species found close to the brine discharge area and suggest overall increased fish density. At the Dhekelia Desalination Plant, these are the native species *Chromis chromis*, *Thalassoma pavo*, *Serranus scriba*, *Oblada melanura* and the alien species *Torquigener flavimaculosus*, *Siganus rivulatus*, *Siganus luridus*, *Parupeneus forsskali* introduced from the Red Sea or Indian Ocean via the Suez Canal. At the Larnaca brine outfall, the main species found are the native species *Chromis chromis*, *Coris julis*, *Muraena helena* and the alien species *Pterois* sp., *Sargocentron rubrum*, *Torquigener flavimaculosus* and *Parupeneus forsskali*, the latter of which all have Indo-Pacific or Red Sea origin. Several individuals of the alien sea cucumber species *Synaptula reciprocans* were also observed suggesting robust populations and clear establishment. Establishment of invasive species is argued to be favoured in already stressed ecosystems [49].

Awareness of the principal environmental impacts of seawater desalination has existed for decades [50], even though detailed knowledge about the nature and scale of these impacts as well as geographic coverage of such studies have been regionally biased and patchy. As highlighted by Fernández-Torquemada et al. [51], there is a shortage of monitoring data concerning effects of the brine effluents from desalination plants and their dispersion in marine systems – and there have been few studies since this one. Worldwide, desalinated water production stands at around 95.37 million m^3/d, with brine production and energy consumption being the key barriers for further deployment of desalination [52]. Brine production is estimated at 141.5 million m^3/d, which is 50% greater than previous estimates. Innovation and developments in brine management and disposal options are required [52]. Historically, the environmental impacts of desalination were severely neglected, with just 118 publications before 2000. However, literature published in this category is now increasing at a fast rate, with an additional ~2000 publications since 2000 [52]. Thus, seawater desalination contributes to and exacerbates the typical anthropogenic stressors on the marine environment in the context of overall global change, especially ocean warming and acidification [53] and, indirectly, contributing to biodiversity loss and creating conditions more conducive to the establishment of alien species. This applies both locally due to the discharge of hypersaline brine, which is in many cases at increased temperatures, and also globally due to the strong production of CO_2 associated with fossil fuel–powered desalination. As far as Cyprus is concerned, the environmental and climate change impacts associated with desalination in Cyprus have not been explored before, which is why the present paper fills an important gap.

Local impacts of brine discharges are marked. The most accurate data about marine environmental impacts of desalination in Cyprus waters presented here relate to the Mediterranean seagrass *P. oceanica* (Fig. 8), which forms expansive climax communities around the island. The data clearly show that desalination reduces both community density and also the ecophysiological performance translating into reduced leaf area (Figs. 8b and c). This study clearly demonstrates a very localised impact of the discharge of desalination waste on *P. oceanica*, with the impact reduced markedly at 150 m from the discharge point. It is important to note that this localised impact is potentially very much dependent on the amount of waste discharged which will be directly correlated to the capacity of the desalination plant. Further research is very much required to determine the extent of the impact spatially and its relationship with the amount of discharge. Temperature and salinity are considered key stressors for seagrasses. This is consistent with recent studies highlighting the multiple effects of salinity and temperature stress on the Mediterranean pioneering seagrass *Cymodocea nodosa* [54,55] – which is relevant in the context of brine discharge [56]. Unlike *P. oceanica*, *Cymodocea* species tend to be euryhaline [57]. Mediterranean seagrasses have also been used for assessing benthic marine environmental quality [58–60]. In the context of seawater desalination, the issue of brine discharge impacting seagrasses has been explored mostly by a number of Spanish studies conducted in the context of the desalination plants in Alicante [51,56], Blanes [47] and Formentera [45,46,61]. One of these studies [61] also provided guidance for designing brine outfalls in order to reduce impact on benthic communities – specifically, to avoid placing such outfalls close to seagrass meadows or, if this is not feasible, to avoid exceeding salinity levels of 38.5 psu anywhere in the meadow for more than 25% of the observations (on an yearly basis) nor 40 psu in any point of the meadow for more than 5% of observations. Studies on seagrass meadows in Spanish coastal waters are complemented by investigations on desalination brine impacts on amphipod communities [62], revealing their high sensitivity, while work on meiobenthic soft-bottom systems in Gran Canaria found that closeness to a brine discharge point significantly altered the ecological macrobenthic fauna pattern [63]. Furthermore, it was observed that meiofauna can be considered a suitable tool for monitoring marine environmental brine impacts on infralittoral, soft-bottom communities [64]. Very recently, Fernández-Torquemada et al. [65] showed that negative effects of brine discharge can be reduced by adequate planning. Such mitigating measures should be adapted to plant type and size, local hydrogeological conditions and benthic communities in the discharge area. This work shows that a suitable discharge location must be selected and the dispersal of brine by surrounding seawater must be optimized in order to minimize negative marine environmental impacts. This should come with a well-planned environmental monitoring program assessing brine plume distribution temporally while monitoring key organisms. If significant impacts can be detected, these can be mitigated by introducing devices that enhance brine mixing with seawater or/and by diluting the effluent prior to discharge. Another recent study [66] reviewed a total of 30 desalination projects submitted for Environmental Impact Assessment (EIA) between 1998 and 2009 and concluded that a review of the EIAs would be recommendable in order to harmonize the monitoring requirements nationally, to optimize their sampling designs (including the essential descriptors when they are absent), and to omit non-relevant descriptors.

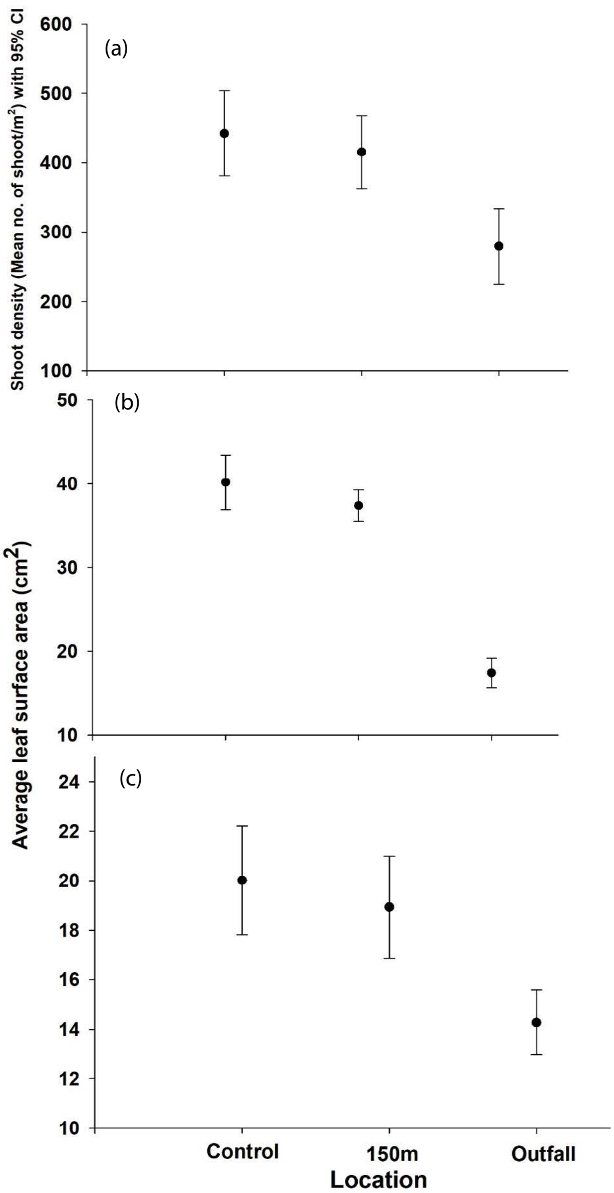

Fig. 8. (a) Average shoot density per quadrat at outfall, 150 m from the outfall and control site. (b) Average leaf area for adult *Posidonia*. (c) Average leaf area for young *Posidonia*. A 95% confidence interval was indicated on the graphs for the three locations.

Such standardization is particularly worthwhile for desalination plants with larger brine production due to their likely more pronounced impacts on the marine environment. Such studies have resulted in recommendations for the design of desalination plant intake and outfall systems as well as the operation of such plants, for example in Spain [66] and the USA [67] as well as the conductance of EIAs of desalination plants in Chile [68].

The aforementioned Spanish studies on desalination impacts contrast with the situation in the Eastern Mediterranean, which is generally less well studied for many aspects of its marine biology and oceanography, which also has an inherently higher need for desalination due to a drier and hotter climate – but where such studies are completely lacking so far. Other marine environmental parameters are scarce, both in Cyprus and worldwide in general, highlighting the urgent need for further research on this front. This is in line with Lattemann and Amy [69], who, after reviewing a substantial body of literature, concluded that while the existing monitoring studies have so far used a wide range of approaches and methods to investigate the environmental impacts of desalination plant discharges, typical shortfalls are that they are limited in scope, short-term, or localized. In essence, many studies fall short of recognizing the potentially synergistic effects of the single waste components of the discharges on marine organisms and the complexity of the potential responses by the ecosystem [69]. Overall, there is still a shortage of studies concerning Mediterranean marine life. Elsewhere in the world, for example, in the Red Sea, such a study has investigated brine impacts on the coral *Fungia granulosa* [70], whereas near Sydney, Australian scientists interestingly observed a strong increase in the abundance of fish around the outlet, which included substantially greater abundances of demersal and pelagic fish, as well as fishes targeted by recreational and commercial fishing near the recently-inaugurated desalination plant [48]. Further research should address the spatial scale of impacts, and also the underlying physicochemical drivers for the effects observed.

In contrast to the government-controlled areas, which rely heavily on seawater desalination, the Turkish-occupied northern sector of the island has been receiving about 72 million m^3 via an undersea pipeline from Alaköprü Dam in Turkey since 2016. However, the pipeline was ruptured by marine currents in January 2020 and took until late summer 2020 to repair, putting water supply in the northern part of the island into jeopardy for months [71] and highlighting the strategic risks associated with dependence on a major water supply source from another country. The dependence of northern Cyprus on water supplies from Turkey has been considered geopolitical "hydraulic patronage", that is, the systemic provision of water resources by a patron state to a client territory [72].

The other major area of concern associated with seawater desalination is that of climate-changing CO_2 emissions associated with producing the energy required for this process. The carbon footprint of different desalination vs. water reuse technologies has been reviewed elsewhere [73]. Unlike a few countries elsewhere in the world such as China [74] or Australia [75,76], few data for the Mediterranean and Middle Eastern region have been published in the peer-reviewed literature in this regard, but, as the present study shows, they may exist in difficult-to-access archives of government authorities and utility companies. In this regard, this study fills an important gap for calculating desalination-associated CO_2 emissions in one of the major users of desalination in the EU. In Europe, an exception are two regional studies from the Canary Islands, investigating the overall energy consumption required for desalination [77] and the carbon footprint associated with water use in hotels [78].

Gude et al. [79] reported possible combinations of desalination processes with renewable processes. Papapetrou et al. [80] report that between 1970 and 2009, 131 renewable

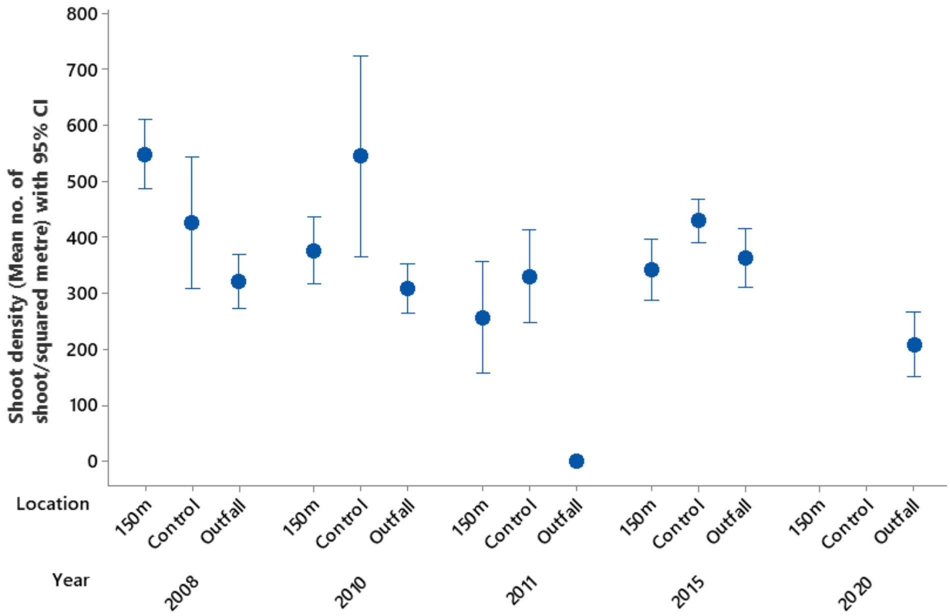

Fig. 9. Temporal variation from 2008 to 2020 in *Posidonia* shoot density at the outfall, 150 m distance and the control area. Data represent average values with 95% CI. Data for 2020 exist only for the Outfall location.

powered desalination plants have been recorded. It must be noted that the vast majority of the RES-D applications employ solar-powered techniques with PV-RO being the dominant combination, amounting to a share of 31% [81].

Given that water desalination is of crucial importance for securing water supply in Cyprus and also that this island nation needs to import 100% of its fossil energy needs, renewable desalination could be considered as a good solution, especially concentrated solar power and other forms of solar energy such as photovoltaic-powered reverse osmosis (PV-RO) and solar thermal powered reverse osmosis (ST-RO; e.g., reviewed by [82]). Equally, seawater desalination in conjunction with energy recovery from waste incineration as highlighted by a theoretical study for Malta should be given consideration [83], also in light of residual waste in Cyprus still being 100% deposed in landfill. A recent study from Australia [76] examines the optimisation of the operation of a 100% renewable energy grid by integrating seawater desalination plants and pipelines as a variable load. We would argue that this constitutes a particularly interesting scenario for Cyprus: the integration of seawater desalination alongside the necessary, further massive expansion of renewables in the Cypriot insular electricity grid constitutes a particularly attractive option for buffering fluctuating electricity output and demand while achieving the two major overarching objectives of becoming a carbon-neutral economy and meeting its freshwater needs. This should be applied within a flexible framework for assessing the sustainability of alternative water supply options in Cyprus [84], also considering that Cyprus has a considerable network of reservoirs and that recycling waste water has been developed considerably in recent years [85,86]. We would suggest applying optimization-based technique for the design of cost-effective desalination networks as described recently [87], integrated with renewable energy sources, subject to the overall carbon reduction targets of Cyprus. Indeed, elsewhere in the world, the trend to renewable-powered desalination plants is well under way, for example, the 60,000 m^3/d PV-RO plant in Al-Khafji, Saudi Arabia, and a wind-powered RO plant in Australia using 48 wind turbines with a maximum output of 80 MW to drive an RO plant of 26 MW [88].

The project SOL-BRINE (LIFE09 ENV/GR/000299) has demonstrated such a brine treatment process (capacity: 2 m^3/d) powered by solar energy at pilot scale [89,90]. Xevgenos et al. [91] valorize the seawater desalination brine at approximately € 6 per m^3 that is currently being discharged at sea or into surface waters. This valorization assumes only the bulk salt compounds and water, as the materials to be recovered. If trace metals (such as rubidium, strontium, lithium, etc.) are also considered, the economic value per m^3 of brine can be significantly increased. Arguably, the present work also provides a useful model case study for larger countries in the Mediterranean – Middle East – North Africa (MENA) region, which includes much larger users of seawater desalination than Cyprus.

Given the global urgency and also the obligations of the Cyprus Government under the Paris Treaty to implement more stringent reduction targets for carbon emissions, as well as the new EU Green Deal that was recently adopted [92] calling for climate neutrality by 2050 in Europe, the changeover to 100% renewable-powered desalination in Cyprus should be implemented within the next few years.

4. Conclusions

Desalination is key for the safe drinking water supply in Cyprus, contributing as much as 70% to the total water supply. However, this comes with significant local environmental effects, both in terms of greenhouse gas emissions and marine environmental impacts. In 2018, 69.6 million m^3 of desalinated water were produced in Cyprus requiring the consumption of around 240.9 GWh of electrical energy, which was mostly produced by burning (imported) fossil fuels (oil and petroleum products). We concluded that this energy consumption results in the release of approx. 169 ktons of CO_2 eq. to the atmosphere. This represents around 2% of the total GHG emissions in Cyprus. Furthermore, the production of this quantity of desalinated water generated around 103 million m^3 of brine effluent as well. It is also important to note that desalination accounts for approximately 5% of the total electricity consumption in Cyprus, while it represents one of the largest shares of electricity consumption within the industrial end-users.

Apart from the carbon emissions, the desalination sector is causing marine environmental impacts in the vicinity of the brine discharge points. After studying two of the largest desalination plants in Cyprus (Dhekelia and Larnaca), the results show mostly strong impacts on seagrass (Posidonia) meadows. A promising solution to both problems – brine discharge and CO_2 emissions – would be renewable-driven (and waste heat-driven) desalination, followed by zero liquid discharge, to recover salts and thus advance the decarbonization of the Cypriot desalination sector and the promotion of circular economy concepts.

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Supporting information

Table S1
Example of the results of measurement of physico-chemical parameters at the outfall of the Larnaca Desalination Plant (survey in July 2008)

Station (depth and position)	Temperature (°C)	Conductivity (mS/cm)	Salinity (ppt)	Oxygen		pH
				mg/L	%	
Brine outfall	25.5	80.4	64.2	5.1	90	7.81
Brine channel (following the brine towards the 150 m station)	25.0	55.2	41.4	6.5	100	7.98
150 m (sea floor)	23.3	52.7	39.1	6.8	102	8.16
Reference (sea floor)	25.7	52.6	39.2	6.3	99	8.17