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Water-energy nexus in a desalination-based water sector: the impact of electricity load shedding programs

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Reliance on water production by desalination as a solution to water scarcity is growing worldwide. High energy demands of seawater desalination raise new challenges for both water and energy management and highlight the importance of understanding the operational dependencies of the water sector on energy supplies. This study provides an in-depth analysis of the impact of the water-energy nexus in a desalination-based water sector, using Israel as a case study. Being large energy consumers, desalination plants are part of the Electricity Load Shedding Program (ELSP), which government energy regulators invoke in times of energy shortage. We focus on the interdependency between the two sectors as manifested at the time of ELSP utilization during an extreme heat wave. We show that energy shedding compensation is 6 to 14 times greater than the economic loss to the desalination plant from no water production, creating an obvious economic incentive to participate in ELSPs. However, this imbalance has a substantial negative impact on the water sector, which may compromise the level of service. Our evaluation concludes that the government authorities regulating water and energy need an official mechanism and policy for joint management strategies that can ensure economic efficiency and reduce the risk of power and water shortages during extreme events.

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INTRODUCTION

Seawater desalination is increasingly being adopted as a strategy to address issues of water scarcity and water quality around the globe, as it is widely seen as a steady and practically unlimited source of water[1,2]. As of early 2020, nearly 21,000 operational desalination facilities with a total desalination capacity of nearly 115 million cubic meters per day (Mm^3/d) were located in at least 177 countries and territories worldwide[3–5]. The desalination sector is demonstrating tremendous growth. Global production of water by desalination in 2016 was twice that of 2008[6], and the size and number of desalination plants (DPs) increased at 6.8% annually between 2010 and 2020[4]. While various techniques are used to desalinate water, all are relatively energy intensive compared to the traditional water supply. This energy consumption represents a significant share of desalination's overall costs and environmental impacts[7–10]. As such, a substantial amount of literature addresses issues relating to the management of energy demand by desalination[10–12] within the broader literature on the water and energy use interdependencies, often referred to as the water-energy nexus[13–15].

The broader water-energy nexus covers both the use of water in the energy sector (e.g., hydropower, pumped storage generation, and water for cooling) and the use of energy in the water sector (e.g., for pumping and treatment). The literature varies in terms of the scope, granularity of data, and synthesis of information covered including: (i) studies focusing on examining energy intensities at different stages of water production (e.g., pumping, treatment, distribution, and collection)[16–19], (ii) studies examining the water-related energy intensity by sectors (e.g., municipal, agricultural, or industrial)[6,17,20,21], and (iii) studies benchmarking energy intensities by water sources (e.g., surface and groundwater) and production or treatment technologies (e.g., reverse osmosis and multi-stage flash)[6,22,23]. Notably, existing studies provide water-related energy estimates at national or global scales relying predominantly on national and international databases, such as the Food and Agriculture Organization of the United Nations, International Energy Agency, and the United States Energy Information Administration[24–26], and extensive literature surveys. Relatively few studies focus on short-term energy demand fluxes resulting from the water sector, including managing peaks or spikes in energy demand that can be particularly taxing on electricity providers[27,28].

In a desalination-based water sector, exploring the short-term dynamics is critical for recognizing the benefits and revealing the unintended consequences of the interdependencies between the water and energy sectors. However, studies at the crude temporal scales or not accounting for the different dimensions of the nexus, may overlook lapses in the integrity of the water sector. To address this gap, this study explores these dependencies on a short-term operational scale considering the different dimensions that contribute to the overall water-energy nexus. These dimensions include the water and energy production, distribution, and demands; weather conditions; the governance and regulatory oversight; data collection and reporting; and economic values. Specifically, we contribute to current knowledge by showcasing the: (a) short-term operational dependencies on energy for water production by desalination, (b) implications of these dependencies in the presence of economic incentives (or disincentives) in the energy and water sectors, and (c) the role of real, high-resolution climatic, energy, and water data in revealing the imbalances in water-energy dependencies and making joint management decisions in the water and energy sectors.

Israel, the study area in this paper, is representative of a water-stressed country that implements advanced measures for water production, including large-scale desalination. In Israel, desalination provides for over 80% of municipal water supplies and nearly

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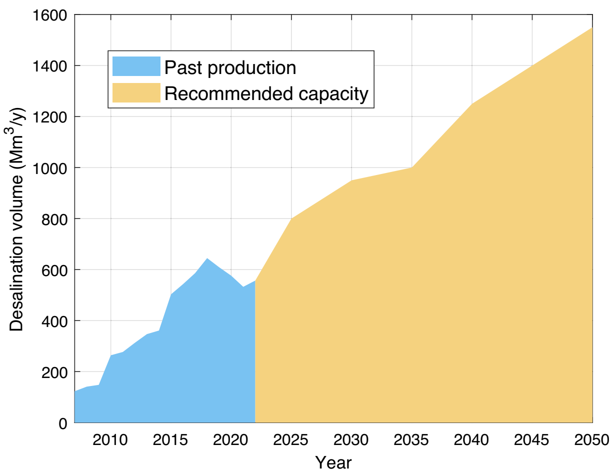

Fig. 1 Past and future annual desalination volumes in Israel. The blue area in the figure shows the past desalination production in Israel and the yellow area represents the Israeli Water Authority recommended desalination capacity. Both past and recommended volumes are in million cubic meters per year.

a third of all freshwater supplies annually[29]. The desalination plants are also large consumers of energy, responsible for 3% of national electricity consumption[30]. The Israeli Electricity Authority employs various demand management programs for managing the electricity sector and balancing energy supply and demand. This study examines a policy's effectiveness in incentivizing desalination plants to reduce production during periods of peak energy demand. Specifically, we ask *how did water production by desalination plants change in response to load shedding incentives and how these changes relate to the national water supply, regulatory system, and the oversight of the energy and water sectors*. Understanding these interactions is challenged by data complexities and barriers for data-sharing between institutions due to the high associated costs, data ownership and sensitivity issues, and lack of a formal mechanism for documenting institutional knowledge. We show the negative implications of current energy policies on the water sector, suggesting that changes in regulation and policy are needed for more efficient and accountable joint management of the water and energy sectors. The present study contributes to the existing water-energy nexus literature by examining the impact of actual policy designed to reduce short-term electricity consumption on the water sector during periods of peak energy and water demand during an extreme weather event. Given the increasing integration of desalination into water supply worldwide, insights gained from this study can inform policy design, regulation, adequacy of data collection and reporting in other desalination-based regions.

RESULTS

Israel water sector

Israel has fully exploited its renewable natural freshwater resources since the late 1960s[31] and Israeli water managers have been facing growing challenges in supplying reliable quantity and quality of freshwater due to the declining and highly variable replenishment of natural water resources and contamination of aquifers[32]. Historically, the average annual replenishment of fresh water was roughly 1390 Mm^3/y. However, natural water replenishment has been declining in recent decades due to various causes[33], and the total is currently estimated at approximately 1100 Mm^3/y with a very high variability of 460 Mm^3/y. This averages between 100 and 150 m^3 per capita per year ($m^3/c/y$). Based on the Falkenmark Index—which defines nations facing water scarcity as those with less than 1000 $m^3/c/y$, and those facing acute water scarcity as those with less than 500 $m^3/c/y$[34]—Israel faces acute water scarcity, as do several of its neighbors with whom it shares its natural water resources[35].

In response, the country has increasingly relied on non-natural sources of water, including wastewater reclamation and desalination. Since 2006, five large seawater DPs and several smaller brackish water DPs have been constructed and are operating in Israel. Desalination in the country now supplies up to 650 Mm^3/y (Fig. 1), representing approximately 80% of municipal demand[23,29]. By 2050, total desalinated seawater production capacity is planned to exceed 1500 Mm^3/y, exceeding that of natural freshwater sources[36,37].

Water management in Israel is highly centralized, with most regulatory oversight concentrated in the Israeli Water Authority, which is responsible, among other things, for approving all drilling and production of natural surface and ground water resources, and issuing the contracts for desalination facilities. All DPs sell their water to the centralized Israeli National Water Supply System (INWSS) managed and operated by Mekorot, the National Water Company.

Israel energy sector

According to the Israeli Ministry of Energy[30], in 2019, the country's total electrical power generation capability was 19.4 GW, of which 12.8 GW is by the government-owned Israeli Electricity Company, 4.3 GW from privately owned conventional production plants, and estimated 2.3 GW of different renewable energies production plants, mainly from solar energy. Most electricity generation is produced from fossil fuel power stations, with approximately 64% gas and 30% coal. Renewable energy accounts for a minor share of electricity production. In terms of consumption, the domestic sector consumes approximately 30% of the electricity demand, the commercial and public sectors 27%, industry and agriculture sectors 28%, the Palestinian Authority 9%, with water pumping accounting for over 6%[38] (This figure does not include the energy of the desalination process itself.)

Peak energy demand is usually recorded during the summer. In 2019, the peak demand was 13.6 GWh in the summer and 13.1 GWh in the winter[39]. Although the total installed power generation capacity is greater than the peak demand, this reserve is only theoretical. The available power generation reserve is determined, at any given time, by different factors, such as temperature, maintenance, plant downtime, etc. In reality, during peak demand hours, the generation reserve is limited and does not exceed a few percent of the production capability[39].

The Electricity Authority is in charge of regulating the electricity sector and the management of the system's daily operation. To balance supply and demand, the Electricity Authority utilizes various demand management strategies, which include advanced metering, variable tariffs, rebates, and price-based strategies[40]. Demand response is any change an energy consumer makes to its normal consumption patterns in response to changes in energy prices[41]. The most basic demand management mechanism is time-varying energy tariffs, which encourage large energy consumers to shift their consumption to low tariff times, in which there is a surplus in energy production. These time-varying tariffs are commonly employed strategies for modulating energy consumption during normal operating conditions[42]. However, a major demand response role occurs during abnormal conditions, in which the power grid becomes unstable[43]. To reduce short-term consumption during periods of peak consumption, the Electricity Authority has set up a voluntary Electricity Load Shedding Program (ELSP), in which large consumers are requested, usually with advance notice of up to a few hours, to shed their power consumption during energy shortage events. In

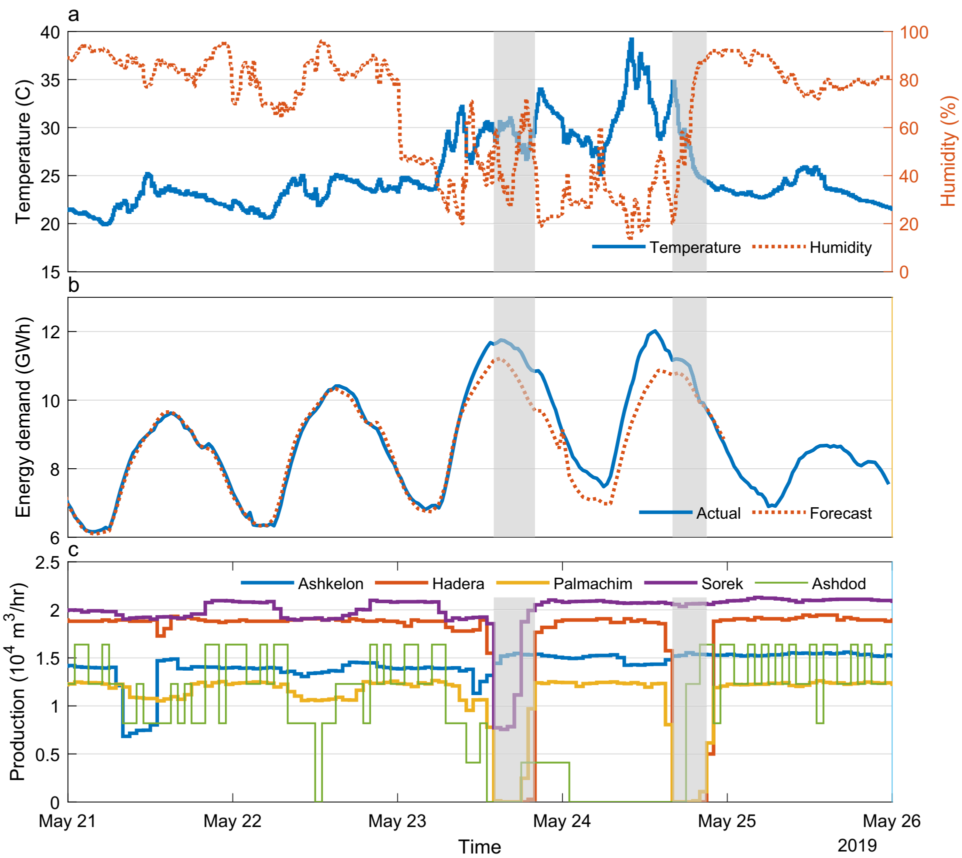

Fig. 2 Weather data, national energy demand, and desalinated water production during the May 2019 heatwave. The figure shows climatological, energy demand, and desalination production data during 21–26 May 2019. Two load shedding events are depicted by the gray background. The top panel **a** shows the temperature in degrees Celsius (blue line) and the humidity in percentage (orange dotted line). The middle panel **b** shows the Israeli predicted (orange dotted line) and actual (blue line) energy demand in GWh. The bottom panel **c** shows the desalinated water production of the Ashkelon, Hadera, Palmachim, Sorek, and Ashdod desalination plants (blue, red, orange, purple, and green lines respectively). Values are in ten-thousand cubic meters per hour.

return, the Electricity Authority compensates these consumers for the power they have shed.

In Israel, the water sector is a particularly large consumer of energy. The water sector is highly dependent on energy for all stages of water treatment, pumping, and transmission and has been long recognized for its ability to balance the energy grid by time-shifting its energy loads by utilizing its water storage facilities[44–47]. The desalination of 650 Mm^3/y, with an average electricity consumption of 3.3 kWh/m^3[19,48], was responsible for about 3% of the national electricity use in 2019, which stood at 72.5 TWh[30]. Given that the overwhelming majority of this consumption is by five large DPs, each one is a very large consumer of electricity and thus a prime candidate for participation in the national ELSP program.

Resource imbalances in the water sector during the extreme event

On May 22–24, 2019, an extreme heat wave was experienced in Israel and the region. In many regions in the country, the temperature exceeded 40 °C, and in several monitoring stations, temperature records were broken[49]. The temperatures along the coast, where nearly 60% of the country's population lives, rose by 15–20 °C compared to the previous days, while humidity dropped to 10%[50]. Figure 2a shows hourly temperature and humidity records between May 21st and 26th. Consequently, peak power demands increased and broke historical records for May with 12 GW[51]. This unusual demand for power exceeded the Electricity Authority's predictions by over 10%. Figure 2b illustrates the predicted and actual hourly power demands between May 21st and 26th.

The Electricity Authority and the Power System Manager have utilized all available electricity production units and the possible ELSPs to manage energy generation and supply energy demands. To reduce energy loads, on May 23rd and May 24th, the Electricity Authority asked large consumers, including some of the DPs, to shed their consumption for four hours. Most of the Israeli DPs operate according to time-of-day based tariffs and are capable of reducing their production with short notice without any significant effect on their performance. The typical production volumes of the five large DPs (located in Ashdod, Ashkelon, Hadera, Palmachim, and Sorek) are shown in Fig. 2c, with the corresponding ELSP hours shaded in gray. As can be seen in Fig. 2c, all of the DPs reduced their production on May 23rd (one, the Ashkelon DP, is not enrolled in this ELSP). Three DPs (Hareda, Palmachim, and Ashdod) ceased production completely, while one (Sorek) reduced production to half capacity on the 23rd and remained at full operating capacity on the 24th.

At the same time, an increase of approximately 25% in water demand from the INWSS was recorded relative to the average demand in the previous week. Mekorot, the National Water Company, utilized the available production wells, surface water supply, and available storage. The extreme weather conditions

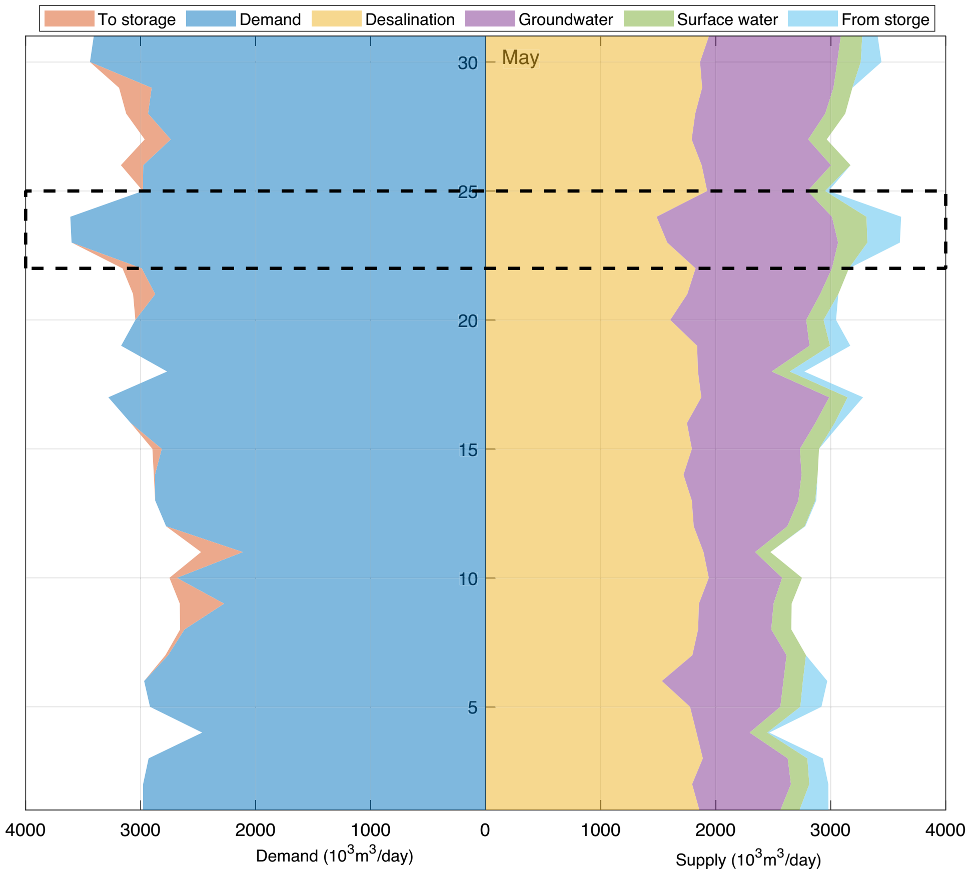

Fig. 3 Total national system daily water demand components (left) and supply from different water sources (right); dashed box denotes the heatwave of 23-24 May 2019. The figure shows the daily different components of the water supply (right side) and the demand (left side), in 1000 cubic meters per day. The supply components are desalination(yellow), groundwater (purple), surface water (green), and supply into storage (cyan). The demand components include the actual demand (blue) and the water storage demand (red). The dashed black rectangle indicates the days of the heatwave.

contributed to over 1,000 fires around the country during 40 h, which increased the pressure for a reliable water supply[52].

The water balance in the INWSS is illustrated in Fig. 3. The left-hand-side of Fig. 3 illustrates the total demand supplied to all different consumers (blue) and storage (orange) by the INWSS, and the right-hand-side illustrates the different water production sources, including desalination (yellow), groundwater (purple), surface (green), and storage (blue). We observe that during the 2-day heat wave (marked in a dashed box in Fig. 3), the water demand peaked, and the water supply utilized all storage, surface, and groundwater resources. A noticeable decrease in desalination water production is observed, despite only a partial 4-h production shortage.

Considering the conflict between the water and energy sectors above, the National Water Company turned to its regulator, the Water Authority, and asked for their intervention to prevent the DPs from engaging in ELSP. Nevertheless, the Water Authority cannot force the DPs to maintain production based on contractual and legal issues. As such, based on the interview with the Head of the Desalination Division of the Water Authority, only non-obligatory requests were made, in which one of the DPs (Sorek) partially rejected the ELSP offer, as can be seen in Fig. 2c.

Economic imbalances between the water and energy sectors

We estimate the economic costs and benefits for a DP that is enrolled in the voluntary ELSP, where all conditions and rates are set by the Electricity Authority[40]. We also relied on additional information obtained from the literature and subject matter experts (e.g., private consultant and Head of Desalination Department in the Water Authority). The voluntary ELSP set up by the Electricity Authority described earlier is intended for consumers with an electricity reduction capability of at least 1 MW, which includes all the DPs. Consumers registered to this ELSP inform the Power System Manager about their reduction capability during a shortage event, the notification time they require to prepare, and the maximum shedding duration they can afford. With this information, in the case of a shortage of electricity that requires load shedding, following the utilization of all production units, the Power System Manager may contact the consumer with a reduction request, which the consumer may accept or reject. The compensation rate for reducing electricity demand is determined mainly according to the notification time prior to the shedding, as agreed upon entering the ELSP arrangement. This rate varies and can reach up to $2 per KWh of electricity shedding for an agreed notification time of up to 30 min before the shedding starts[40].

This analysis examined two scenarios, one attempting to reproduce realistic assumptions (as occurred during the event on May 22–24, 2019) and another with more conservative assumptions regarding production flows, energy intensity, production costs, and shedding tariffs. Table 1 summarizes the costs and benefits of a DP in realistic and conservative load shedding scenarios. Although the actual rates were in New Israeli Shekels (NIS), we present figures in US dollars (USD) using a conversion rate of 3.61 NIS/USD from May 23rd 2019, the first day of the heat wave event. Both scenarios are for a typical shedding event that lasts four hours. As can be seen in Fig. 2c, the typical hourly

Table 1. Economic costs and benefits for a desalination plant under conservative and realistic scenario.

Line	Description	Conservative	Realistic
Estimated benefits			
1	Number of shedding hours	4	4
2	Estimated production flow (m^3/h)	10,000	15,000
3	Energy intensity (kWh/m^3)	3.0	3.3
4[1]	Energy shed (kWh)	120,000	198,000
5	Energy shed compensation ($/kWh)	0.831	1.662
6[2]	Total income from shedding ($)	99,720	329,076
Estimated costs			
7	Water selling price ($/$m^3$)	0.693	0.693
8	Energy price ($/kWh)	0.102	0.102
9[3]	Energy production cost ($/$m^3$)	0.306	0.337
10	Auxiliary production costs ($/$m^3$)	0.139	0.139
11	Nonproduction penalty rate ($/$m^3$)	0.2	0.2
12[4]	Lost revenue ($)	27,720	41,580
13[5]	Nonproduction penalty ($)	8,000	12,000
14[6]	Saved energy cost ($)	(12,240)	(20,220)
15[7]	Saved auxiliary cost ($)	(5,560)	(8,340)
16[8]	Total nonproduction cost ($)	17,920	25,020
17[9]	Total net benefits ($)	81,800	304,056

(1) multiplication of lines 1, 2 and 3; (2) multiplication of lines 4 and 5; (3) multiplication of lines 3 and 8; (4) multiplication of lines 1, 2, and 7; (5) multiplication of lines 1, 2, and 11; (6) multiplication of lines 1, 2, and 9; (7) multiplication of lines 1, 2, and 10; (8) summation of lines 12–15; (9) line 6 take away line 16.

production rate of a DP ranges between 10,000 and 20,000 m^3/h, and the energy intensity for the production of desalinated water is estimated at 3.3 kWh/m^3 [19,48]. For a typical 4-h event with an average production rate of 15,000 m^3/h, the total energy load shed is estimated at 198,000 kWh. With a tariff of 1.662 $/kWh[40], the benefits from the energy load shed event can be estimated based on Eq. (3), resulting in the total compensation of $329,076 per single load shed event (Table 1, line 6). Using the more conservative assumptions, the compensation per single-load shed event is estimated at $99,720.

At the same time, during an energy load shed event, the DP would not produce water and would lose associated revenues while simultaneously saving some variable production costs. In most cases, according to the contractual agreement between the DP and the Water Authority, the DP could make up for the non-produced water in the remaining hours of the day or in the following days[53]. However, in this analysis, we consider the case in which the DP will fail to compensate for the production loss. During the four shedding hours, the DP will experience a revenue loss of $41,580 from not selling 60,000 m^3 of water (expected production flow during the load shed hours) at a unit price of 0.693 $/$m^3$ [48]. Of this, the value of variable costs, such as energy and auxiliary production costs (e.g., chemicals) that would be saved, equals $28,560, bringing the lost operating profits to $13,020. The energy price of 0.102 $/kWh is adopted from the Israel Electric Company[54]. The additional production costs are assumed at 0.139 $/$m^3$, based on discussions with desalination professionals. Additionally, a nonproduction penalty rate of 0.2 $/$m^3$ could be incurred by the desalination facility for not producing according to its contracted schedule[53]. This would result in a total penalty of $12,000. Thus, the total nonproduction cost is $25,020 under the realistic case. Under the conservative case, the estimated nonproduction cost is $17,920.

Subtracting the cost of nonproduction of water (see Eq. (1)) from the benefits of energy load shed (see Eq. (2)) yields net benefits of $304,056 for the desalination plants in the realistic case and $81,800 for the conservative case. Overall, we observe that compensation for shedding energy load is approximately 6 to 14 times greater than the nonproduction cost. Thus, there is an obvious incentive for the DPs participation in ELSPs.

DISCUSSION

Integrated water-energy nexus frameworks have gained popularity in environmental management in recent years among academics and decision-makers alike[55–57]. This is in direct response to mounting pressures across resource sectors and changing environments at spatially and temporally varying scales[58]. An integrated water-energy framework can promote a cross-sectoral and synergistic approach to resource governance[55] that is focused on system efficiency optimization across sectors rather than on single-sector productivity by helping to identify and incorporate intersectoral synergies and tradeoffs[58,59]. The analysis presented in this work reveals organizational, regulatory, and information gaps that need to be considered for an accountable cross-sector water-energy management.

A wealth of literature covers different approaches and methods for the potential application of integrated and optimized water-energy planning[60–64]. However, implementation of such integrated methods in actual planning and policy has been much less developed[61,65]. Many reasons have been given for why implementation in practice lags behind theory[62]. One such reason is the existence of institutional arrangements such as separate government ministries or agencies, which raises the possibility of a lack of coordination between goals and actions[66].

In the case presented here, the economic analysis shows that current tariff structures under the ELSPs are imbalanced in favor of the energy sector. There is a clear agency problem according to which there is a mismatch between the objectives of individual actors and those of the sector as a whole. The DPs have a clear economic incentive to accept compensation under the existing system, even though the economic costs to the water sector as a whole from their participation may outweigh the value of the benefits. Such an outcome is possible because of a lack of coordinated policy and regulation between the electricity and water sectors in Israel. Although the Israeli Water Authority and the Israeli Electricity Authority are both governmental authorities and are currently housed in the same ministry, they lack an official mechanism to develop joint management strategies to reduce the risk of power and water shortages. This lack of coordination may stem from the fact that each Authority was given broad powers and near autonomy to regulate resources under its mandate. This institutional structure was undertaken to ensure professionalism and insulate the Authorities from political interference. However, one of the unintended consequences is that it does not mandate coordination between the two, nor does it provide mechanisms for prioritizing or objectives that may conflict. Such coordination should include aligned economic incentives that take into consideration both private and sector-wide costs and benefits, especially as the role of the private sector grows in terms of production and distribution and as water and energy are increasingly market-driven tradable commodities[67–70].

During the short (2-day) extreme weather event, the Israeli water sector experienced compounding events: water demand peaked, water supply utilized all storage, surface, and groundwater resources, and a noticeable decrease in water production by desalination was observed, despite only a partial 4-hour production shortage. Current agreements between the DPs and the Water Authority do not consider short-term water production targets, hence allowing the DPs to shed water production, as appeared in this case study[53]. As the frequency, duration, and intensity of extreme weather events are expected to intensify[71], the interconnections between the two sectors will play a critical role in attaining a resilient water sector. Accountable resource management will require overseeing and monitoring the usage of resources, establishing new targets and objectives, and ensuring the resources are being used effectively and efficiently to achieve the desired outcomes and minimize unintended negative implications. For instance, participation of the DPs or other large energy consumers within the water sector in energy shedding programs could be made conditional on various indicators of the status and needs of the water sector. In addition, incentives to postpone production in desalination facilities during periods of peak energy demand could be incorporated into the DPs' contracts at fixed or otherwise agreed-upon rates. As utilities and regulators increasingly adopt smart meters and smart grids, this should be more feasible[72]. Alternatively, with the increased integration of renewables and batteries, DPs can explore pathways to reduce reliance on the centralized energy supply. Several studies and use cases can be found exploring the potential for desalination powered with renewable energy[9,73,74]. Currently application of renewables for operating desalination plants can be found primarily in small- and medium-scale desalination plants[75]. Applications in large-scale desalination facilities, like those in Israel, are still limited and challenging. Renewables may, however, prove to be a viable pathway towards more sustainable desalination in the future.

Coordinated water-energy management could be more cost efficient for the electricity regulator, and the water sector could provide more stability and predictability regarding both energy demand and water supply to the community that it serves. Other studies have highlighted the importance of the lack of optimization of long-term planning regarding energy consumption by the water supply sector[62]. This study shows the critical need for coordination of very short-term events as well. Instruments such as benefit-cost analysis and optimization management models have been proposed to attempt to provide decision support tools for integrated water-energy systems[60]. Such instruments could be extended for assisting in the optimization of peak demand and other short-term issues.

Regulation and response mechanisms for the coordinated management of water and energy sectors during short-term events will necessitate real-time adequate quality and quantity of data to support the analysis, make informed decisions, and take effective actions. Data inadequacy – when data is not available, does not exist, or not shared between the two sectors in a systematic and coordinated manner – can lead to ineffective solutions and disproportionately impact the two sectors and communities they serve. Different mechanisms will require different types and granularity of data; hence a rigorous assessment of mechanism-specific data standards is needed. This study revealed that much of the data is being collected. However, currently data collection is challenging because access to much of the information is available only upon request from various agencies, divisions, and even individuals. For instance, detailed data on water production from natural resources was obtained from the National Water Company while data on desalination was from the Water Authority.

Currently there is no standardized format for data storing, nor a centralized, shared location for all the relevant data. Beyond standardizing data collection, data sharing introduces additional challenges such as data ownership and proprietary data, where some data contains sensitive information that is critical to maintaining confidentiality and security. Furthermore, institutional and tacit knowledge that is embodied in the people who work in an organization is difficult to capture and document[76]. Tacit knowledge is often a critical resource of information, and at the same time, makes knowledge transfer challenging; for example, individuals and groups often have detailed knowledge only of the system component they manage[77]. The challenges related to tacit knowledge sharing are common among many engineering sectors and industry and have been previously reported in the literature[78,79]. In sum, while some data is available, the various data-related challenges need to be considered for a successful implementation of advanced coordinated management mechanisms. As desalination becomes an increasingly viable option in many water-stressed countries around the globe, cascading implications of water-energy dependencies are likely to be exacerbated. This necessitates synergistic energy and water governance, including improved data collection and sharing, reporting, and communication mechanisms within and between the two sectors.

METHODS

Data sources and types

Exploring the interdependency between the water and energy sectors during an extreme weather event requires the (1) measured and forecasted weather conditions (e.g., temperature), (2) information about the water supply system (e.g., facilities, users, storage), (3) water production and water consumption data, (4) information about the contracts and agreements between the energy and water sectors (e.g., load shedding program and prices structure), and (5) energy consumption and forecasted demand before and during the extreme event. To meet these data needs, our approach involved collecting different data types, including temporal data, organizational information, and institutional knowledge, from different data sources such as government and regulatory agencies, private and public sectors, and literature through online publicly available information and personal communication. Figure 4 illustrates the different data sources and types collected in this study.

First, climatic temporal data including hourly temperature and humidity recorded by the Israeli Meteorological Service was used to identify the historical event of extreme heat wave during May 2019. Then, hourly electricity demand forecasts and historical electricity demand data were obtained from the Electricity Authority to estimate the state of the energy sector before and during the extreme heat event. Detailed information regarding the ELSPs programs and their respective pricing structures were obtained from the Electricity Authority.

Estimating the state of the water sector involved synthesizing data from multiple data sources, since unlike the energy sector, which is managed by the Electricity Authority, the water supply sector involves complex public-private partnerships, in which the natural water sources are primarily managed by the National Water Company (Mekorot) and desalinated water are produced by privately operated DPs under the supervision of the Israeli Water Authority. As such, to estimate the state of the water sector we analyzed two different databases: (1) a database provided by the National Water Company, which included the daily water production from natural resources (e.g., aquifers' wells and surface water) and operational reservoir volumes in the regional water supply system, and (2) a database provided by the national Water Authority, which included the hourly water production rates from each DP (Ashdod, Ashkelon, Hadera, Palmachim, and Sorek).

In addition, we collected information on the DPs contracts and pricing mechanisms obtained from the Ministry of Finance and the Electricity Authority to examine the economic incentives available to the DPs for participating in electricity load shedding programs. Finally, to understand the interactions between the main stakeholders involved, we interviewed the Head of Desalination Department in the Water Authority, who had been in contact with the various DPs during the event, to better understand actual concerns and interests raised during the decision-making process for this event.

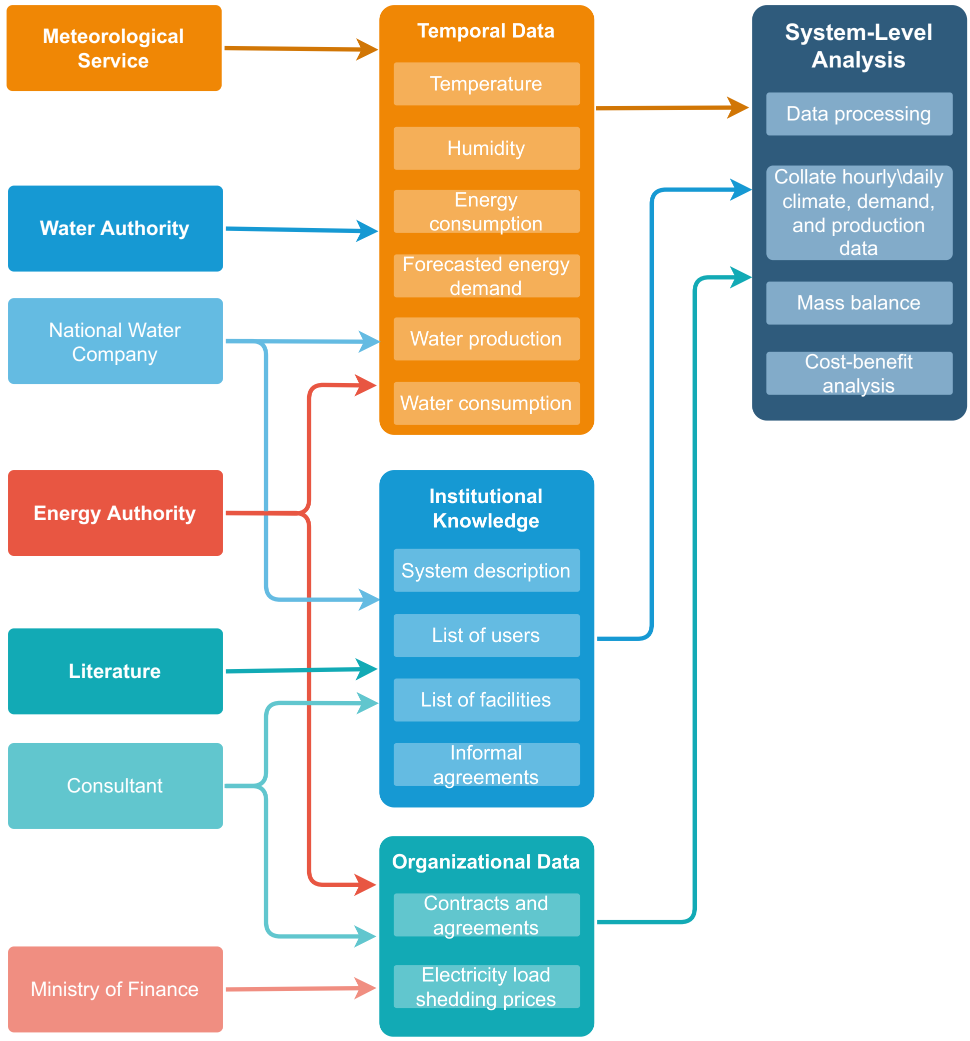

Fig. 4 Methodology data sources, types, and analysis components. The figure shows the different data sources (left column), the data types (middle column), and the analysis (right column). The data types are grouped into three groups, temporal data (orange), institutional knowledge (blue), and organizational data (green).

Data analysis

System-level analysis. Hourly data on measured temperature and humidity, actual and forecasted energy demands, and water production by each of the five desalination plants (Ashdod, Ashkelon, Hadera, Palmachim, and Sorek) were collated and aligned temporally to showcase the changes in the weather conditions, and the response of energy users and water production by desalination.

To estimate the overall state of the Israeli National Water Supply System (INWSS) we calculated the total change in daily storage in the system based on the daily supply from different water sources and demands as follows:

$$\Delta S_{t+1} = Q_{GW,t} + Q_{SW,t} + Q_{DW,t} - D_t \quad (1)$$

where ΔS_{t+1} is the total change in daily water storage (i.e., the sum of all storage changes in all the operational reservoirs), $Q_{GW,t}$, $Q_{SW,t}$, $Q_{DW,t}$ are the total daily ground, surface, and desalination water production, respectively, and D_t is the total daily water demand in the INWSS. This mass balance analysis is necessary to quantify the available daily capacity of the water sector to satisfy water demands, and the contribution of the different water sources (i.e., groundwater, surface water, and desalination) to this capacity.

Benefit-cost analysis. Having obtained and synthesized all the information related to contracts and pricing mechanisms, we performed a benefit-cost analysis, using a cash flow comparison, of the engagement of DPs in ELSPs under conservative and realistic scenarios of water production rates and energy shedding compensation. For each DP participating in a load-shedding program, we estimate the cost associated with the loss of revenue, the penalty from not producing the expected water volumes, and the saved operating costs. The total cost associated with nonproduction of water (CNPW) for a DP is calculated as follows:

$$CNPW = \sum_t (SP + PR - EP \times EI - AC) \times Q_t \quad (2)$$

where t (hr) is the duration of the nonproduction event, SP (\$/m^3) is the unit selling price of water, PR (\$/m^3) is the penalty rate for nonproduction of water, EP (\$/kWh) is the unit energy price, EI (kWh/m^3) is the energy intensity of producing desalinated water, AC (\$/m^3) is the auxiliary unit cost associated with water production (e.g., chemicals), and Q_t (m^3/h) is the expected flow rate at hour t. Overall, the first and second terms represent the lost revenue and the penalty, and the third and last terms represent the saved variable production costs (which is the cost to produce one unit of water) associated with nonproduction.

Additionally, we account for the benefits from electricity shedding compensation and the savings from the energy required for the production of desalinated water and other production costs. Hence, the total benefit from energy load shed (BELS) to a DP is estimated as follows:

$$BELS = \sum_t CR \times EI \times Q_t \quad (3)$$

where t (hr) is the duration of the load shed event and CR ($/kWh) is the compensation rate for reducing electricity demand. Details related to the analyzed events, volumes of water, energy loads, and associated costs and prices, are presented and analyzed in Economic Imbalances between the Water and Energy Sectors.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on request.

CODE AVAILABILITY

The underlying code used to produce the results of the current study is available from the corresponding author on request.

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E.S.: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing - original draft, Writing—review & editing. M.H.: Conceptualization, Methodology, Writing—review & editing, Supervision, Funding acquisition. D.K.: Analysis, Writing—review & editing. L.S. Conceptualization, Writing—review & editing, Funding acquisition.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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