International Journal of
Sustainable Energy Planning and Management

Securing future water supply for Iran through 100% renewable energy powered desalination

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ABSTRACT

Iran is the 17th most populated country in the world with several regions facing high or extremely high water stress. It is estimated that half the population live in regions with 30% of Iran's freshwater resources. The combination of climate change, increasing water demand and mismanagement of water resources is forecasted to worsen the situation. This paper shows how the future water demand of Iran can be secured through seawater reverse osmosis (SWRO) desalination plants powered by 100% renewable energy systems (RES), at a cost level competitive with that of current SWRO plants powered by fossil plants in Iran. The optimal hybrid RES for Iran is found to be a combination of solar photovoltaics (PV) fixed-tilted, PV single-axis tracking, Wind, Battery and Power-to-Gas (PtG) plants. The levelised cost of water (LCOW) is found to lie between 1.0 €/m^3 and 3.5 €/m^3, depending on renewable resource availability and water transportation costs.

Keywords:

Levelised cost of water:
Fossil fuel independency;
Seawater reverse osmosis;
Iran;
Hybrid renewable energy systems

URL: http://doi.org/10.5278/ijsepm.3305

1. Introduction

Iran is ranked in the top 10 water stressed countries globally, with the industrial, agricultural and domestic sectors in the country facing high to extremely high water stress [1]. High water stress implies that greater than 40% of the renewable water resources available is being withdrawn, indicating the use of fossil groundwater. Gleeson et al. [2] show that the area of the Persian aquifer required to sustain the current groundwater withdrawals and dependent ecosystems is 10–20 times larger than the actual area of the Persian aquifer. A study by Joodaki et al. [3] on groundwater in the Middle East found that from 2003 to 2012, Iran suffered the largest groundwater depletion at a rate of 25 ± 3 Gt per year. The reduction is attributed to both climate change and increasing water withdrawals.

The World Resources Institute (WRI) projects that even in an optimistic scenario, as explained in the Intergovernmental Panel on Climate Change 5th assessment report, Iran will continue to rank in the top 15 water stressed countries [1]. At present, the annual renewable water resources per capita in Iran is less than 1700 m^3 and is expected to decrease to 800 m^3 by 2021. The water crisis threshold is 1000 m^3 of annual renewable water resource per capita [4]. A joint report by the Heinrich Böll Foundation and Small Media [5] has identified the water crisis to pose the greatest threat to Iran in the coming decades, with the potential to render vast areas of the country uninhabitable.

Alipour et al. [6] suggest that over-extraction of groundwater resources in the Greater Tehran area of Iran, has led to land subsidence at the rate of several centimeters a year. Land subsidence results in damage to buildings, roads and infrastructure contributing towards economic losses. In addition, the water shortage has rendered lakes and wetlands across the country dry. It is

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Nomenclature

a	annum
b€	billion Euro
CAGR	compound annual growth rate
crf	capital recovery factor
D	debt
E	equity
FLH	full load hours
GWI	Global Water Intelligence
HVDC	High Voltage Direct Current
LCOE	levelised cost of electricity
LCOC	levelised cost of curtailment
LCOS	levelised cost of storage
LCOT	levelised cost of water transportation
LCOW	levelised cost of water
PtG	power-to-gas
PV	photovoltaic
SEC	specific energy consumption
SNG	synthetic natural gas
SWRO	seawater reverse osmosis
WACC	weighted average cost of capital

also argued that over extraction of water and diversion of the rivers that feed the lakes in Iran is the main contributor to the diminishing lakes in the country. The report by Heinrich Böll Foundation and Small Media [5] reasons these to be causes for the shrinking Lake Urmia and Lake Houman.

Madani [7] explains that Iran receives an average annual rainfall of 250 mm, less than 1/3rd of the global average. The precipitation is distributed unevenly across the country, with 25% of the country receiving 75% of the precipitation, more specifically, the Northern and Western regions. In addition, 75% of the precipitation occurs during the winter period, when not required by the agricultural sector. This high variability in rainfall, both in a spatial and temporal resolution, has sustained Iran's reliance on dams and reservoirs to regulate water flows. As of 2016, Iran had 171 dams with a total storage capacity of 4907 bn m^3 from which only 60% was full [8].

Various sources mention that the government's response to the water shortage has been the construction of more dams [4, 7, 9]. Madani [7] argues that dams worsen the water crisis by blocking water flow to lakes, degrading water quality, destroying ecosystems and encouraging downstream development under the impressions of water availability. Similar arguments are expressed by Foltz [9] and Tahbaz [10]. Madani [7] reasons that the main factors that have contributed to Iran's water crisis are population growth, mismatch between population distribution and available water resources, promotion of unsustainable agriculture practices and poor management of water resources. In addition, Gorjian and Ghobadian [4] and Tahbaz [10] highlight the impact of climate change and the resulting droughts and floods on the water resources in Iran.

The Heinrich Böll Foundation and Small Media [5] discuss water demand management and increase in efficiency in the agricultural sector as some of the most effective ways of overcoming water stress in Iran. According to GWI [11], the Iranian government is looking to secure water availability through water efficiency, water reuse particularly for irrigation and the increased use of seawater desalination. In November 2015, the Iranian Energy Minister announced project plans to desalinate and transfer drinking water from the Persian Gulf and the Sea of Oman to 47 million people located within the 16 central provinces of the country [12]. A report by The Iran Project explains that construction of the project has already started and is being called the largest water transfer project in the Middle East [13]. Collins [14] provide another example of a desalination facility being built in Bandar Abbas to provide desalinated water to an iron ore mine 300 km inland and at an elevation of 1700 m. This will further be expanded to provide water to a copper mine at 2700 m altitude. The first phase of the project, constructing a 100,000 m^3/day SWRO plant in Bandar Abbas, is reported to have been completed in 2018 and supplying water to the region [15].

The installed desalination capacity in Iran, as of 2015, is estimated to be 809,607 m^3/day, out of which 21.6% is seawater reverse osmosis (SWRO) [11]. Approximately, 62% of the desalinated water is used by the industrial sector and the remaining 38% to meet the domestic demand. According to Gude [16], Iran is ranked as one of the top 20 countries with the largest desalination market in recent years. Currently, the desalination plants for domestic demand are situated in the southern provinces of Hormozghan as well as Sistan and Baluchestan.

The growth of seawater desalination as an alternative water resource has raised concerns about the high energy consumption of desalination and the dependence of the industry on fossil fuels [4, 17–22]. Therefore, despite helping to meet the water demand of society, the desalination industry also further contributes to climate change, only exacerbating water stress situations globally. Razmjoo et al. [23] studied different energy sustainability indicators for a group of countries, including Iran. It was found that Iran ranked the least in terms of environmental and social aspects, highlighting the high shares of fossil fuel used in the country.

Connolly and Mathiesen [24] discuss the risks associated with the current fossil based energy system and analyse the feasibility of achieving 100% renewable energy systems across different sectors for the case of Ireland. With the increasing threat of runaway climate change, various literature and reports address the aspects of 100% renewable energy based systems on a local and global scale [25]. The adoption of renewable energy to power the desalination sector has also been explored. Østergaard et al. [26] investigated the impacts of running desalination plants with increasing wind capacities on the Jordanian energy system, considering the large demand for desalination in Jordan. In addition to increasing the penetration of renewable energy in the system, the study also investigated the flexibility options that different desalination technologies may provide to the energy system. The main concerns with renewable energy power plants are their intermittency and need for energy storage [20–22, 27]. In Caldera et al. [27], it was shown that the global water demand of 2030 can be met by SWRO plants powered by 100% hybrid renewable energy power plants at a cost level competitive with that of fossil powered SWRO plants today. The hybrid power plants were comprised of solar photovoltaic (PV), wind energy, battery and Power-to-Gas (PtG) plants and allowed for the optimal utilisation of the installed desalination capacity.

This paper focuses on the water stress in Iran and assesses the techno-economic feasibility of alleviating the country's water crisis through 100% renewable powered SWRO systems by 2030. The proposed research will enable Iran to produce water for the country without concern of fossil fuel consumption and, consequently, greenhouse gas emissions. The system envisaged to meet the future water demand of Iran is presented in Figure 1.

SWRO desalination plants along the coastline are powered by hybrid renewable energy power plants being cost optimized by storage. High voltage direct current (HVDC) power lines transport power to the desalination plants on the coast of the Persian Gulf and the Gulf of Oman. The water produced is transported to meet the demands of the domestic, industrial and agricultural sectors throughout the country. Water storage at the desalination plant site ensures reliable water supply.

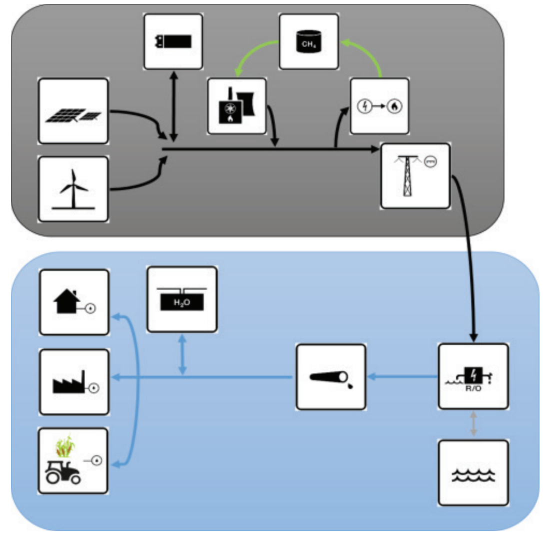

Figure 1: The desalination system proposed to meet the future water demand of Iran. The different components are the renewable energy power plant configuration (top panel), water demand of the municipal, industrial and agricultural sectors (bottom panel) and SWRO plants located on the coast line (bottom panel)

2. Methodology

2.1. Overview

The feasibility of a 100% renewable energy powered SWRO desalination system for Iran can be determined by comparing the water production costs of the system with that of fossil powered SWRO plants in operation today. In this study, the system, illustrated in Figure 1, is analysed for the 2030 optimistic scenario in Iran. In addition, it is assumed that there are no thermal power plants using fossil fuels in the future scenario for Iran, in alignment with the COP21 agreement to achieve a net zero greenhouse gas emission system. The feasibility of a 100% renewable energy based power system in Iran has already been illustrated by Aghahosseini et al. [28] and Ghorbani et al. [29, 30]. The assumption of no fossil fuel based plants is further validated by recent literature that discuss the transition to 100% renewable energy power systems of different countries and regions [25, 31–33]. Thus, the 2030 total water demand of the agricultural, domestic and industrial sectors, excluding that of thermal power plants in Iran, is considered.

The unit production cost of water (€/m^3) or the levelised cost of water (LCOW) is calculated as discussed in [27]. The LCOW includes the unit production cost of water at the site of the desalination plant, electricity costs, water storage at the site of demand and the water transportation to the region of desalination demand. Equation 1 summarizes the approach used to calculate the LCOW.

$$LCOW_{desal} = \frac{Capex_{desal} \times crf_{desal} + opex_{fixed\ desal}}{Total\ water\ produced\ in\ a\ year} + (LCOE_r \times SEC) \quad (1)$$

Equation 1: Levelised cost of water (LCOW). Here, $\boldsymbol{Capex_{desal}}$ is the CAPEX of the desalination plant in €/(m^3·a) and crf_{desal} is the annuity factor for desalination plant. Total water produced in a year is in m^3, $\boldsymbol{Opex_{fixeddesal}}$ is the fixed OPEX of the desalination plant in €/(m^3·a), $\boldsymbol{LCOE_r}$ is the levelised cost of electricity and is in €/kWh. SEC is the specific energy consumption in kWh/m^3. The product of the LCOE and SEC is the energy cost of the desalination plant in €/(m^3 a).

The approach to calculate the LCOE for a region as summarised in Equation 2.

$$LCOE_r = LCOE_{prim,r} + LCOC_r + LCOS_r + LCOT_r \quad (2)$$

Equation 2**:** Levelised cost of electricity for a region. Here, $LCOE_{prim,\ r}$ is the levelised cost of electricity for a primary generation source, $LCOC_r$ is the levelised cost of curtailment, $LCOS_r$ is the levelised cost for energy storage in the region and $LCOT_r$ is the levelised cost of transmission of electricity in the region *r*.

To project the SWRO CAPEX, a learning rate of 15%, presented in the maiden paper on learning curves [34] for SWRO CAPEX, was used. The research by Caldera and Breyer [34] demonstrates, that when the historic global cumulative online SWRO capacity doubled, the SWRO CAPEX decreased by 15%. In addition to the 15% learning rate, a cumulative annual growth rate (CAGR) of 35% was assumed to meet the global desalination demand by 2030.

2.2. Model and Input Data

The LUT energy system model used for the global study of the LCOW in [27], is utilised for the Iran specific study. The model determines the LCOW for regions with high or greater water stress in Iran, based on Equation 1. The energy system model allows determination of the optimal renewable energy mix required, at an hourly temporal resolution and a spatial resolution of $0.45^\circ \times 0.45^\circ$. The optimal renewable energy mix, based on the energy and desalination sector constraints defined in [28] and [31], allows for the least cost of electricity (LCOE). The objective of the target function is to minimise the total annual costs of the energy and desalination sectors and is described in Equation 2.

$$min \left(\begin{array}{l} \sum_{t=1}^{tech} (CAPEX_t \times crf_t + OPEXfix_t) \times instCap_t + OPEXvar_t \times E_{gen,t} \\ + rampCost_t \times totRamp_t + \sum_{dt=1}^{desal\ tech} (CAPEX_{dt} crf_{dt} + OPEXfix_{dt}) \\ \times instCap_{dt} + \sum_{dd=1}^{desal\ distance} (CAPEX_{dd} \times crf_{dd} + OPEXfix_{dd}) \times distance_{dd} \end{array} \right)$$

Equation 2: Target function. Here, *t* is tech and includes storage and transmission technologies, $CAPEX_t$ is capital expenditures for technology *t*, is capital recovery factor for technology *t*, $OPEXfix_t$ is fixed operational expenditures for technology *t*, $OPEXvar_t$ is variable operational expenditures for technology *t*, $instCap_t$ is installed capacity in the country for technology *t*, $Egen_t$ is annual electricity generation by technology *t*, $rampCost_t$ is cost of ramping of technology *t* and $totRamp_t$ is sum of power ramping values during the year for the technology *t*. *dt* represents the desalination components of SWRO plants and water storage. *dd* represents the horizontal and vertical water pumping distances.

As details of how the model works and the required input data are provided in [28] and [31], the following sections present an overview of the input data required specific to Iran:

1. Regions in Iran with high or extremely high water stress in the 2030 optimistic scenario are considered. The WRI Aqueduct Atlas estimates the water supply and water demand values for 15,006 global water catchments, thus not covering all catchments in a country [35]. For the study of Iran, the water stress data from WRI was compared with a detailed map of renewable water resources in Iran.
2. Figure 2 represents the average renewable water resource, based on 1990 – 2002 data, per capita for all basins in Iran [36]. The lower resolution data from WRI suggest high water stress for the northern and western parts of Iran by 2030 [35]. This contradicts the current high renewable water availability in these regions as shown in Figure 2. Due to the lack of high-resolution water stress data for Iran, it was decided to

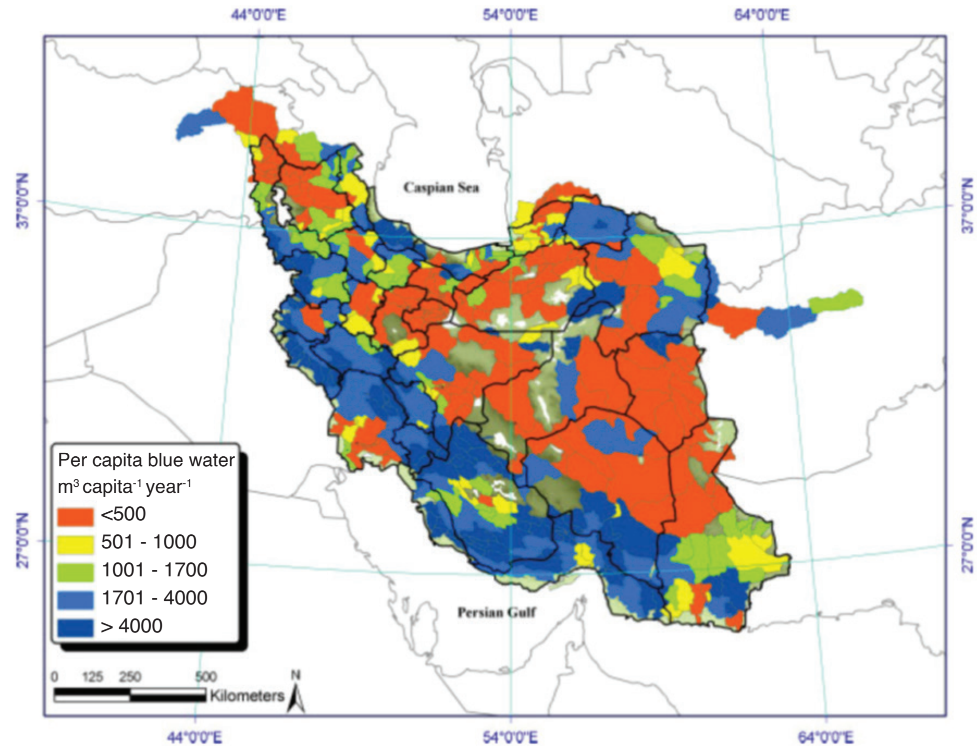

Figure 2: Renewable water resource availability per capita per year for Iran based on 1990 – 2002 water resource data. Water scarcity threshold is 1000 m3 per capita per year. Reproduced with permission from the original publisher [36]

reduce the future water stress in the northern and western parts of the country to low – medium water stress level. This ensures that desalination demand is not considered in the model for these regions. The water demand will increase in 2030. However, the water stress will not be high due to the high renewable water availability. In contrast, the water stress in the central and southern regions of the country deteriorate further, with a high desalination demand. The resulting map is presented in Figure 3. Despite being an optimistic scenario, there are large regions of the country where renewable water resources are scarce and fossil water is used.

3. The total water demand for regions in 2030 with high or extremely high water stress are also considered. To determine the total water demand, the change in water demand factor for 2030, provided by the WRI, were used. This factor estimates the increase in the water demand, from the currently reported water withdrawals, for nodes within the relevant water catchments by 2030. The total water demand for the country is the sum of the water demand across all the nodes in the country and estimated to be about 345 million m^3/day. In contrast, in 2005, the total water consumption of Iran was approximately 246 million m^3/day.
4. The desalination demand is calculated based on a logistic function of the total water demand and the water stress level. The resulting desalination demand or the required SWRO capacity per region is presented in Figure 4. The total required desalination capacity by 2030, to meet the water demands of agricultural, industrial and municipal sectors, is found to be 199 million m^3/day.
5. In this study, only the Gulf of Oman and the Persian Gulf are considered as sources of seawater to satiate Iran's desalination demand. The Caspian Sea is excluded due to environmental concerns with the use of saline lakes as feed water for large desalination capacities [37]. In addition, Mirchi and Madani [38] discuss the environmental disasters such as deforestation and biodiversity loss in the surrounding region as a result of transferring water from the Caspian

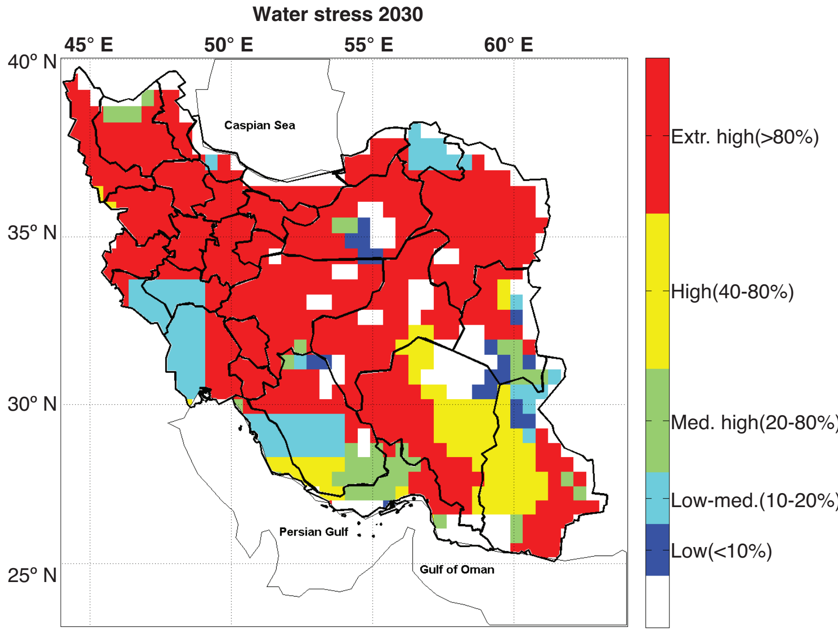

Figure 3: Projected water stress for the 2030 optimistic scenario in Iran. The water stress is the ratio of the total water demand in the region to the annual renewable water resources available in that region. The white regions represent those regions that are arid, have low water or have no available data. The water stress in the northern and western parts of the country were reduced as per Figure 2

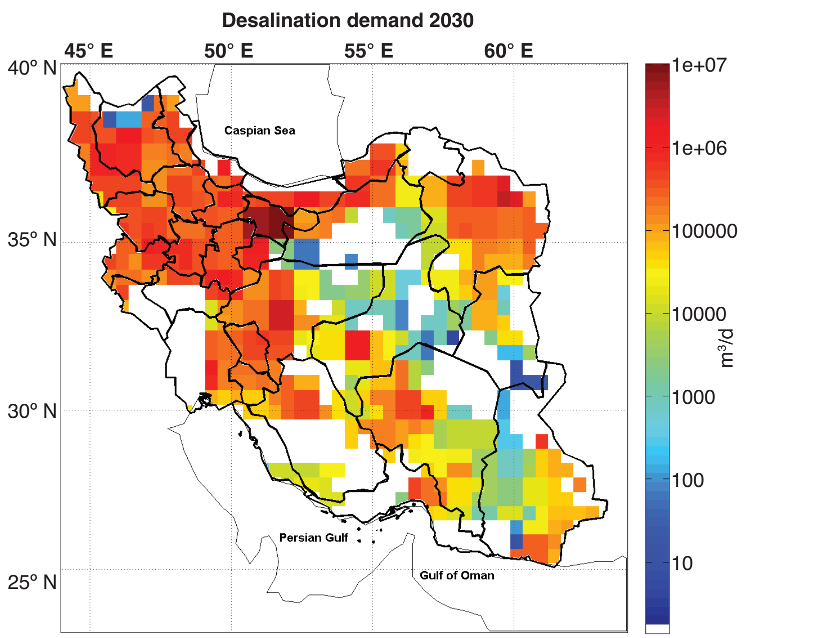

Figure 4: Desalination demand for the 2030 optimistic scenario in Iran. This includes the water demand of the agricultural, domestic and industrial sectors, excluding thermal power plants [39, 42, 46–48]

Sea. The 2030 total desalination demand of Iran is estimated to be about 247 million m^3/day. As mentioned earlier, the total water demand, and consequently the desalination water demand, for Iran excludes the water demand for the power sector. For the Iranian model, the fresh water consumption of thermal power plants was obtained from Spang et al. [39].

6. The SWRO desalination system, water transportation costs, energy consumption and hybrid renewable power plant component costs for 2030 are provided in Table 1. All detailed numbers can be found in [27]. The SWRO CAPEX for 2030 has been found based on the 15% learning rate [34] and a CAGR of 35%. This growth rate would enable to meet the global desalination demand of 2030. In addition, CAPEX of the PV power plant components have been updated as per recent literature and reports [40, 41].
7. The model optimizes the location of the SWRO desalination plants based on the distance between the desalination and demand node. In addition, the highest elevation on the optimal path is found using the ETOPO1 global relief model [42] and considered for the water transportation infrastructure. Future work on water pumping routes may consider the availability of existing infrastructure for water pumping such as electrical grids and roads.
8. Solar irradiation and wind energy data for Iran, for the year 2005 are used as a reference in hourly temporal and 0.45° x 0.45° spatial resolution. The global historical solar and wind data were obtained from NASA datasets [43, 44]

Table 1: Key assumptions for the SWRO desalination plant, water storage, water transportation and hybrid renewable energy components in the model for 2030 [27, 31, 34, 42, 46]. A WACC of 7% is considered. The HVDC transmission grid is assumed to have a power loss of 1.6% per 1000 km. Water storage of a minimum of 7 days at the demand site is assumed.

SWRO Desalination System		
Capacity	m^3/a	equal to desalination demand of 0.45°x0.45° spatially resolved region
CAPEX	€/(m^3·a)	1.90
$OPEX_{fixed}$	€/(m^3·a)	4% of CAPEX
Full load hours	hrs	system optimum
Energy consumption	kWh/m^3	Calculated for desalination site. Approximate range is 2.80 – 3.30, depending on salinity of feed water
Water Storage		
CAPEX	€/m^3	65
Water Transportation		
Pipes CAPEX	€/(m^3·a·km)	0.053
Horizontal pump CAPEX	€/(m^3·hr·km)	19.23
Horizontal pump energy consumption	kWh/(m^3·hr·100km)	0.04
Vertical pump CAPEX	€/(m^3·hr·m)	15.40
Vertical pump energy consumption	kWh/(m^3·hr·100m)	0.36
Hybrid Renewable Energy Power Plant CAPEX		
PV fixed-tilted plant	€/kW	390
PV single-axis tracking plant	€/kW	429
Wind plant	€/kW	1000
Batteries	€/kWh	150
PtG	€/kW	Water electrolysis : 380 CO_2 Direct Air Capture : 356 Methanation : 234
Gas storage	€/kWh	0.05

in a 1° x 1° spatial resolution and temporal resolution of 3 h for a 22 year period. The data was reprocessed by the German Aerospace center to a 0.45° x 0.45° spatial resolution [45].

Based on the above parameters, the model compares the use of different hybrid renewable energy power plant combinations. The least cost system that meets the 2030 desalination demand of Iran is considered to be the optimal system.

3. Results: An Optimal System Design for Iran

The model was used to analyse four different combinations of hybrid renewable energy plants to power the 2030 SWRO desalination capacity for Iran:

1. PV fixed-tilted, Wind, Batteries
2. PV fixed-tilted, Wind, Batteries, PtG
3. PV single-axis tracking, PV fixed-tilted, Wind, Batteries
4. PV single-axis tracking, PV fixed-tilted, Wind, Batteries, PtG

It was found that a combination of PV, Wind, Batteries and PtG power plants offers the least cost solution for Iran. The figures that follow present and discuss the optimal energy and SWRO desalination system for Iran.

Figure 5 (a) illustrates the PV fixed-tilted and single-axis tracking capacities required per region. A region is defined as an area of 50 km x 50 km (exactly 0.45° x 0.45° in units of latitude and longitude). A total of approximately 201 GW of PV fixed-tilted and 360 GW of PV single-axis tracking power plants are required. Figure 5 (b) shows that there is a higher contribution from PV to the hybrid PV-Wind power plants in most regions. On average 82% of the energy generated by the hybrid PV-Wind power plants is provided by PV power plants. Figure 5 (c) shows the total full load hours (FLH) provided by the hybrid PV-Wind power plants. Higher FLH allow for optimal utilisation of the desalination capacity and therefore lower LCOW. However, to allow for the optimal FLH of the SWRO desalination plants, batteries and PtG power plants

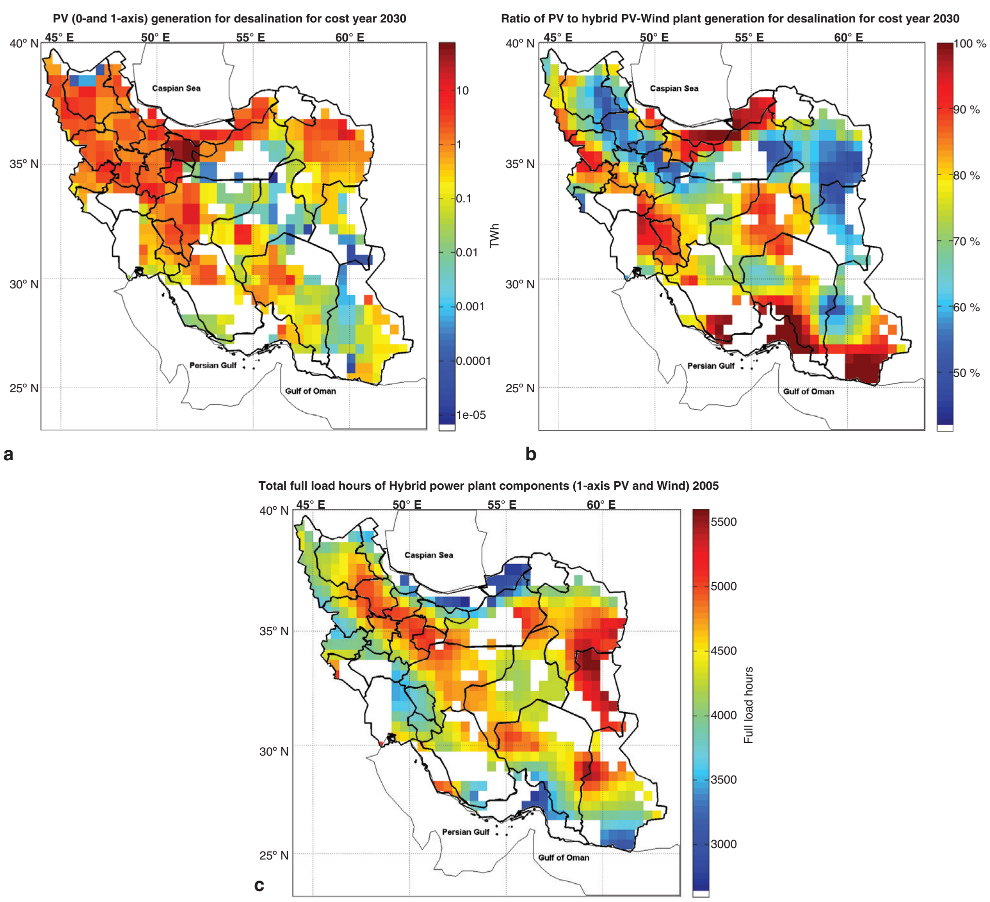

Figure 5: (a) Installed PV capacities required Installed PV capacities required for the 2030 SWRO capacity (b) Contribution of PV to the installed capacities of the hybrid PV-Wind Power Plant (c) Total full load hours provided by the hybrid power plant

have to be used. The required battery, PtG and water storage capacities at the demand site are presented in Figure 6.

The required battery capacity is almost 360 TWh and provides up to 22% of the total energy demand. The batteries have to be charged almost daily with up to 315 cycles per year in some regions. The total electrolyser capacity required for Iran is 91 GW_{el}. The storage capacity required for the produced synthetic natural gas (SNG) is 103 TWh_{th}. The PtG plants provide up to 15% of the total energy demand and decreases the excess energy of the system by 75%. As a result, the total required PV capacity is reduced by 20%, wind capacity is increased by 17% due to a good match with the PtG requirements, battery storage capacity is reduced by 23% and total water storage capacity is decreased by 51%.

Figure 6 (c) presents the ratio of the excess energy to the total energy generated by the system. In most regions, this value is between 5% and 7%.

The resulting LCOE of the complete energy system, taking into account losses in the transmission lines, and the final LCOW for the regions with desalination demand is presented in Figure 7. Figure 7 (a) shows that the 2030 LCOE range for the complete system in Iran is approximately 0.06 €/kWh – 0.11 €/kWh, including electricity generation, power transmission, storage and curtailment. Higher LCOE values are prevalent in the northern regions of Iran. This is attributed to the increased battery and PtG storage requirements in these regions. The resulting LCOW, presented in Figure 7 (b), is of the range 1.0 €/m^3 – 3.0 €/m^3, most prevalent being the 1 €/m^3 – 2.5 €/m^3 range. In comparison, the global LCOW range is mostly between 0.70 €/m^3 and 2.00 €/m^3 [27].

The higher LCOW than the global average can be attributed to the large water pumping distances, both vertical and horizontal, necessary in Iran. As illustrated in Figure 7 (b) the LCOW increases further away from the coast line due to the longer distance and larger elevation. Figure 8 (a) presents the contribution of the energy used for water pumping to the LCOW, which is

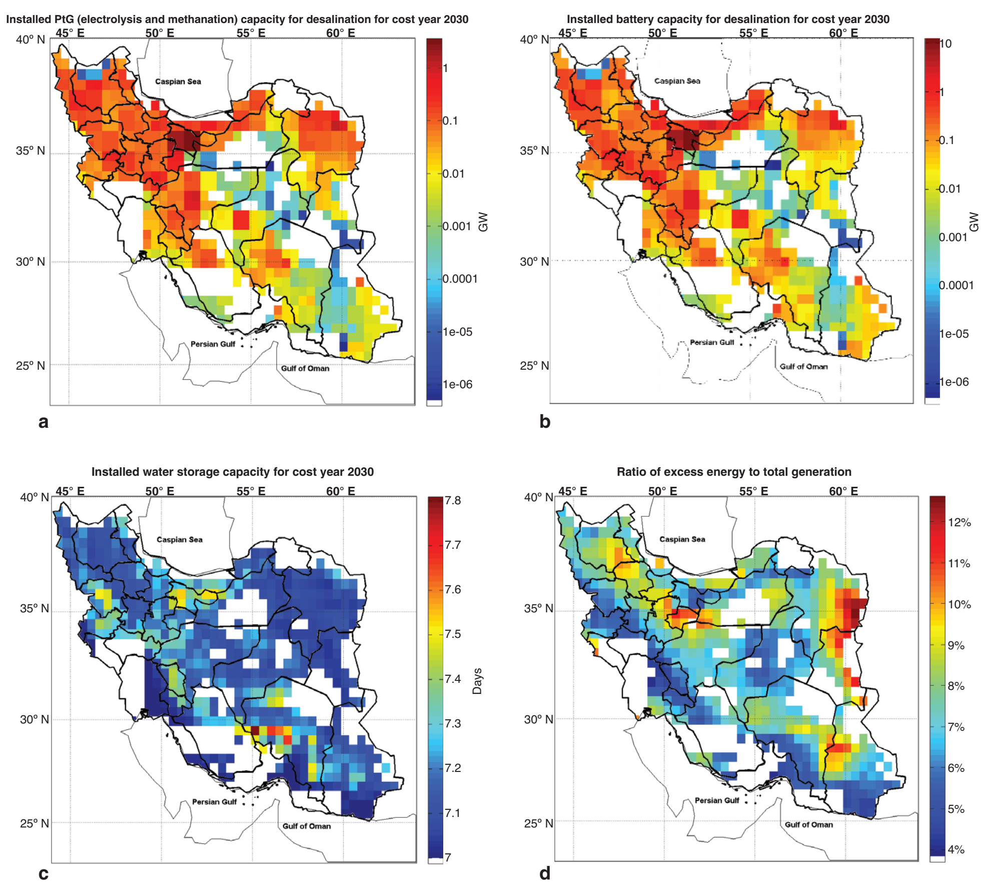

Figure 6: (a) Installed battery capacity required for the 2030 SWRO capacity (b) Installed PtG capacity required for the 2030 SWRO capacity (c) Optimal water storage capacity required for regions with desalination demand in 2030 (d) Ratio of excess energy to total energy generation of the system in 2030

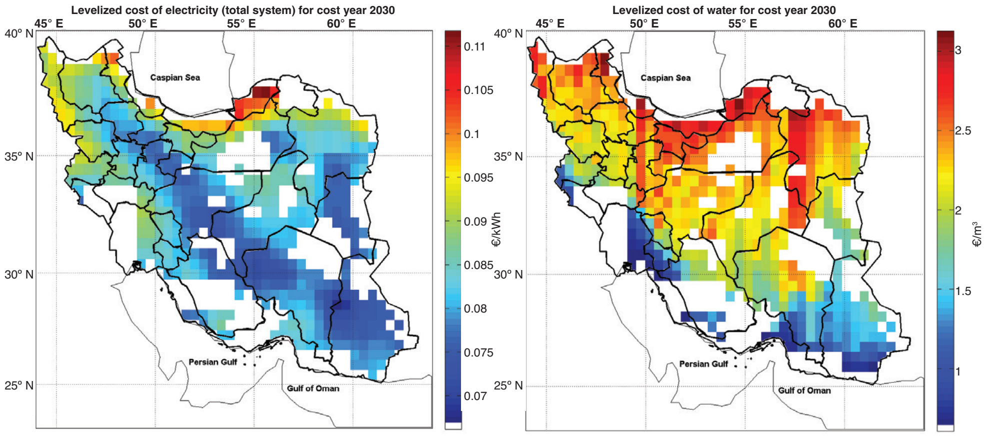

Figure 7: (a) LCOE range for a complete system in Iran for the year 2030 (b) LCOW range for a complete system in Iran for the year 2030

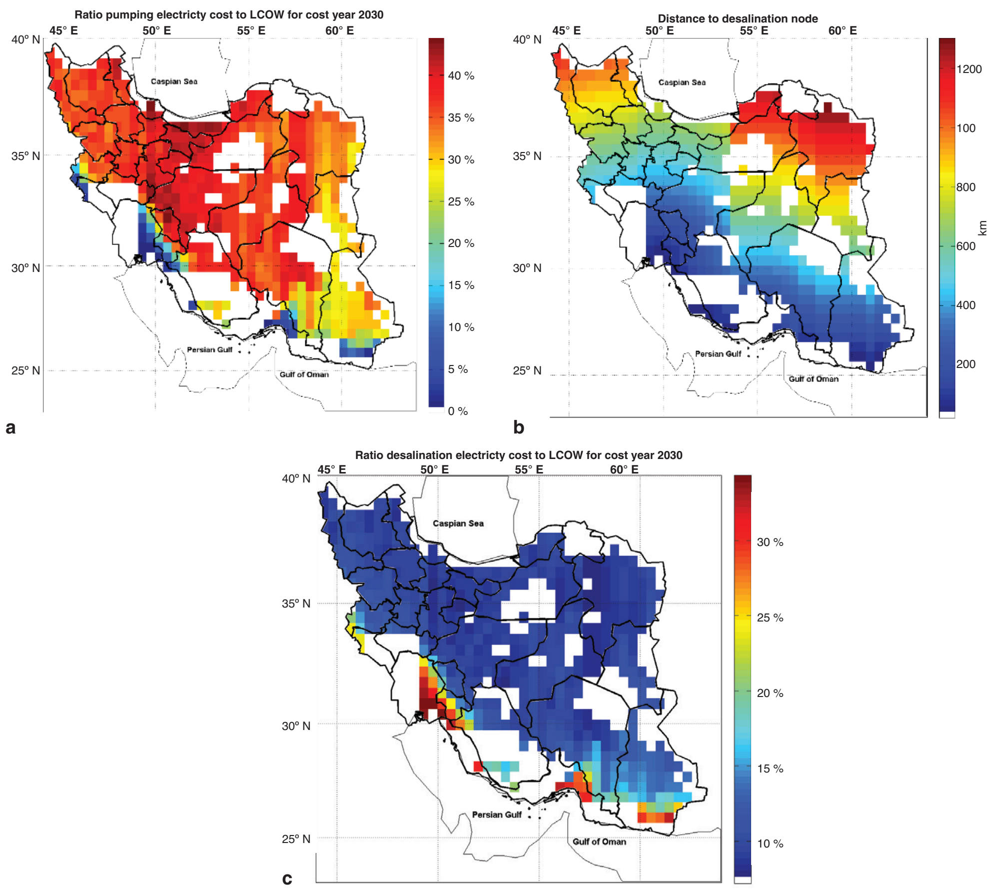

Figure 8: (a) Contribution of the pumping electricity cost to the LCOW in Iran for the year 2030 (b) Distance from desalinated water demand regions to the desalination node (c) Contribution of desalination electricity cost to the LCOW in Iran for the year 2030

approximately 38% in Iran. In contrast, the global average is 16% [24]. Figure 8 (b) presents the optimal distance, determined by the model, between the desalination demand region and the desalination node. It can be observed that as the distance from the desalination nodes increases, the contribution of the pumping electricity costs increases. There are some regions in the eastern part of Iran that have larger distances from the desalination node than in the west, but the contribution of pumping electricity cost is lower. This may be due to the fact that the north eastern regions of the country have a lower elevation than the north western region. Thus, the resulting electricity required for vertical pumping, and ultimately the total electricity required for pumping, is lower in the north eastern regions than in the north western regions. Figure 8 (bottom) shows the contribution of the electricity for SWRO desalination to the final LCOW. On average the contribution is approximately 10% towards the LCOW. For desalination demand nodes along the coast line, the electricity demand for pumping is low. Thus, the contribution of electricity for the desalination plants to the final LCOW is higher in the nodes along the coast line.

The CAPEX of the total system contributes on average 64% to the final LCOW of the system. The total system CAPEX refers to the sum of the CAPEX of the PV, Wind, Battery, PtG, power lines, water storage, desalination plants and the piping system.

Figure 9 (a) presents the contribution of the CAPEX towards the LCOW.

Figure 9 (b) represents the spread of the capital costs of the 2030 system for Iran. The largest contribution is from the vertical transportation infrastructure, 25%, followed by the single-axis tracking PV plants with a

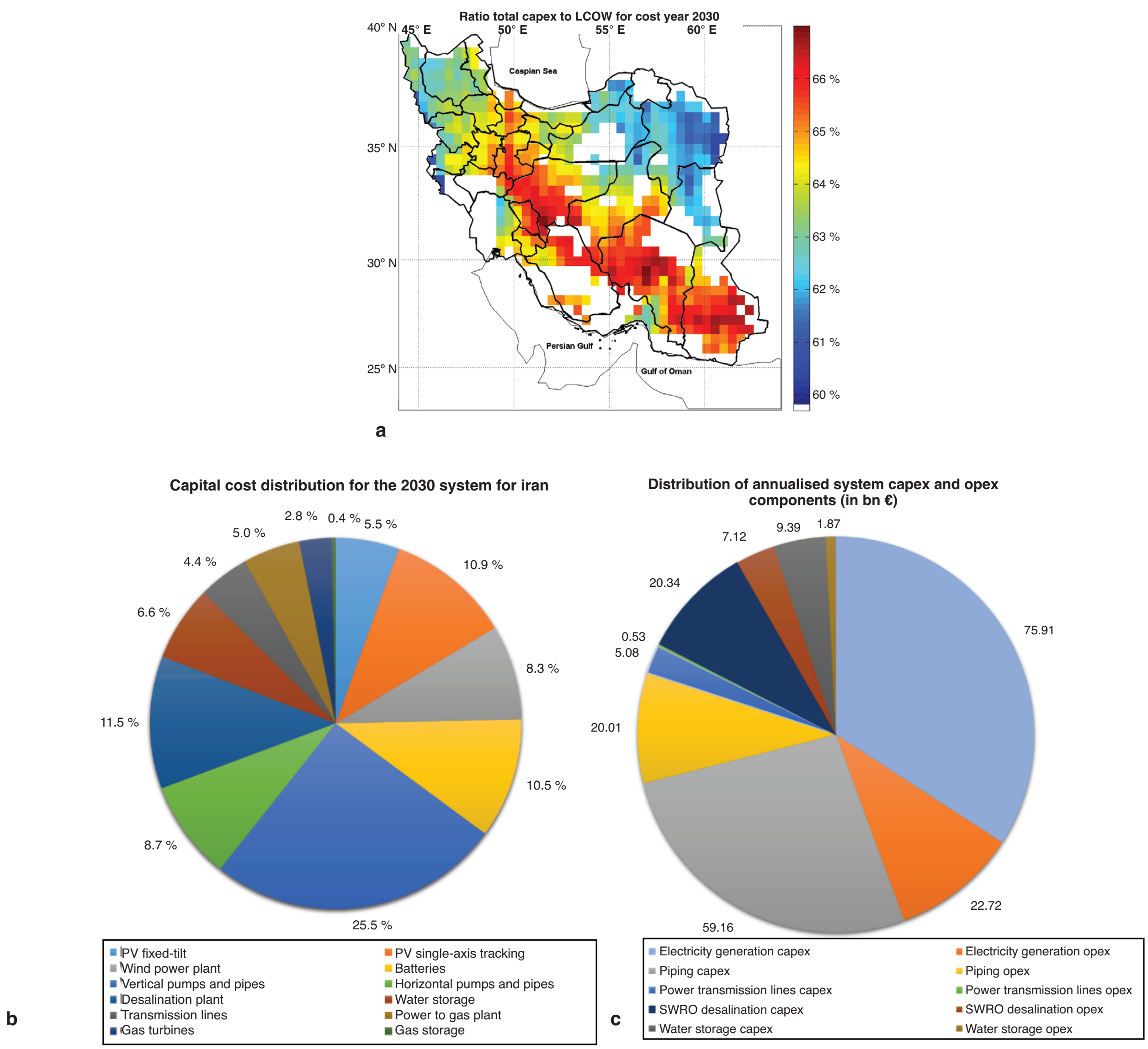

Figure 9: Contribution of the CAPEX to the final LCOW (b) Distribution of the 2030 system capital cost (c) Distribution of annualised system CAPEX and OPEX components (in b) of the proposed 2030 system for Iran

cost contribution of 11%. The desalination plants is the fourth largest contributor with 10% of the total costs. Batteries contribute a slightly higher percentage with 12% of the total costs. The higher contribution of the single-axis tracking PV and batteries can be attributed to the energy requirements for water transportation.

Figure 9 (c) presents the distribution of the annualised CAPEX and OPEX for all the system components. The annualised CAPEX cost for the solution for Iran by 2030 is estimated to be approximately 170 b€ and OPEX cost of 52 b€. The hybrid PV-Wind power plants, together with the batteries and PtG, account for the largest annualised CAPEX of 75 b€. This is followed by the water transportation infrastructure and the desalination plants, with annualised CAPEX of 59 b€ and 20 b€, respectively.

4. Discussion

The LCOW range for Iran when SWRO desalination plants, in 2030, are powered by hybrid PV-Wind-Battery-PtG plants is found to be between 1.0 €/m^3 and 3.0 €/m^3. The prevalent LCOW range is between 1.0 €/m^3 and 2.5 €/m^3. The corresponding LCOE range for Iran is 0.06 €/kWh and 0.11 €/kWh, mostly prevalent between 0.06 €/kWh and 0.09 €/kWh.

GWI [11] provides water production costs for fossil powered SWRO desalination plants, located in southern province of Hormozgan. The water production cost alone is approximately 0.70 €/m^3. In Figure 7 (b), the LCOW, including the water transportation and storage costs, for this region is approximately 1.0 €/m^3-1.50 €/m^3. The higher LCOW range of the model can be attributed to the high water transportation costs and energy required for water pumping, as shown in Figure 8 (a). The cost provided by DesalData only reflects the water production cost at the desalination plant.

The results show that it is possible to meet the increasing water demand of Iran with SWRO desalination plants, located solely along the southern coast line, powered by hybrid renewable energy power plants. In the near future the production cost of clean water from the hybrid system will be competitive with the cost of fossil powered SWRO plants today. As mentioned in Caldera et al. [27] this will be driven by the increase in global desalination demand and the continued decrease in solar PV and storage costs due to learning curve effects. However, the final LCOW may be high due to the requirements of the transportation infrastructure.

Table 2: Summary of the key technical and cost data for the 2030 optimal system design for Iran

		2030 optimal system for Iran
SWRO total desalination demand per day	**m^3/day**	**199 mill**
PV capacity installed	GWp	561
PV fixed-tilted	GWp	201
PV single-axis tracking	GWp	360
Wind capacity installed	GW	117
Battery capacity installed	TWh	360
PtG electrolyser capacity installed	GW_{el}	91
Average excess energy curtailed	%	7
Total CAPEX	b€	1420
Annualised costs	b€	222
LCOW range	€/m^3	1.0 – 3.0
Prevalent LCOW range	€/m^3	1.0 – 2.5

Table 2 summarises the key technical and financial aspects of the system proposed for Iran for 2030. The costs are for a WACC of 7%.

Water management and increase in water efficiency in different sectors are paramount to enabling Iran overcome the water crisis. However, for regions where there is high water demand but inadequate surface or groundwater available, transport of desalinated water, powered through renewable energy, from the Persian Gulf and Gulf of Oman is the next best alternative. Marjanizadeh et al. [49] evaluates the impacts of different policies and trends on the Karkheh river basin. It was found that in a scenario where agricultural, livelihood and environmental demands were addressed, wheat self-sufficiency of the country could not be satisfied. In such scenarios, seawater desalination can supplement the sustainable use of renewable water resources. Gohari et al. [50] evaluates the impact of inter-basin water transfer as a solution to the water scarcity. The study was done for the Zayandeh-Rud River Basin, one of the most important and water stressed river basins in Central Iran. The results showed that water transfer solutions are inadequate and provide misconceptions of water availability in a river basin. Gohari et al. [50] stressed the need for improvement of irrigation efficiency, cultivation of water-efficient crops and water demand management to overcome future water scarcity issues. As illustrated in this research, renewable energy powered seawater desalination can aid to relieve the water stress in this river basin. The potential for desalination to aid in alleviating water scarcity, in conjunction with other water management tools and policies, has also been discussed by Zetland [51].

Despite the role that renewable energy based desalination can play in meeting Iran's water demand, the negative environmental impacts of the discharged brine from the desalination plants have to be considered. The recent paper by Jones et al. [52] highlights the fact that the Gulf countries, such as UAE, Qatar and Kuwait, account for more than half of the world's brine discharge. Therefore, the rise of the desalination sector in Iran will contribute to the brine discharged, further threatening the ecology of the Gulf. Countries such as USA and Australia have adopted strategies like mixing brine with alternative water sources (treated waste water or water used for power plants) before discharge and the use of pressurized nozzles to spray the brine to prevent the brine settling [34]. Jones et al. [52] also discuss these concepts and the idea of harvesting scarce metals such as lithium from the brine. While the latter concept is only in its infancy, the ability to obtain precious metals from desalination brine at reasonable costs would create new economic opportunities.

Meanwhile various researchers have already analyzed the glaring potential for Iran to adopt renewable energy technologies and set up an effective energy strategy for the country. Saleki [53] investigated the potential for solar PV and wind power integration in Tehran to power the city's residential and commercial sectors. The results indicate that solar PV currently offers the most lucrative solution for small-scale projects. Aghahosseini et al. [28] have analysed a 100% renewable energy system for the power, desalination and industrial synthetic natural gas (SNG) production in Iran by the year 2030. The integrated scenario accounts for the power sector electricity demand as well as that of SWRO desalination and industrial SNG production in Iran. It is concluded that the additional flexibility offered by the desalination system and the industrial gas demand sector reduces the specific energy system LCOE. Further expanding on this research, Ghorbani et al. [29, 30] present a least-cost energy transition pathway for Iran, from the current fossil-based power system to a 100% renewable energy based system by 2050. The work takes into account the existing fossil based power plants in Iran and discontinues the plants based on the lifetimes. The 2050 levelised cost of electricity and the levelised cost of water respectively is about 41 €/MWh and 0.77 €/m^3. The combination of solar PV and battery storage provides the most lucrative solution to meet Iran's electricity demands. Thus, this research presents a blueprint for Iran's energy transition.

5. Conclusions

An energy model was used to estimate the viability of meeting the 2030 Iranian water demand, based on the optimistic scenario, with SWRO plants powered by renewable energy. Hybrid renewable energy power plants offer higher full load hours and therefore allow for better utilization of the desalination plant capacity. The 2030 costs for SWRO desalination and different renewable energy technologies were used.

The total desalination demand of Iran by 2030 is estimated to be 199 million m^3/day. The least cost system is found to be a combination of PV fixed-tilted, PV single-axis tracking, wind energy, battery and PtG power plants. The LCOW range is predominantly between 1.0 €/m^3 and 2.50 €/m^3. The current LCOW of fossil powered SWRO plants, excluding water transportation, in Iran is around 0.70 €/m^3, compared to about 1.0 €/m^3 based on 100% renewable energy along the coastlines and including transportation cost. The vertical transport infrastructure has the highest contribution to the final LCOW.

The work shows that in the near future, SWRO plants powered by renewable energy will produce water at similar prices to that of today's fossil powered plants in Iran. Depending on the terrain, the water transportation costs can contribute significantly to the final LCOW.

However, there are gaps in the research data, specific for Iran. These can be summarised as below:

1. Lacking updated water transportation costs, specifically for Iran accounting for factors like the local soil condition and infrastructure availability (like roads and electrical grid).
2. Modelling desalination demand needs of Iran after water management strategies are implemented. This is in particular for the agricultural sector of Iran that currently accounts for 90% of the country's water demand. Future water demand should also consider the complete removal of fossil fuel powered thermal power plants. These strategies further reduce the desalination demand of the country. By filling in the data gaps, a more accurate model of the future Iranian water scenario and water production costs can be built. This will enable a better understanding of the potential role for SWRO desalination and renewable energy systems in meeting the water supply challenges of Iran in the decades to come.

Acknowledgements:

The LUT authors gratefully acknowledge the scholarship offered by the Reiner Lemoine Foundation, public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14. We also thank Michael Child for proofreading and Narges Ghorbani for suggestion of articles relevant to the water crisis in Iran. The authors acknowledge that all data used in this study is available in the references cited.

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