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Integrated Pumped Hydro Reverse Osmosis systems

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ABSTRACT

Ideal head height for pumped hydro energy storage/generation systems and reverse osmosis desalination plants coincide (500–700 m). Many drought stricken coastal regions have nearby mountains of sufficient elevation to support upper reservoirs at this ideal head height. A good symbiotic match might thus be realized by co-locating a pumped hydro plant with a reverse osmosis desalination plant, which we call an Integrated Pumped Hydro Reverse Osmosis (IPHRO) system. Combining systems reduces capital investment, such as pump costs, and solves the desalination brine disposal challenge since 10–20 times more water is required to generate one person's power needs than to generate their fresh water needs, so brine outflow can be diluted by the turbine output water reducing costs of diffusing outflow pipes. This paper describes an algorithm that weights distance from the ocean and mountain height to explore where around the world such IPHRO systems might be located. Design equations are presented to preliminarily explore the size and cost of an IPHRO system and enable first order site feasibility assessment. An example is given for providing power and water for one million people with an IPRHO system in southern California. Analysis and consideration of other sites is included in a supplementary document.

1. Introduction

Many coastal regions, such as those in California, have severe drought conditions [1]. Reverse osmosis (RO) desalination plants can be built to generate fresh water, but require electricity from the grid that if generated by fossil fuels may exacerbate climate change and worsen droughts [2]. Meanwhile, drought in the Middle East creates humanitarian crises and is politically destabilizing with dire consequences [3]. Governments in the region are beginning to focus on managing their abundant energy supplies, with an eye towards solar and wind energy, meanwhile they also need to produce fresh water.

Rather than consider energy and water systems separately, cost savings might be obtained by combining systems. For example, combining pumped hydro energy storage (PH) with RO desalination. Furthermore, additional cost savings and revenues can be realized by combining other harvest activities such as offshore wind turbines and aquaculture [4], or energy storage [5], or extracting uranium from seawater [6,7].

Water management, including desalination, and renewable energy strategies might be best considered together; however large scale use of renewables requires utility-scale electricity storage as a key element [8,9]. Currently pumped storage hydro accounts for 95% of global grid storage capacity [10], but may incur significant evaporative water losses depending on local temperatures and humidity. Most pumped storage hydro utilizes large lakes, and if a small dedicated deep lake was used that was almost completely cycled every day, evaporation could be minimized with the use of floating cover elements [11–13] which are commercially available as hexagonal elements made from recycled plastic (e.g., http://www.awtti.com/hexprotect_cover.php).

For islands, or regions without a strong grid, RO systems can be economically operated by an intermittent renewable energy supply [14,15]. Large scale energy storage to enable continuous operation would be economically more efficient in terms of capital recovery and reduced membrane costs. This was demonstrated with a system that utilizes wind power combined with flywheels and batteries that enabled an RO system to run continuously in the Canary Islands [16].

Desalination, however, also creates brine. Brine disposal into the ocean is common in many parts of the world with the use of long (and costly) diffusing outflow pipes, but may be a contentious issue in some areas such as Hawaii and the Gulf of Aqab. An alter-

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nate strategy would be disposal of the brine by evaporation, with recovery of salt and minerals as a byproduct [17,18]. In the current proposal we show that if excess renewable power is stored in a high reservoir, the water needed for power generations is >10X more than for freshwater generation, and thus the brine can be combined with the water for power generation so it is automatically diluted, thus saving brine outflow pipe disposal or evaporative pond costs.

Hydropower plants have been in operation for centuries, and pumped hydropower plants have been in operation for decades where an upper reservoir works in conjunction with a lower reservoir to store energy or produce power using a pump/turbine. Many pumped storage hydro facilities have been designed to receive power from nuclear energy systems operating at night so the reactor can run 24/7 at full power thus during peak demand the system essentially provides twice the power that the reactor alone can. Hydropower plants can last for tens of thousands of cycles (essentially decades, and even then can be cost effectively rebuilt). Additionally an important feature of pumped hydro that is often taken for granted is its ability to stabilize a grid and/or to restart a large grid that has suffered a blackout[1]. Furthermore, like any other energy storage system, pumped hydro plants also enable intermittent renewable energy machines, such as wind turbines and PV solar power panels, to function as baseload power systems.

While there are many freshwater pumped hydro plants in operation, it is often difficult to cite a new plant because of geography, population pressure, and scarcity of fresh water in many locations. The oceans, however, represent an essentially infinite lower reservoir in coastal locations where there are nearby mountains. Only one pumped seawater hydro plant currently exists, a 30 MW unit in Japan, which is supplied with excess power from the grid [19,20], and it has been successfully operating for many years. An earlier seawater pumped hydro storage was to be built in Egypt [21]. Currently, a 300 MW pumped seawater hydro system powered entirely by solar PV is under tender in Chile, but no significant RO is currently planned [22]. Several alternatives were also proposed in the 1980s which also were to include RO plants coupled to a renewable energy system [23]. The Red Sea Dead Sea project has been around for decades and recently a detailed study showed it was economical to closely couple the desalination system with the pumped storage hydroelectric system where the brine output from the RO system was pumped uphill to a holding lake where it was released through a power turbine when needed with outflow to the dead sea [24]. In the 1990s a combined pumped hydro and RO system was proposed for the Aqaba Jordan region [25,26] but perhaps not enough detail was available to convince the region at the time that it should develop such a system.

2. Symbiotic approach: co-location of Pumped Hydro and Reverse Osmosis Systems

Pumped storage hydro facilities are typically operated by power companies, distinct from water companies. Given the lack of freshwater in arid coastal locations, it is logical to consider using the ocean as a lower reservoir and pumping seawater to an upper reservoir to store energy. The electricity produced could then be used by a conventional RO plant. There have been studies on the total cost of desalination, capital and operating costs [27,28] but detailed breakdown of system element costs are difficult to come by. Total capital costs for brackish water are reported on the order of $2/gallon/day to $4/gallon/day [29] to $1.5/gallon/day to $3/gallon/day [30,31]. The process equipment costs are about 49% of this total [32]. Consensus appears to be that in order to accurately predict costs for a project, a site specific design study must be undertaken [33,34].

As a modern example of an efficient seawater RO plant, the Ashdod desalination plant in Israel had a total CAPEX of $400 M dollars, where the costs of the membranes and associated equipment was about 10% and the pumps was about 10%. The civil engineering and piping costs were about 20% of the total due to the 3 km distance from the sea. The plant operates with sea water intake = 220,000,000 m^3/year; desalinated water output = 100,000,000 m^3/year; brine discharge = 120,000,000 m^3/year; and electrical power required for the process = 3.5 kWh/m^3 of desalinated water (including pumping and transport to 3 km from the sea) [35–38].

Hence, it will be assumed here that the potential for reducing costs by eliminating the high pressure pumps for the RO system, and the long brine diffusing outflow pipe, should result in significant costs savings, but in order to quantify these savings, a detailed design will need to be conducted for a specific site. However, the primary challenge is the selection of a site where the large seawater flow in/out of the system can be placed in addition to the upper reservoir. The RO desalination plant will be relatively modest in its siting needs, but at the very least could share the water inflow infrastructure. Once a site is selected, a program such as WTCOST could be used to perform detailed cost analysis with a granularity down to the component level to estimate capital and operation and maintenance costs for desalination plants [39]. The detailed costing, down to the pump selection level, could then be able to determine weather the RO plant should be operated stand-alone or have its pressurized pre-treated saline water supplied from the upper reservoir, with the brine discharged into the water inflow to the pump/turbine.

Fig. 1 shows a symbiotic system where a pumped hydro energy storage system and RO desalination plant share elements to potentially increase efficiency and reduce capital costs. This strategy implies identifying regions having renewable energy sources (sun, wind) and geography (ocean access and >500 m high mountains) in close proximity to locations with needs for power and water. If the water is needed in regions near the level of the reservoir, the RO plant might be operated with electricity, but the low pressure brine output could still be discharged into the lake to be highly diluted before exiting to the sea through the turbine when it is generating power. If the water is needed at near sea level, then the RO plant would not need high pressure pumps, and pretreated water from the upper reservoir could flow further downhill in pipes to directly supply the RO membranes.

When a significant portion of a region's power comes from inherently intermittent solar and wind power systems, energy storage becomes important for a stable profitable grid. Options include batteries, flywheels and pumped hydro systems. These systems, however, actually add little to the requirement for generating power, they only smooth out the intermittencies of renewables, and themselves consume power to operate. They become part of the parasitic losses a grid must endure. Meanwhile, as more fresh water is needed to counter drought conditions, more electric power is required. A desalination plant can act as an absorber of excess power, but RO plants, for example, function best when they are run constantly; hence there must also be a way to store excess power.

Pumped hydro systems can be used to store vast amounts of excess energy sometimes generated by renewable power systems, e.g. wind turbines operating at night; and it turns out that a highly efficient operating point for such systems occurs at a hydraulic head of about 500–700 m, precisely what is needed for an RO plant. A seaside PH system in Japan, created as an energy storage system in a country with scarce land that is in need of PH systems to work

[1] http://www.dena.de/en/press-releases/pressemitteilungen/netzstabilitaet-und-versorgungssicherheit-durch-pumpspeicherwerke.html.

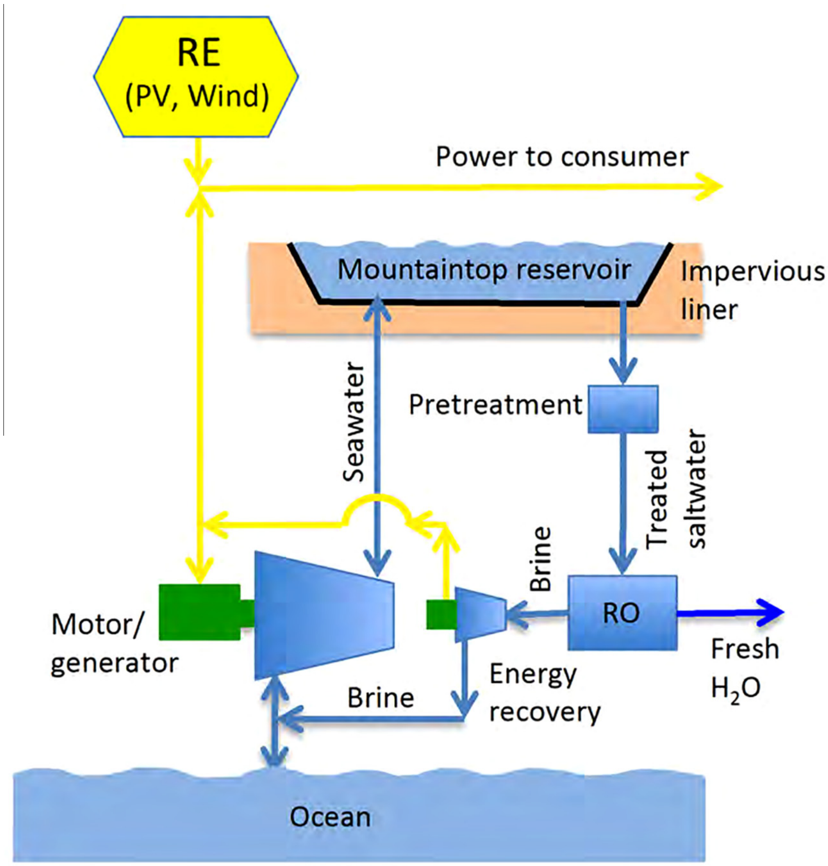

Fig. 1. Schematic of potential IPHRO system: Seawater is pumped up into a lined mountaintop reservoir. About 5% of the reservoir water flows through low pressure pretreatment filters and to an RO unit. High pressure brine flows to energy recovery unit where power output is sent to grid. Low pressure brine combines with seawater flowing into or out of the pump/turbine depending on weather power is being generated or energy stored by pumping water up to the reservoir.

in conjunction with conventional and nuclear power plants, demonstrated the viability of seawater PH systems [18]. Although PH energy storage technology have often operated in steady state where full-on pumping or generating occurs, modern adjustable speed systems can accommodate power fluctuations throughout the day and can assist with frequency regulation and load following whether pumping or generating. Such systems have been envisioned for the US Northwest, and a relatively recent study [40] examined the issues of siting, state of art technologies, costs, and implementation. The advent of offshore wind power presents additional possibilities.

In a renewable energy economy significant portions of electric power for a region could come from IPHRO systems, which would be supplied with excess power from wind and solar power sources. In such systems, as will be shown, an order of magnitude or more volume of seawater is needed for storing energy than for desalination; hence the brine leaving the RO plants energy recovery system can be fed directly into the pipe leading from the sea to the turbine. The brine will either be diluted with the seawater flowing through the turbine and back out to the sea, or by the seawater being pumped by the turbine up to the reservoir.

Interestingly, PH technology was exploited widely for the nuclear industry so nuclear plants could be run at near full power continuously. However, terrestrial uranium supplies are limited and uranium mining is environmentally traumatic. For decades researchers have been developing methods for extracting uranium from seawater [41,42], and high seawater flow rates through the collection media can enhance collection efficiency: the inflow and outflow from the IPHRO plant can flow over the uranium collection media. Other minerals can also be extracted from brines and should be considered as a further resource [43].

RO desalination operates by providing a large pressure gradient across a membrane to force fresh water through [44–46]. A pressure gradient must be maintained along the length of the tubes which contain the membranes, with entry pressure typically about 50–70 atm (about 500 −700 m of hydraulic head) and exit pressures about 90% of the inlet pressure [47–50]. The high exit pressure contains significant energy potential. Current RO systems recover about half of this energy by using the pressurized brine input to a recuperator to help provide initial pressurization of salt water input to the system. An electric powered pump is used to provide the balance of high pressure salt water to the system. An additional cost item is brine disposal [18]. The plant's output brine has a salinity of 4.5–7% for volume conversion rates of 25–50%. Different methods for brine disposal exist ranging from evaporation in lined ponds to discharge into the sea. If brine is simply discharged back into the sea, local salinity increases can devastate marine life; thus, long outflow pipes with diffusers are typically used. These systems require pressurized brine to flow which further contributes to parasitic losses. Although these systems are mature, they still represent significant capital and operating costs.

A desalination plant will be likely be operated 24/7 to maximize membrane life. When the hydro system is operating as a generator, the brine combined with the turbine output will be sufficiently diluted to dump directly into the sea. When the hydro system is operated as a pump, the brine can merge with the seawater being pumped up to the reservoir. It will also be highly diluted and will not significantly affect the salinity flowing into the RO plant. Thus the brine is discharged directly into the large pipe that connects the ocean to the turbine unit that operates as a pump/generator. This operation mode will necessitate a separate pipe leading from the reservoir first to the pretreatment station, which can be located tens of meters below the reservoir so no pump is required, and then to supply very steady pressure saltwater to the RO plant as shown in Fig. 1.

In summary, comparing an IPHRO system to separate pumped storage hydro energy storage and conventional RO desalination plants, the former can use one set of very large turbines to supply all the high pressure flow at a constant feed pressure, and the brine produced can be diluted with the high seawater flow required for energy storage and power generation. In addition, civil works, land area, and some buildings can be shared. Any region contemplating energy storage and RO desalination should thus examine the design of an IPHRO system in addition to separate systems to determine the best option for the site-specific conditions. This paper presents a first order analysis procedure for this comparison and identifies some regions around the world where it might be applicable.

2.1. System example

Here a generic scenario is considered for symbiotically providing power and water for one million people accustomed to a US lifestyle (2 kW average electric power and 500 L/day water consumption). Note for most parts of the world, half this value would be excellent. Fig. 2 shows the spreadsheet output based on the above analysis. The spreadsheet, *IPHROS.xls*, and details of the calculation methodology are provided in the Supplementary Materials A. Values in the spreadsheet are easily adjusted to represent local consumption allowing users to explore scenarios for their local needs and situations.

The first item to note is that the energy needed to produce fresh water appears to be significantly lower than is typically cited in RO literature. The theoretical minimum energy for desalinating 35% salinity seawater to yield 50% freshwater is 1.06 kWh/m^3. Current SWRO systems are cited as having gross power consumption of between 3 and 4 kWh/m^3 of freshwater produced [44] of which about 1 kWh/m^3 is needed for peripheral support items (intake, pretreatment, post treatment, and brine discharge) [46], for a net desalination energy of about 2–3 kWh/m^3. The IPHROS system inherently includes these peripheral items which is how it can achieve a lower gross energy requirement, which is predicted to be 2.2 kWh/m^3 for 35% salinity water, 45% conversion to freshwater with 50 atm of seawater pressure supplying the membranes. If the required pressure were 60 atm to yield 50% conversion, the gross desalination energy would be 2.7 kWh/m^3. In general, larger machines cost less per unit function accomplished, and having fewer pumps will also mean lower maintenance costs. The pumped hydro system has a high round trip efficiency >80% [51] which also contributes to the savings. Further advantage is obtained by discharging the brine into the large pipe that connects the ocean to the turbine unit as discussed above.

Fig. 3 shows the renewable system parameters associated with providing power (2 kW/person) and water (500 L/day/person) to one million people assumed in Fig. 2. This is for a California lifestyle, and for many regions around the world half the power would be more than welcome. It should be noted that for a 30 m water depth change in the storage reservoir located 500 m above sea level, it takes about 1.3 km^2 to serve the needs of one million people (20 m water depth change at 500 m requires about 2 km^2 - use the spreadsheet provided in Supplementary Materials A to play your own "what if" scenarios).

The land areas required for renewable energy harvesting devices are reasonable, especially with good urban planning. Solar panels can be located on rooftops, especially on large flat industrial rooftops and in some cases incorporated into the reservoir as floating panels. Large wind turbines are not suitable for being placed in cities, but can readily be placed among central pivot irrigated fields, or offshore. Fig. 4 shows the economic factors associated with the IPHRO system, excluding real estate costs which should be minimal if the renewable energy harvesting devices are placed on rooftops and amidst farmland; and the IPHRO lake and turbine system is assumed to be placed on public lands. In general, the costs assumed for solar, wind, and PH are conservative (high) and should be expected to decrease, especially with the great increase in volumes that could be brought on by widespread adoption of IPHRO systems. The cost of the salt water RO desalination system will be less than for a conventional system [27,46] because the IPHRO system will not require pumps and brine outfall subsystems; however, the capital cost is still very small compared to the renewable energy systems, and thus for the analysis here conventional RO system costs are assumed. The real savings will be in lower amount of energy required to produce fresh water.

Reasonably conservative assumptions were made for the economic analysis shown in the figure and show a good rate of return over the 20 year period for the project loan of 2.4% is reasonable for the scale and importance of the project and potential to provide power and water using renewable energy sources. If the civil engineering challenges were more significant so the cost of the hydropower component were greater, at $3/installed Watt, then the annual rate of return would still be an accepTable 1.2%. The spreadsheet is provided in the supplemental materials so other scenarios and sensitivities can be investigated. Other potential income from symbiotic activities such as aquaculture or uranium harvesting from the seawater flow would likely be a fraction of revenue from water and electricity, and thus are best left to secondary effort once the primary system becomes operational.

3. Geographic potential assessment

In order to investigate the applicability of IPHROS in various regions, a geographic information system (GIS) based topographic analysis was performed using shuttle radar topography mission (SRTM) digital elevation models (DEM) from NASA [52–55]. First, 3-arc second (~90 m) was used to determine the locations of regions that had elevations 500 m. Next, the elevation of each location was divided by the distance to the seacoast, resulting in what is referred to here as the "A-Index". The higher the A-Index, the greater the potential suitability for IPHROS.

The A-Index is a currently a qualitative measure intended to identify geographical regions that can even be considered, those which meet a minimum height requirement and within regionally acceptable tunneling distance from shore, and colorize the region so as to allow for rapid assessment of an area under scrutinization. It would be analogous to forming an A-list of options (the first place to go looking). The A-Index thus serves as an indicator for a region to identify where the reservoir might be placed. The greater the value of the A-Index, the higher the reservoir, or the closer to the shore a region might be, both factors that can increase the value of a project either by providing greater energy storage potential or lower construction costs. It might be possible in the future to create a more quantitative index.

For the United States, more detailed analysis was conducted using higher resolution 1-arc second (~30 m) SRTM DEM from NASA. The potential energy per cycle (reservoir filled and then drawn down) of areas with a high A-Index was determined using the formula

$$E_{pot} = \eta_{rt}\rho_{sw} g h_L dS, \quad (1)$$

where η_{rt} = IPHROS round-trip efficiency (based on typical values found for pumped storage hydroelectric systems), ρ_{sw} = seawater

People Served	
Number of people for which electricty provided, *N_pe*	**1,000,000**
24/7 average electric power per person, *P_pe* (W)	**2000**
Energy consumed by each person every day, *E_p24* (kWh)	**48**
Total electrical energy the system must deliever to people every day, *E_er* (GWh)	**48**
Number of people for which water provided, *N_pfw*	**1,000,000**
Average daily consumption per person, *V_pfw* (liters)	**500**
Total fresh water volume the system must deliever every day, V_fw (m^3)	**500000**
Ratio people served fresh water/people served electricity, *gamma_fwe*	**1.0**
Pumped Hydro System	
Height of reservoir above sea level, h_L (m)	**700**
Round trip efficiency (typical) pumped storage hydro system	**80%**
Pumping efficency, *eta_hp*	**89.4%**
Turbine generator efficency, *eta_ht*	**89.4%**
Roundtrip efficiency	**80.0%**
Hours per day system acts to pump water up to reservoir, *Pump_hrs*	**12**
% renewable energy used to pump water up to reservoir for electricity & fresh water generation, *gamma*	**50%**
Energy for consumers to be generated by turbines fed from reservoir, E_pht (GWh)	**23.4**
Volume seawater daily to be pumped up to reservoir to generate power and freshwater, V_wp (m^3)	**14,357,096**
Volume of water flowing from reservoir daily directly into turbine, V_swht (m^3)	**13,357,096**
Energy required daily to pump sea water up to reservoir, E_php (MWh)	**31,413**
Rated power of pump to pump sea water up to reservoir, P_php (MW)	**2,618**
RO Plant	
Head height needed for RO membranes (must be <h_L), h_ROmembranes	**600**
Head height needed for pre-treatment, h_pt	**100**
Head height needed for pre-treatment *and* RO membranes (must be <h_L), h_RO	**700**
Percent pressure leaving RO tubes, *eta_Roio*	**90%**
Effective head leaving RO tubes (flows to unit at sea level), *h_RO* (m)	**540**
% of salt water into RO system converted to freshwater, *eta_RO*	**50%**
Density seawater, *rho_sw* (kg/m^3)	**1027**
Density brine from RO tubes, *rho_ROo* (kg/m^3)	**1054**
Ratio of brine outflow to flow from reservoir direct into turbine	**27**
Volume seawater daily from reservoir diverted to RO plant, V_wRO (m^3)	**1,000,000**
% water from pumped hydro reservoir sent to RO plant, gamma_RO	**7.0%**
Volume fresh water produced daily, *V_fwRO* (m^3)	**500,000**
Volume brine produced daily, *V_brine* (m^3)	**500,000**
Gross energy consumed daily by desalination process, E_RO (MWh)	**1957**
Gross energy consumed to produce fresh water, *E_fwp* (kWh/m^3)	**3.91**
Efficiency of pressurized brine energy recovery device, eta_bER	**80.0%**
Energy produced daily by turbine from brine output of RO plant, E_htRO (MWh)	**620**
Energy used for pre-treatment, E_pt (kWh/m^3)	**280**
Net energy consumed daily by desalination process, E_ROnet (MWh)	**1337**
Net energy to make fresh water (not including pre-treatment)	
IPHRO system, E_*fwpnet* (kWh/m^3)	**2.7**
Typical RO system, *E_ROtyp* (kWh/m^3)	**3.5**
Increase in efficiency of freshwater production achieved by IPHROS, *eta_fwinc*	**23.6%**
Salinity of ambient seawater (%)	**35**
Allowable increase in salinity (%)	**5%**
Salinity of brine outflow (%)	**68.21**
Maximum allowable salinity of turbine outflow (%)	**36.75**
Actual salinity of turbine outflow (%)	**36.23**
Increase in salinity of outfow from system	**3.5%**
Dilution enough?	**Yes**
Renewable Energy system	
Net 24/7/365 daily energy output from energy harvesting system to provide electricity & water, E_R (MWh)	**55,413**
Total energy spent to pump water up to reservoir and to make fresh water, E_sysop, (MWh)	**7,413**
Energy lost to pumped hydro system round trip inefficiency (MWh)	**6,076**

Fig. 2. IPHRO System parameters for serving one million people (inputs in black and outputs in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

density, g = gravity, h_L = elevation above sea-level, d and S are the depth and surface area respectively of the IPHROS reservoir. For the following analysis, η_{rt} is taken to be 80% and d is estimated to be 30 m. If smaller surface areas are desired for the lake deeper depths can be used. The results of the GIS-based analysis for various sites across the globe are presented in this section, additional sites are presented in Supplementary Materials A.

3.1. Southern California

Southern California is very dry with a very large population, and takes water from the Owen's valley, so if this water was no longer needed, farming in the valley might flourish [56,57,1]. In southern California, the mountains around Malibu and San Clemente have great promise for IPHRO systems as shown in Figs. 5 and 6.

Based on the resulting qualitative A-Index (good mountain height within tunneling distance from shore) for areas around Malibu and San Clemente, regions highlighted were selected for further analysis (Figs. 5 and 6). These regions have a total upper reservoir (lake) area potential of approximately 14.7 km^2. Assuming these are all developed into IPHROS lakes in which 30 m of water is pumped up and down with each cycle, these regions could provide power and freshwater for about 28 million people. A reservoir depth of 30 m is considered reasonable because it is a depth easily reached by divers if any maintenance is needed, although a smaller area or more people served could be realized with greater

Net 24/7/365 average requirements on renewable energy harvesting system	
Daily gross energy output to provide electricity and water E_R (MWh)	**55,413**
Power from solar and wind energy harvesting systems, P_WPV (MW)ROUNDUP	**2,309**
Lake size required	
Volume of water pumped up to lake each day (m^3)	**14,357,096**
Depth of lake pumped each day (m)	**30**
Lake length/width ratio	**1**
Width required (km)	**0.69**
Length required (km)	**0.69**
surface area (km^2)	**0.48**
Solar PV electric	
Percent power to be obtained from solar PV, pppv	**80%**
Average 24/7/365 power to be obtained by solar PV, P_PVavg (MW)	**1,847**
Avg daytime solar insolation, insol (W/m^2)	**600**
Average lifetime efficiency of PV cells, eta_PV	**18%**
24/7/365 capacity factor, CF_PV (daylight, storms...)	**30%**
Total PV nameplate power required, P_PVtotnp (MW)	**6,157**
Coverage density on ground, PVcovdens	**40%**
Average 24/7/365 solar electric power density, P_PVdens (MW/km^2 land)	**13.0**
Required land area for solar PV, A_PV (km^2)	**143**
Ratio length to width of area dedicated to PV	**2**
Width required (km)	**8.4**
Length required (km)	**16.9**
Wind	
Percent power to be obtained from wind turbines, ppwt	**20%**
Average 24/7/365 power to be obtained by wind, P_WTavg (MW)	**462**
Turbine nameplate power rating, P_wtnp (MW)	**5.0**
Land area required for each turbine, A_lwt (km^2)	**1.0**
Capacity factor, CF_WT	**35%**
Total wind nameplate power required, P_WTtotnp (MW)	**1319**
Average 24/7/365 wind power energy density, P_WTdens (MW/km^2 land)	**1.75**
Required land area for wind, A_WT (km^2)	**264**
Ratio length to width of area for wind turbines	**2**
Width required (km)	**11.5**
Length required (km)	**23.0**
Total land area required for renewables (km^2)	**406**

Fig. 3. Renewables allocation for IPHRO system for one million people (inputs in black and outputs in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depth of draw. As shown in Fig. 2 the amount of seawater needed for desalination is only 4.7% of the total pumped to the lake. If the priority is for more freshwater for piping to interior regions, freshwater for 236 million people could readily be provided by diverting about 37% of the flow to the RO system. This was determined using the minimum allowable turbine diversion to the brine outflow, an ambient seawater salinity of $S_{sw} = 3.5\%$, a desired brine outflow salinity of no more than $S_{ht} = 4\%$ (in keeping with California guidelines and regulations [58]), a seawater density of $\rho_{sw} = 1027$ kg/m^3, and a freshwater density of $\rho_{fw} = 1000$ kg/m^3. Details are provided in the Supplementary Materials A. By comparison, the population of Malibu and San Clemente are 12,645 and 63,522 respectively, while the Greater Los Angeles region is 18.55 million [59].

3.2. Baja California

The cities of Ensenada and Tijuana, 84 km to the north, have a combined population of 1.77 million [60]. The mountains around Ensenada are well-suited for an IPHRO system as shown in Figs. 7 and 8.

Following a similar analysis to that done for southern California, regions selected for further analysis are highlighted in Figs. 7 and 8 and detailed in Tables 1,2 respectively. These regions represent a total lake area of approximately 31.3 km^2 and could provide power and freshwater for about 28.8 million people; hence significant water export, perhaps via a pipeline to Southern California, could be realized.

3.3. Hawaii

Lanai in particular is well suited to an IPHRO system because the population is small but in great need of freshwater and electricity. In addition, single private ownership of most of the island and the desire to develop the island's resort potential could enable rapid responsible development of an IPHRO system which would then serve as a powerful learning project for the other islands. Fig. 9 depicts the resulting A-Index for the island and highlights regions further detailed in Table 3. From this analysis, it can be seen that the highlighted regions represent a total lake area of approximately 5.8 km^2, which, if developed for IPHROS, could provide power and electricity for nearly 5.4 million people. With a population of only 3102 [59], by Fig. 2 only about 3366 m^2 of this total lake area must be developed into IPHROS in order to provide the entire island with power and freshwater. However the island of Lanai is also in need of irrigation water for agriculture. Investiga-

Economics	
Electricity	
Average sales price of electricity ($/kW-hr)	**$0.08**
Annual value of electricity	**$1,618,068,615**
Water	
Annual volume of freshwater produced (m^3)	**182,500,000**
Sales price of water ($/m^3)	**$1.50**
Annual value of water	**$273,750,000**
Capital costs	
Wind power system	
cost of installed wind power ($/Watt nameplate)	**$1.50**
total cost of installed windpower system, tcwp	**$1,979,046,740**
Solar PV power system	
cost of installed PV ($/Watt nameplate)	**$1.50**
total cost of installed PV system, tcpv	**$9,235,551,455**
Pumped hydro system	
Cost ($/Watt nameplate includes equipment and civil engineering)	**$2.00**
Total cost of pumped hydro system, tcpsh	**$5,235,551,455**
RO system	
Capacity, C_RO (m^3/day)	**500,000**
Conventional RO Investment cost (includes pumps) (=7100*C_RO^0.81), tcRO	**$293,375,641**
Return On Investment Considerations (taxes not considered)	
Total capital cost for renewable energy and fresh water system, tscc	**$16,743,525,291**
"$/installed nameplate Watt" figure of merit	**$2.24**
"$/delivered Watt" figure of merit	**$8.37**
% annual gross spent on operation and maintenance	**20%**
net annual funds to pay off capital costs	**$1,513,454,892**
annual interest rate on capital, intrate	**3%**
number of years to repay project financiers, tloan	**20**
Monthly based Capital Recovery Factor, CRF	**0.005546**
Equivelent annual payment, eap	**$1,114,310,269**
Annual net profit, anp	**$399,144,623**
Net annual rate of return on investment, aroi	**2.4%**

Fig. 4. Renewables economics for IPHRO system for one million people (inputs in black and outputs in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

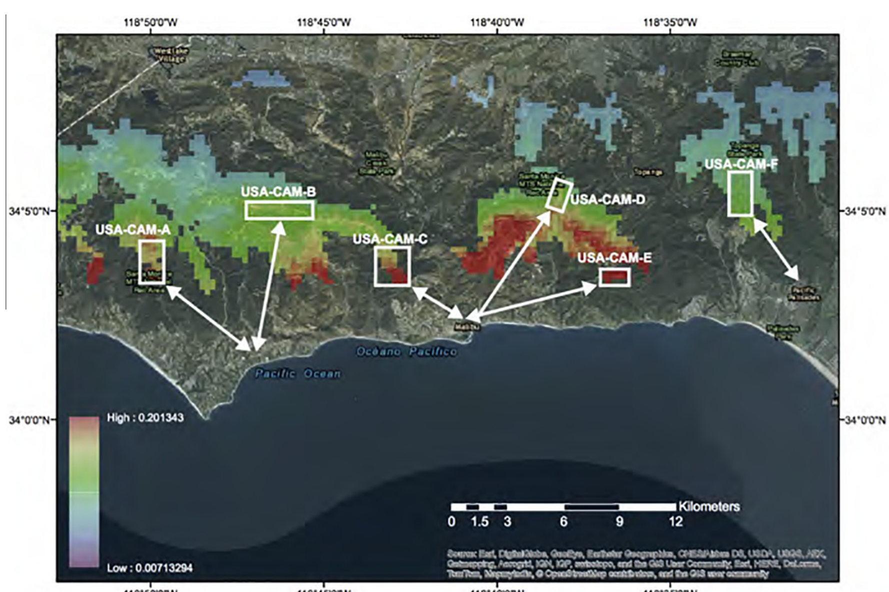

Fig. 5. A-Index for topography near Malibu, California. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Malibu and Pacific Palisades in the case of region USA-CAM-F, indicated by arrows.

tion of a hybrid irrigation water and freshwater system are underway.

More populated than Lanai, the island of Maui also faces significant electricity and freshwater demand challenges. The resulting A-Index for the island is shown in Fig. 10 with these areas detailed further in Table 3. The total highlighted regions have a combined lake area of 16.5^2, which represent power and electricity for 15.2 million people. As in the case of Lanai, the population of Maui is

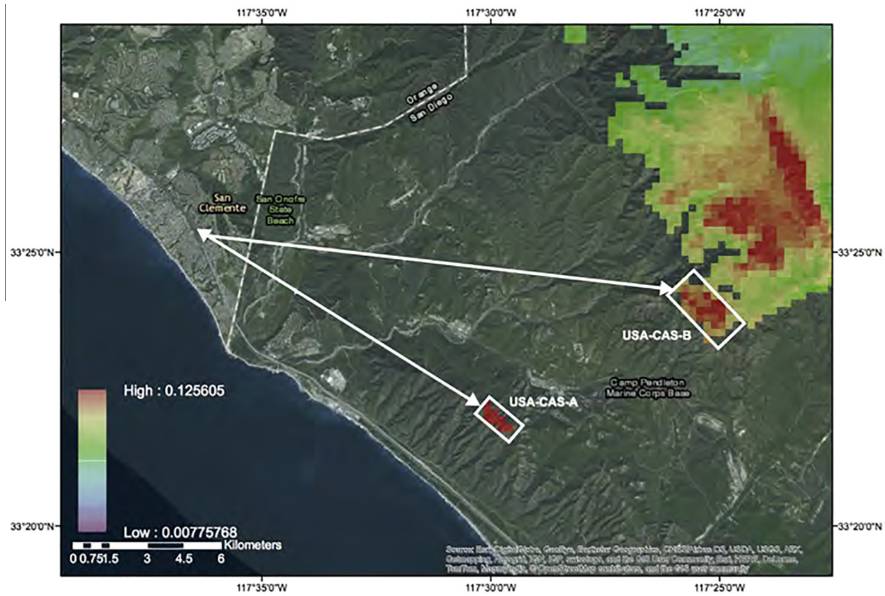

Fig. 6. A-Index for topography near San Clemente, California. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, San Clemente, indicated by arrows.

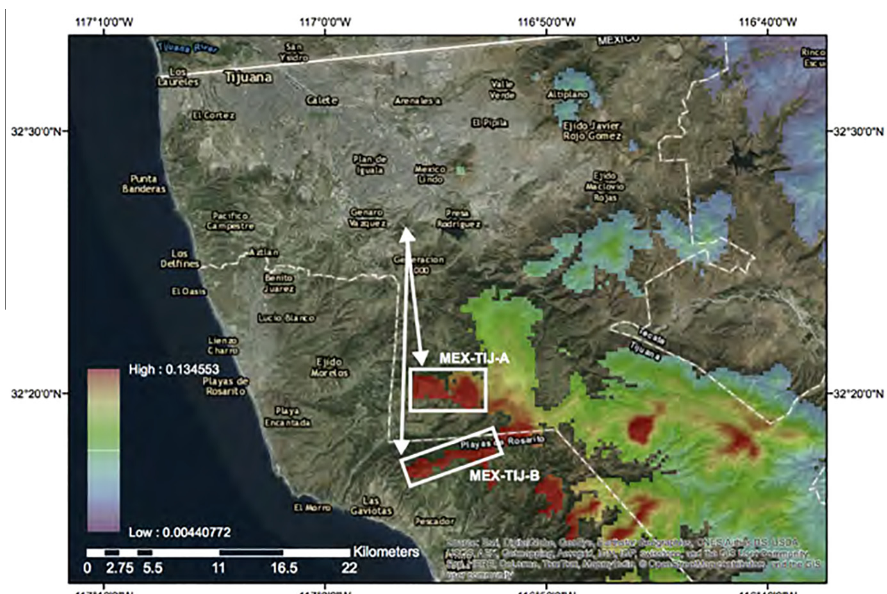

Fig. 7. A-Index for topography near Tijuana, Mexico in Baja California. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Tijuana, indicated by arrows.

much smaller than the total population potential that could served by all possible IPHROS installations on the island. In fact, to serve the entire population of 144,444 [59], would only require an IPHROS system with a lake area of 0.16 km^2. In fact, the existing Auwahi Wind site located on the wind-rich Ulupalakua Ranch on the southeast coast of Maui, is at an elevation with a high A-index. An IPHRO system could thus be added to the wind farm to provide needed energy storage and freshwater for the Hawaiian owned farms in the region which are in great need of freshwater for irrigation.

The most populated of the Hawaiian islands, Oahu is faced with even greater electricity and freshwater challenges than Lanai and Maui. The A-Index resulting from geographical analysis of the island are depicted in Fig. 11. Regions highlighted in white were selected for further investigation and the details of the IPHROS viability are listed in Table 3. From this data, there exits approximately 20 km^2 that could be developed into IPHROS, providing electricity and power for 18.5 million people. With the population of Oahu about 953,207 [59], only a little over 1 km^2 is required to meet the energy and water needs of the resident population.

3.4. Peru

The region around the city of Lima holds great promise for IPHRO systems. Fig. 12 shows an image of the region and the potential lake area. With a population of nearly 8.5 million people, if all the highlighted regions were developed for IPHROS, they could provide enough power and water for 87 million people.

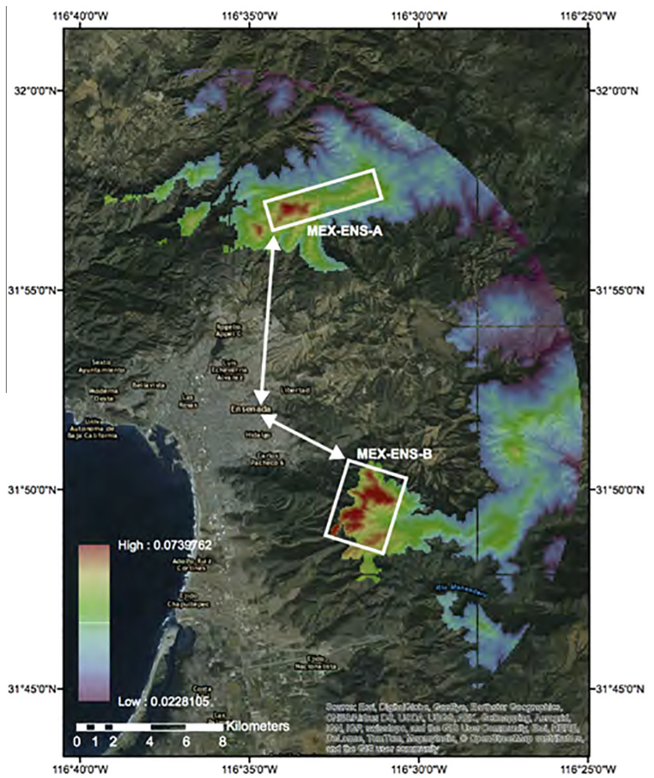

Fig. 8. A-Index for topography near Ensenada, Mexico in Baja California. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Ensenada, indicated by arrows.

Therefore, only 10% need to be developed to serve the entire population of Lima. Highlighted regions are further detailed in Table 4.

3.5. Chile

In Northern Chile, the city of Iquique lies on the Pacific ocean and at the base of a high plateau which makes it an ideal site for an IPHRO system as the region is very dry. Fig. 13 shows an image of the region and the potential lake area. Valhalla Energy already has done nearby site engineering and obtained approval for a pumped hydro energy system approximately 98 km south of Iquequi[2], and thus this site could perhaps be the best first application for the IPHRO system anywhere in the world simply because a seawater pumped hydro and renewable energy system is already being planned. Indeed, other water starved regions around the world with IPHRO potential may want to invest in this early project as a means of also gaining rapid insight into the project and the process by which it is executed.

Again, regions selected for further analysis are highlighted in Fig. 13 and detailed in Table 5. These regions represent a total lake area of approximately 24.3 km^2 and could provide power and freshwater for about 22.4 million people. Given that the population of Iquique is only 180,601 [61], this "extra" water could be used to develop farms in the high desert, or for mining operations.

3.6. Middle East

The Middle East has great natural resources of many forms, including a rich history of great civilizations whose citizens accomplished amazing feats of civil engineering. Unfortunately now as in the past, water scarcity has often been a source of contention between peoples. Presently water shortages can be relieved by RO plants, but this currently mostly involves burning hydrocarbons to generate the power required. Fortunately there are many excellent IPHRO system sites in the Middle East as well as the will and means in many countries to plan and create for the future.

3.6.1. Northern Red Sea (Egypt, Israel, and Jordan)

The region around the northern Red Sea along the borders of Egypt, Israel, and Jordan is also a region with large IPHRO potential. The mountains close to the coast of the Red Sea and the great need for freshwater in the bordering countries makes this an ideal site to investigate. Fig. 14 highlights the regions around the cities of Taba in Egypt, Eilat in Israel, and Aqaba in Jordan that have high A-Indices. As can be seen from the figure, for each of the major cities in the region, there are corresponding areas that can be developed for IPHROS. Table 6 summarizes these results.

For the case of Taba, Egypt, the region highlighted by REDSEA-A could provide enough power and freshwater for nearly 11 million people, while REDSEA-B could do the same for up to 3.45 million people in Eilat, Israel and REDSEA-C represents the opportunity to provide over 29 million people with power and freshwater in Aqaba, Jordan. It is important to note that the entire population of Israel is only 8 million people and that of Jordan is 7 million people, therefore if only a fraction of the areas highlighted are developed for IPHROS, they still present a great opportunity to provide both power and freshwater to a vast majority of local inhabitants. Given extreme drought in the region and migration of people from war torn regions, IPHRO systems have the potential to employ many and provide power and fresh water to enable formation of new stable centers of civilization along the coasts.

3.6.2. Iran

The population of Iran has its greatest density around Tehran which is close to the Caspian sea, but the region is chronically short of water. Fortunately there is great IPHRO system potential here. This could also help catalyze the renewable energy industry and negate the need for nuclear power plants. This might trigger substantial investment interest from the international community and enable Iran to emerge as a leader in the region for sustainable development.

Iran, one of the founding members of OPEC, has the world's fourth largest proven crude oil reserves and the second largest proven natural gas reserves. Naturally, oil and gas have played a dominant role in the country's energy dynamics, though the combination of Iran's mountainous topography and IPHROS could catalyze development of a long term renewable and sustainable energy industry. Energy consumption in 2012 was roughly 278 billion kWh [62], with forecasts estimating a mean annual growth of 1.8% until 2018 [63].

The Tehran metropolitan area has a population of close to 14 million people, and serves as the nation's political and economic capital. Over the past two decades, pollution has progressed relatively unchecked, and the air quality of Tehran has reached alarmingly dangerous levels [64]. Furthermore, water scarcity has evolved to be a significant issue for the city, and the nation at large, with disruptions and cuts arising frequently [65]. Essentially, these environmental issues pose a national security problem. In light of these issues, renewable sources of energy may alleviate some of the environmental strains while supplanting carbon-emitting power plants.

The IPHROS potential of sites near the capital of Tehran is shown in Fig. 15, with further details of highlighted regions in Table 7. The best sites for IPHROS are located over 100 km away from the edge of the city. Nested between the Caspian Sea and the Tehran metropolis lies the Alborz mountain range, running

[2] See http://valhalla.cl/en/espejo-de-tarapaca/.

Table 1
Energy potential of IPRHOS in regions surrounding in Southern California.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
USA-CAM-A	612	2.9	5.2	0.112	Malibu	5.9	119
USA-CAM-B	684	2.2	7.7	0.089	Malibu	8.8	101
USA-CAM-C	528	1.7	4.3	0.123	Malibu	3.3	59
USA-CAM-D	678	0.9	6.9	0.098	Malibu	8	42
USA-CAM-E	518	1.3	2.7	0.192	Malibu	8	44
USA-CAM-F	545	2.4	7.2	0.076	Pacific Palisades	7.9	89
USA-CAS-A	505	0.5	4.1	0.123	San Clemente	14	17
USA-CAS-B	552	2.8	13.3	0.042	San Clemente	20	104

Table 2
Energy potential of IPHROS in regions in Baja California, Mexico.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
MEX-ENS-A	886	3.5	15	0.059	Ensenada	9.2	119
MEX-ENS-B	636	2.7	9.6	0.066	Ensenada	7.6	101
MEX-TIJ-A	567	14.5	12.7	0.045	Tijuana	12.8	483
MEX-TIJ-B	542	10.7	8.2	0.066	Tijuana	18.8	388

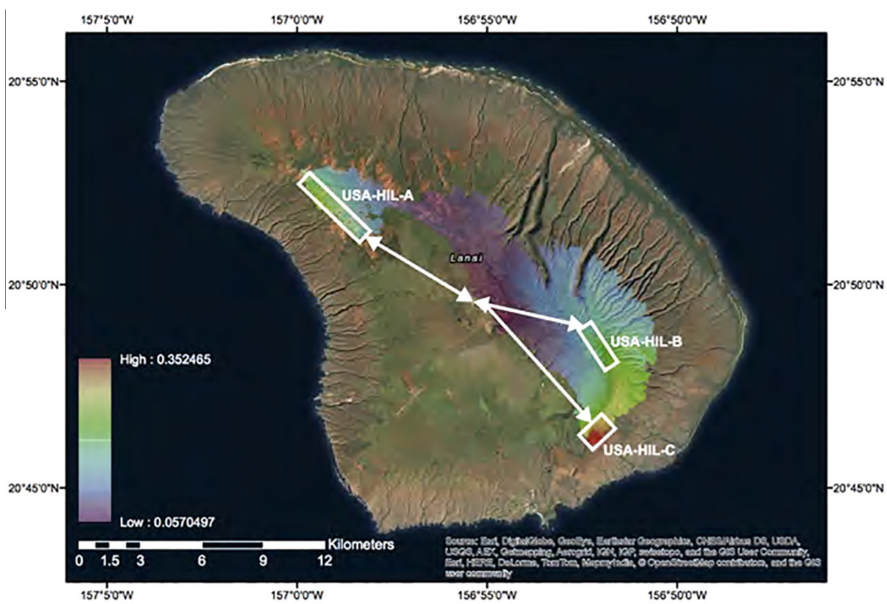

Fig. 9. A-Index for topography of the island of Lanai, Hawaii. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city indicated by arrows.

Table 3
Energy potential of IPHROS in regions in Hawaii.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
USA-HIL-A	516	2.3	3.3	0.157	Lanai City	6.6	103
USA-HIL-B	953	1.2	6.0	0.159	Lanai City	5.0	80
USA-HIL-C	552	1.6	2.1	0.268	Lanai City	8.6	59
USA-HIM-A	1300	5.9	7.5	0.173	Kahului	7.6	515
USA-HIM-B	2757	11	11	0.257	Kihei	21	1963
USA-HIO-A	1192	0.65	8.5	0.140	Mililani Town	14	52
USA-HIO-B	650	5.5	4.4	0.148	Honolulu	12	238
USA-HIO-C	714	2.2	7.2	0.099	Honolulu	7.5	106

along the coastline for 950 km [66]. Therefore may not be viable sources of direct freshwater via pipelines due to the significant amount of pipe losses across such long distances, although water from the Owens valley in CA has long supplied Los Angeles from similar distances. Recent experience gained by Chinese engineers building a canal from the south of China to the north could perhaps be applied here. Thus it is envisioned that a combination of canals and tunnels could reasonably provide a means to deliver immense amounts of freshwater to the parched interior. Indeed, the combined potential of the regions represents a lake area of approxi-

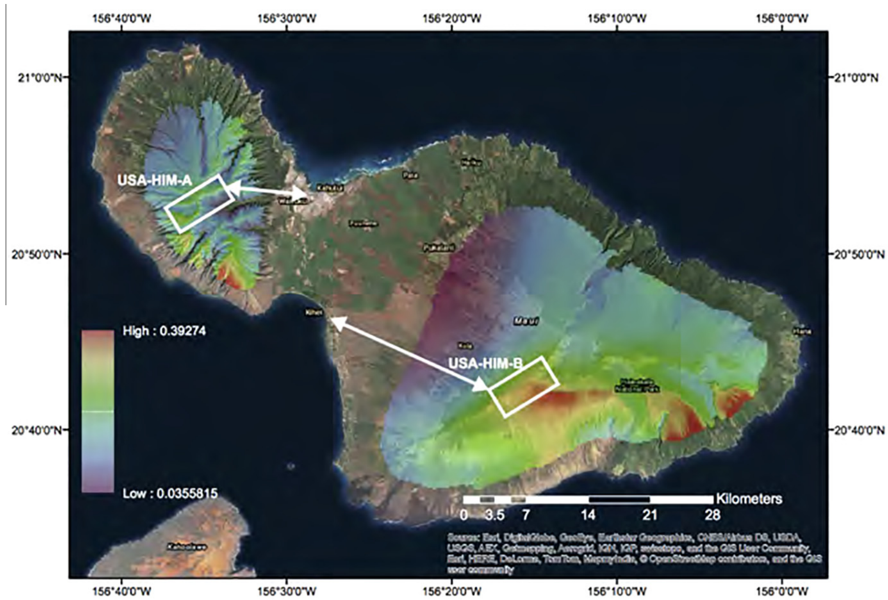

Fig. 10. A-Index for topography of the island of Maui, Hawaii. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city indicated by arrows.

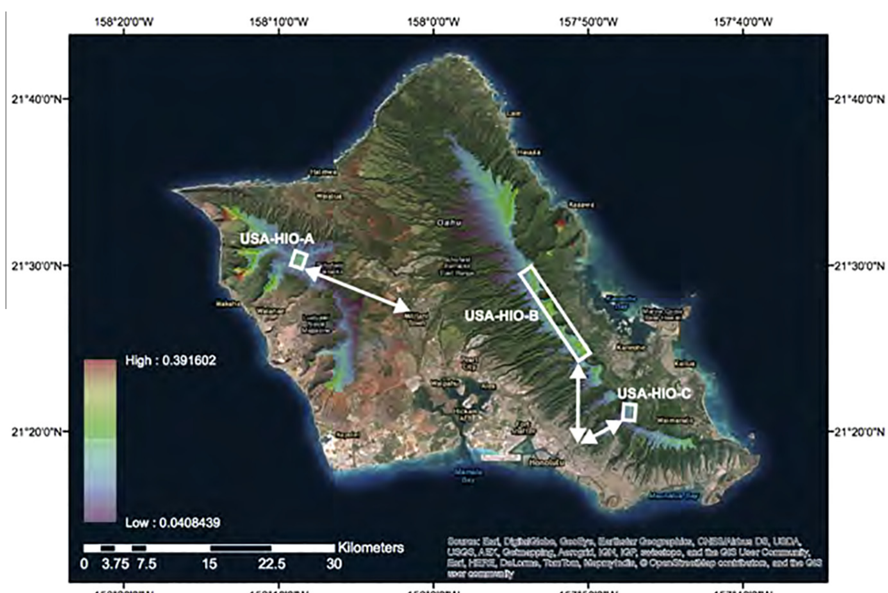

Fig. 11. A-Index for topography of the island of Oahu, Hawaii. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city indicated by arrows.

mately 125 km^2 and could provide enough electricity for over 115 million people. This far exceeds the population of Tehran, for which IPHROS would require only about 15 km^2 of lake area.

To the south lies the Zagros mountain range spanning the west and south of the country, hugging the northern coast of the Persian Gulf. Several cities derive the entirety of their energy needs from the oil fields of this region; namely, Shiraz and Bushehr. There is tremendous potential in IPHROS sites meeting the energy and economic needs of this region. The well-ordered topography of this region is ideally suited for the development of IPHROS technology, and the close proximity of major city and industrial centers provide a strong consumer base. The oil and natural gas industry can provide further economic motivation for the development of IPHROS as freshwater is needed for processing.

To the south, the IPHROS potential near the city of Shiraz is shown in Fig. 16. The highlighted region, detailed in Table 7, represents a lake area of 245 km^2, if fully developed. Again, the distance between the reservoir and city is too great ($\sim$ 200 km) for the system to directly pump freshwater to Shiraz, however IPHROS in this area could provide electricity for over 225 million people. With a population of approximately 1.5 million [67], a system of only 1.72 km^2 of lake area would be required to meet all of the electricity needs of the city. (see Fig. 17).

Farther east, the IPHROS potential near the city of Bandar 'Abbas is depicted in Fig. 16. The highlighted regions, detailed in Table 7, represent a total lake area of 183 km^2, if fully developed. As before, with extremely long distances between the reservoir and the city, these regions may not be viable as a direct freshwater supply, how-

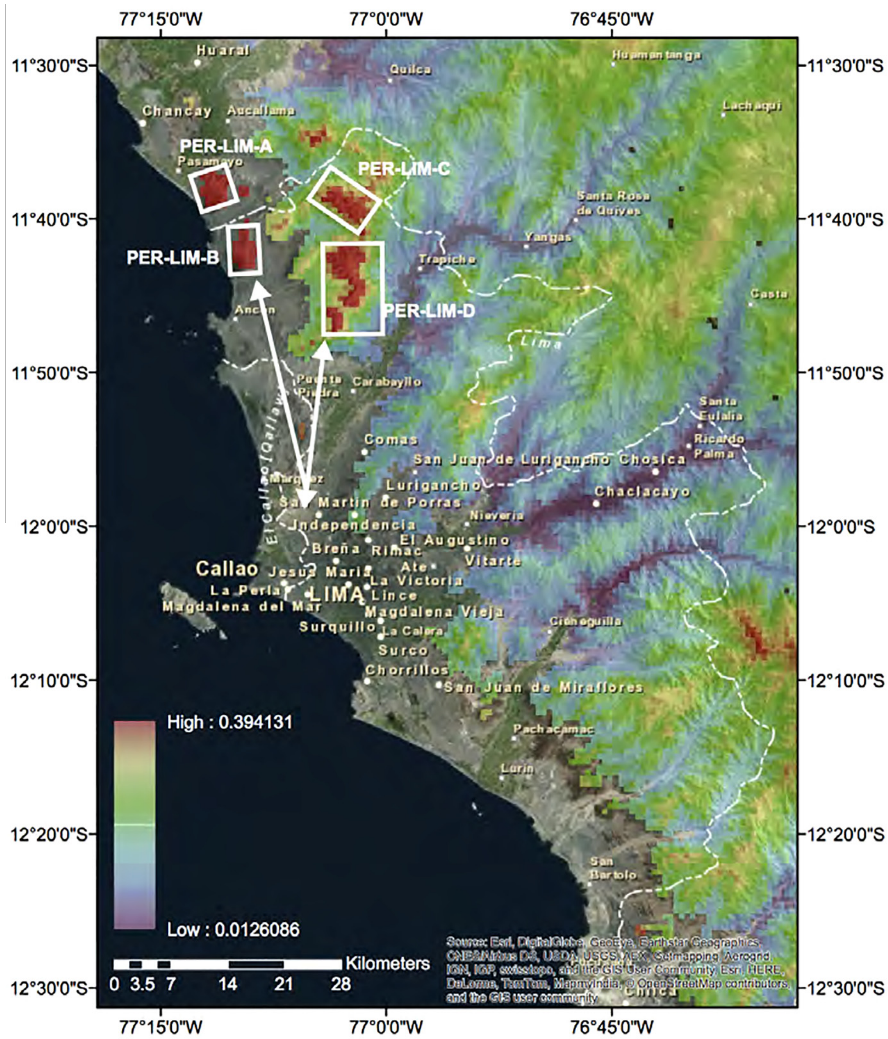

Fig. 12. A-Index for topography near Lima, Peru. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Lima, indicated by arrows.

Table 4
Energy potential of IPHROS in regions in Peru.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
PER-LIM-A	592	17	2.9	0.203	Lima	38.5	704
PER-LIM-B	574	16	3.2	0.179	Lima	30.5	627
PER-LIM-C	1339	25	1.6	0.078	Lima	31	2214
PER-LIM-D	1184	36	14	0.083	Lima	20.5	2854

ever they could provide electricity for over 169 million people. With a population of only 435,000 [67], a system of only 0.46 km^2 of lake area would be required to meet all of the electricity needs of the city. The freshwater produced could irrigate farms which can provide produce for local and export consumption.

Given the challenging state of relations between Iran and much of the international community, any opportunity that can potentially build trust and enhance confidence should be considered and studied in detail with a potential fast track demonstration project undertaken to show that we can all really work together to create a better world for all. Joint-ventures of renewable energy projects perhaps can build on the relationships established by current nuclear power discussions between Iran and the P5 + 1. Not only might IPHROS projects engage the educated and talented workforce of Iran, but they could provide the government a means by which to focus national attention on sustainable energy and water production development. Indeed, if the IPHROS technology could be developed as imagined, there would simply be no need for nuclear power plants in the region.

3.6.3. United Arab Emirates

The United Arab Emirates (UAE), led by Khalifa bin Zayed bin Sultan Al Nahyan and other leaders within the UAE, has demonstrated a clear vision to plan for a renewable energy based future.

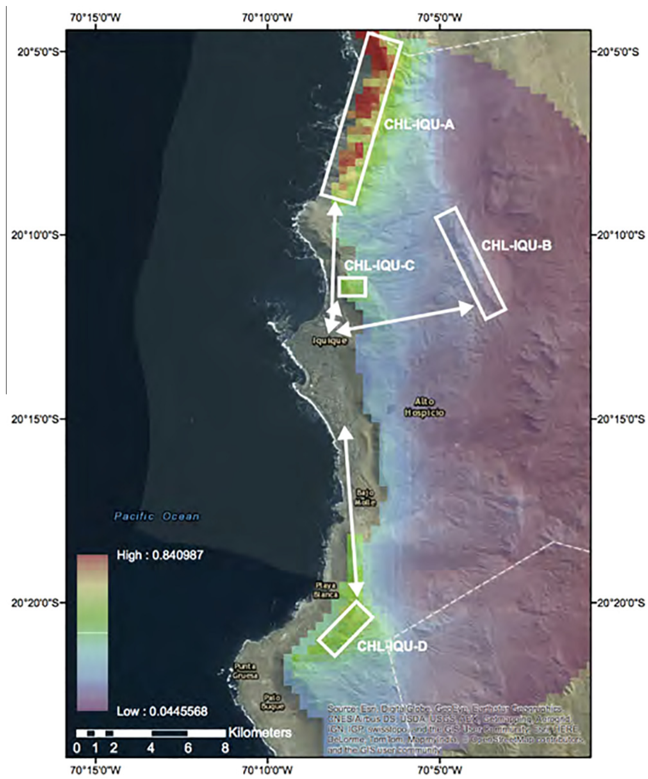

Fig. 13. A-Index for topography near Iquique, Chile. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Iquique, indicated by arrows.

For example, the Masdar Institute was created to develop renewable resource technologies and itself have a zero carbon footprint [68]. The total population of the UAE is about 15 million, with native Emiratis comprising just over 9 million [67]. The mountains west of Masafi have good IPHRO potential as shown in Fig. 18. Indeed given likely great wind energy potential high in the mountains and the vast desert (and mountain) regions available for solar PV plants, the entire country could be powered and watered with renewables, thus obfuscating the need for the full build-out of nuclear power plants that are currently planned [69].

The IPHROS potential for the eastern United Arab Emirates is shown in Fig. 18. Further detailed in Table 8, the highlighted regions represent a lake area of nearly 13.5 km^2. If fully developed, these regions could provide enough electricity and freshwater for 12.4 million people. If freshwater is the desired output of the system, this area could provide enough water for nearly 104 million people.

4. Discussion

Throughout history, as populations have grown to overtake local opportunities, large migrations have resulted. Although the world is finite, wind and solar power in combination with a modernized infrastructure should be able to satisfy most of humanity's electrical energy needs; thus a new era might be possible where power and fresh water generated by renewables form the foundation for economic growth without the need for extensive migration. For example, local factories can be built to manufacture solar panels for use in energy parks built to supply regional IPHRO systems, while workers build and maintain the IPHRO systems. In some locations the depth change of the pumped hydro system's storage reservoir can be designed to be small (≈10 m) providing a means for incorporating aquaculture into the system, which would create more jobs in the community. Residents realize that having more renewable energy generated locally, such as by having solar panels on their rooftops, leads to reliable power for industry and more fresh water and better food.

A reservoir designed to have a small depth change will necessarily have a relatively large surface area and thus higher evaporation losses. In any case, in hot dry regions reservoir surface coverings might be warranted. A simple and effective method for example is to use floating empty food transport containers not reusable for food transport [70–72,11].

The system adds additional advantages in the form of increased grid stability that need to be further researched and developed including: increasing the spinning reserves; offering additional operating reserves like primary, secondary and tertiary grid frequency controls; possibility of continuous control of reactive power in the grid (e.g in synchronous condenser mode w/o active power supply); and improving conventional thermal power plants utilization (i.e. they can run as base load resulting in higher efficiency). The majority of pumped hydro systems have black start capability even in the event of a grid outage, i.e. they can be brought very quickly into operation from stand still and without any external power supply. In addition to their black start capability, pumped hydro is able to provide system services in the further process of grid restoration. While grid restoration is in progress, further generators and controllable consumers are connected under control so that individual stable partial grids (isolated networks) can be established for a start. But once grid frequency and line voltage have returned to within tolerances, a major part of the consumers go online again uncontrolled. This results in considerable load variations that are difficult to predict while the grid is being restored. When partial grids are reconnected to each other, there will also be sharp jumps in load. Pumped hydro can easily balance these variations because they are able to follow steep power gradients, have short response times and feature motor-generators with a high rotating mass inertia. This ensures stable behavior over the entire output range, from no load to full load.

A further symbiotic potential is found as the system is designed and built: the engineering, economic, and environmental analysis conducted should be well documented and used to form the basis for classroom lessons in local schools so students can experience the power of collaborative, deterministic and creative thought. Hands-on learning can include students "Facing the Sun" to design, build, install, and operate solar panels and compete to see which teams can collect the most energy in a year, and which teams' systems continue to operate year after year. Real time active problem solving of challenges that arise will not only be invaluable from an education perspective, the students might suggest great solutions. [73].

Table 5
Energy potential of IPHROS in regions in Chile.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
CHL-IQU-A	738	9.9	1.3	0.572	Iquique	7.4	483
CHL-IQU-B	981	9.4	7.2	0.136	Iquique	9.0	388
CHL-IQU-C	586	1.2	1.6	0366	Iquique	3.0	208
CHL-IQU-D	893	3.9	2.3	0.388	Iquique	9.5	113

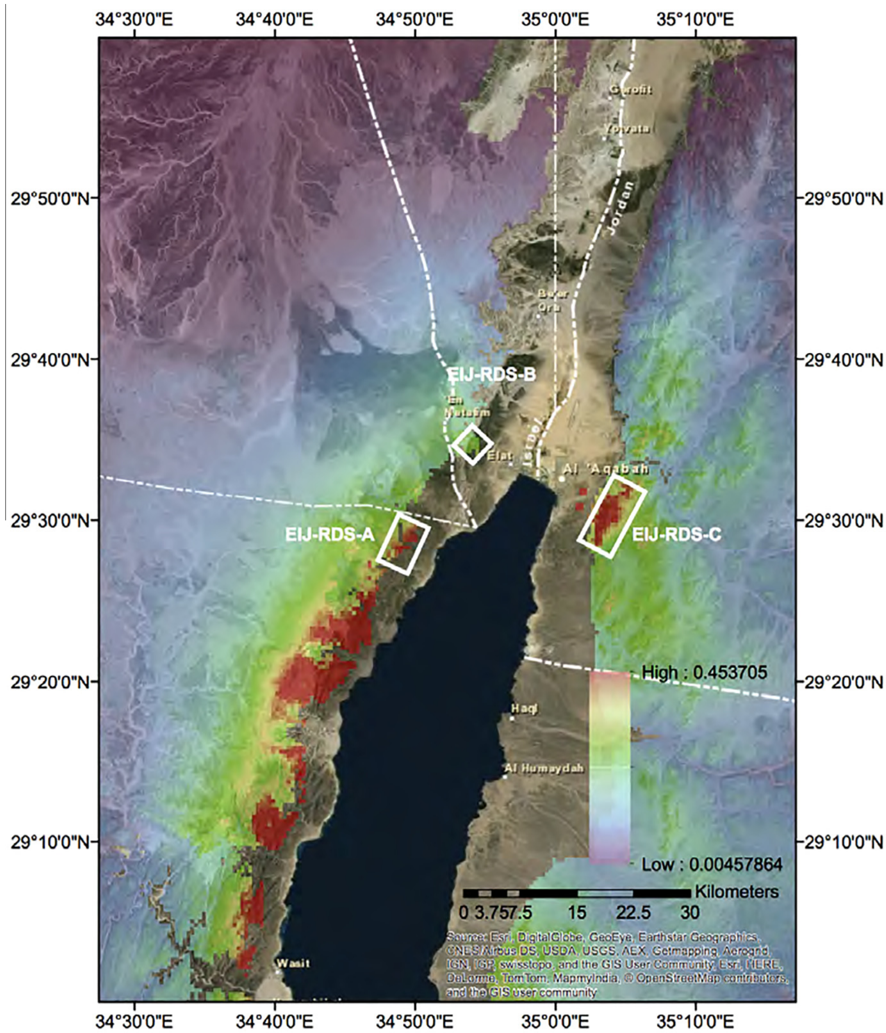

Fig. 14. A-Index for topography of regions in the northern Red Sea. Regions for potential IPRHOS applications highlighted in white. The closest city to the regions REDSEA-A, REDSEA-B, and REDSEA-C are Taba in Egypt, Eilat in Israel, and Aqaba in Jordan, respectively.

Table 6
Energy potential of IPHROS in regions around the northern Red Sea.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
REDSEA-A	573	12	5.5	0.105	Taba	6.67	13503
REDSEA-B	560	3.8	7.2	0.0.078	Eilat	3.62	4380
REDSEA-C	817	32	8	0.102	Aqaba	5.11	13503

The pieces of the puzzle now can be seen to come together to form a picture of an efficient system that in addition to storing energy and generating power and fresh water may also offer other opportunities for researchers to consider:

1.Excess power from renewable energy machines flows to a seaside PH system.
   (a)Saltwater is pumped up into an upper lined reservoir in adjacent mountains.
      (i)The often changed "fresh" seawater can support aquaculture with less use of medicines to keep fish disease free.
      (ii)Floating solar panels can reduce evaporation losses and generate additional power. If not solar panels, recycled materials can be used to limit evaporation losses.
         A.Fish tend to eat at twilight and hence might grow faster if the lake is partially covered [74].

2.When power is needed, seawater flows down from the reservoir. A portion of the flow is diverted to the RO plant.
   (a)Power is generated by the turbine.
   (b)Fresh water is produced to meet population needs.
   (c)Utilities are provided an additional resource to stabilize the grid.
   (d)Typically 5% of the water initially pumped uphill to the reservoir will leave the system as brine which then exits the RO plant at 90% of the input pressure and can flow through a turbine to also generate electricity
   (e)Total system outflow, can be discharged directly into the ocean because the brine from the RO plant will be diluted by the seawater output from the main power generation turbine.
      (i)Before exiting to the sea, the water could flow past adsorption polymers for harvesting uranium.

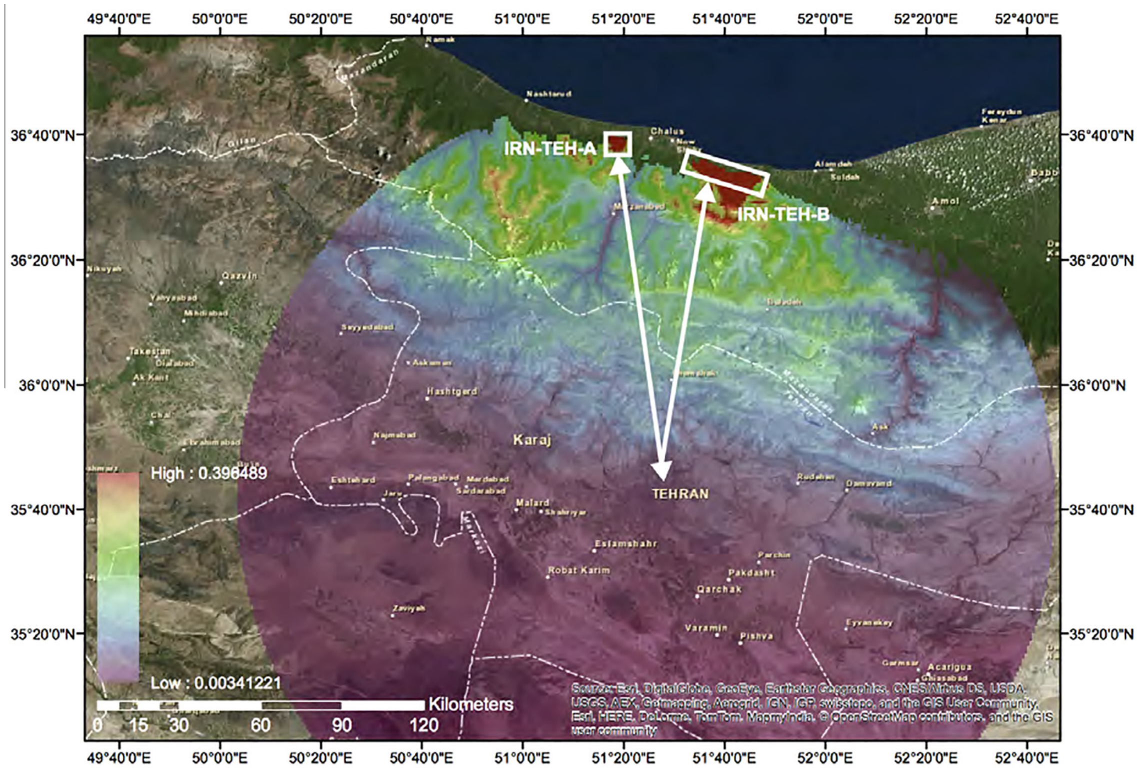

Fig. 15. A-Index for topography of region near Tehran, Iran. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Tehran, indicated by arrows.

Table 7
Energy potential of IPHROS in regions in Iran.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
IRN-TEH-A	778	32	6.4	0.122	Tehran	132	1672
IRN-TEH-B	888	93	4.2	0.211	Tehran	100	5547
IRN-SHI-A	565	245	8.4	0.067	Shiraz	200	9297
IRN-BAN-A	645	75	5.9	0.110	Bandar 'Abbas	128	3240
IRN-BAN-B	730	109	9.3	0.078	Bandar 'Abbas	72	5339

5. Conclusions

The intent of the current paper has been to show that large-scale energy storage and fresh water production are readily realizable in many dry coastal heavily populated regions of the world. Significant further focused regional study is required to address issues such as transportation costs of solar and/or wind energy from nearby suitable sites, and fresh water transportation to large populated regions; and then compare other alternatives that might exist such as distributed PV with residential battery storage systems and conventional RO desalination plants. A detailed site specific analysis will be required to obtain an accurate LCOE as well as delivered cost of fresh water.

In this paper, a symbiotic system for producing both freshwater and electric power from solar and wind resources were presented with a generic example of economically meeting the needs for one million people. Site specific case studies for Southern California, Baja, Hawaii, Chile, Peru, and the Middle East are investigated. In Southern California the power and freshwater needs for 28 million people could be realized. Significant employment opportunities resulting from building and maintaining the system can also be realized, as well as economic growth when a region can offer reliable power and freshwater supplies. On the other hand, the environmental trade-off of creating IPHROS lakes in the region must be weighed against the effects of drought and further drawing down reservoirs, as well as burning fossil fuels to create electricity for RO plants. Weighing in on the decision to build IPHRO systems, further research could examine how much water would be required to support enough flora to reverse desertification and help create a self-sustaining local climate, such as occurs in the (perhaps soon to be?) former Amazon rain forest.

The Supplementary Materials A for this paper investigates additional case studies for IPHRO systems around the world including Brazil, Morocco and China. The A-Index and energy potential for all the regions that have currently been analyzed is summarized in Fig. 19. Many regions in Chile, Hawaii, China, and Iran have an extremely high A-Index. Of the top ten regions, the area around Tehran not only has a high A-Index, but also has a large energy potential. Similarly, studies have been done considering connecting the Red Sea to the Dead Sea which lies about 410 m below sea level, where in one scenario the desalination plant would be collocated with a hydroelectric plant near the Dead Sea so both are fed by the difference in altitude between the dead sea and the oceans [75]. Due to environmental concerns projects have not moved forward; however, creating an IPHRO system in the mountains of Jordan near the Red Sea would be feasible and the brine outflow (or all the plant outflow) could be to the Dead Sea. Areas of Africa are also in need of such systems [76]. Also in the

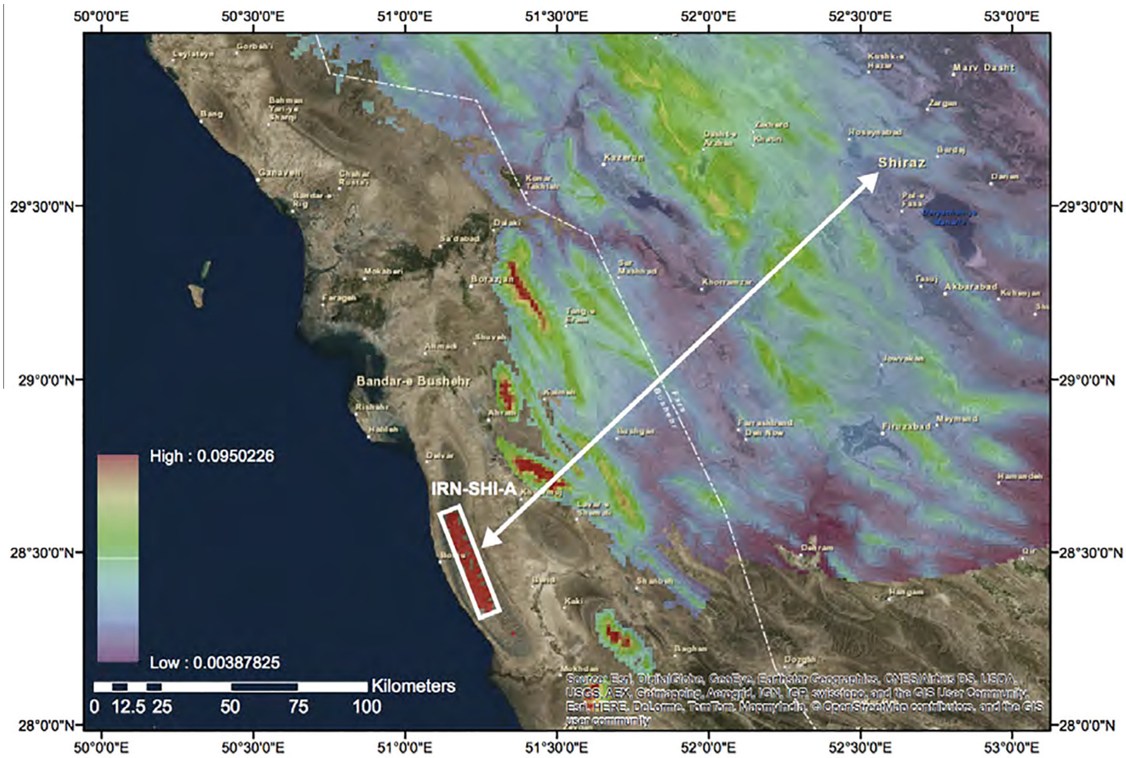

Fig. 16. A-Index for topography of region near Shiraz, Iran. Regions for potential IPRHOS applications highlighted in white with distance to nearest major city, Shiraz, indicated by arrows.

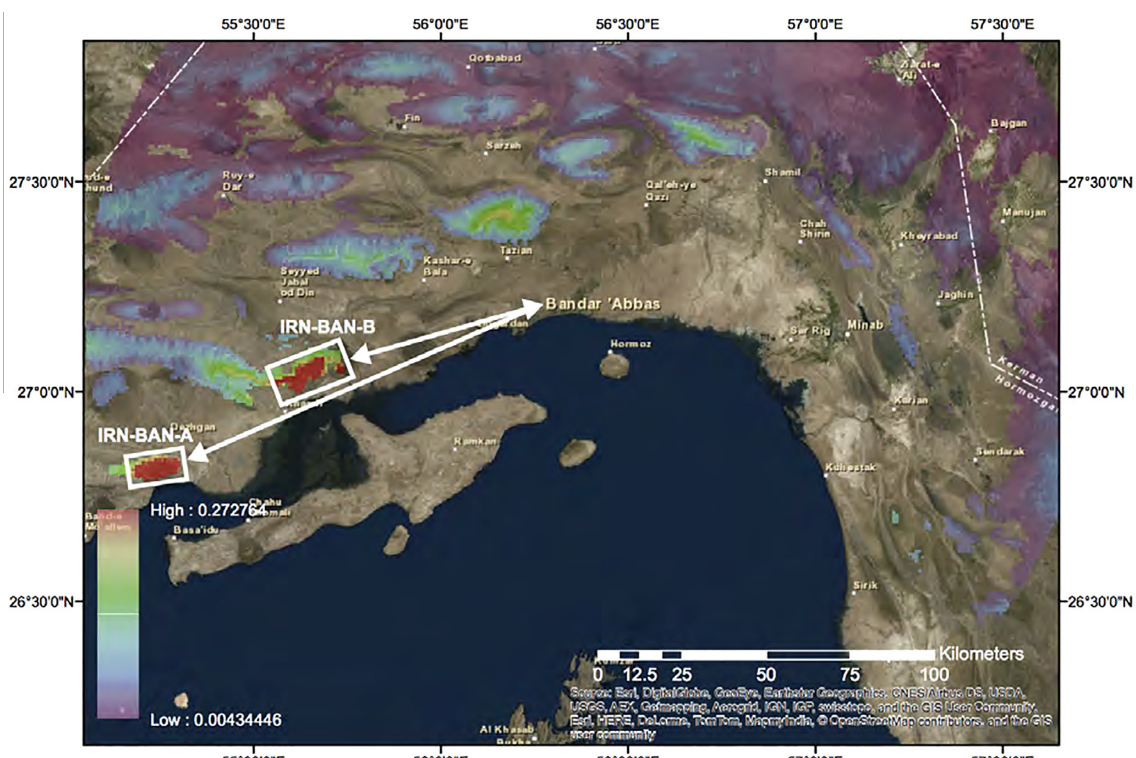

Fig. 17. A-Index for topography of region near Bandar 'Abbas, Iran. Regions for potential IPHROS applications highlighted in white with distance to nearest major city, Bandar 'Abbas, indicated by arrows.

Supplementary Materials A is a high-resolution analysis of the economics of an exemplary project in Southern California using real time power demand information and a wide array of economic factors. The first order analysis indicates feasibility of the approach,

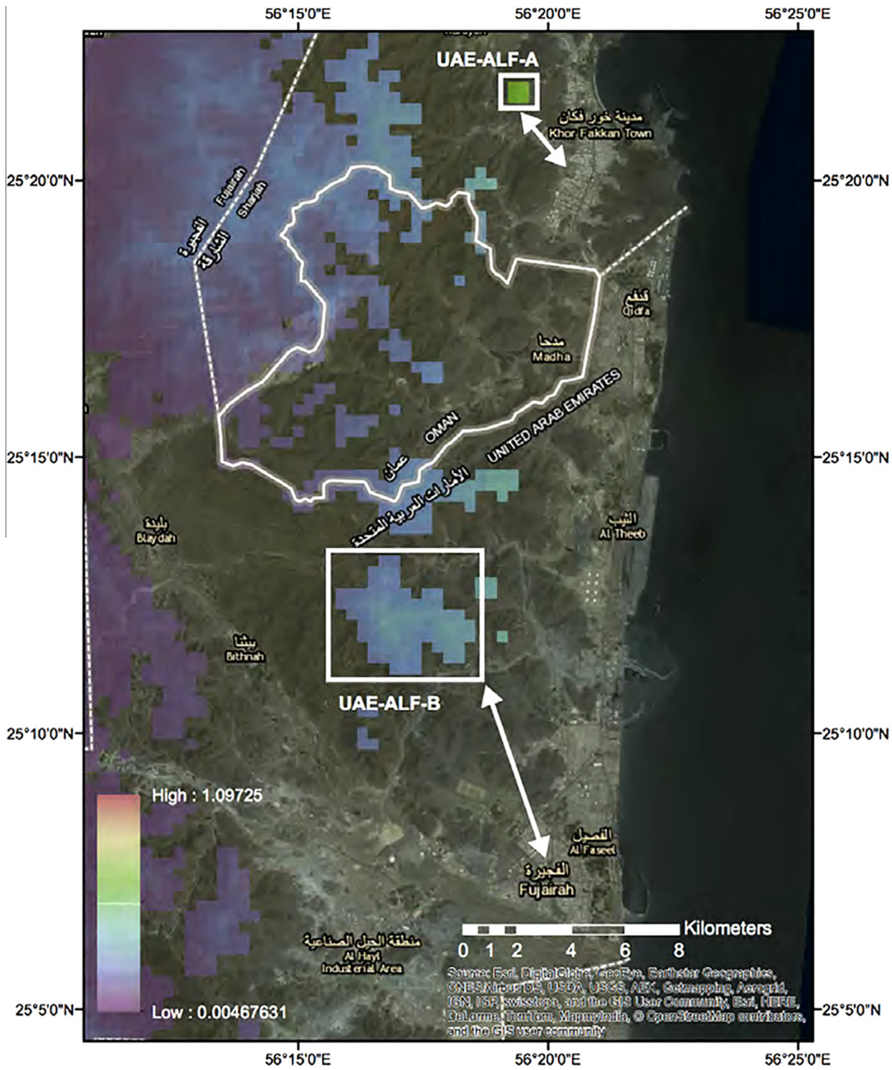

Fig. 18. A-Index for topography of the eastern United Arab Emirates. Regions for potential IPHROS applications highlighted in white with distance to nearest major city indicated by arrows.

Table 8
Energy potential of IPHROS in regions in the United Arab Emirates.

Region	Head (m)	Surface area (km^2)	Distance from coast (km)	A-Index	Nearest major city (NMC)	Distance to NMC	Energy potential (GWh/cycle)
UAE-ALF-A	529	0.64	2.8	0.186	Khor Fakkan	2.7	23
UAE-ALF-B	619	12.8	8.5	0.073	Fujairah	7.3	533

but a much more detailed analysis is warranted as part of any significant effort to move forward. Such detailed analysis helps to understand the effect of actual market prices, regulatory obligations, system configuration, capital and operating cost on the project's technical and financial performance. This detailed analysis shows that although at current prices PV alone has a higher return on investment than an full IPHROS system, if modest (and realistic) price increases occur returns become higher for the full IPHROS system than the PV alone in similar conditions and the rates of return meet the hurdle rate of infrastructure funds.

With careful planning and execution, large scale energy storage can convert volatile and intermittent energy associated with renewable energy systems into an economical controllable base load generation source with similar quality and availability as provided by thermal generation systems (e.g., coal or gas fired systems). In addition, a IPHRO system can also serve as an effective base load source for fresh water generation via a simplified RO plant to help provide power and water for all, and create whole new economies as envisioned in Fig. 20.

6. Further work and considerations

In the debate over the cost of converting converting to carbon free energy systems verses affordability and jobs, it should be considered that the Gross World Product is on the order of 75 trillion dollars, and at a cost of $5000/person to provide 1 kW of power and 500 liters of fresh water per day, it would only take 5% of the GWP every year for 10 years to enable 7 billion people to go green, a much better option than all the future wars that may otherwise be fought by displaced people fighting for scare resources.

The decision to build an IPHRO system should depend not only on the LCOE and delivered cost of water as compared to conven-

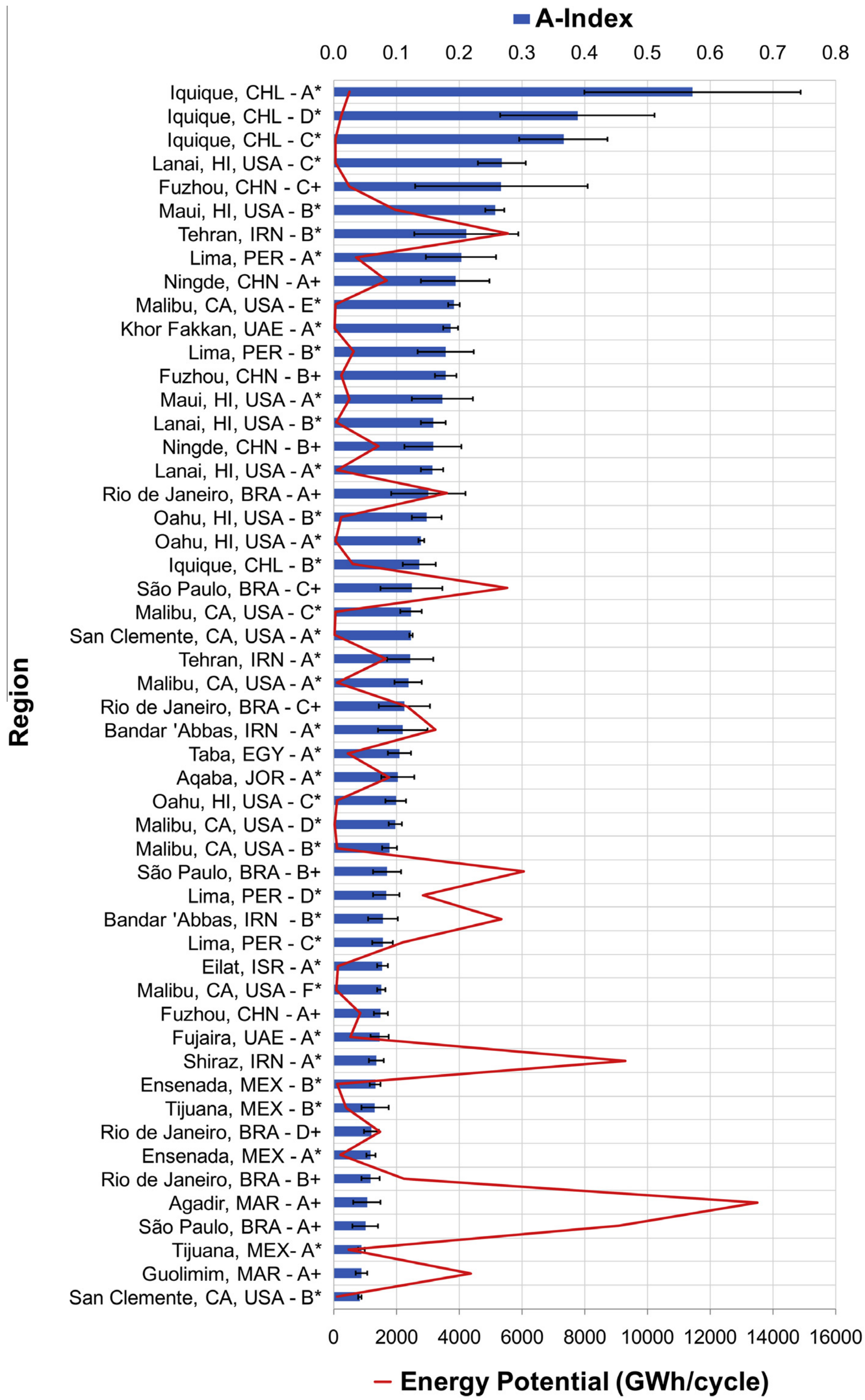

Fig. 19. Summary of A-Index and energy potential of all regions investigated in this paper (*) and its supplemental materials (+).

tional systems, but also on to the long term prognosis for alternatives as regional impacts of climate change create policy uncertainties.

In addition, the development of IPHRO systems is not just about providing renewable energy and freshwater, it is also about creating a societal approach to supplying two of our greatest needs; and since renewable power systems tend to be widely distributed and it will take decades to build all the systems needed, many skilled jobs can be created and sustained. As IPHRO related systems come on line, workers will also be needed to maintain these systems and replace and recycle systems at their end of useful life. The question of IPHRO systems is thus perhaps not 'does it work?', but 'what does it make possible?' (Adopted from Brian Massumi in the translator's forward of Deleuze and Guattari's 'A Thousand Plateaus'

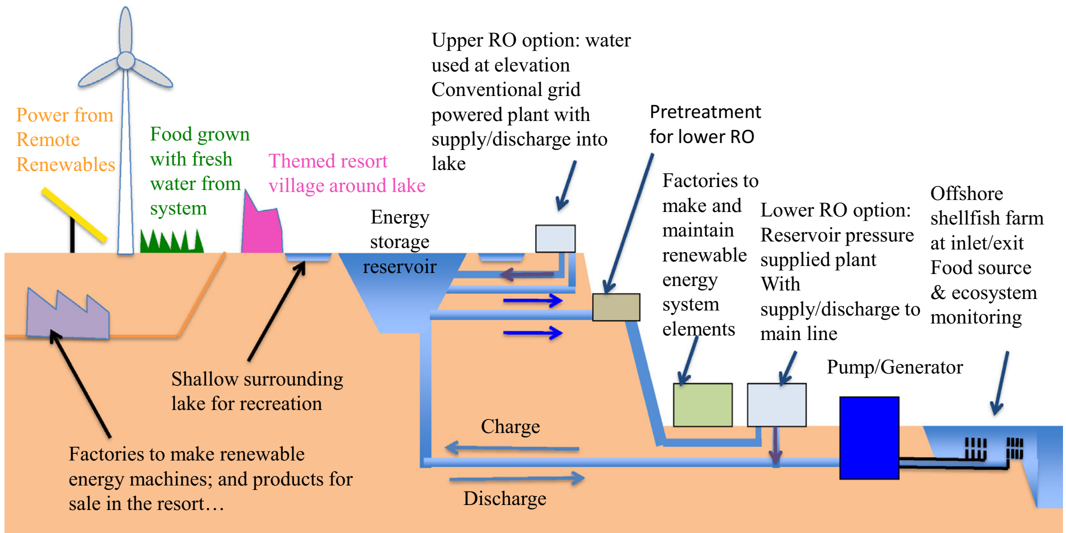

Fig. 20. IPHROS is more than a "battery" it is full system solution that can supply renewable energy, fresh water, grid stability, and jobs for the region.

[77], this philosophy well describes the symbiotic approach to engineering systems design considered here.) Indeed an economy based on renewable energy and desalinated water could be critically important for the near and long term future of human civilization in view of rapid climate change.

As an example of how an IPHRO system might do far more for a region than just provide renewable energy and fresh water, it is hypothesized here that migration issues might be better addressed by creating opportunities in regions from which migrants come, for example in accordance with the Desertec vision [78]. If a portion of the resources currently allocated to resettling refugees in Europe, as much as 25,000 euros per year per refugee, were used to build IPHRO systems in the Middle East, a new mutually beneficial ecosystem could be created. This could show how we can all do better by putting *The World First*:

The most important calculations are those that will save nations,
Like building wind plantations, instead of more gas stations,
And seeking new destinations in space, is complicated,
The Earth is worth saving from troubles that we created,
It's time to double efforts, in land, water and sky,
It's time to come together, it's time to solarize,
The answer is blowing in the wind and flowing in the water,
The polar caps are melting, sea levels are on a rise,
Surprised that super storms still haven't opened our eyes,
Some scientist theorize, and politicians decide,
That man is not at fault, so they gamble with our lives,
Let's get off the sidelines and show we're not psychotics,
Insane, awaiting change from the same planned periodic,
Debates with fate at stake, of our consequent generations,
Reversing the complications, requires more impatience,
No time to be wasted, this fight is not symbolic,
A catastrophic plight, or relationship symbiotic…Decide…It's Time…
Action, no longer passive, too massive to stagnate,
Reaction, we seize the moment, accelerate to create,
With force, remove mobs from desperate situations,
Renewed energy jobs, will lay the foundations,
Question, research, guess, test, analyze with a passion,
Cause building what we create, is the prevalent high fashion,
Our fate's in our control, so let's stand hands united,
The only way we'll fold, is in a world divided
It's time we all put the World First

Marc Graham and Alexander Slocum (2015)[3]

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seta.2016.09.003.

References

[1] Williams AP, Seager R, Abatzoglou JT, Cook BI, Smerdon JE, Cook Edward R. Contribution of anthropogenic warming to california drought during 2012–2014. Geophys Res Lett 2015.
[2] Gillis J. Hotter planet fuels drought, scientists find. New York Times; 2015.
[3] UN Economic and Social Council, The International Center for Agricultural Research in the Dry Areas. Drought in the arab world. Regional Conference on Land Degradation Issues in the Arab Region, Cairo; 2007.
[4] Buck BH, Krause G, Rosenthal H. Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints. Ocean Coastal Manage. 2004;47(3):95–122.

[3] Rap performance available at: http://www.untoldrecords.com/marcgraham-phd/music.html.

[5] Slocum AH. Symbiotic offshore energy harvesting and storage systems. Sustainable Energy Technol Assess 2015;11:135–41.
[6] Picard M, Baelden C, Wu Y, Chang L, Slocum AH. Extraction of uranium from seawater: design and testing of a symbiotic system. Nucl Technol 2014;188(2):200–17.
[7] Haji MN, Vitry C, Slocum AH. Decoupling the functional requirements of an adsorbent for harvesting uranium from seawater through the use of shell enclosures. Proceedings of the 2015 ANS Winter Meeting and Nuclear Technology Expo.. La Grange Park, IL: American Nuclear Society; 2015.
[8] Farid AM, Lubega WN. Powering & watering agriculture: application of energy-water nexus planning. Global Humanitarian Technology Conference (GHTC). IEEE; 2013. p. 248–53.
[9] Kassakian JG, Schmalensee R, Desgroseilliers G, Heidel TD, Afridi K, Farid AM, Grochow JM, Hogan WW, Jacoby HD, Kirtley JL. The future of the electricity grid: an interdisciplinary mit study. Tech Rep Cambridge, MA; 2011.
[10] Simbolotti G, Kempener R. Electricity storage. International Renewable Energy Agency, Tech. Rep; 2012.
[11] Simon K, Shanbhag R, Slocum AH. Reducing evaporative water losses from irrigation ponds through the reuse of polyethylene terephthalate bottles. J Irrig Drain Eng 2015:06015005.
[12] Thoresen R. Device for preventing of evaporation of water, March 26 1998. WO Patent App. PCT/NO1997/000,246.
[13] Froekjaer T. A floating tag for the reduction of evaporation from liquid reservoirs, January 11 2012. EP Patent 1,697,234.
[14] Gilau AM, Small MJ. Designing cost-effective sea water reverse osmosis system under optimal energy options for developing countries. In Proceedings of the International Conference on Renewable Energy for Developing Countries. p. 1.
[15] Espino T, Penate B, Piernavieja G, Herold D, Neskakis A. Optimised desalination of seawater by a pv powered reverse osmosis plant for a decentralised coastal water supply. Desalination 2003;156(1):349–50.
[16] Carta JA, Gonzalez J, Subiela V. Operational analysis of an innovative wind powered reverse osmosis system installed in the canary islands. Solar Energy 2003;75(2):153–68.
[17] Ahmed M, Shayya WH, Hoey D, Mahendran A, Morris R, Al-Handaly J. Use of evaporation ponds for brine disposal in desalination plants. Desalination 2000;130(2):155–68.
[18] Ahmed M, Shayya WH, Hoey D, Al-Handaly J. Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates. Desalination 2001;133(2):135–47.
[19] Fujihara T, Imano H, Oshima K. Development of pump turbine for seawater pumped-storage power plant. Hitachi Rev 1998;47(5):199–202.
[20] Okinawa Sea Water Pumped Storage. http://www.jpower.co.jp/english/international/consultation/detailold/seasjapan24.pdf. Accessed on: 7 June 2016.
[21] WPDC. Egypt plans seawater pumped-storage plant, water power & dam construction. World News; 1989.
[22] Hristova D. Chile Valhalla mulls partners for pumped storage, solar project – report. See News; 2015.
[23] Murakami M. Hydro-powered reverse osmosis (ro) desalination for co-generation: a middle east case study. Desalination 1994;97(1):301–11.
[24] Novosel T, Ćosić B, Krajačić G, Duić N, Pukšec T, Mohsen MS, Ashhab MS, Ababneh AK. The influence of reverse osmosis desalination in a combination with pump storage on the penetration of wind and pv energy: a case study for jordan. Energy 2014;76:73–81.
[25] Murakami M. Managing water for peace in the middle east; alternative strategies. United Nations University Press; 1995.
[26] Kobori I, Glantz MH, et al. Central Eurasian water crisis: Caspian, Aral and Dead Seas. United Nations University Press; 2004.
[27] Wittholz MK, O'Neill BK, Colby CB, Lewis D. Estimating the cost of desalination plants using a cost database. Desalination 2008;229(1–3).
[28] Bergman R, Elarde J, Huehmer R. Cost of membrane treatment: current costs and trends. Membrane Technology Conference Proceedings. American Water Works Association; 2012.
[29] Arroyo J, Shirazi S. Cost of brackish groundwater desalination in Texas. Texas Water Development Board; 2012.
[30] Younos T. The economics of desalination. The economics of desalination. J Contemp Water Res Educ 2005;132(1):39–45.
[31] Burbano AA, Adham SS, Pearce WR. The state of full-scale ro/nf desalination-results from a worldwide survey. Am Water Works Assoc J 2007;99(4):116.
[32] Membrane Desalination Costs. http://www.amtaorg.com/wp-content/uploads/6MembraneDesalinationCosts.pdf. Accessed on: 7 June 2016.
[33] Alspach B, Watson I. Take it with a grain of salt: What you need to know about swro costs. Membrane Technology Conference Proceedings. Long Beach, CA: American Water Works Association; 2011.
[34] Alspach B, Watson I. Swro costs: Don't believe everything you read. IDA J Desalin Water Reuse 2011;3(2):22–8.
[35] The Seawater Desalination Plant in Ashdod. http://www.mekorot.co.il/Eng/newsite/Projects/Pages/TheAshdodDesalinationFacility.aspx. Accessed on: 7 June 2016.
[36] Ashdod Desalination Plant, Ashdod, Israel. http://www.water-technology.net/projects/ashdod-desalination-plant-ashdod/. Accessed on: 20 July 2016.
[37] Shary D. personal communication. Minrav Holding Ltd, construction company which built the Ashdod plant; 2016.
[38] A. Kanarek. personal communication. IVM-JV, operator of the Ashdod plant.
[39] Moch I, Querns WR, Steward D. WTCost II: modeling the capital and operating costs of thermal desalination processes utilizing a recently developed computer program that evaluates membrane desalting, electrodialysis, and ion exchange plants. United States Department of Interior, Bureau of Reclamation; 2008.
[40] MWH. Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest. Technical Report MWH-HDC-T12, U.S. Army Corps of Engineers Northwest Division, Hydroelectric Design Center; 2009.
[41] Davies RV, Kennedy J, McIlroy RW, Spence R, Hill KM. Extraction of uranium from sea water. Nature 1964;203(4950):1110–5.
[42] Kim J, Tsouris C, Mayes RT, Oyola Y, Saito T, Janke CJ, Dai S, Schneider E, Sachde D. Recovery of uranium from seawater: a review of current status and future research needs. Sep Sci Technol 2013;48(3):367–87.
[43] Al-mutaz IS, Wagialla KM. Techno-economic feasibility of extracting minerals from desalination brines. Desalination 1988;69(3):297–307.
[44] Elimelech M, Phillip WA. The future of seawater desalination: energy technology, and the environment. Science 2011;333(6043):712–7.
[45] Electric Power Development Company. Okinawa Sea Water Pumped Storage; 1989.
[46] Fritzmann C, Löwenberg J, Wintgens T, Melin T. State-of-the-art of reverse osmosis desalination. Desalination 2007;216(1):1–76.
[47] Menningmann J. Seawater desalination with reverse osmosis; 2011.
[48] Lenntech. Reverse osmosis desalination process; 2015. [Online, Accessed on 22 July 2015].
[49] Menningmann J. Ro membrane technology- advances improve global access to clean water. Water Qual Prod 2005;10(4):18.
[50] Cohen-Tanugi D, Grossman JC. Water permeability of nanoporous graphene at realistic pressures for reverse osmosis desalination. J Chem Phys 2014;141(7):074704.
[51] Rehman S, Al-Hadhrami LM, Alam MM. Pumped hydro energy storage system: a technological review. Renewable Sustainable Energy Rev 2015;44:586–98.
[52] Farr TG, Kobrick M. Shuttle radar topography mission produces a wealth of data. Eos, Trans Am Geophys Union 2000;81(48):583–5.
[53] Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D, Alsdorf D. The shuttle radar topography mission. Rev Geophys 2007;45(2).
[54] Kobrick M. On the toes of giants–How SRTM was born. Photogramm Eng Remote Sens 2006;72(3):206–10.
[55] Rosen PA, Hensley S, Joughin IR, Li FK, Madsen SN, Rodrguez E, Goldstein RM. Synthetic aperture radar interferometry. Proc IEEE 2000;88(3):333–82.
[56] Kahrl WL. Water and power: the conflict over Los Angeles' water supply in the Owens valley. University of California Press; 1982.
[57] Mulholland C. William Mulholland and the rise of Los Angeles. University of California Press; 2000.
[58] Jenkins S, Paduan J, Roberts P, Schlenk D, Weiss J. Management of brine discharges to coastal waters: recommendations of a science advisory panel. Technical Report 692, Costa Mesa: Southern California Costa Water Research Project; 2012.
[59] United States Census Bureau. Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2014; 2010.
[60] Secretara de Desarrollo Social. Catlogo de Localidades; 2010.
[61] Instituto Nacional de Estadsticas. Census; 2012.
[62] U.S. Energy Information Administration. Iran; 2014.
[63] Hossein A, Yazdan GF, Ehsan AG. Energy consumption in Iran with Bayesian approach 1. OPEC Energy Rev 2012;36(4):444–55.
[64] Erdbrink T. Annual buildup of air pollution chokes Tehran. The New York Times; 2013.
[65] Rezaian J. Iran's water crisis the product of decades of bad planning. The New York Times; 2014.
[66] Ghorbani M. The economic geology of Iran. Netherlands: Springer; 2013.
[67] United Nations Statistics Division; 2015.
[68] Heap T. Masdar: Abu Dhabi's carbon-neutral city. BBC News; 2010.
[69] Dyck E, Evrensel A. From consideration to construction: the United Arab Emirates' journey to nuclear power. IAEA Department of Nuclear Energy; 2015.
[70] Cullen AP. Covering or blanketing liquid surfaces and float members for effecting same; 1976. US Patent 3,938,338.
[71] Santafé MR, Soler JBT, Romero FJS, Gisbert PSF, Gozálvez JJF, Gisbert CMF. Theoretical and experimental analysis of a floating photovoltaic cover for water irrigation reservoirs. Energy 2014;67:246–55.
[72] Ruskowitz JA, Suárez F, Tyler SW, Childress AE. Evaporation suppression and solar energy collection in a salt-gradient solar pond. Solar Energy 2014;99:36–46.
[73] Graham M, Slocum AH, Moreno Sanchez R. Teaching high school students and college freshmen product development by deterministic design With PREP. J Mech Des 2007;129(7):677–81.
[74] Barnes ME, Miller J, Durben DJ. Partial overhead tank cover use during feral brown trout rearing. North Am J Aquacult 2005;67(4):319–23.
[75] McPhail A, Lintner S. Red sea dead sea water conveyance study program overview; 2013.
[76] May D. The trans-africa pipeline: Building a sustainable water generation and distribution network. http://transafricapipeline.org/PDFs/TAPDMayPaper.pdf, 2011.
[77] Deleuze G, Guattari F. A thousand plateaus: capitalism and schizophrenia. Minneapolis, MN: University of Minnesota Press; 1987.
[78] Desertec. Desertec website. http://www.desertec.org/.