Assessing the potential for renewable energy powered desalination for the global irrigation sector

Caldera Upeksha, Breyer Christian

DOI: 10.1016/j.scitotenv.2019.133598

Assessing the potential for renewable energy powered desalination for the global irrigation sector

Upeksha Caldera[1] and Christian Breyer[1]

[1] LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland

E-mail: upeksha.caldera@lut.fi, christian.breyer@lut.fi

Abstract

By 2050, it is estimated that the annual cereal production would need to increase by about 140% and total global food production increase by 70%. Meanwhile, total water withdrawals for irrigation is projected to increase by 11%. In contrast, poor management of existing water resources, pollution and climate change has resulted in limited freshwater resources. The aim of this paper is to assess how improved irrigation efficiency and renewable energy based desalination maybe used to secure future water supplies for the growth of rice, wheat and maize.

The efficiencies of the existing irrigation sites were obtained and improved based on a logistic curve. The growth was projected such that by 2050, all existing irrigation sites would have an efficiency of 90%. The new irrigation efficiencies were used to obtain the reduced irrigation demand for the years 2030 and 2050. The desalination demand was estimated and an energy system model used to optimise the corresponding renewable energy based power system.

It was found that improving the average irrigation efficiency to 60% by 2030, led to a 64% reduction in total desalination demand. Similarly, an improvement towards 90% irrigation efficiency, by 2050, translates to an 80% reduction in global desalination demand. In 2030, the total water cost is mostly within 0.7 €/m^3 – 2 €/m^3 including water transportation costs. Literature reports that farmers may be willing to pay up to 0.63 €/m^3 for their irrigation water. The global range in 2050 is estimated to be 0.45 €/m^3 – 1.7 €/m^3 reflecting the lower system costs in 2050.

The above results indicate that as conventional water prices increase, renewable energy based seawater reverse osmosis desalination, offers a cost effective water supply for the irrigation sector. Adoption of high efficiency irrigation systems alleviate water stress and can eliminate need for additional water supply.

Keywords

irrigation efficiency, water stress, seawater reverse osmosis, solar photovoltaics, wind power plants

1 Introduction

The conundrum of how to provide food security, at affordable prices, for an increasing global population, on a planet with finite resources, has been addressed by various researchers and organisations [1,2,3]. The recent IPCC SR1.5 report [1] explains that with the inevitable

temperature rise of 1.5°C above pre-industrial levels, extreme weather events will become common, threatening water and land availability for food production. Failing to achieve net zero emissions by 2050 and thereby overshooting the 1.5°C limit, will result in even more dire consequences. Therefore, it is crucial to secure land and water resources required for global food production [1,2,3].

Irrigated agriculture accounts for 70% of the total global water withdrawals and meets 45% of the global food demand [2]. Steduto et al. [2] explain the crucial role that irrigation and water management has played in the last 50 years to enable countries to grow food crops in drier conditions and improve livelihoods. By 2050, the Food and Agricultural Organisation of United Nations (FAO) predicts that annual cereal production should increase by about 140% and total global food production increase by 70% [4]. Total water withdrawals for irrigation are projected to increase by 11% [2]. The challenge is meeting the water demand, in the face of depleting freshwater resources, climate change and increasing demand from the municipal and industrial sectors [2]. It is reported that in the 20th century the global water demand has been growing more than twice the rate of the population growth [2].

Seawater desalination offers a climate-independent alternative to global freshwater resources and is projected to play a crucial role in future water supplies [5]. The seawater reverse osmosis (SWRO) technology accounts for 30% of the installed global desalination capacities and is projected to retain most of the market share. Literature explains that the increase in SWRO desalination capacities globally is due to improved technologies, decreasing capital costs, energy consumption and increasing water scarcity [5,6,7]. However, according to Jones et al. [5], 62% of the desalinated water is used for the municipal sector, 30% is used for the industrial sector, and only 1.8% is used for irrigation. Burn et al. [8] notes that, despite the advancements made, seawater desalination for irrigation is still expensive compared to traditional freshwater sources. However, due to the reducing costs of desalination, potable water is considered

economically feasible for cash crops such as vegetables, flowers and fruits. In addition, Burn et al. [8] summarises the benefits of the use of desalinated water that include reliable supply, consistent quality and recovery of saline soils. Countries that currently use desalination for irrigation are Spain, Canary Islands and Israel [8,9]. The implementation of desalination for irrigation is also being considered by Chile, China and Australia [8].

Burn et al. [8] report that farmers in Australia are willing to pay up to 0.68 €/m^3 (1 AUD/m^3 at 1.48 AUD/€ exchange rate) for their irrigation water. According to data collected by the FAO [10], the price paid for irrigated water, based on volume, can be as little as 15.3 €/1000 m^3 (20 USD/1000 m^3 at 1.3 USD/€ exchange rate) or as high as 1243/1000 m^3 (1330 USD/1000 m^3 at 1.07 USD/€ exchange rate). The article also notes that in most countries the full cost of water pumping is never recovered. OECD countries, such as Japan, parts of Australia, France, Spain and the Netherlands, are the few exceptions where 100% of the operation and maintenance costs are retrieved. Fischer et al. [11] show that, due to climate change and increased agricultural withdrawals, the subsidised costs for irrigation water will increase, at a minimum, by 23.8 €/m^3 (30 USD/m^3) to 39.6 €/m^3 (50 USD/m^3). Fischer et al. [11] note that due to increased competition for water, energy and decreasing subsidies, the future increase in water and energy costs will be much higher than what their research estimates. As freshwater resources become more scarce, the true cost of using water increases. Takatuska et al. [12] show how the increased use of ground or surface water in South Florida for irrigation will increase the economic losses. A recent study by Qiu et al. [13] analyses the economic and environmental impacts of decreasing groundwater levels in the North China Plain (NCP) – one of China's most important agricultural regions. It was found that energy consumption for pumping water has doubled in seven years, rendering irrigation not viable for the farmer. In addition, the total economic cost for energy consumption and corresponding emission reduction is estimated to cost 10.3% of the local GDP. Therefore, the increasing dependence

on diminishing groundwater poses a major threat to China's agricultural development. Qiu et al. [13] suggest to substantially reduce the water withdrawn by using more efficient irrigation technologies, such as pressurized systems which can reduce water consumption by 10% - 66%. In addition, the authors propose the use of solar pumps to overcome the fuel costs and greenhouse gas emissions produced by conventional electrical or diesel pumps. Nevertheless, this would still lead to declining groundwater levels, although at reduced rates compared to the present situation. The increments in irrigation efficiency are supported by the United Nations' Sustainable Development Goal 6.4, which targets a substantial increase in water use efficiency across all sectors by 2030 [14].

The conducted literature review highlights the trends of increasing water costs and movement towards improved irrigation to limit the rise in global water demand and costs [14]. Jägermeyr et al. [15] describe the generic concept of irrigation efficiency as the ratio of the water consumed through transpiration, evaporation and interception to the total water withdrawn from the water source. Therefore, irrigation efficiency may imply several definitions in different sources. Beneficial irrigation efficiency is a concept introduced by Jägermeyr et al. This measure of irrigation efficiency is the ratio of the water transpired to the total water withdrawn from the source. Thus, beneficial irrigation efficiency is a precise indicator, but does not account for lost water that may be reused from the basin. The global area weighted beneficial irrigation efficiency, based on the current distribution of different irrigation systems and crops grown, is estimated to be 33%. Jägermeyr et al. [15] conducted a study on the global water saving potential of improved irrigation systems and noted that water withdrawals can be reduced by up to 68%. It is suggested that changing from the extensive surface irrigation systems to pressurized irrigation systems, namely sprinkler and drip technology, will result in higher irrigation efficiency and increased water savings. The efficiency of surface irrigation systems can lie between 30 – 60%, while that of sprinkler and drip is between 50 – 70% and

70 – 90% respectively. Drip irrigation is considered the most efficient and cost effective, particularly in water stressed areas. Fyles et al. [16] report that 86% of the global irrigated area has adopted surface irrigation systems, while 11% and 3% of the total area use sprinkler and drip irrigation systems respectively. High shares of surface irrigation are mainly found in Central, South and Southeast Asia due to widespread rice cultivation with low efficiency [15].

Qiu et al. [14] posit that even with improved irrigation efficiency, there are still declining groundwater levels and increasing water demand from other sectors [2]. Multsch et al. [17] share similar views regarding the availability of water in the Nile Basin. The widening gap between water supply and demand and declining costs present a new role for seawater desalination in the irrigation sector. Vanham et al. [14] explain that the exclusion of desalination from the definition of the SDG target 6.4 is a drawback and should be accounted for to realistically assess water scarcity. Vanham et al. also note the increasing energy consumption of desalination plants. Conventional desalination plants are heavily dependent on diminishing and costly fossil fuels, while also resulting in greenhouse gas emissions [6]. Prior work done by the authors of this manuscript has shown how renewable energy based SWRO desalination can produce potable water at costs comparable with that of current fossil powered SWRO desalination plants [18]. This renders SWRO desalination an attractive water supply source for regions with high water scarcity and increasing demand, while overcoming concerns about greenhouse gas emissions. Furthermore, the rapidly dropping costs of renewable energy power plants portends a reduction in electricity costs, which translate to a corresponding reduction in water production costs. Ghaffour et al. [6] illustrate the decline in desalinated water costs and the increase in the cost of the use of conventional freshwater resources.

The purpose of this work is to link and establish solutions to meet the increasing water withdrawals for irrigation via improved irrigation efficiency technologies and use of renewable energy (RE) based SWRO plants. The objectives of this study are to: (1) determine the impact of substantial increases in irrigation efficiency on the future water demand; (2) project the

SWRO capacities required to supplement the water demand for irrigation sites after improved irrigation efficiency; (3) model the energy system required to power the global SWRO capacities required as supplemental water supply for current irrigation sites; (4) project water production costs with the proposed system. The objectives are analysed for the years 2030 and 2050 to understand the potential for RE-based SWRO desalination in the irrigation sector over time.

2 Methods

The approach utilised for this research can be summarised in the following points:

1. Determine the irrigation efficiency of existing irrigation sites and project efficiency up to 2050.
2. Estimate water withdrawals for irrigation before and after improved irrigation efficiency. Use irrigation site-specific water stress and demand values to project the desalination capacity necessary to augment existing renewable water supplies. The desalination demand for irrigation is projected for the years 2030 and 2050.
3. After establishing the global desalination demand for irrigation sites, the energy system required for the SWRO desalination capacities is modelled and the cost of water production for the irrigation sites projected for the two time periods.

The following sub-sections describe the approach, data input and the model used in detail.

2.1 Global irrigation efficiency

Jägermeyr et al. [15] model the beneficial irrigation efficiency for different crops on a gridded scale of 0.5°x0.5°. The efficiency is dependent on the irrigation technology (surface, sprinkler or drip) in use and the crops being planted.

For this research, the beneficial irrigation efficiency values of irrigation sites growing the major cereals wheat, maize and rice [19] are obtained from Jägermeyr et al. It is assumed that rice is grown with surface irrigation systems while wheat and maize are grown with sprinkler irrigation systems [19]. If a node has both wheat and maize irrigation, it is assumed that the sprinkler area is equally utilised by both wheat and maize. The available data is in a 0.5° x 0.5° spatial resolution, whereas our research is conducted on a spatial resolution of 0.45° x 0.45°. Therefore, based on the latitude and longitude values of the 0.5° x 0.5° grid, the irrigation efficiency values were redistributed to the required 0.45° x 0.45° grid structure. When the latitude and longitude values in the two grid structures did not match, the irrigation efficiency in the nearest 0.5° x 0.5° node was taken. Nodes that had a spatial difference greater than 0.5°, in both latitude and longitude, were not considered.

Figure 1 presents the area weighted average of the beneficial irrigation efficiency for the crops rice, wheat and maize. The prominent irrigation efficiency range is low and between 20% - 40%.

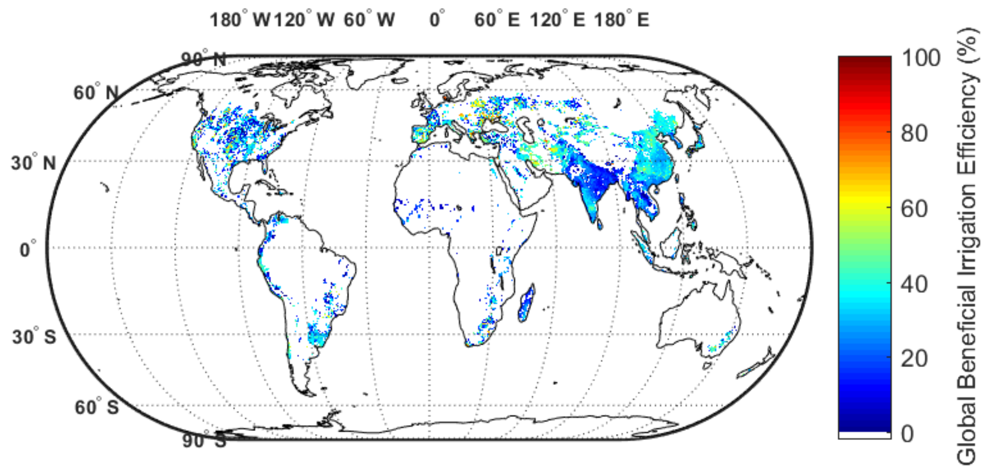


Figure 1 Global beneficial irrigation efficiency for irrigation sites growing rice, wheat and maize [19]

To understand the historical and projected growth in irrigation efficiency for existing irrigation sites, a literature review was done. Hanasaki et al. [20] collected literature on irrigation efficiency development and suggested the highest growth rate to be 0.3% per year, relative to the respective basis. This helps to explain the currently low irrigation efficiencies found in many regions. Wada et al. [21] estimate that a linear 1% increase in irrigation efficiency per annum will reduce the water stressed global population by 2% in 2050, compared to a business as usual scenario. For this research, a logistic curve is used to derive a possible development scenario of irrigation efficiency up to 2050, as show in Figure 2. The scenario is labelled the highest possible irrigation efficiency (HPIE) scenario. Reflecting the use of drip irrigation technology today and the corresponding high efficiencies available, it is assumed that by 2050 all sites will be able to achieve an irrigation efficiency of 90% [19]. The efficiency may be higher in some places depending on the implementation and use, but a more conservative value was adopted to be applied globally. Companies like Netafim [22] show that highly efficient irrigation systems can already be used to grow thirsty crops such as rice and wheat. The compound annual growth rate of the drip irrigation market is estimated to be 15.6%, with marked growth in countries like India and China [23]. India is reported to have started using drip irrigation systems for rice production, on a small scale [24]. Furthermore, Steduto et al.

[2] note that there is an urgent need to transition to highly efficient irrigation systems, and the withholding factor is political will and funding.

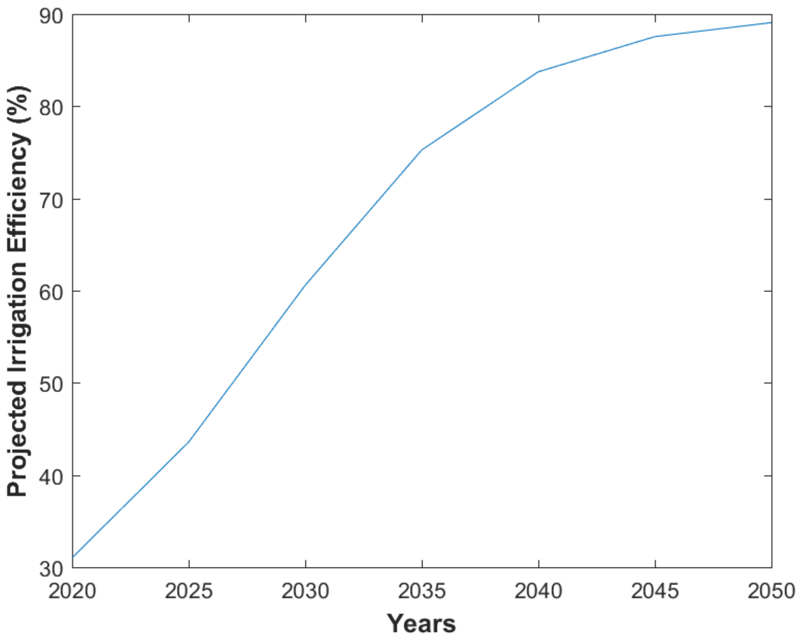


Figure 2 Projected irrigation efficiency up to 2050 for the HPIE scenario

The logistic growth of the irrigation efficiency was based on the approach of Breyer et al. [25] for the development of renewable energy electricity production globally. Equation 1 defines the logistic function used for this research.

$$irrigEffHPIE_{(year)} = A + \frac{K-A}{(1+Qe^{-B\times(t-M)})^{\frac{1}{v}}}$$

Equation 1 where *A* is the maximum value of efficiency (90%), *K* is the minimum value of efficiency (20%), *B* is the growth rate (20%), *t* is the time in years, *v* is the factor affecting near which asymptote the maximum growth occurs (14), *Q* is the scaling parameter depending on f(0) (75) and *M* is time of maximum growth (2020).

2.1.1 Global water withdrawals for irrigation and corresponding desalination demand

Caldera et al. [18] estimate the desalination demand for regions based on the water stress and demand values obtained from the Aqueduct Water Risk Atlas [26]. The Aqueduct Water Risk Atlas projects the decadal water stress, supply and demand values for 15,006 global water catchments. General circulation models and socioeconomic variables drive the climate variables used in the Atlas. Caldera et al. [18] use the water stress and demand values from the Atlas to determine the desalination demand for regions with water stress greater than 40%. The study was done for the year 2030.

The Aqueduct Water Risk Atlas projects the future water demand using irrigation efficiency based on the historically low growth rates. The change in water demand and stress factors are presented for global water catchments for the decades 2020, 2030 and 2040. The water demand change factor accounts for the increase in water withdrawals from 2010 [27] for the municipal, industrial and agricultural sectors. To obtain the change in demand in 2050 for every catchment, the respective data from 2030 to 2040 is extrapolated. For the purpose of this work, the water demand and stress values projected by the Atlas is considered to be a Base scenario.

Table 1 illustrates the total water withdrawals assumed for the period from 2020 to 2050. The compound annual growth rate of 4% from 2030 to 2040 is also observed for the period from 2040 to 2050.

Table 1 Total water demand projections from 2020 to 2050 in the Base scenario

		2020	**2030**	**2040**	**2050**
Total water demand	billion m^3/day	14	16	17	19

To project the desalination demand after substantial improvements in irrigation efficiency of existing sites – the HPIE scenario - the following approach was taken. The analysis was carried out for the years 2030 and 2050 :

1. Current irrigation water withdrawals of each country are obtained from the FAO Aquastat database [27] and assumed to be distributed equally amongst the current irrigation sites.
2. Current irrigation efficiency for the irrigation site is obtained, as shown in Figure 1.
3. Water withdrawals for irrigation in the years 2030 and 2050 are projected using the demand change factors presented in the Aqueduct Water Risk Atlas.
4. The irrigation efficiency is increased based on Figure 2.
5. New irrigation water withdrawals are calculated for the higher irrigation efficiency, as illustrated in Equation 2.
6. The municipal and industrial sector water withdrawals are the numbers estimated for the specific year in the Base scenario.
7. The corresponding total water demand, is the sum of the municipal, industrial and new irrigation water withdrawal numbers estimated for the specific year.
8. New water stress is found from the Base water stress, Base total water demand and reduced new total demand.
9. Desalination demand for irrigation node is calculated as a logistic function of the new water stress and new irrigation water demand, as described in Caldera et al. [18].

$$irrigDemandNew(i,y) = \frac{origirrigDemand}{\left(\frac{1 + \left(irrigEffHPIE_{(y)} - irrigEff(i)\right)}{irrigEff(i)}\right)}$$

Equation 2 where *i* and *y* are the 0.45° x 0.45° node and year under consideration respectively, $irrigDemandNew$ is the water withdrawal for irrigation at the node *i* after improved efficiency, $origirrigDemand$ is the water withdrawal for irrigation at the node *i* before improved efficiency, $irrigEffHPIE_{(y)}$ is the irrigation efficiency in the HPIE scenario for the year *y*, $irrigEff(i)$ is the initial irrigation efficiency for the node obtained from [15].

2.1.2 Desalination demand and Energy System Model

The energy system, based solely on renewable energy resources, required to run the SWRO desalination capacities for irrigation are modelled using the LUT Energy System model. The modelling approach is similar to that described in [18]. The results of the modelling will provide the levelised cost of electricity (LCOE), or the cost of electricity production, for each node with desalination demand. The LCOE values can be used, as presented in ***Equation 3***, to determine the levelised cost of water (LCOW) for nodes with desalination demand. ***Equation 3*** has been summarised from [18] and [28]. The LCOW includes the cost of water pumping from the desalination plant on the coast to the irrigation site.

$$LCOW_{desal} = \frac{(capex_{desal} \times crf_{desal} + capex_{water\ storage} \times crf_{water\ storage}) + opex_{fixed}}{Total\ water\ produced\ in\ a\ year} + opex_{var\ desal} \times SEC$$

$$LCOW = LCOW_{desal} + LCOT_{desal}$$

Equation 3 $capex_{desal}$ is the capital expenditures of the SWRO desalination plant in €/m^3, $capex_{water\ storage}$ is the CAPEX of the water storage tank at the desalination site in €/m^3, crf_{desal} is the annuity factor for the desalination plant, $crf_{water\ storage}$ is the annuity factor for water storage, Total water produced in a year is in m^3 and $opex_{fixed}$ is the total fixed annual operational expenditures of the desalination system in €/m^3. The total fixed OPEX is the sum of the fixed OPEX of the desalination plant in €/m^3 and the OPEX of the water storage tank in €/m^3. The value $opex_{var\ desal}$ is the variable OPEX of the desalination plant and is equal to the levelised cost of electricity (LCOE) of the plant 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. $LCOT_{desal}$ is the levelised cost of water transportation from the desalination plant to the irrigation site in €/m^3, $LCOW$ is the resulting levelised cost of water in €/m^3. The horizontal pumping distance is the shortest path from the irrigation site to the coast where the SWRO desalination plants are located. The highest elevation on the path is found using the ETOPO1 global relief model [29] and considered to be the vertical pumping distance. For landlocked countries, the desalinated water may have to be transported through other countries.

Table 2 defines the key cost assumptions made for the SWRO desalination system in 2030 and 2050. The costs projections are based on the SWRO capex learning curve defined in [7]. The energy consumption projections of SWRO plants are based on [30]. The cost for

remineralisation of the desalinated water with Magnesium has been considered as discussed by Yermiyahu et al. [31]. Water storage is located at the site of the desalination plant and allows the SWRO plants to store excess water that may be utilized during times of low electricity production.

Table 2 Key assumptions for the SWRO desalination system in 2030 and 2050

SWRO Desalination System			
		2030	**2050**
CAPEX	€/(m^3·a)	2.75	1.17
Fixed OPEX	€/(m^3·a)	4% of CAPEX	4% of CAPEX
Mg remineralisation cost	€/m^3	0.035	
Energy consumption	kWh$_{el}$/m^3	3.15	2.6
Lifetime	yrs	30	
Water Storage			
CAPEX	€/m^3	65	
Fixed OPEX	€/(m^3)	2% of CAPEX	
Lifetime	yrs	30	
Horizontal pumping and piping			
Horizontal pipes CAPEX	€/(m^3·a·km)	0.053	
Horizontal pipes Fixed OPEX	€/(m^3·a·100 km)	0.023	
Horizontal pump CAPEX	€/(m^3·hr·km)	19.23	
Horizontal pump Fixed OPEX	€/(m^3·hr·km)	2% of CAPEX	
Energy consumption	kWh$_{el}$/(m^3·hr·100km)	0.04	
Lifetime	yrs	30	
Vertical pumping and piping			
Vertical pipes CAPEX	€/(m^3·a·km)	0.053	
Vertical pipes Fixed OPEX	€/ (m^3·a·100 km)	0.023	
Vertical pump CAPEX	€/(m^3·hr·m)	15.40	
Vertical pump Fixed OPEX	€/(m^3·hr·m)	2% of CAPEX	
Energy consumption	kWh$_{el}$/(m^3·hr·100m)	0.36	
Lifetime	yrs	30	

The LUT Energy System model is a linear optimisation model that uses the MOSEK ApS optimisation software to determine the least cost renewable energy system required to meet the

defined energy demand. The system optimisation is done on an hourly resolution so that the energy demand of every hour is met by renewable energy resources at a minimum cost. In addition, a spatial resolution of 0.45° x 0.45° is considered. The system optimisation minimises the total annual cost of the installed capacities of the different technologies, cost of energy generation and cost of generation ramping. Detailed description of the complete model can be found in [30], [32].

Figure 3 is a block diagram of the LUT Energy System model used for this research and illustrates the renewable energy generation technologies, energy storage technologies and energy sector bridging technologies. The hybrid RE power plants modelled are comprised of single-axis tracking PV, fixed-tilted PV, wind, batteries and power-to-gas (PtG) power plant. The hourly and spatially resolved profiles for the RE resources, solar photovoltaics (PV) and wind, are calculated as discussed in [30] & [32].

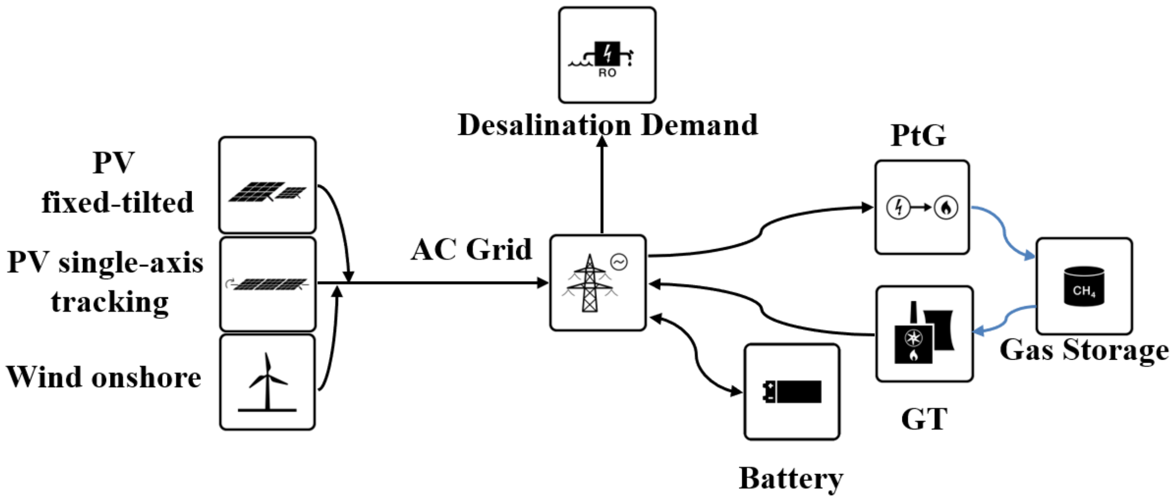


Figure 3 Block diagram of the LUT Energy System model

The key technical and financial parameters of the technologies that are used in the LUT Energy System model are listed in Table 3**Table *3*** . The learning curves, based on the historical trends of the relevant technologies, are utilised to project the financial and technical assumptions for 2030 and 2050.

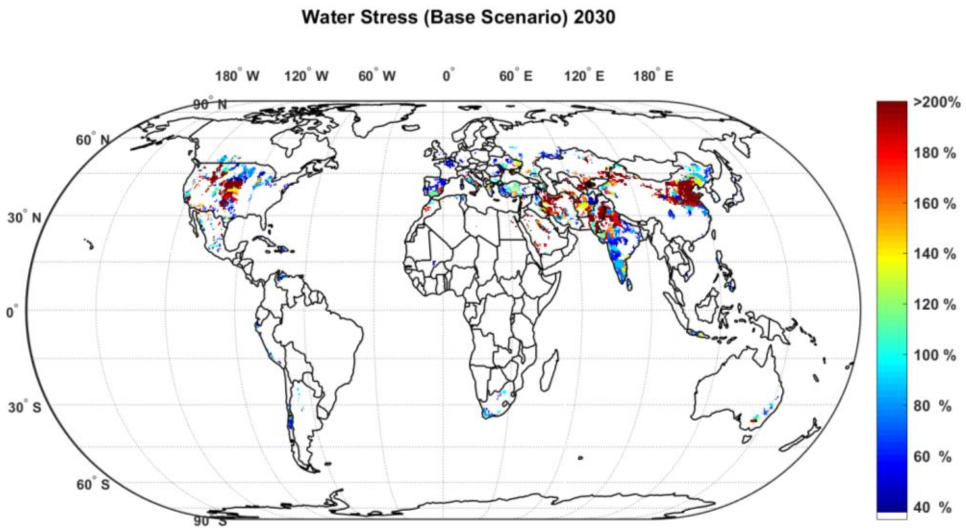
Table 3 Key assumptions for the renewable energy technologies used in the LUT Energy System model [30]

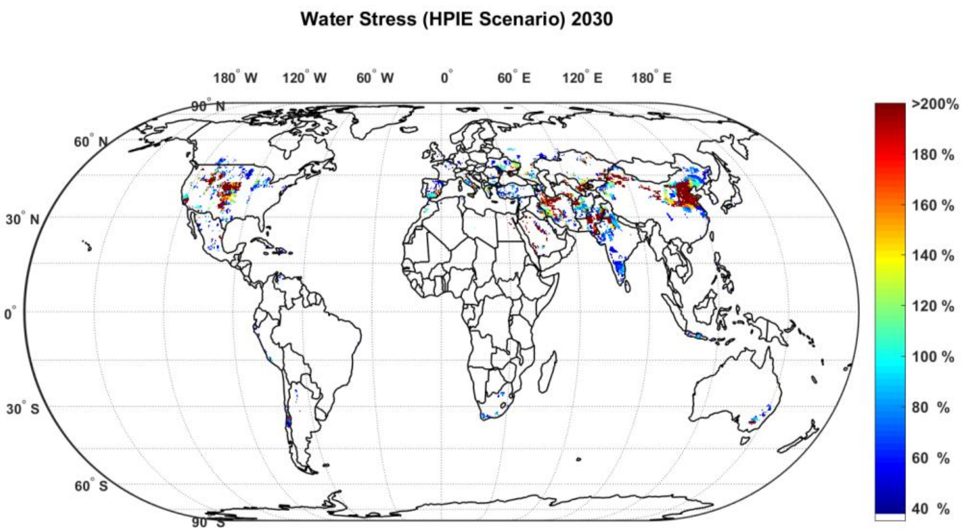
Fixed-tilted PV plant			
		2030	**2050**
CAPEX	€/kW	390	246
OPEX	€/(kW·a)	3% of capex	3% of capex
Lifetime	yrs	35	40
Single-axis tracking PV plant			
CAPEX	€/kW	429	271
OPEX	€/(kW·a)	3% of capex	3% of capex
Lifetime`	yrs	35	40
Wind plant			
CAPEX	€/kW	1000	900
OPEX	€/(kW·a)	2% of CAPEX	
Lifetime	yrs	25	
Battery system			
CAPEX	€/kWh$_{cap}$	150	75
Fixed OPEX	€/(kWh·a)	2.5% of CAPEX	
Lifetime	yrs	20	
PtG			
Water electrolysis CAPEX	€/kW$_{H2}$	363	248
Water electrolysis Fixed OPEX	€/(kW$_{H2}$·a)	13	8.7
Lifetime	yrs	30	
CO_2 direct air capture CAPEX	€/tCO_2	356	154
CO_2 direct air capture OPEX	€/(tCO_2·a)	9.1	5.7
Lifetime	yrs	30	
Methanation CAPEX	€/kW$_{SNG}$	278	190
Methanation OPEX	€/(kW$_{SNG}$·a)	11.1	7.6
Lifetime	yrs	30	
Gas storage	€/kWh	0.05	
Lifetime	yrs	50	

3 Results

3.1 Projected Impact of Improved Irrigation Efficiency

Increasing the irrigation efficiency reduces the total water demand and consequently the water stress across the basins. ***Figure 4*** provides insights into the relationship between irrigation efficiency and water stress in 2030 and 2050.





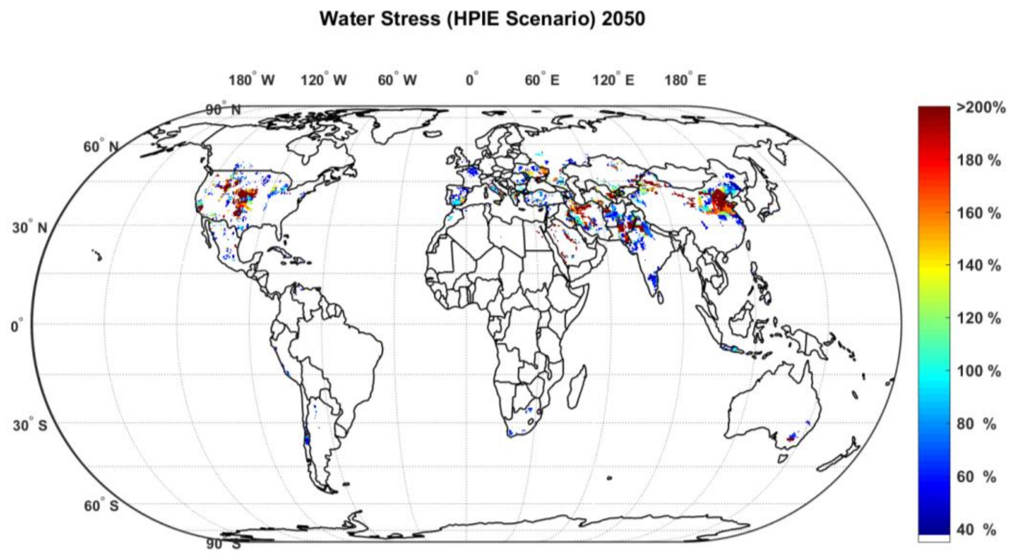


Figure 4 Water stress of irrigation sites in the year 2030 base scenario (top), water stress of irrigation sites in 2030 HPIE scenario (centre) and water stress of irrigation sites in 2050 HPIE scenario (bottom)

Figure 4 (top) presents the water stress in 2030 for a base scenario, where there are no significant improvements in irrigation efficiency. The dependence on fossil groundwater is highlighted in regions where water stress is greater than 100%, such as regions in Northeast China and Central United States. ***Figure 4*** (center) illustrates the situation in 2030 if the average beneficial irrigation efficiency is improved to about 60%. Marked decreases in water stress levels are observed in India, China, Central Asia, Mediterranean and North America. However, there are still regions of high or extremely high stress in central United States and Northeast China. This could be attributed to the fact that the regions face high water demand from the other sectors, namely industrial and municipal. ***Figure 4*** (bottom) shows the declining water stress trends in the 2050 HPIE scenario. By this year the beneficial irrigation efficiency is expected to be 90%.

Figure 5 illustrates the desalination demand for irrigation sites in the HPIE scenario for the years 2030 and 2050. The desalination demand for irrigation sites in 2030 is found to be $8.32 \cdot 10^8$ m^3/day. China, Iran and Pakistan account for approximately 55% of the total demand. In 2050, the total desalination demand decreases to be $6.25 \cdot 10^8$ m^3/day due to the higher

irrigation efficiency, illustrated in ***Figure 2***. The countries China, Iran and Pakistan account for 50% of the total demand.

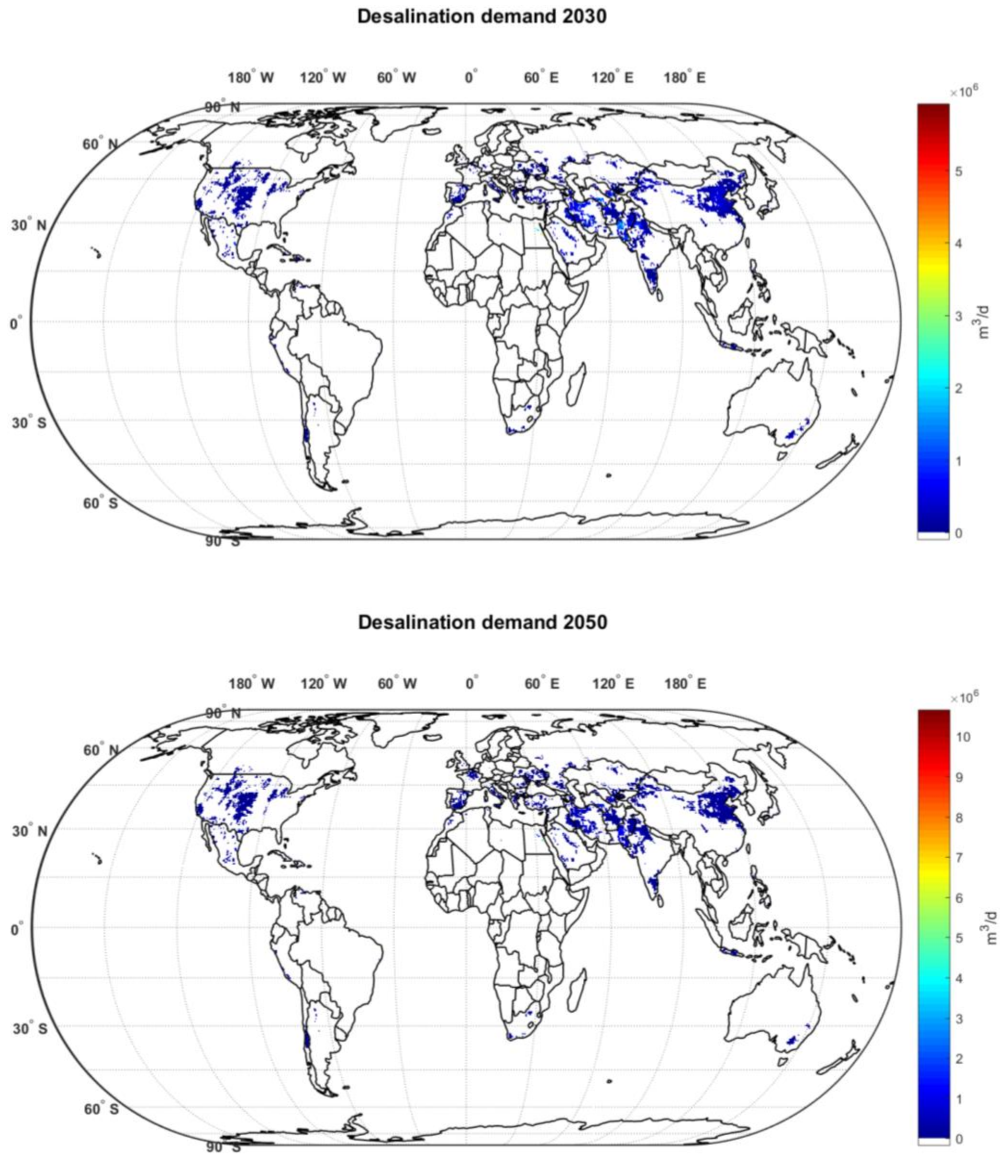


Figure 5 Desalination demand for irrigation sites in the HPIE scenario for the year 2030 (top) and 2050 (bottom)

Table 4 presents the total irrigation water and desalination demand values for 2030 and 2050, in a base and HPIE scenario. If the irrigation efficiency is improved to 60% by 2030, a 27% reduction in total water demand and 64% reduction in total desalination demand is observed. Similarly, an improvement towards 90% irrigation efficiency, by 2050, will result in 36%

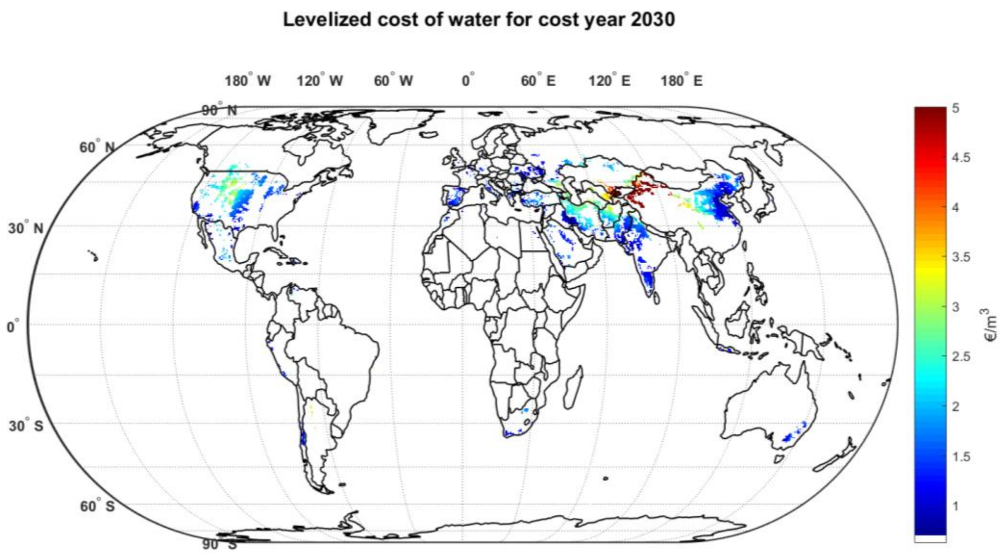
reduction in total water demand for irrigation. This translates to an 80% reduction in global desalination demand. The remaining demand for desalination can be explained by the increasing total water withdrawals for irrigation in regions of high water stress.

Table 4 Global Irrigation Water Demand in Base and HPIE scenarios

		Base Scenario 2030	**Base Scenario 2050**	**HPIE Scenario 2030**	**HPIE Scenario 2050**
Water demand for irrigation	m^3/day	$1.10 \cdot 10^{10}$	$1.30 \cdot 10^{10}$	$8.06 \cdot 10^{9}$	$8.32 \cdot 10^{9}$
Desalination demand for irrigation	m^3/day	$2.31 \cdot 10^{9}$	$3.10 \cdot 10^{9}$	$8.32 \cdot 10^{8}$	$6.25 \cdot 10^{8}$

3.2 The modelled RE-based SWRO desalination system

As mentioned in Section 2, the optimal system to produce water from the SWRO capacities show in ***Figure 5***, is modelled using the LUT Energy System model. ***Figure 6*** (top) illustrates the estimated LCOW range for the irrigation sites in 2030. The global range is from 0.7 €/m^3 – 6 €/m^3, while the prevalent range is 0.7 €/m^3 – 2 €/m^3. ***Figure 6*** (bottom) shows the corresponding LCOW diagram for 2050. The global range in 2050 is estimated to be 0.45 €/m^3 – 6 €/m^3 reflecting the lower costs of the SWRO and renewable energy power plants in 2050. The prevalent LCOW range is found to be 0.45 €/m^3 – 1.7 €/m^3, and particularly low in the sites closer to the coast where water transportation costs are low. Some nodes, such as in central United States, experience an increase in desalination demand, compared to 2030. This requires more pumping capacities, contributing to a slightly higher LCOW in 2050 compared to 2030.



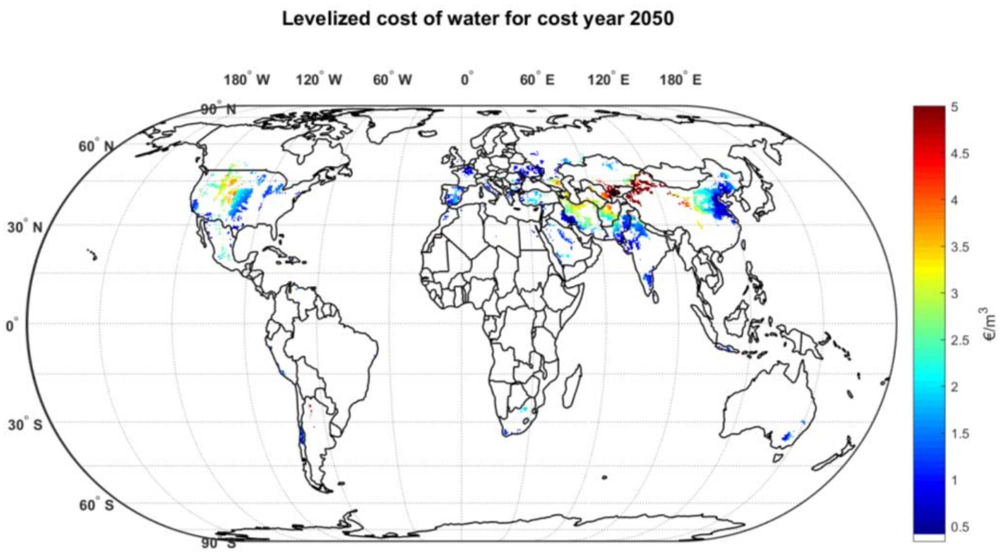


Figure 6 LCOW in the year 2030 (top) and 2050 (bottom)

Figure 7 shows the optimised levelised cost of electricity at the irrigation sites for 2030 and 2050. As illustrated, the LCOE range reduces from 0.08 €/kWh – 0.13 €/kWh in 2030 to 0.05 €/kWh – 0.10 €/kWh in 2050. The least cost combination of RE power plants for the irrigation sites comprised of single-axis tracking PV, fixed-tilted PV and wind power plants, highlighting the solar and wind resources at the sites. Battery and power-to-gas plants are used to ensure continuous running of the SWRO desalination plants, which would technically not be required, but had been found the least cost operation mode [33]. Figure 8 (top) shows the contribution

of PV and wind power plants to the total electricity generated for the year 2050. The global range is from as little as 26% in central regions of North America to as high as 96% in South Asia. The steeper reduction in solar PV costs and the location of most irrigation sites in regions with abundant solar resources can explain the higher share of PV generation. Similar generation shares are observed in 2030.

Figure 8 (bottom) illustrates the extent to which the electricity cost contribute to the final LCOW. The range is not varied and all values lie between 23% to 42%. Regions that have large desalination demand or have large water pumping distances have higher contribution from the electricity cost. In 2030, the range is larger from 25% to 60%. The higher shares can be attributed to the higher cost of electricity in 2030, compared to 2050.

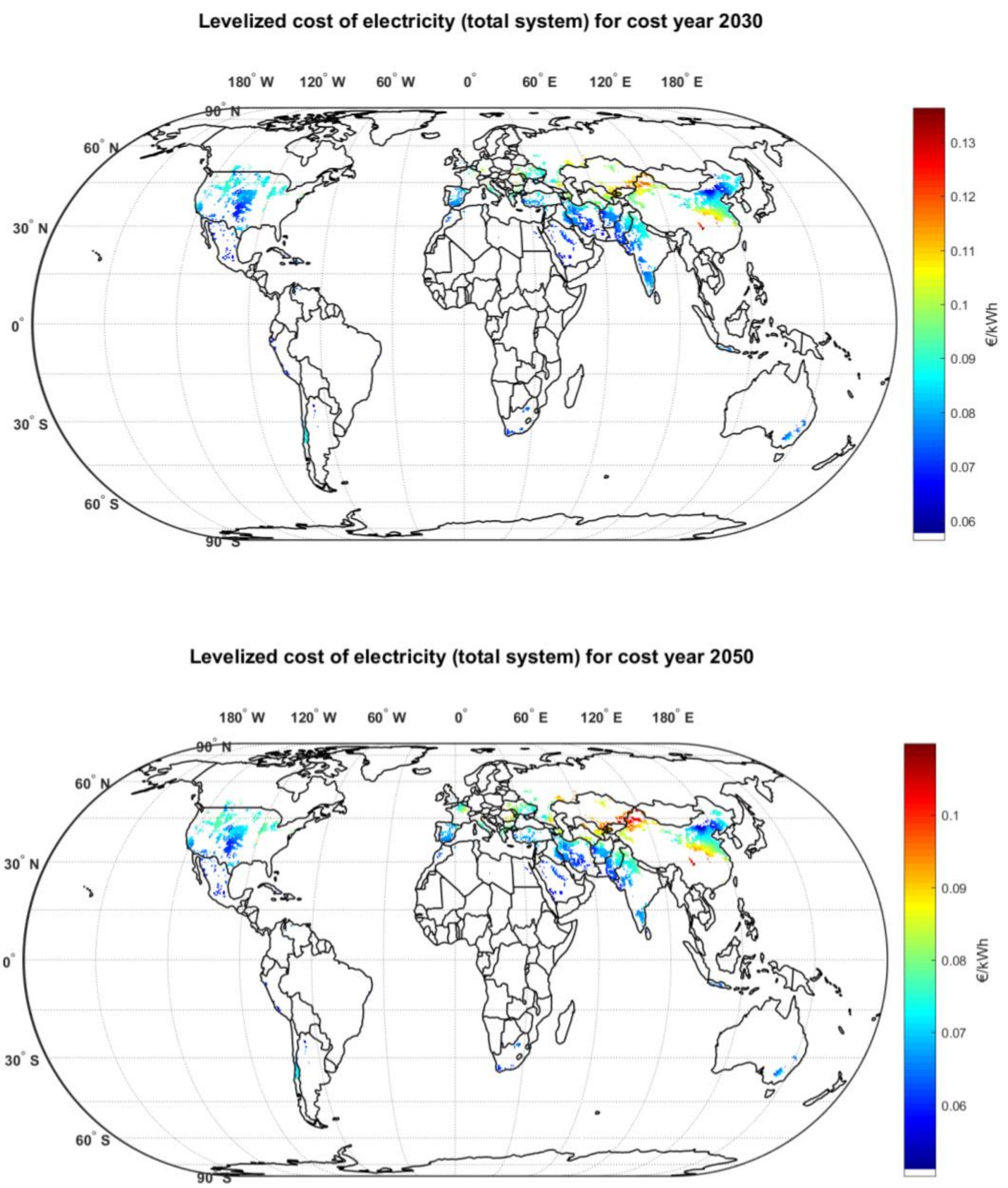


Figure 7 LCOE in the HPIE scenario for the year 2030 (top) and 2050 (bottom)

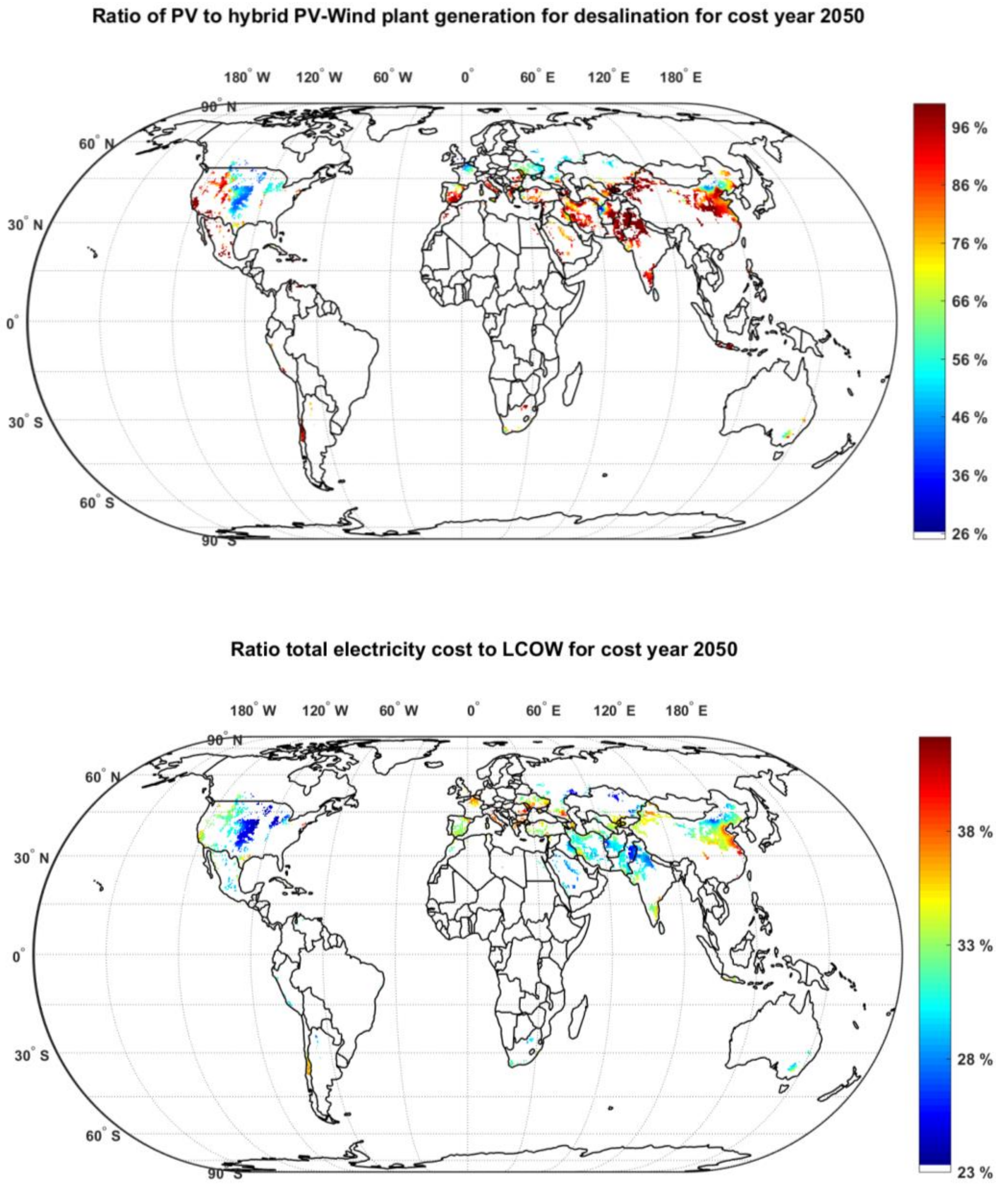


Figure 8 Ratio of PV to PV-Wind plant generation (top) and ratio of total electricity cost to the LCOW (bottom) both for the year 2050 and the HPIE scenario

Table 5 presents key parameters of the modelled system for the countries with the highest desalination demand in 2030 and 2050. China, Iran and United States have higher average LCOW due to the larger pumping distances, in both vertical and horizontal directions. The longer pumping distances are reflected in the slight increase in LCOW from 2030 to 2050, despite the decrease in LCOE. China, Iran and Pakistan account for 53% of the global investment costs.

Table 5 Overview of the RE-based SWRO desalination system required for countries with the largest desalination demand in 2030 and 2050

	2030					
Country	**Demand**	**LCOE**	**LCOW**	**Total PV capacity**	**Total Wind capacity**	**Total investment cost**
	m^3/day	€/kWh	€/m^3	GW	GW	b€
China	2.25E+08	0.09	2.23	650	68	1570
India	5.53E+07	0.08	1.53	93	2	249
Iran	1.26E+08	0.07	2.16	349	47	852
Pakistan	1.11E+08	0.07	1.42	185	5	477
United States	4.91E+07	0.07	2.01	82	31	297

	2050					
Country	**Demand**	**LCOE**	**LCOW**	**Total PV capacity**	**Total Wind capacity**	**Total investment cost**
	m^3/day	€/kWh	€/m^3	GW	GW	b€
China	1.23E+08	0.08	2.66	391	29	812
India	2.79E+07	0.07	1.51	45	0.20	102
Iran	8.98E+07	0.06	2.65	257	29	566
Pakistan	9.41E+07	0.06	1.36	146	3	317
United States	4.06E+07	0.06	2.14	71	22	215

The technical and financial aspects of the RE systems required to power the SWRO capacities in 2030 and 2050 are summarised in Table 6. The results show that adopting RE-based SWRO systems for the irrigation sector will require 32% and 18% less investment and annualised costs respectively in 2050, relative to 2030. This is due to the projected lower costs in RE and SWRO systems by 2050, compared to 2030. The higher total opex costs in 2050 are due to the increase in demand and pumping distances in some regions.

Table 6 Key parameters of the RE-based power system required to meet the global desalination demand in 2030 and 2050

		2030 global system	**2050 global system**
Installed PV capacity	GW	2107	1650
Fixed-tilted PV	GW	1171	801
Single-axis tracking PV	GW	938	848
Installed Wind capacity	GW	264	164

Installed Battery capacity	GWh_{cap}	4212	2772
Installed PtG capacity	GW_{el}	213	200
Total Capex	b€	5380	3620
Total OPEX	b€	201	249
Annualised costs	b€	644	543

4 Discussion

The results obtained show that RE-based SWRO desalination can be a cost competitive water supply option for irrigation in many regions in the world. In Australia, where farmers are reluctant to pay more than 0.63 €/m^3 (1 AUD/m^3) [9], ***Figure 6*** shows that desalinated water can be supplied reliably for less than 1 €/m^3. It should be noted that increasing the efficiency of the irrigation sites on the eastern states decreases the demand for desalination by 50% from 2030 to 2050. This indicates the impact of irrigation on the water stress levels at the sites. The ongoing drought in Australia, stated to be the longest in recent history, has resulted in an increase in demand for desalination capacities to ensure reliable water supply to the eastern states [34].

In the North China Plain (NCP), the cost of water for irrigation can be as little as 1 €/m^3 in 2030 and 2050. The issues of farmers, about increasing costs due to declining groundwater levels and fuel costs, can be overcome by the increased irrigation efficiency and RE-based SWRO desalination systems presented. Similarly, in Colorado, Dolan et al. [35] estimate a cost of 2.4 €/m^3 for produced water, excluding cost of transportation. Based on ***Figure 6***, the LCOW for this region can range from 2 – 3 €/m^3, including the transportation costs.

The FAO literature survey shows that the prices paid by farmers in countries, in particular developing countries, do not help to recover the operation and maintenance costs. Rosegrant et

al. [36] explain that some countries in Asia subsidise up to 90% of the O&M costs of the irrigation sector. Countries like United States, India, Pakistan and Egypt are reported to spend billions on subsidies for irrigation water a year. While subsidies are supposed to encourage equity and ensure people the basic access to water, the lack of recovery of the full costs of water has resulted in poorly maintained water infrastructure and mismanagement of water for irrigation. Rosegrant et al. present a sustainable water use scenario, where water resources are managed and made available for people and the environment. The scenario expects the cost of water for the agricultural sector in developed countries to double, compared to a business as usual scenario, by 2025. The cost of water in developing countries is expected to triple. In contrast, in a water crisis scenario, where there is no regulation of the water price and groundwater is overdrafted, sharp increases in the cost of rice, wheat and maize is projected. Ghaffour et al. [6] also discuss the increase in cost of water from traditional water resources and the growing potential for desalinated water.

Based on the results in Figure 4, countries with most irrigation sites closer to the coast, such as Algeria, Morocco, Israel, Philippines, Venezuela and Italy, can produce water for costs less than 0.5 €/m^3. Countries with larger desalination demand and pumping distances, such as China and the United States, experience higher water production costs in the range of 0.5 €/m^3 – 4.5 €/m^3. Countries in Central Asia have the largest average water production costs, ranging from 3 €/m^3 – 5.8 €/m^3. This is due to the absence of a coastline and therefore longer pumping distances. In addition, desalinated water would need to be transported from regions with access to the sea, between international boundaries, posing further challenges. For regions such as these, water demand management, through techniques such as improved irrigation efficiency, maybe vital to overcoming the water scarcity issues. Figure 2 already indicates marked decrease in water stress in the regions of Central Asia where rice, wheat or maize is grown. Karimov et al. [37] provides insights into the ensuing issues between the Central Asian

countries over the use of shared water resources. For instance, Tajikistan, as upstream water users, want to use the river water for electricity generation, but this causes conflict with downstream users in Uzbekistan, who want to use the water for cotton irrigation. To avoid potential water conflicts, the authors recommend the adoption of solar PV and wind power for electricity generation and drip irrigation technologies for farming.

The high desalination demand in 2030 and 2050, for some irrigation sites, despite the increase in irrigation efficiency, suggests that these irrigation sites are located in highly water stressed hydrological basins. This is owing to the demands from the industrial and municipal sectors which are projected to experience an even larger growth by 2050 compared to the agricultural sector. Nevertheless, ***Figure 4*** shows that in most regions, increasing the beneficial irrigation efficiency results in significant reduction of the water stress and demand for desalination. Therefore, it is imperative that the beneficial irrigation efficiency is improved if water demand is to be controlled in the decades to come. The current average global irrigation efficiency is as little as 33%. The very low growth rates of 0.3% per annum, observed by Hansaki et al. [20], do not make a significant dent in the future water withdrawals for irrigation. It has to be noted that the present study only considers the cost of water supply to the irrigation sites and does not account for investments required to upgrade infrastructure at the sites. Various reports have made estimations on the costs involved for irrigation system upgrades in different parts of the world [38,39]. For a comprehensive assessment of the costs entailed in high efficiency irrigation scenarios, the costs of improving the irrigation systems have to be accounted for.

The SWRO plants operate in a baseload manner throughout the year, utilising the combination of solar PV and battery storage, to minimise the cost of water production. The higher capital expenditures of SWRO plants entail that the plants are operated at higher full load hours to minimise the LCOW [33]. To overcome the seasonal requirements of irrigation water demand, a reservoir maybe used as buffer between the desalination plant and the irrigation site to ensure

that the irrigation water is supplied as per the demand throughout the year. Such a strategy has been discussed by Serrano-Tovar et al. [40] for a local desalination plant in the Canary Islands. This is another aspect that should be considered for a comprehensive cost assessment of upgrading irrigation infrastructure.

Amidst growing global concern over the impacts of climate change, various reports and literature already highlight the global transition towards renewable energy resources [1]. In addition, the costs of renewable energy and storage technologies are projected to decline, securing a cost competitive energy source for desalination plants [30]. Similarly, research has shown that the increase in desalination capacities globally [7] drive the decline of the capital costs of SWRO plants. Therefore, SWRO desalination systems coupled to RE power plants help overcome the environmental concern of greenhouse gas emissions and can be a reliable water supply for irrigation. Various researchers echo similar views on the need to drive the uptake of RE- based desalination [5,6,41]. Jones et al. [5] shed light on the issue of increasing quantities of concentrated brine from desalination plants being discharged into the marine environment, without proper treatment. This can lead to the pollution of coastal waters, damage of sensitive marine life that will ultimately threaten the food chain. In order to minimise the impact on the environment, more complex infrastructure is required, leading to an increase in the final costs of the project. For instance, in Australia, SWRO plants located in environmentally sensitive areas required the implementation of suitable outfall structures that led to a 30% increase in the final cost [42]. Jones et al. [5] acknowledge the increasing importance of desalinated water in the future global water supply and suggest using the brine discharge for economic gains. This maybe for new opportunities such as commercial salt production and recovery of precious metals.

Various literature and reports discuss viable ways to secure water supply for irrigation and to ensure global food security. Some of the discussed approaches include investments in improved

technologies, removal of subsidies, the use climate resilient crops, off-grid greenhouses watered by desalination systems, uptake of plant-based diets, reductions in losses in the global food systems and efficient usage of nutrients and fertilizers [2,43,44,45]. Other approaches proposed maybe more radical and redefines the conventional concept of food production. Solar Foods [46] is a Finnish enterprise, established in 2017, and provides the means to produce single-cell protein using CO_2, renewable electricity and water as raw materials. The protein, Solein, with a texture similar to that of wheat flour, is reported to consume as little as 10 liters of water per kg. According to Solar Foods, the technique can be used to produce food independent of climate, irrigation or soil. These projects highlight the variety of work being done on the topic of achieving global food security in the decades to come.

The purpose of this research is to shed light on how improved irrigation efficiency and RE-based SWRO desalination can help the agricultural sector deal with the yawning gap between water supply and demand. RE-based SWRO can provide water at costs suitable for farmers in various irrigation sites, particularly closer to the coastline. Improved irrigation efficiency is crucial to ensure the sustainability of the water supply. Furthermore, as costs of obtaining ground and surface water increase due to scarcity, fossil fuel-based electricity costs and removal of government subsidies, RE-based SWRO desalination offers a steady and cost-effective water supply.

5 Conclusion

By 2050, it is estimated that the annual cereal production would need to increase by about 140% and total global food production increase by 70%. Total water withdrawals for irrigation is projected to increase by 11%. In contrast, poor management of existing water resources, pollution and climate change has resulted in limited freshwater resources for irrigation.

The aim of this paper is to gauge how improved irrigation efficiency and RE-based SWRO desalination maybe used to secure water supplies for the agricultural sector. Desalination is currently being used in countries like Israel and Spain for cash crops. In this research, the focus was on the use of SWRO desalination for growth of the main cereals: rice, wheat and corn.

Estimates of the beneficial irrigation efficiencies of the current locations were obtained. The irrigation efficiency growth was projected such that by 2050, all existing irrigation sites would have an efficiency of 90%. This was labelled an HPIE scenario. The new irrigation efficiencies were used to obtain the reduced irrigation demand for the years 2030 and 2050.

Based on previous research, the desalination demand for the HPIE scenario was estimated. The LUT Energy System model was used to define a least cost RE power system based on solar PV and Wind resources, to power the estimated desalination demand.

It was found that improving the average irrigation efficiency to 60% by 2030, led to a 64% reduction in total desalination demand. Similarly, an improvement towards 90% irrigation efficiency, by 2050, translates to an 80% reduction in global desalination demand. There was a marked decrease in water stress across many countries, resulting in the lower desalination demand. However, regions in China and USA, where there is increasing demand for the industrial and municipal sectors, still experienced high water stress levels.

In 2030, the global LCOW range is mostly within 0.7 €/m^3 – 2 €/m^3 including transportation costs. Literature reports that farmers may be willing to pay up to 0.63 €/m^3 for their irrigation water. The global range in 2050 is estimated to be 0.45 €/m^3 – 1.7 €/m^3 reflecting the lower costs of the SWRO and renewable energy power plants in 2050. Countries in Central Asia have a higher LCOW range of 3 €/m^3 – 5.8 €/m^3 due to the absence of a coast and long transportation distances.

The above results indicate that as conventional water prices increase, due to scarcity, fossil fuel-based electricity costs and removal of government subsidies, RE-based SWRO desalination offers a steady and cost effective water supply. In addition, a fast transition towards higher irrigation efficiencies will help control the increasing future water demand.

Acknowledgements

The first author gratefully acknowledges the scholarship offered by the Reiner Lemoine-Foundation.

Conflicting interests

The authors declare no conflict of interest

6 References

1. Intergovernmental panel on climate change, 2018, Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland
2. Steduto P, Schultz B, Unver O, Ota S, Vallee D, Kulkarni S, Garcia M D-J, 2018, Food security by optimal use of water: Synthesis of the 6th and 7th world water forums and developments since then. In: Irrigation and Drainage, 67, 327 – 344
3. Assouline S, Russo D, Silber A, Or D, 2015, Balancing water scarcity and quality for sustainable irrigated agriculture. In: Water Resources Research, 51, 3419–3436, doi:10.1002/2015WR017071
4. Food and Agricultural Organisation of the United Nations, 2009, Issue Brief: How to feed the world in 2050, Rome, Italy. http://www.fao.org/wsfs/forum2050/wsfs-background-documents/hlef-issues-briefs/en/
5. Jones E, Qadir M , Vliet M T H V, Smakhtin V, Kang S, 2019, The state of desalination and brine production: A global outlook. In: Science of the Total Environment, 657, 1343 – 1356
6. Ghaffour N, Missimer M T, Amy L G, 2013, Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. In: Desalination, 309, 197-207
7. Caldera U, Breyer Ch, 2017, Learning curve for seawater reverse osmosis desalination plants: capital cost trend of the past, present, and future. In: Water Resources Research 53, 10523 - 10538
8. Burn S, Hoang M, Zarzo D, Olewniak F , Campos E, Bolto B, Barron O, 2015, Desalination techniques – A review of the opportunities for desalination in agriculture. In: Desalination, 364, 2 – 16
9. Martinez-Alvarez V, Gonzalez-Ortega M J, Soto-Garcia M, Maestre-Valero J F, 2018, Seawater desalination for crop irrigation – current status and perspectives. In: Emerging Technologies for Sustainable Desalination Handbook, Butterworth - Heinemann

10. Food and Agricultural Organisation of the United Nations, 2019, Annex 1 Water charging for irrigation – data from literature, Rome, Italy. http://www.fao.org/docrep/008/y5690e/y5690e0b.htm

11. Fischer G, Tubiello F N, Velthuizen H V, Wiberg D A, 2007, Climate change impacts on irrigation water requirements: Effect of mitigation, 1990 – 2080. In: Technological Forecasting and Social Change, 74, 1083 – 1107

12. Takatsuka Y, Niekus M R, Harrington J, Feng S, Watkins D, Mirchi A, Nguyen H, Suokp M C, 2018, Value of irrigation water usage in South Florida agriculture. In: Science of the Total Environment, 626, 486 – 496

13. Qiu G Y, Zhang X, Yu X, Zou Z, 2018, The increasing effects in energy and GHG emission caused by groundwater level declines in North China's main food production plain. In: Agricultural Water Management, 203, 138 – 150

14. Vanham D, Hoekstra A Y, Wada Y, Bouraoui F, Rooa A, Mekonnen M M, Bund W J, Batelaan O, Pavelic P, Bastiaanssen W G M, Kummu M, Rockström J , Liu J, Bisselink B, Ronco P, Pistocchi A, Bidoglio G, 2018, Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress". In: Science of the Total Environment, 613-614, 218 - 232

15. Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W, 2015, Water savings potentials of irrigation systems: global simulation of processes and linkages. In: Hydrology and Earth System Sciences, 19, 3073 – 3091

16. Fyles H, Madramootoo C, 2016, Water Management. In: Emerging Technologies for Promoting Food Security, Woodhead Publishing (Elsevier), Sawston, United Kingdom

17. Multsch S, Elshamy M E, Batarseh S, Seid A H, Fred H G, Breuer L, 2017, Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin. In: Journal of Hydrology: Regional Studies, 12, 315 – 330

18. Caldera U, Bogdanov D, Breyer C, 2018, Desalination costs using renewable energy technologies. In: Renewable Energy Powered Desalination Handbook: Application and Thermodynamics, Butterworth-Heinemann (Elsevier), Oxford, Great Britain

19. Awika J M, 2011, Advances in Cereal Science: Implications to Food Processing and Health Promotion, ACS Symposium Series; American Chemical Society, Washington, DC

20. Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, Hijioka Y, Kainuma M, Kanamori Y, Masui T, Takahashi K, Kanae S, 2013, A global water security assessment under shared socio-economic pathways – part 1: water use. In: Hydrology and Earth System Sciences, 17, 2375 - 2391

21. Wada Y, Gleeson T, Esnault G, 2014, Wedge approach to water stress. In: Nature GeoScience, 7, 615 - 617

22. Netafim, 2018, Drip irrigation for rice is changing the rules of the game, Hatzerim, Israel. https://www.netafim.com/en/crop-knowledge/rice/

23. Cision PR Newswire, 2018, Global Drip Irrigation Systems Market to 2026 - Increasing Benefits of Drip Irrigation Systems and Rising Agricultural Activities in Emerging Economies, Chicago, United States. https://www.prnewswire.com/news-releases/global-drip-irrigation-systems-market-to-2026---increasing-benefits-of-drip-irrigation-systems-and-rising-agricultural-activities-in-emerging-economies-300763526.html

24. Soman P, 2012, Drip Fertigation for Rice Cultivation. Presentation at the Asia Irrigation Forum, Manila, Philippines. https://k-learn.adb.org/system/files/materials/2012/04/201204-drip-fertigation-rice-cultivation.pdf

25. Breyer C, Heinonen S, Ruotsalainen J, 2017, New consciousness: A societal and energetic vision for rebalancing humankind within the limits of planet Earth. In: Technological Forecasting and Societal Change, 114, 7 - 15

26. Luck, M., M. Landis, F. Gassert, 2015, Aqueduct Water Stress Projections: Decadal Projections of Water Supply and Demand Using CMIP5 GCMs. Technical Note. Washington, D.C.: World Resources Institute. https://www.wri.org/sites/default/files/aqueduct-water-stress-projections-technical-note.pdf
27. Food and Agricultural Organisation of the United Nations, 2015, AQUASTAT database, Rome, Italy, http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
28. Caldera U, Bogdanov D, Breyer Ch (2016) Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate. In: Desalination, 385, 207-216
29. Amante C, Eakins B W, 2009, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA, Colorado, USA
30. Caldera U, Bogdanov D, Afanasyeva S, Breyer C, 2018, Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. In: Water, 10, 3
31. Yermiyahu U, Tal A, Ben-Gal A, Bar-Tal A, Tarchitzky J, Lahav O, 2007, Rethinking desalinated water quality and agriculture. In: Science, 318, 920 – 921
32. Breyer Ch, Bogdanov D, Gulagi A, Aghahosseini A, Barbosa L S N S, Koskinen O, Barasa M, Caldera U, Afanasyeva S, Child M, Farfan J, Vainikka P, 2017, On the Role of Solar Photovoltaics in Global Energy Transition Scenarios. In: Progress in Photovoltaics: Research and Applications, 25, 727 – 745
33. Caldera U, Breyer C, 2018, The role that battery and water storage play in Saudi Arabia's transition to an integrated 100% renewable energy power system. In: Journal of Energy Storage, 17, 299 – 310
34. Water Desalination + Reuse, 2018, Australia's demand for desalination jumps amidst drought, West Sussex, UK. https://www.desalination.biz/news/0/Australias-demand-for-desalination-jumps-amid-drought/9090/
35. Dolan F C, Cath T Z, Hogue T S, 2018, Assessing the feasibility of using produced water for irrigation in Colorado. In: Science of the Total Environment, 640 – 641, 619 – 628
36. Rosegrant M W, Cai X, Cline S A, 2003, World water and food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington D.C. https://reliefweb.int/sites/reliefweb.int/files/resources/1B0BBA6D1080C010C1256C6E002E1D17-ifpri-water2025-16oct.pdf
37. Karimov K S, Akhmedov K M, Abid M, Petrov G N, 2013, Effective management of combined renewable energy resources in Tajikistan. In: Science of the Total Environment, 461 – 462, 835 – 838
38. Rosegrant Mark W, Sulser Timothy B, Mason-D'Croz D, Cenacchi N, Nin-Pratt A, Dunston S, Zhu T, Ringler C, Wiebe K D, Robinson S, Willenbockel D, Xie H, Kwon H Y, Johnson T, Thomas T S, Wimmer F, Schaldach R, Nelson G C, Willaarts B, 2017, Quantitative foresight modeling to inform the CGIAR research portfolio. Project Report for USAID. Washington DC, International Food Policy Research Institute,
39. Palazzo A, Valin H, Batka M, Havlík P, 2019, Investment Needs for Irrigation Infrastructure along Different Socioeconomic Pathways. Policy Research Working Paper. Washington DC, World Bank Group
40. Serrano-Tovar T, Suarez P B, Musicki A, Bencombo F A J, Cabello V, Giampietro M, 2019, Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. In: Science of the Total Environment, 689, 945 - 957
41. Fornarelli R, Shahnia F, Anda M, Bahri A P, Ho G, Selecting an economically suitable and sustainable solution for a renewable energy-powered water desalination system: A rural Australian case study. In: Desalination, 435, 128 - 139

42. Water Reuse Association Desalination Committee, 2012, Seawater Desalination Costs. White Paper, Water Reuse Association, Virginia, United States of America. https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf.

43. Kahiluoto H, 2019, The concept of planetary boundaries. In: Encyclopedia of Food Security and Sustainability, General and Global Situation, Elsevier, Amsterdam, Netherlands

44. Kahiluoto H, Kaseva J, Balek J, Olesen J E, Ruiz-Ramos M, Gobin A, Kersebaum K C, Takáč J, Ruget F, Ferrise R, Bezak P, Capellades G, Dibari C, Mäkinen H, Nendel C,Ventrella D, Rodríguez A, Bindi M, Trnka M, 2019, Decline in climate resilience of European wheat. In: Proceedings of the National Academy of Sciences, 116, 123 – 128

45. Shekarchi N, Shahnia F, 2018, A comprehensive review of solar-driven desalination technologies for off-grid greenhouses. In: International Journal of Energy Research, 43 (4), 1357 - 1386

46. Solarfoods, 2019, The revolutionary protein by solar foods, Lappeenranta, Finland. https://solarfoods.fi/