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POTENTIAL OF DESALINATION TO SUSTAINABLY MITIGATE BLUE WATER SCARCITY

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ABSTRACT (ITALIANO)

La scarsità d'acqua è una sfida globale sempre più pressante, alimentata dai cambiamenti climatici, dalla crescita della popolazione e da un consumo idrico insostenibile.

La desalinizzazione può rappresentare una soluzione valida per affrontare questo problema, fornendo una fonte alternativa di acqua nelle aree in cui le risorse naturali sono insufficienti. Questo studio mira a identificare i Paesi in cui la desalinizzazione è essenziale e a quantificare il volume di acqua desalinizzata necessario per soddisfare la domanda in modo sostenibile.

La ricerca si basa su un quadro metodologico che valuta tre parametri: disponibilità di acqua rinnovabile, domanda idrica e consumo di acqua. I Paesi vengono classificati in base al loro bilancio idrico, distinguendo tra quelli in grado di soddisfare la domanda in modo sostenibile e quelli che affrontano una situazione di scarsità di acqua blu (BWS). Per questi ultimi, lo studio stima il volume di acqua desalinizzata da produrre per evitare un prelievo idrico insostenibile. Vengono considerati diversi scenari di efficienza per le reti di distribuzione dell'acqua, al fine di valutare possibili miglioramenti nella gestione delle risorse.

Oltre ai bisogni idrici, lo studio quantifica anche i relativi requisiti energetici, concentrandosi sull'osmosi inversa, la tecnologia più efficiente dal punto di vista energetico e la più adottata. Data l'elevata richiesta di energia per la desalinizzazione, un aspetto chiave dell'analisi è l'uso di fonti rinnovabili per alimentare gli impianti. Lo studio stima l'area necessaria per l'installazione di impianti fotovoltaici e agrivoltaici, confrontando queste esigenze spaziali con la disponibilità di terreni agricoli non irrigati adatti alla conversione in sistemi agrivoltaici.

I risultati indicano che, sebbene la desalinizzazione sia un metodo efficace per affrontare la scarsità d'acqua, l'elevata impronta energetica rende necessaria un'integrazione sostenibile con le energie rinnovabili. In generale, i sistemi agrivoltaici possono fornire l'energia necessaria. Lo studio evidenzia l'importanza di un approccio integrato, in cui desalinizzazione, energie rinnovabili e strategie efficienti di gestione dell'acqua lavorano insieme per garantire la sicurezza idrica a lungo termine.

ABSTRACT (ENGLISH)

Water scarcity is an increasing global challenge, driven by climate change, population growth, and unsustainable water consumption.

Desalination can be a viable solution to address this issue by providing an alternative water source where natural resources are insufficient. This study aims to identify the countries where desalination is essential and to quantify the amount of desalinated water required to meet demand sustainably.

The research is structured around a methodological framework that evaluates three key parameters: renewable water availability, water demand, and actual water use. Countries are classified based on their water balance, distinguishing between those that can meet demand sustainably and those experiencing blue water scarcity (BWS). For the latter, the study estimates the minimum desalinated water volumes required to prevent unsustainable water extraction. Multiple efficiency scenarios for water distribution networks are considered to account for potential improvements in resource management.

Beyond water needs, the study also quantifies the energy requirements for desalination, focusing on reverse osmosis (RO), the most energy-efficient and widely adopted technology. Given the high energy consumption of desalination, a key aspect of the analysis is the potential for powering desalination plants through renewable energy sources. The study estimates the land area required for photovoltaic (PV) and agrivoltaics (AV) installations, comparing these spatial demands with the available rainfed cropland suitable for agrivoltaics conversion.

The results indicate that while desalination is an effective means of addressing water scarcity, its large energy footprint necessitates sustainable integration with renewable energy. In general, agrivoltaics systems could provide the necessary energy while optimizing land use efficiency. The study highlights the importance of a combined approach, where desalination, renewable energy, and efficient water management strategies work together to ensure long-term water security in regions facing severe water stress.

INTRODUCTION

WATER SCARCITY

Water scarcity is a growing global crisis that affects billions of people and threatens ecosystems, economies, and social stability. According to the SDG 6 of the 2030 Agenda, adopted by all United Nations Member States in 2015, 2.4 billion live in water-stressed countries (in 2020) and 2.2 billion people do not have access to safely managed drinking water.

Furthermore, in 2022 (only 8 years before the SDGs achievement deadline) up to 3.5 billion people lacked safely managed sanitation and 2.2 billion lacked basic hand washing facilities.

In the very same year, it was estimated that, in order to meet the target of providing drinking water to everyone, the pace of progress should have been accelerated by six times.

This alarming situation is driven by many factors and sometimes by the combination of many, such as extreme poverty, inaccessible technologies, inaccessible water resources, inefficient water distribution systems, climate change, population growth, lifestyle changes (like increase of meat consumption) and unsustainable water consumption practices.

Population Growth and Increased Water Demand

The world's population reached 8 billion at the end of 2022 and is projected to reach 9.7 billion by 2050: this growth is bringing and will bring to a significant increase of water demand but not only due to a larger number of consumers. In fact, as economies grow and urbanization accelerates, the greater purchasing power and the change of lifestyle \will lead to an increase of water consumption per capita. Middle-class lifestyles, characterized by higher consumption of goods and services, have further escalated water use.

For example, the production of a single cotton shirt requires approximately 2,700 liters of water, while a kilogram of beef requires up to 15,000 liters. This rise in consumption emphasizes the need for effective water management practices to maintain balance.

Beyond population growth, climate change is exacerbating water scarcity by disrupting traditional weather patterns and altering the availability of freshwater. Prolonged droughts, reduced rainfall, and increasing evaporation rates are reducing the reliability of natural water sources, making it harder to meet growing demand.

Water scarcity and unsustainable water resource consumption

Water scarcity is one of the most pressing global challenges. Excessive water consumption, often surpassing natural replenishment rates, threatens water security in many regions. Agriculture, according to FAO, accounts for approximately 70% of global freshwater withdrawals, is a major contributing factor, particularly when inefficient irrigation practices or water-intensive crops are involved.

Beyond the immediate issues of scarcity, a more silent and insidious threat looms: the unsustainable use of non-renewable water resources.

In many regions, water consumption far exceeds the natural recharge capacity of aquifers, which supply nearly 30% of the world's freshwater. This over-extraction leads to the gradual depletion of underground reserves, causing land subsidence, reduced agricultural productivity, and geopolitical tensions over water access. A well-known example is Saudi Arabia, where half of total fossil water has already been exploited due to the expansion of agricultural activities in this and in the last century.

Without the adoption of sustainable water management strategies, the current consumption model risks irreversibly compromising future reserves, threatening food security, economic stability, and environmental sustainability for generations to come. It is therefore essential to promote responsible water use practices, improve efficiency in agricultural and industrial sectors, and implement fair and sustainable global water management policies.

Desalination as a Solution

Desalination involves removing salt and other impurities from seawater or brackish water to produce potable water. Over the past few decades, technological advancements have made desalination an increasingly viable solution to address water scarcity.

Modern desalination plants utilize techniques such as reverse osmosis (RO) and multi-effect distillation (MED), which have become more efficient and cost-effective. As of 2021, there were over 20,000 desalination plants globally, with a combined production capacity exceeding 100 million cubic meters of water per day.

The growth of desalination is driven by its ability to provide a dependable water supply independent of traditional sources like rivers, lakes, and groundwater. This reliability is particularly important in regions affected by climate-induced disruptions, prolonged droughts, or limited natural water reserves.

Through desalination, not only is it possible to provide water for areas of the world which currently are suffering water deficits, but it can also be possible to avoid situations of renewable water resources over-exploitation, by increasing the amount of water available in a certain area and consequently do not rely only on the local freshwater resources.

While desalination offers significant benefits, its adoption is not without challenges. High energy consumption remains a primary concern, as most desalination processes rely on fossil fuels, contributing to greenhouse gas emissions.

Additionally, the disposal of brine, a highly concentrated salt byproduct, poses environmental risks to marine ecosystems. These challenges necessitate continued innovation to improve energy efficiency and develop environmentally sustainable brine management methods.

The introduction of desalination as a viable solution to global water scarcity reflects the growing recognition of its potential to address one of humanity’s most pressing challenges.

By examining the situations of unsustainable water use and of water scarcity, it is possible to understand how much water should be desalinated and which impacts it would imply.

INTRODUCTION TO DESALINATION PLANTS

Desalination is the process of removing salts and minerals from saline water sources to make it suitable for human consumption, as well as domestic, industrial and agricultural use. [M. Di Martino et al.; 2021]

Although desalination offers human health and socio-economic welfares by providing reliable water supply irrespective of natural freshwater ecosystems and presenting relief from water stress and scarcity, many concerns are still raised due to the potential negative impacts.

Desalination has an impact on the environment in different ways and at different levels, such as brine production and high energy consumption and consequently also high emissions if the energy is not produced through renewable methods.

Desalination is either classified according to the desalination technology used or the feedwater source.
Feedwater type is separated into six categories according to DesalData (2018), each one characterized by a certain range of Total Dissolved Solids (TDS), expressed in ppm:

- Brine (BR): >50000 ppm TDS
- Seawater (SW): 20000–50000 ppm TDS
- Brackish water (BW): 3000–20000 ppm TDS
- River water (RW): 500–3000 ppm TDS
- Pure water (PW): <500 ppm TDS
- Wastewater (WW)

Despite having a typically low salinity, the desalination of RW is practiced for a range of different sectoral uses (e.g. drinking water, irrigation) to reduce water salinity below specific sectoral thresholds. PW as a feedwater source is typically used for industrial applications which require very high-quality water, such as the pharmaceutical and food production industries. [Jones et al.; 2019]

According to desalination technology, it can be classified into three main classes: membrane, thermal, and emerging desalination processes. The most common technologies currently working are reverse osmosis (a membrane process) and multi-stages flash and multi-effect distillation (both thermal)

Historically, thermal separation techniques were developed earlier, in the 1950s, indeed they were the primary method for purifying saline water. However, advancements in membrane technology have led to the growing popularity of membrane-based methods in the 1980s, particularly reverse osmosis desalination [Di Martino et al.; 2021].
Reverse osmosis plants are very versatile both in quantity and typology of feedwater used, while thermal desalination technologies are usually applied to large-scale plants to obtain high economic feasibility, and for water–power cogeneration, like in the case of GCC (Gulf Cooperation Council) countries [Jones et al.; 2019].

DESALINATION TYPOLOGIES

The main desalination technologies currently in use are thoroughly discussed in the 2021 paper by Curto, Franzitta, and Guercio. In the following pages, an overview of the various desalination systems is provided.

1 - Multi-Effect Distillation (MED)

The first Multi-Effect Distillation (MED) plant was realized in Kuwait in the 1950s and it was the first desalination technology implemented. However, this type of plant did not spread because it is particularly affected by the scaling problem on the pipes in comparison with other thermally supplied desalination technologies. Since the 1980s, research has focused on operating at lower temperatures to reduce scaling and corrosion, improving its viability.

MED systems operate by preheating saline water through heat recovery exchangers, which reuse energy from brine and freshwater streams. The water is sprayed onto evaporator surfaces in the first chamber, forming a thin film that facilitates boiling and evaporation due to the low pressure inside the chamber. Vapor generated in one chamber is condensed in the next, where the lower pressure enables further evaporation. This process is repeated across multiple chambers, extracting more freshwater and recycling thermal energy.

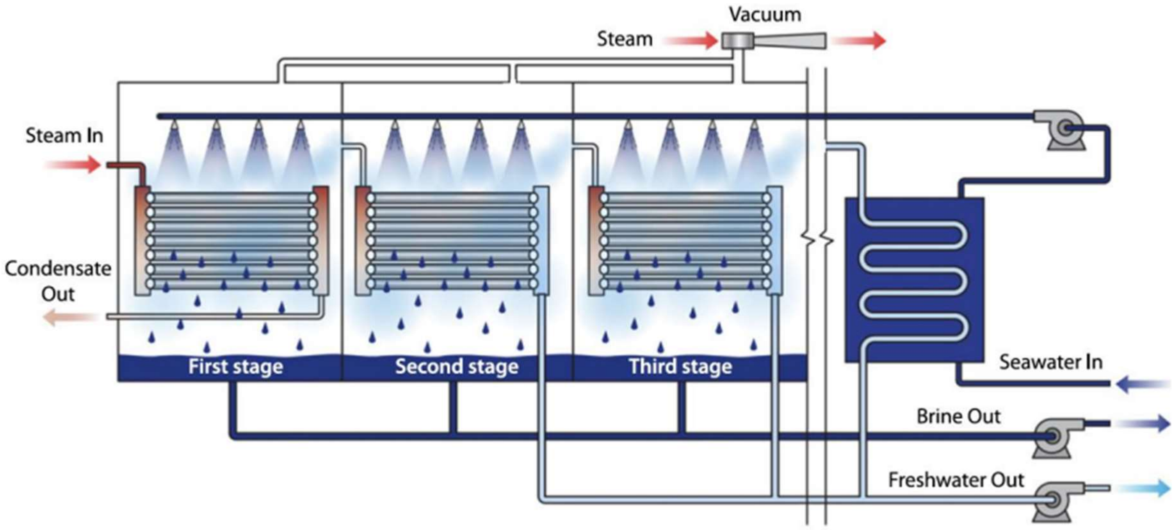


Figure 1: diagram of a Multi-Effect Distillation (MED) desalination unit

According to the Top Brine Temperature (TBT), MED can be classified as Low Temperature (below 90 °C) or High Temperature (over 90 °C).

Brine temperatures are kept below 120°C in order to avoid the calcium sulphate scaling, while the pressure in each chamber is maintained below atmospheric levels using a vacuum system.

Depending on the configuration, MED systems can have between 4 and 21 effects, with effects arranged in series or parallel lines to optimize heat recovery.

MED plants produce 2,000 to 20,000 m³/day of freshwater and are often combined with thermal or mechanical Vapor Compression units to enhance energy efficiency.

The largest MED facilities are found in China and the Middle East, where they play a crucial role in the water demand satisfaction. This technology is also currently used in the food industry to extract juice from sugarcane and to produce salt from seawater [Curto et al.; 2021].

2 - Multi-Stages Flash (MSF)

The first Multi-Stage Flash (MSF) desalination plant was built for the first time in Scotland in the 1950s. After a few years, it became the most widely used desalination technology.
This technology is usually used on ships and along coastlines in regions like the USA, the Middle East, and Korea to convert seawater into freshwater.

The MSF process is similar to the MED one: it relies on an initial heat source, typically steam from a power plant, and uses decreasing pressure to encourage vapor production.
The system can be divided into two main sections:

- Brine Heater section: feedwater is heated using steam from an external source.
- Heat Recovery section: recovery of thermal energy to preheat the incoming feedwater.

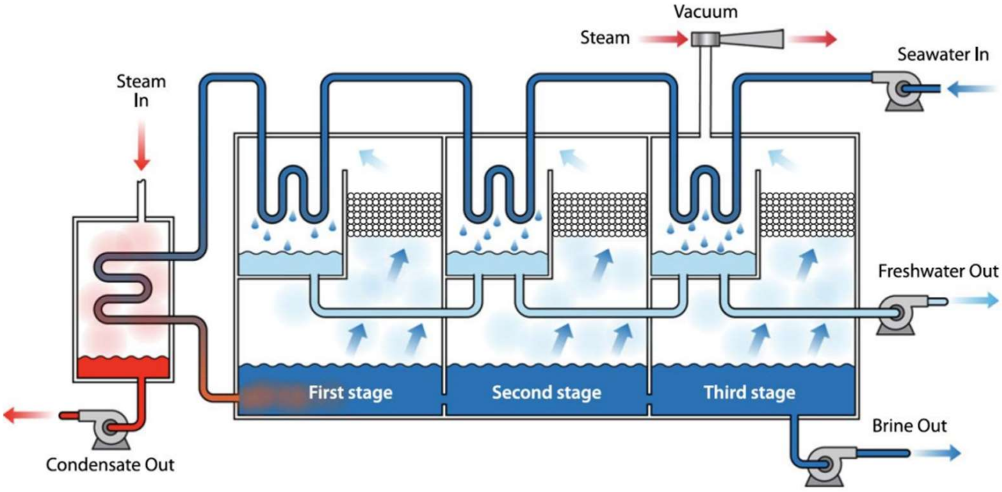


Figure 2: diagram of a Multi-Stages Flash (MSF) desalination unit)

The seawater is initially used in the plant as cooling water for the condenser before being used as the raw source for freshwater production, so the temperature of the feedwater increases gradually as it flows through pipes that form the heat exchangers in the flash stages.
Steam from a power plant heats the water in the brine heater, where it condenses outside the tube bundle and can be reused in the power plant.
Since the saline water flows through pipes during heating, maintenance to remove scaling is simpler compared to MED systems. This ease of maintenance has made MSF the most used thermal desalination method, accounting for 17.6% of global desalination capacity.
After heating, the saline water enters the first flash stage. Due to the pressure drop, the heated water boils rapidly (this is why it is called flash), producing vapor. The vapor condenses as the heat is absorbed by the cooler feedwater in the heat exchanger. The remaining brine flows into subsequent chambers, where the

pressure is further reduced in each stage, creating more vapor. Vacuum conditions are maintained using either steam ejectors or vacuum pumps.

MSF plants are typically made up of 15-25 flash stages, with larger plants having more stages to meet higher freshwater demands, ranging from 4000 to 57000 m³/day. The system operates at temperatures between 90°C and 110°C.

Recent advancements in MSF technology include the addition of heat rejection sections with two or three flash stages. In this setup, seawater is used as a cooling fluid, and part of it is mixed with brine from the final flash stage to improve energy efficiency. Modern MSF plants can have up to 40 flash stages, including heat rejection stages.

Over the past 20 years, MSF systems have become more reliable due to improvements in scaling control (using chemical additives), better materials, and automated control systems.

Like MED, MSF is widely used in regions with low-cost thermal energy, such as Saudi Arabia, the United Arab Emirates and Kuwait [D. Curto et al.; 2021].

3 - Vapor Compression (VC)

Vapor Compression (VC) desalination relies on the phase transition between liquid and vapor. There are two typologies of this process: the mechanical VC (MVC) and the thermal VC (TVC).

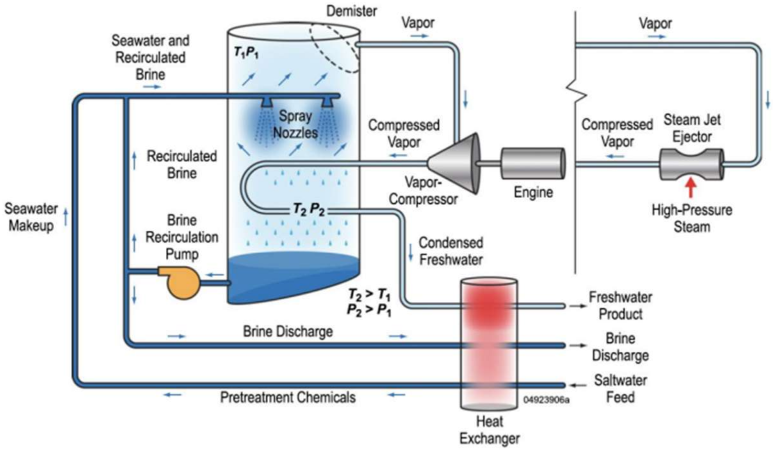


Figure 3: diagram of a Vapor Compression (VC) desalination unit.

MVC

Mechanical Vapor Compression (MVC) relies primarily on electricity to operate, making it suitable for small-scale standalone desalination units with freshwater production capacities ranging from 100 to 3,000 m³ per day.

After the feedwater is heated, the vapor produced inside the chamber is extracted with a vapor compressor. Due to the compression, the vapor increases its temperature and pressure. By raising the temperature and using a heat exchanger, the pressurized vapor can transfer heat to the saline water inside the chamber and produce vapor.

The energy consumption of the system is reduced with the utilization of an heat recovery exchanger, used to transfer heat from the brine discharge and the condensed freshwater to the incoming saline water. After preheating, the saline water is mixed with a recirculating brine flow and sprayed onto the main heat exchanger in the desalination unit.

TVC

In Thermal VC, instead of mechanical compression, a thermal compressor powered by high-pressure steam is utilized, typically sourced from a power plant.

TVC systems require both thermal energy (for compression) and electrical energy (to run circulation pumps). Sometimes, TVC units are integrated with MED systems, creating a hybrid solution known as a MED-TVC desalination plant.

In a TVC-MED setup, steam is used to create a vacuum in the condenser and the final stage of the MED system. The steam that meets saline water is condensed in the first effect and contributes to the freshwater output. This configuration is capable of meeting larger freshwater demands, typically between 10,000 and 30,000 m^3 per day [Curto et al.; 2021].

4 - Reverse Osmosis (RO)

Reverse osmosis is a desalination technology that works thanks to the use of semi-permeable membranes, which are specific layers allowing the passage only to selected molecules.

This method of desalination is named as such because it generates drinking water by reversing the natural process of osmosis: in nature, if two solutions with different concentrations of solutes are separated by a semi-permeable membrane, the solvent flows spontaneously from the more diluted solution to the more concentrated one, in order to balance the energy potential of both solutions.

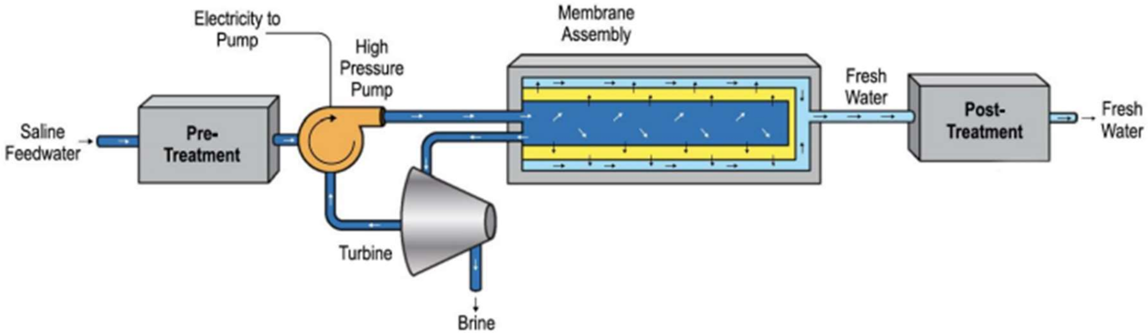


Figure 4: diagram of a Reverse Osmosis (RO) desalination unit.

As the external pressure gradient applied to the membrane increases, the flow is progressively reduced. The specific pressure gradient value at which the flow stops is referred to as osmotic pressure Δp_{OSM}.

So, if the external pressure gradient is greater than Δp_{OSM}, the solvent flow is inverted, and the solvent can be extracted from the concentrated solution.

For each solution the absolute osmotic pressure p_{OSM} can be defined according to van't Hoff's equation:

$p_{OSM} = \iota[c]R\tau$

Where:

- ι is the dimensionless van't Hoff index (also called the number of osmotically active particles)
- [c] is the molar concentration of the solute.
- R is the ideal gas constant equal to 8.31441 J $K^{-1}mol^{-1}$.
- τ is the absolute temperature of the solution.

In freshwater, the salt concentration is negligible, and consequently, its osmotic pressure is equal to the osmotic pressure of saline water, that has a salinity between 0.51 and 0.68 mol L^{-1}.
Assuming a water temperature of 25 °C, the osmotic pressure value is between 25 and 33 bar. However, there are also extreme cases, like the Dead Sea one, where Δp_{OSM} can reach 290 bar.

As already explained, if an external pressure gradient that exceeds the osmotic pressure is applied, freshwater is separated from saltwater. In desalination systems, pressures between 15 and 25 bar are typically applied for brackish water, while seawater requires higher pressures, ranging from 54 to 80 bar. In order to work, RO relies on electrical or mechanical energy to power the pumps that elevate seawater pressure before it passes through the semi-permeable membrane.
Before entering the RO desalination system, seawater undergoes pre-treatment to remove solid particles and is then pressurized by a high-pressure pump (HPP). In desalination, the Recovery Ratio (RR) is defined as the proportion of freshwater produced relative to the saline feedwater supplied:

$RR = Qf / Qs$

Under typical operating conditions, RR values range from 35% to 50%, so only about half (or less) of the seawater becomes freshwater, while the remainder is discharged as brine.

This means that for each liter of freshwater produced, also 1-1.5 liter of brine is produced too. Although increasing the pressure before the membrane could improve freshwater recovery, technical limitations, primarily the mechanical strength of the membrane, restrict this approach. Additionally, since semi-permeable membranes are not entirely efficient, a small amount of salt can still be present in the extracted freshwater.
The brine discharge retains significant energy potential because its pressure is nearly identical to the input saline water pressure. The pressure drop within the brine circuit is minimal, typically around 2-3 bar, highlighting its potential for energy recovery.
Since the 1970s, significant research has been conducted to minimize the energy consumption of desalination processes. Beyond improving the properties of membranes, a primary focus has been on recovering energy from the brine flow through the development of Energy Recovery Devices (ERDs). There are two ERDs typologies: centrifugal devices and isobaric devices [Curto et al.; 2021]

CENTRIFUGAL DEVICES

Among the centrifugal solutions, two key technologies have been developed. The first, introduced in the 1980s, involves the use of a Pelton hydro turbine. This turbine captures energy from the brine flow and transfers it to the high-pressure pump (HPP). To fully meet the pump's energy requirements, an electric motor supplements the system. The HPP raises the pressure of the entire saline feedwater flow [Khawaji et al.; 2008].

Pelton turbines, commonly used in hydropower for high heads (300–1000 m), transfer about 70% of the brine flow's energy to the feedwater. This limitation arises from the two-step energy conversion: from fluid to mechanical shaft and back to fluid [Shokri et al.; 2022]. Later in the 1980s, a more efficient centrifugal ERD was introduced: the turbocharger ERD.

The turbocharger system pressurizes saline water in two stages. Initially, an HPP driven by an electric motor handles the first stage, while a turbocharger device performs the second. The turbocharger comprises a hydro turbine and a directly coupled pump. This system improves energy efficiency compared to the Pelton turbine, as the turbocharger’s rotational speed can be independently controlled, allowing for better adaptability [Di Martino et al.; 2021].

ISOBARIC DEVICES

Isobaric devices are a more recent innovation designed to transfer energy from the brine flow to the saline feedwater flow directly, without intermediate energy conversions. This direct energy exchange enhances overall efficiency and reduces energy consumption in desalination processes [Curto et al.; 2021].

5 - Nanofiltration (NF)

Nanofiltration is a membrane filtration process designed to remove dissolved ions and organic matter, producing soft water with a reduced concentration of scaling ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). While similar in principle to reverse osmosis (RO), NF differs in its mechanism for ion removal from saltwater.

NF is utilized in various fields, including water and wastewater treatment, as well as pharmaceutical and food processing industries.

However, its application for seawater desalination is limited, as the semi-permeable membranes used in NF are more porous, allowing some dissolved solids to pass through. Indeed, the term "Nano" refers to the pore sizes of NF membranes, which range from 1 to 10 nanometers.

This size is smaller than those in microfiltration and ultrafiltration but larger than in RO membranes. Consequently, NF effectively removes divalent ions like Ca^{2+} and Mg^{2+} with an efficiency of 90% to 98%, while its efficiency for monovalent ions is lower, ranging from 60% to 85%.

Due to the higher ion concentration in NF-treated water compared to RO, NF membranes require a lower pressure gradient, typically between 34 and 48 bar. This lower energy demand makes NF an attractive option for seawater desalination, and research is ongoing to develop dual-stage NF systems for this purpose [Curto et al.; 2021]

6 - Electrodialysis (ED)

Introduced commercially in the 1970s, electrodialysis is an electrochemical desalination process that uses semi-permeable membranes and an electric field to remove dissolved ions from water.

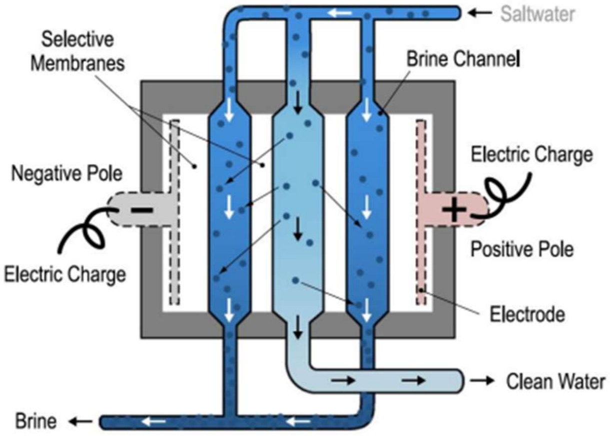


Figure 5: diagram of an Electrodialysis (ED) desalination unit.

The electrodes, powered by direct current, attract cations (e.g., Na^+, Ca^{2+}) to the anode and anions (e.g., Cl^-, HCO_3^-) to the cathode. Alternating anionic and cationic membranes selectively allow specific ions to pass, trapping them in brine channels and separating them from freshwater.

To prevent salt buildup, electrode polarity is periodically reversed, switching the roles of brine and freshwater channels. ED plants efficiently desalinate brackish water with salinity up to 2000 ppm (sea water is around 35000 ppm) [Curto et al.; 2021].

CURRENT SITUATION

Since its development in the 1950s, desalination has developed into a reliable method for ensuring water supply, driven by advancements in technology and improvements in cost efficiency.
Global desalination capacity has increased rapidly in the last 2 decades, rising from approximately 35 million m^3/day in 2005 to around 95.37 m^3/day in 2019 (34.81 billion m^3/year).
Of this total, 62.25% is utilized for municipal purposes, while 30.2% is dedicated to industrial applications. Although the municipal and industrial sectors dominate global desalination capacity, the power sector (4.8%) and irrigation sector (1.8%) also utilize a small but not negligible share of the desalinated water produced .

The Kingdom of Saudi Arabia (KSA) is the world's largest producer of desalinated seawater, accounting for 17% of the global capacity, equivalent to 17.2 million m^3 per day. Over the next two decades, KSA is projected to increase its desalination output by an additional 6 million m^3 per day. This process is powered by the combustion of the country's oil reserves: more than 1.5 million barrels of oil consumed daily to meet the energy demands of desalination [Jones et al.; 2019].

Desalination technologies diffusion and productivity worldwide

Regarding desalination capacity, the Middle East and North Africa (MENA) region, including the Gulf Cooperation Council (GCC) countries, account for 47.5% of the desalinated water, followed by East Asia and the Pacific at 18.4%, and North America at 11.9%. In terms of the number of desalination plants, these regions hold 30.3%, 22%, and 14.7% respectively of the global total, which were 15906 in 2019.

Desalination technologies are considered semi-specialized, as their efficiency and economic viability often depend on the type of source water they process. Consequently, certain feedwater-technology combinations are far more prevalent than others.

Early desalination plants primarily relied on thermal technologies, particularly in oil-rich but water-scarce regions like the Middle East. For instance, before the 1980s, 84% of the world's desalinated water was produced using the two major thermal technologies: MSF and MED.

However, the rise of membrane technologies after 1980 gradually shifted dominance away from thermal processes. By 2000, the global production of desalinated water was nearly evenly split between thermal technologies (dominated by MSF) and RO, with each contributing approximately 11.6 million m^3/day and 11.4 million m^3/day, respectively. Together, these technologies accounted for 93% of the total desalinated water production at that time.

Since then, the number and capacity of RO plants have grown exponentially, while thermal technologies have seen only marginal increases. Currently, reverse osmosis systems represent the 85% of total desalination plants and produce 65.5 million m^3/day, 69% of the total volume of desalinated water globally.

MSF and MED contribute approximately 18% and 7% of the global desalination capacity, respectively. However, they represent only 2.1% and 5.6% of the total number of desalination plants.

Together, RO and thermal technologies produce 94% of total desalinated water, the remaining 6% is composed by NF (3%), ED (2%) and others typologies of plants like VC (<1%) [Di Martino et al.; 2021].

Feedwater sources and technologies distribution

Seawater (SW) desalination represents 61% of the total desalinated water produced, reflecting its prevalence as a feedwater source and its quality. Brackish water and river water follow, contributing 21% and 8% of the global desalinated water output, respectively. Combined, these three sources account for 90% of the total production, while the remaining 10% comes from wastewater (6%), pure water (4%), and brine (<1%).

Reverse osmosis is an economically viable method for treating various feedwater sources, with the selection largely dictated by local resource availability. Approximately 50% of desalinated water from RO plants is sourced from seawater, while 27% comes from brackish water, corresponding to 34% and 19% of the global desalination capacity, respectively. Furthermore, river water (RW) contributes 7%, and wastewater (WW) accounts for 5%, both representing significant portions of the worldwide desalination output.

Thermal desalination technologies are predominantly employed for treating low-quality, highly saline feedwater. Nearly 96% of multi-stage flash plants and 80% of multi-effect distillation plants utilize feedwater with > 20,000 ppm of total dissolved solids (TDS), primarily drawing from seawater. In fact, sea water accounts for 99.9% of the desalinated water produced by MSF plants and 92% by MED plants, contributing to global market shares of 18% and 6%, respectively.

In contrast, electrodialysis plants typically require higher-quality feedwater with lower salinity levels. Desalinated water from ED plants is sourced predominantly from brackish water (60%) and river water (20%) [Di Martino et al.; 2021].

Reverse osmosis success

As previously mentioned, reverse osmosis is the most widely used desalination technology worldwide, offering significant advantages over thermal processes, such as higher energy efficiency, lower space requirements, and greater process and plant compactness. In particular, in the USA 88% of desalinated water is produced using this method. Most U.S. desalination plants treat brackish water (BW) and river water (RW), with only a few seawater desalination facilities located in California and Florida.

Globally, the choice of desalination technology varies by region, reflecting differences in energy availability, feedwater types, and infrastructure.

In the Middle East, thermal technologies such as multi-stage flash (MSF) and multi-effect distillation (MED) dominate seawater desalination. This is primarily due to the region's abundant and inexpensive supply of fossil fuels, which makes the energy-intensive thermal processes economically viable. Additionally, thermal plants are well-suited to handle the high salinity and extreme environmental conditions of the region. Inland, Saudi Arabia also hosts numerous large BW-RO plants, demonstrating a more balanced approach to technology use. Outside the Middle East, thermal plants are rare, and RO is the prevailing technology for desalination across a variety of feedwater types. For instance, Australia relies almost exclusively on RO to desalinate seawater, brackish water, and wastewater. In Western Europe, particularly Spain, RO dominates desalination efforts and is applied to diverse feedwater sources. However, alternative technologies like electrodialysis (ED) and nanofiltration (NF) are also widely used. In Asia, seawater reverse osmosis (SW-RO) is the primary technology in coastal areas, while numerous BW-RO and RW-RO plants operate inland [Di Martino et al.; 2021].

The main characteristic that has made RO the most successful desalination system is its relatively low energy requirement. While MSF, MED, and mechanical VC require at least 21, 15, and 7 kWh/m^3 respectively, current membrane plants consume just 3 kWh per cubic meter of water produced.

Furthermore, recent advancements in RO technology are reducing this value to below 2.7 kWh/m^3.

Given that energy consumption is one of the most critical aspects of desalination, this reduction makes RO even more attractive compared to thermal plants [Berenguel-Felices et al.; 2020]. Also, the use of renewable energy as a power source for desalination represents a promising avenue for innovation, particularly for membrane-based processes like RO, which generally have energy demands that can be met easier [Abdelkareem et al.; 2018].

Moreover, RO is a great desalination option because of the low water consumption that it requires: for each cubic meter of water produced, the system needs only $8.16 \cdot 10^{-3}$ m^3 of blue water. This means that RO is a freshwater gain process as the utilized freshwater amount is around 0.8% of the one produced.

Chemical cleaning of the RO membrane is the main contributor of water consumption, accounting for over 90% of the total water consumption.

Since the need for chemical cleaning is influenced by the quality of seawater, improving membrane quality and enhancing seawater pretreatment are key strategies for reducing the water footprint. [Zhang et al.; 2022]

PRETREATMENT

The main goal of the pretreatment process is to prepare the feedwater for the desalination stage that follows. Pretreatment steps are usually common regardless of the type of desalination, because high-quality feedwater substantially enhances the productivity and operability of the plant, reducing downtime duration and frequency.

Pretreatment plays a key role in preventing fouling, which can lead to increased energy demands to maintain the pressure required in the RO cases for sustaining plant output. In SWRO, pretreatment is primarily aimed at removing suspended and colloidal particles and is commonly carried out using coagulation, flocculation, and filtration, with various chemicals being introduced and seawater impurities being eliminated [Pramanik et al., 2017].

Chemicals used in pretreatment include coagulants such as ferric salts, aluminum salts, and polyelectrolytes. Biocides, primarily chlorine-based compounds like chlorine gas or sodium hypochlorite, are also employed to control biofouling.

However, in RO desalination plants, bisulfite salts must subsequently be added to neutralize free chlorine, as it can severely damage the membranes if not removed.

Acids, typically sulfuric acid, and anti-scalants are added during pretreatment to prevent the deposition of mineral salts like calcium carbonate and sulfate on membranes. Corrosion inhibitors are also included to reduce corrosion of metallic components [Elsaid et al., 2020].

Nonetheless, the use of stainless steel in membrane desalination is much lower than in thermal desalination, as corrosion-resistant polymeric materials are more commonly used [Eke et al., 2020].

Optimizing the pretreatment phase is essential for reducing the environmental impact of membrane desalination. Choosing the right chemicals and accurately determining their dosages play a critical role in minimizing the harmful effects of their discharge alongside the brine.

For example, biocides used to control biofouling can generate disinfection byproducts (DBPs) that are toxic to marine ecosystems and aquatic organisms, driving a move toward less harmful alternatives. Similar environmental concerns are related to anti-scalants, acids, and corrosion inhibitors, which can also negatively affect marine environments when released into the ocean with the brine [Elsaid et al., 2020].

REVERSE OSMOSIS ENERGY REQUIREMENT

Energy consumption is one of the main operating cost components of desalination plants, and so also one of its main critical aspects. Of course, the amount of energy required varies based on several factors, including the desalination method (membrane or thermal), the specific process employed (MSF, MED, VC etc.), the type of feedwater and its quantity (brackish or seawater), system recovery rates, plant capacity, and system design [Jones et al., 2019].

Additionally, the use of energy recovery devices significantly influences energy consumption, so energy consumption is highly case-specific [Werber et al., 2017].

Energy usage is typically expressed as specific energy consumption, measured in kWh per cubic meter of product water. The type of energy required also depends on the process.

For instance, thermal desalination relies on both thermal and electrical energy, while reverse osmosis systems require only electrical energy. Thermal desalination plants are often co-located with power plants, allowing them to share energy sources for both power and water production.

This integration improves overall energy efficiency [Dawoud et al., 2012]. In the end, the choice of desalination process greatly impacts energy requirements, influencing not only fossil fuel consumption but also associated factors such as greenhouse gas emissions, cooling needs, power plant size, and land use. In this work, only the energy requirements of reverse osmosis will be analyzed, as this technology is both the most widely used currently and by far the most adopted in recently built plants [Di Martino et al., 2021].

In the 1980s, the first RO plants were built and coexisted with thermal process desalination plants (mainly MVC at the time) and they immediately demonstrated significant advantages over the systems used up to that point. In fact, while MVC plants consume approximately 15 kWh/m³, the first RO systems required “only” 8–10 kWh/m³. Over time, advancements in energy recovery systems led to substantial reductions in the specific energy consumption of RO desalination.

Thanks to successive technological innovations, energy consumption for RO desalination has decreased to approximately 3 kWh/m³, playing a pivotal role in the dramatic expansion of production capacity. Today, reverse osmosis processes have been achieved under 2.7 kWh/m³, thanks to gradual improvements in energy recovery technologies and enhanced membrane efficiency, the core component of the desalination process [Berenguel-Felices et al., 2020].

For single-stage RO, the minimum specific energy can be simply represented as a function of feed salinity and system recovery as follows:

$SE_{MIN}\ (RR,\ p_{OSM}) = p_{OSM}\ /(1\text{-}RR)$

where: RR = recovery, p_{OSM} = osmotic pressure of feedwater.

Energy requirements for membrane desalination differ mainly on the feedwater sources, i.e., brackish water or seawater. Energy requirements for RO seawater desalination are usually higher, as it operates at higher levels of over 60 bars, in order to increase the production of freshwater.

In reverse osmosis desalination, the main energy consumption arises from feed pumps that generate the hydraulic pressure necessary for operation. However, a significant portion of this energy remains in the high-pressure brine flow exiting the RO unit. As already said in the desalination typologies section, energy recovery devices have been developed to harness this energy, allowing for partial recovery of the energy retained in the brine before discharge.

The use of renewable energy as a power source for desalination represents a promising avenue for innovation, particularly for membrane-based processes like RO, which generally have lower energy demands compared to thermal desalination methods.

Recent studies have explored integrating various renewable energy technologies, such as solar (both photovoltaic and thermal), wind, and geothermal energy, into desalination systems.

Advances in renewable energy technologies and the development of efficient energy storage solutions have expanded the potential for wider adoption of renewables in powering desalination processes [Berenguel-Felices et al., 2020].

Renewable energy

Initially, renewable energies were not efficient enough to meet the energy demands of large desalination plants. However, recent technological advancements now allow wind or solar plants to reliably supply the electricity needed for desalination processes. As a result, it has become common to award contracts for seawater desalination plants in combination with photovoltaic or wind energy installations.

For instance, in 2019, ACWA Power awarded the Taweelah desalination plant contract in the United Arab Emirates, with a reverse osmosis capacity of 909,000 m^3/day, alongside the construction of a 40 MW solar photovoltaic plant. In 2020, ACWA Power also awarded the construction of the Jubail 3A reverse osmosis plant in Saudi Arabia, which has a capacity of 600,000 m^3/day and is paired with a solar energy facility.

Saudi Arabia is currently the largest producer of desalinated seawater, accounting for 17% of the world's capacity (17.2 million m^3 per day).and in the next 20 years is expected to increase this production by 6 million m^3 per day. Currently, the country relies on the combustion of oil reserves to generate the energy required for desalination, consuming over 1.5 million barrels of oil per day. Each barrel of oil provides enough energy to produce approximately 5 m^3 of desalinated water. However, this heavy reliance on fossil fuels for desalination raises concerns about greenhouse gas (GHG) emissions.

Before 2016, the electricity generated from oil production was low-cost and subsidized by the government, but this support has been gradually reduced in recent years. This shift has spurred interest in using renewable energy for desalination, although only about 0.02% of global freshwater production from desalination is currently powered by renewable sources. Photovoltaic (PV) and solar thermal energy represent the majority of this small share, as these technologies are well-suited to the Middle East's abundant solar resources.

Given the region's dry, sunny, and remote conditions, renewable desalination is an ideal solution where no other power sources are available [Saeed et al.; 2021].

RO LAND FOOTPRINT

Land footprint is actually a really difficult aspect to estimate about desalination plants, because it can be very different regardless of the plant productivity.

For example, the Sorek plant in Israel, which produces 624,000 m^3 of water daily, occupies roughly 1 km^2, slightly less than the Torrevieja plant in Spain, which produces 240,000 m^3 per day and covers an area of 1.2 km^2.

Although both Sorek and Torrevieja are reverse osmosis (RO) plants, the design of each system and the type of membranes used significantly impact the overall land footprint.
However, there are general trends in the area occupied based on plant productivity. For instance, plants with a production capacity of 5,000-10,000 m^3/day typically require around 10,000 m^2 [A. Shokri et al.;2022], while plants producing 200,000-300,000 m^3/day require an area approximately 10 times larger [Einav et al.; 2003].

ENVIRONMENTAL IMPACTS OF MEMBRANE DESALINATION PROCESSES

The environmental impacts of desalination have been severely overlooked in the past century, with only 118 publications addressing the topic before 2000. Since then, however, research in this area has expanded rapidly, with nearly 2,000 new studies published after the turn of the millennium. [Edward Jones et al.; 2019]

The EIs of reverse osmosis desalination can be related to the following components:

- feedwater supply
- feedwater pretreatment
- desalination process
- energy requirement
- brine discharge

Among these, brine discharge is considered the primary source of environmental impacts (EIs) from desalination, as it contains most of the liquid waste and pollutants produced during the process, like chemicals from pretreatment, corrosion byproducts, filter backwash water, and concentrated brine from RO desalination. However, also the high energy requirements of desalination, being an energy-intensive technology, represent a significant contributor to environmental impacts. [Khaled Elsaid et al.; 2020]

Environmental impacts of brine disposal from RO desalination

Brine discharged from desalination processes is considered the major waste stream, both quantitatively and qualitatively.
In membrane desalination, the ratio of brine stream to the product water stream is in the range of 1 to 2 at 50 to 35% recovery, respectively, which is the common range for SWRO desalination.
This high volume of brine presents challenges for the expansion of desalination facilities and represents a significant share of the process's economic costs, ranging from 5-33%.

Although most brine is produced in coastal areas, with nearly 80% generated within 10 km of the shore, a considerable amount is produced in locations where discharging it into surface waters is impractical [B. K. Pramanik et al.; 2017].
Countries generating large volumes of brine are mainly located in the MENA region, Southeast Asia, USA and Australia. In many of these nations, brine production far exceeds 1 million m^3/day, particularly in the Middle East. Within this region, the four main producers, namely Saudi Arabia, UAE, Qatar, and Kuwait, collectively generate 72.2 million m^3/day of brine within 10 km of the coastline.
Seawater desalination plants are responsible for most of the brine production, contributing 124.5 million m^3/day, or 87.9% of the total. In contrast, plants treating other feedwater types produce significantly smaller volumes of brine: brackish water plants account for 10.23 million m^3/day (7.2%), river water plants for 1.80 million m^3/day (1.3%), and wastewater plants for 3.57 million m^3/day (2.5%).
Among individual processes, SW-MSF leads brine production, making up 43% of the total, followed by SW-RO (31%), SW-MED (12%), and BW-RO (7%), which together dominate global brine production [Edward Jones et al.; 2019].

The environmental impacts of brine on marine ecosystems and aquatic life are primarily attributed to factors such as salinity, temperature, acidity/alkalinity, heavy metal content, and residual chemicals.
An environmental impact assessment (EIA) is usually carried out during design stages in order to minimize and mitigate the EIs of desalination plants [Elsaid et al., 2020].

Thus with proper selection of plant location, intake and outfall locations, and design, these impacts can be reduced. It is important to highlight that the effects of brine temperature and pH on the environment are relatively minor, particularly in membrane desalination processes.
The temperature increase in the brine is minimal, with a maximum difference of 2 °C respect to the feedwater temperature. This slight increase is mainly due to heat generated by high-pressure pumps and friction within the RO module channels.

Regarding pH, the feedwater is slightly acidified in order to minimize scaling issues, and after the freshwater production, brine is usually neutralized prior to discharge and after it, thanks to the natural buffering capacity of seawater to mitigate any potential pH-related impacts.
Normally, acid dosage of 170 ppm/m^3 product water is usually applied to maintain a pH of 6.7, with the addition of about 67 ppm/m^3 NaOH for neutralization purposes [Khawaji et al., 2008].

Biocides, mainly chlorine compounds, are usually neutralized by the addition of sulfite compounds, such as sodium bisulfite and thiosulfate. This is primarily to protect the membranes due to their sensitivity to free chlorine: in fact, chlorine oxidizes the membranes functional groups, destroying their active layer.
Chlorine dose range from 1 to 1.4 ppm/m^3, which is followed by a dosage of sodium bisulfite to neutralize the free chlorine [Dawoud; 2012].

SALINITY

The salinity is considered the main aspect of brine stream that impacts the marine environment, as brine has 1.5–2 times the salinity of seawater fed to SWRO desalination plant at 35–50% recovery respectively, with salinity range of 65–85 g/l. Salinity represent a potential threat on marine environment in many different ways:

Physical impacts:

- Alteration of water column stratification caused by the development of convective currents resulting from density differences.

chemical impacts:

- Increases the salinity of the water at the receiving and mixing zone.
- Elevates sediment salinity due to the higher salinity and negative buoyancy of the brine.
- oxygen solubility reduced, and hence dissolved oxygen content.

biological impacts:

- Mortality of seawater organisms, when exceeds organisms' salinity tolerance.
- Changes benthic community structure and possible introduction of non-indigenous species
- Changes in the photosynthesis, metabolic and growth rates.

CHEMICAL ADDITIVES (coagulants, flocculants, anti-scaling agents)

Coagulants (ferric chloride and aluminum sulfate) and flocculants (polyelectrolyte) are utilized in order to eliminate suspended solids and removed after from seawater in multimedia filters followed by cartridge filters. Typical doses of 1-5.2 ppm/m^3 of ferric chloride and 0.2-1.4 ppm/m^3 of polyelectrolyte are added for SWRO desalination. Recently, ultrafiltration (UF) and nanofiltration (NF) have been adopted as pretreatment for RO desalination to improve the quality of feedwater and reduces membrane fouling.

Anti-scaling agents are usually added to control scaling by sparingly soluble salts. The most utilized compounds are: carbonates of calcium, carbonates of magnesium and sulfates of calcium, barium, and strontium.

The common dose used of these agents is around 1–3 ppm/m^3: this allows to maintain plant productivity and reduce downtime, especially at increased recovery. All of these chemical additives, if not removed from the brine discharge, can affect the environment in different aspects:

Physical impacts:

- water turbidity increasing due to suspended solids, which affects light penetration depth.

Chemical impacts:

- introduction of foreign chemicals in the marine environment
- light penetration depth affected by water discoloration due to iron salts used as coagulants

Biological impacts:

- increased mortality of seawater organisms due to intolerance to chemicals.
- metabolic and growth rates change due to the assimilation of chemicals and decreased light penetration depth.

DISINFECTION BYPRODUCTS (DBPs)

DBPs are generated because of the reaction of the free chlorine, injected for disinfection purposes, with natural organic matter in feedwater. This process generates chlorinated byproducts (CBPs), like trihalomethanes (THMs) and haloacetic acids (HAAs). Bromine, from bromide present in seawater, can form brominated byproducts (BBPs), where both CBPs and BBPs pose some ecotoxicity to aquatic life [Elsaid et al.; 2020]. However, the concentration of such DBPs is at levels of sub-micro to micrograms per liter, with specific toxicity to sensitive species, hence, minimizes its EIs [Miller et al.; 2015].

HEAVY METALS

The brine from RO desalination may contain also traces of chromium, nickel, copper, iron, molybdenum and some other heavy metals released due to corrosion. However, heavy metals contamination is usually not a big threat, as non-metal polymeric components and stainless steel are predominant materials in RO desalination plants. The following proximate concentrations for heavy metals have been calculated in SWRO brine, which are way lower than acute and chronically toxic concentration levels for marine species [Soliman et al.; 2021]:

- copper 15 ± 20% μg/l
- chromium 3.5 ± 20% μg/l
- nickel 3 ± 20% μg/l
- iron 0.4 ± 20% μg/l
- molybdenum 0.13 ± 20% μg/l

Current brine disposal strategies

In order to minimize all the EIs that have just been shown, brine must be submitted to proper management. The removal of contaminants is necessary to ensure safe disposal into open water bodies or to enable the beneficial use of reclaimed brine solutions.

Various conventional treatment schemes have been used for the treatment of brine, including chemical precipitation coagulation, oxidation, and biological processes, either alone or in combination [Curto et al.; 2021].

Once properly treated, brine can be disposed of using various methods, including surface water discharge (the most common and cost-effective approach), deep well injection, land application, evaporation ponds, and conventional crystallizers.

These different methods are described in the study of Biplob Kumar Pramanik, Li Shu, and Veeriah Jegatheesan, published in 2017.

The selection of the appropriate disposal method depends on several factors, such as brine volume and quality, geographical location, site availability, environmental regulations, public acceptance, and associated costs. Disposal expenses typically constitute between 5% and 33% of the total operating costs, depending on brine characteristics, the level of treatment required prior to disposal, and the chosen method.

SURFACE WATER DISCHARGE

Discharging brine into surface water bodies, including seas, rivers, lakes, and lagoons, is among the most common and cost-effective management practices.

Since nearly half of the brine is produced within 1 km of the coast, and almost 80% within 10 km, discharging brine is considered the dominant global method for brine management.

The expenses for this method include transporting the brine to the outfall site, constructing and operating the outfall infrastructure, and monitoring the environmental effects, such as assessing water quality, because coastal desalination plants often directly discharge brine into the sea.

Mitigation measures, such as using diffusers, mixing zones, and blending brine with seawater or treated wastewater, can help reduce salinity and minimize environmental impacts.

There are also some plants that mix brine with power plant cooling water or municipal wastewater to dilute its salinity before discharge. However, concerns remain about the long-term effects of elevated salinity and temperature on marine ecosystems, particularly on dissolved oxygen levels and so on aquatic life.

DEEP WELL INJECTION

This strategy consists in injecting the brine into deep, porous aquifers located beneath freshwater sources. It is a process that is often used for the disposal of industrial, municipal and liquid hazardous waste, and it depends on having suitable geological conditions.

This method is suitable for brine without significant concentrations of heavy metals or monovalent cations, as it avoids their precipitation before disposal.

Even if this is a very effective solution, deep well injection requires thorough geological assessments, including identifying a suitable site and ensuring long-term stability.

The capital and operational costs of this method are relatively high, and challenges such as corrosion and potential leakage into groundwater can pose risks. For these reasons, deep well injection method is usually adopted only when other disposal options are unavailable.

LAND APPLICATION

Land application consists in a reuse of the brine discharge by applying it to salt-tolerant vegetation, such as lawns, parks, or golf courses.

This process can provide a beneficial use where vegetation may require certain nutrients, but is subject to several conditions, including the availability of land, the cost of installation and operation of irrigation systems, the salinity tolerance of target plants, and the need to meet groundwater quality standards.

Excessive salinity can negatively impact soil structure, reducing permeability and crop yield and can also contaminate underground aquifers. To mitigate these effects, brine can be blended with freshwater to lower salinity levels, making it suitable for agricultural use.

EVAPORATION PONDS

Evaporation ponds have been widely used for brine disposal in many arid and semi-arid areas because they utilize solar energy to evaporate water from brine, while precipitated salts accumulate on the ground. This system is simple, cost-effective, easy to construct and requires minimal maintenance compared to mechanical systems.

Usually, the ponds are built in series to ensure uninterrupted operation. This technology has been practiced in many countries including Australia, Israel, the Middle East and the USA, where 6% of the desalination plants were using this process up to 1993 and only 2% were using it after 1993.
This reduction was mainly caused by the increase in land price, as this process requires a large land area. However, the efficiency of this strategy depends also on climate characteristics, such as temperature and humidity, that affect the evaporation rate of the brine.
Environmental concerns of evaporation ponds include the potential for groundwater contamination and land use competition, especially in regions where land prices are high.
Improvements in pond design and operation can enhance evaporation rates, reducing the required land area and making this method more viable in various regions.

CONVENTIONAL CRYSTALLIZERS

Recovery of metals from brine provides a promising solution to address disposal challenges while offering economic benefits: by extracting rare and valuable components from brine can reduce the environmental impact of brine disposal are reduced and the overall economics of the process are improved.

Brine crystallizers are employed in the final stages of brine disposal systems but are more expensive compared to the other methods. However, when evaporation pond construction costs are high, solar evaporation rates are low, or deep well injection is expensive, crystallizers are a viable option. Crystallization can be combined with evaporation ponds in order achieve zero liquid discharge, making it a viable option despite the need for further economic analysis.

STATE OF THE ART AND RESEARCH GAP

The growing global water crisis has made desalination a crucial area of research, not only for its technological implications but also for its role in addressing scarcity of freshwater. Blue Water Scarcity (BWS), defined as the shortage of renewable water resources relative to demand, affects many regions worldwide, driving the need for sustainable solutions.
Desalination is one of the most viable strategies to mitigate BWS, yet its high energy demand remains a major challenge, particularly in regions with limited access to affordable energy sources.

Numerous studies have analyzed the energy requirements and environmental impacts of desalination, comparing different technologies and exploring potential future improvements in the field. These include possible integrations with renewable energy systems such as solar, wind, geothermal, and ocean energy. Given that desalination is an energy-intensive process, researchers have focused on mitigating its energy demands and identifying strategies to make it a more sustainable technology.

For instance, the Argyris Panagopoulos' study of 2021 explores different desalination technologies and their compatibility with renewable energy. It identifies reverse osmosis (RO) as the most energy-efficient method but also emphasizes that its sustainability depends on the energy source used. The study highlights that desalination's reliance on fossil fuels undermines its environmental benefits and stresses the importance of transitioning to renewable-powered systems to reduce carbon emissions and operational costs.

Another significant work, conducted by study by Zolghadr-Asli et al. and published in 2023 examines the role of desalination in agriculture, a sector that accounts for a major share of global freshwater consumption. It argues that while desalination can support food production in water-scarce regions, its long-term viability depends on sustainable energy use. The study proposes an integrated approach that balances water, energy, and food security to ensure that desalination does not create additional stress on energy resources or increase greenhouse gas emissions.

Zhenyu Li et al., in their study published in 2018 present an innovative approach to powering desalination plants using ocean-based renewable energy. This research outlines the potential of wave and tidal energy as sustainable energy sources that could mitigate desalination's environmental footprint while ensuring continuous operation. The study acknowledges that while ocean energy offers great potential, it remains underdeveloped and requires further investment in technology and infrastructure to become a commercially viable alternative.

Another particularly relevant study, conducted by Esmaeilion et al. (2021), investigated the combined use of desalination with solar, wind, wave, and geothermal energy in arid regions of Iran. This study assessed Iran's current desalinated water production capacity and calculated the country's total energy requirements for expanding desalination operations.

By analyzing geographical and climatic characteristics, the study identified optimal locations for renewable energy production and suggested a region-specific strategy to maximize efficiency. The study concluded that while Iran has significant potential to integrate renewables into its desalination infrastructure, additional investments in energy storage and grid connectivity would be necessary to ensure long-term sustainability.

While previous studies have provided valuable insights into desalination technologies, the integration of renewable energy, and practical examples of water scarcity mitigation through desalinated water, a critical gap remains in the literature: a comprehensive global assessment of the interplay between these three aspects.
This research aims to bridge that gap through a multidimensional approach that comprehends:

1. A global analysis of blue water scarcity (BWS), identifying regions where desalination is essential for water security and categorizing countries based on their water demand and availability.
2. A precise quantification of desalinated water requirements, determining the exact volumes needed to prevent BWS conditions on a national scale for every country worldwide.
3. An assessment of energy demands of desalination, considering the most efficient desalination plants (RO) and evaluating their compatibility with photovoltaic energy production.
4. The integration of agrivoltaics systems to optimize land use efficiency while simultaneously addressing energy and water scarcity in a sustainable manner, followed by a comparison between the total non-irrigated cropland convertible to agrivoltaics in each country and the required agrivoltaics area needed for desalinated water production.

Unlike previous studies that primarily focus on energy consumption, this research not only assesses the energy footprint of desalination but also proposes realistic and scalable solutions to enhance its sustainability.
It does so by incorporating country-specific factors such as energy availability and land constraints.
Specifically, this study estimates, at a national scale, the minimum volume of desalinated water that each country worldwide would need to produce in order to avoid falling into a BWS state.
The corresponding minimum energy demand to do so are then quantified and, in the case of photovoltaic and agrivoltaics energy use, the minimum land area required to generate this energy sustainably.

Finally, by comparing the land requirements for agrivoltaics systems with the actual areas that could be converted for such use, this study evaluates whether desalinated water production could feasibly be powered by solar energy in each country.

METHODS

COUNTRIES CLASSIFICATION

The aim of this study is to identify the countries where desalination is essential to meeting water demand sustainably and to quantify the necessary volumes of desalinated water required.
The study then estimates the amount of energy these countries would need to desalinate the required water volume and assesses the land area required if this energy is generated using photovoltaic and agrivoltaics systems.
Finally, the agrivoltaics spatial requirements are compared with the rainfed cropland where each country can implement an agrivoltaics system.

The assessment of each country's desalinated water need was based on three key parameters: renewable water resources availability (AVLB), water demand (DEM) and water consumption or water use (USE).

Renewable water resources availabiliy (AVLB):
Availability refers to the amount of renewable water a country can exploit annually, so the water volume that can be used without jeopardizing future resources. It also includes the share of renewable water sources from transboundary bodies, as allocated under international agreements with neighboring countries.

Since availability is considered in terms of renewable water exploitable for human consumption, the AVLB values must also account for the portion of renewable water resources that must be preserved to sustain ecosystems, known as Environmental Flow Requirements.

Water demand (DEM):

Represents the volume of water required for a country in order to meet agricultural, industrial, and municipal activities. This parameter is crucial for assessing the need for desalination in a country, as if it exceeds the available renewable water resources (AVLB), it indicates that the country lacks sufficient resources to meet its needs sustainably.
The situation where DEM > AVLB is known as Blue Water Scarcity (BWS).

Water consumption (USE):

Represents the actual consumption of water resources, both renewable and non-renewable, used to meet the water demand.
A country with a 100% water distribution efficiency, meaning no water losses during transport, could have an actual use equal to its demand to satisfy it.
Naturally, a country aiming for sustainable water usage must have water withdrawal lower than the availability of renewable water resources (AVLB), while still striving to meet its water demand.

There are six possible combinations of these three parameters, corresponding to a specific country situation:

1) AVLB > USE > DEM – SUSTAINABLE SITUATION

The use is lower than the availability but higher than the demand, so the demand is satisfied at a sustainable rate

2) USE > AVLB > DEM – OVEREXPLOITATION

The use is enough to satisfy the demand, but it is higher than the availability, so the demand is satisfied at an unsustainable rate.

However, the demand is lower than the availability, so improvement in the water distribution system could allow decrease the water consumption and reach the optimal situation AVLB > USE > DEM.

3) AVLB > DEM > USE – ECONOMIC WATER SCARCITY (EWS)

In this case, the water demand is not met, even though the availability of RWR is sufficient to satisfy it sustainably. However, the actual water use remains significantly lower due to limited access, inadequate infrastructure, and economic or institutional barriers. Indeed, this situation is usually known as Economic Water Scarcity.

4) USE > DEM > AVLB – BWS WITH DEMAND SATISFACTION

This situation, like the next two, represents a case of blue water scarcity (BWS), where the availability of RWR is lower than the required demand. This means that regardless of improvements in water distribution efficiency or the full exploitation of available resources, countries facing this challenge will never be able to meet their water demand in a sustainable way.

In this case in particular, the demand is satisfied, but obviously at a non-sustainable rate.

5) DEM > AVLB > USE – BWS WITH POSSIBLE IMPROVEMENT

In this BWS scenario, water use is lower than both the demand and the available RWR. As a result, while the demand cannot be sustainably met, water withdrawals could still be increased without compromising resource availability. This situation represents both BWS and economic water scarcity, as part of the DEM-USE gap is due to limited access, infrastructure constraints, or economic and institutional barriers, rather than an absolute lack of water.

6) DEM > USE > AVLB – BWS WORSE SCENARIO

This scenario is the exact opposite of the optimal one, indeed it presents three major issues: the water demand is not met, it cannot be met sustainably, and water use exceeds the availability of RWR. In this case, water resources are being overexploited, yet the extracted amount is still lower than what is needed.

DATA SOURCES

DEM

Water demand values have been calculated as the sum of the monthly demands from the domestic, irrigation, livestock, electricity, manufacturing, and mining sectors, provided by the study *"Global Monthly Sectoral Water Use for 2010–2100 at 0.5° Resolution Across Alternative Futures"* by Zarrar Khan et al.

These demand values are expressed in km³/year and represent the average over the period 2010–2020 for the SSP2 RCP4.5 scenario, averaged across all climate models used by the dataset's authors.

USE

The values for water use have been assumed to be equal to the 2020 Total Water Withdrawal data provided by AQUASTAT, the FAO's Global Information System on Water and Agriculture.

Total water withdrawal is defined as the annual quantity of water withdrawn for agricultural, industrial, and municipal purposes and is expressed in km³/year.

AVAILABILITY

The evaluation of the renewable water availability starts by considering the 2020 Total renewable water resources (TRWR) values provided by AQUASTAT, expressed in km³/year.

Total RWR is defined in Aquastat as the sum of internal renewable water resources and external renewable water resources (ERWR). In the remark of definition the following two points are also reported:

1. [Total renewable water resources] = [Total renewable surface water] + [Total renewable groundwater] - [Overlap between surface water and groundwater].
2. It corresponds to the maximum theoretical yearly amount of water available for a country at a given moment.

To better clarify what the total RWR includes, the definitions of external and internal RWR are also provided:

Internal Renewable Water Resources (IRWR): long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation. Double counting of surface water and groundwater resources is avoided by deducting the overlap from the sum of the surface water and groundwater resources.

External Renewable Water Resources (ERWR): that part of the country's long-term average annual renewable water resources which are not generated in the country. It includes inflows from upstream countries (groundwater and surface water), and part of the water of border lakes and/or rivers.

An important aspect to point out is that the ERWR considers the quantity of flow reserved by upstream (incoming flow) and/or downstream (outflow) countries through formal or informal agreements or treaties. This is a crucial point, as it underscores that the total RWR values already account for existing constraints and agreements that limit the exploitation of transboundary water resources, such as the Nile, Danube, and Indo rivers, which flow through 11, 10, and 4 countries, respectively.

AVLB evaluation - environmental flow requirements issue

Unfortunately, the total RWR values downloaded alone are not enough to evaluate the real availability of renewable water resources. Indeed, they do not consider an important aspect: the environmental flows requirements (EFR). According to FAO, the EFR are defined as the quantity and timing of freshwater flows required to sustain ecosystems, and the human livelihoods and well-being that depend on them.

Therefore, the actual amount of water that each country can sustainably exploit is lower than the total RWR values reported by Aquastat.

However, the FAO dataset also provides EFR data for countries worldwide, except for a few but crucial nations. These values are expressed in km³ per year, like water availability and withdrawal.

The main issue with these data, aside from the absence of values for all countries in the Arabian Peninsula, Libya, and Uzbekistan (regions generally located in desert areas with low precipitation and limited water resources) is that the reported EFR are determined by individual nations, not necessarily on a real environmental analysis. Therefore, these values may not accurately reflect the actual needs of the ecosystems that depend on them: the EFR given could be way lower than the theoretical ones.

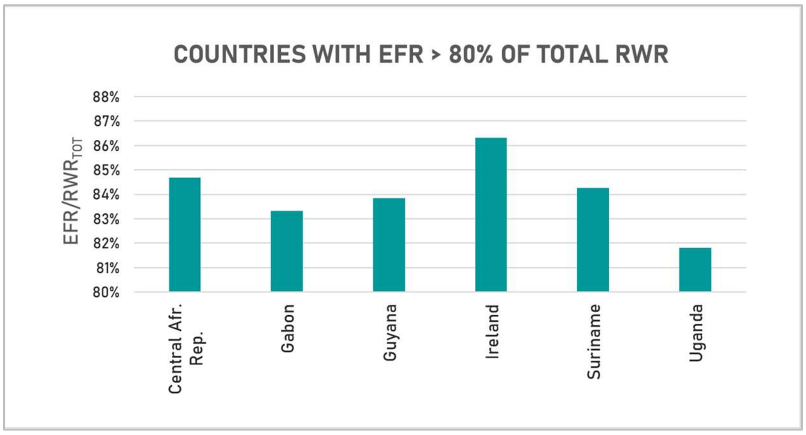
However, the ‘correct’ global EFR values can be easily estimated thanks to an index provided by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA): the Water Exploitation Index Plus (WEI+).
This index is defined as the level of water stress expressed as the ratio between water consumption, which is the withdrawal of water net of returns, and the natural availability of renewable water resources, for a given time period and a specific territory. According to ISPRA, a WEI+ greater than 20% indicates a situation of water stress, while a WEI+ greater than 40% indicates a situation of severe water stress. [G. Braca et al.; 2023]

Therefore, to prevent a situation of severe water stress, the environmental flow requirements should be at least 60% of the total renewable water resources. To avoid even 'normal' water stress scenarios, this value should rise to 80%.

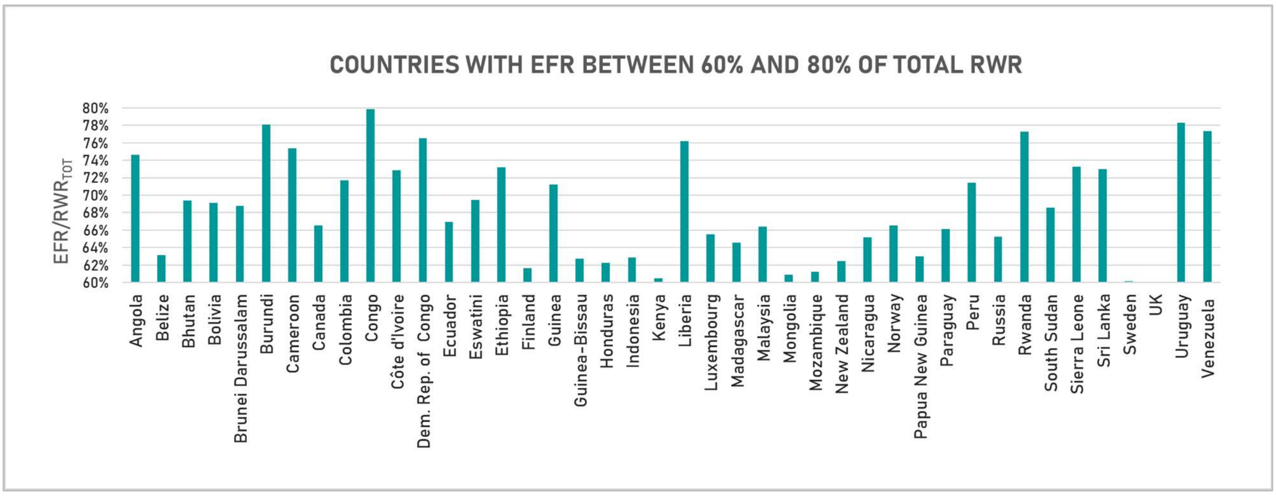
According to the data provided by AQUASTAT, most of the countries do not respect these thresholds.
By calculating the ratio between the EFR and total RWR, it was found that in some extreme cases environmental flows are even lower than 10% of renewable water availability, as seen in countries like Egypt (5%) and Jordan (4%).

Furthermore, another very interesting aspect emerged from the data downloaded: there are many different countries that are not in a blue water scarcity situation with the current environmental flows, but even with very low WEI+ values would end up in that scenario: it is the case of Palestine (29.15%) and Egypt (25.75%). However, even excluding these few extreme examples, many countries would suffer a BWS state by respecting the EFR suggested by ISPRA, or even less restrictive values.

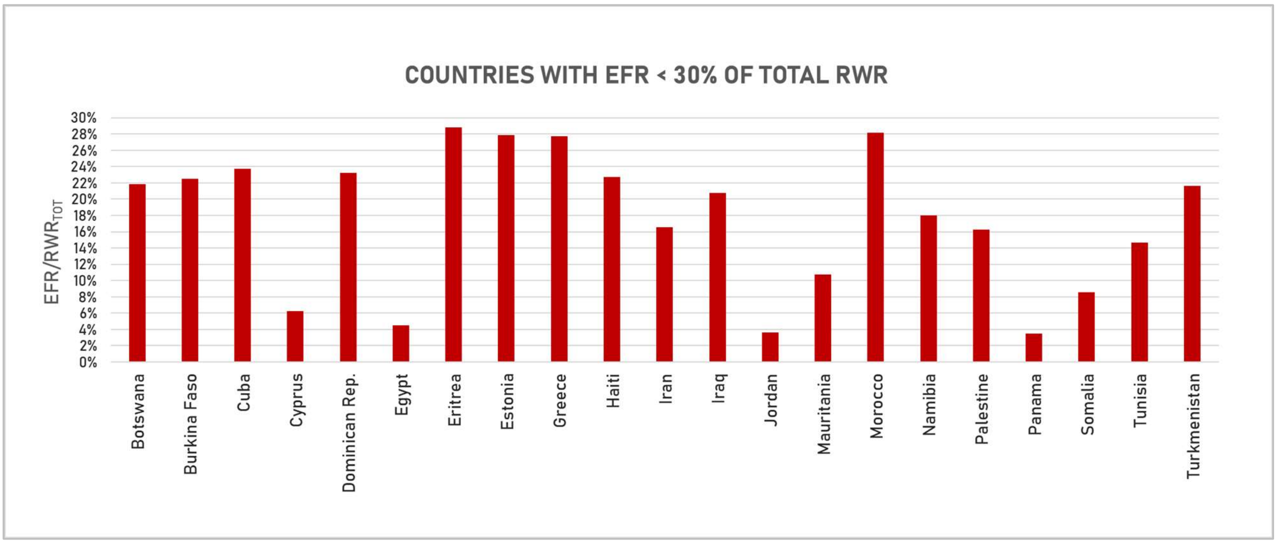
The countries which are currently not in a water stress situation and in a severe water stress situation are reported in graphs 1a and 1b respectively, while in graph 2 the countries with EFR lower than 30% of their RWR_{TOT} are shown.



Graph 1a: EFR/RWR_{TOT} ratio of countries with an EFR/RWR_{TOT} ratio higher than 80%



Graph 1b: EFR/ RWR_{TOT} ratio of countries with an EFR/ RWR_{TOT} ratio between 60% and 80%



Graph 2: EFR/ RWR_{TOT} ratio of countries with an EFR/ RWR_{TOT} ratio lower than 30%

The assessment based on DEM, USE, and AVLB has been conducted for three different scenarios: considering the actual EFR and considering the ones that, according to WEI+ ISPRA index, avoid the situation of water stress and severe water stress. Therefore, the AVLB values have been estimated for each country as:

- Actual situation: $AVLB = RWR_{TOT} – EFR$
- Severe Water Stress situation: $AVLB = RWR_{TOT} \cdot 0.4$
- Water Stress situation: $AVLB = RWR_{TOT} \cdot 0.2$

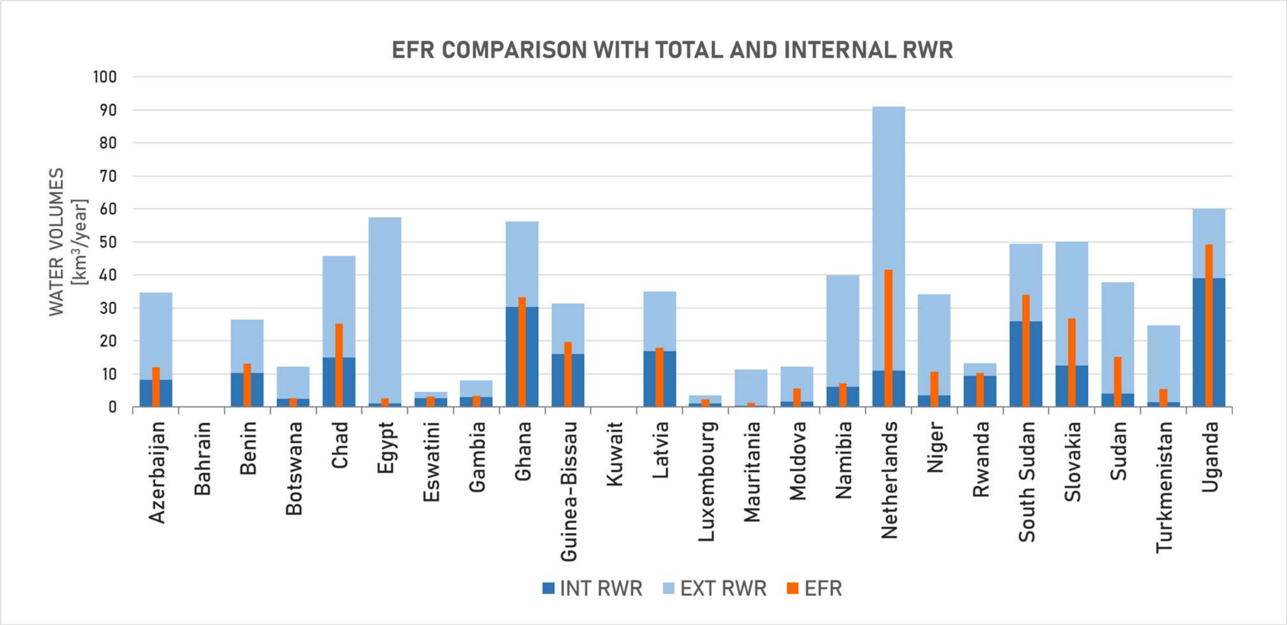
The problem with the evaluation of AVLB for the actual situation is that EFR values are not available for certain countries, specifically: Bahrain, Jamaica, Kuwait, Libya, Oman, Qatar, Saudi Arabia, the United Arab Emirates, Uzbekistan, and Yemen.

The EFR/RWR_{TOT} ratios for the Arabian Peninsula countries have been assumed equal to Jordan's ratio (4%), as Jordan is the closest country with comparable conditions. Similarly, Jamaica and Uzbekistan ratios have been assumed equal to the one of Cuba (24%) and Turkmenistan (22%) respectively.

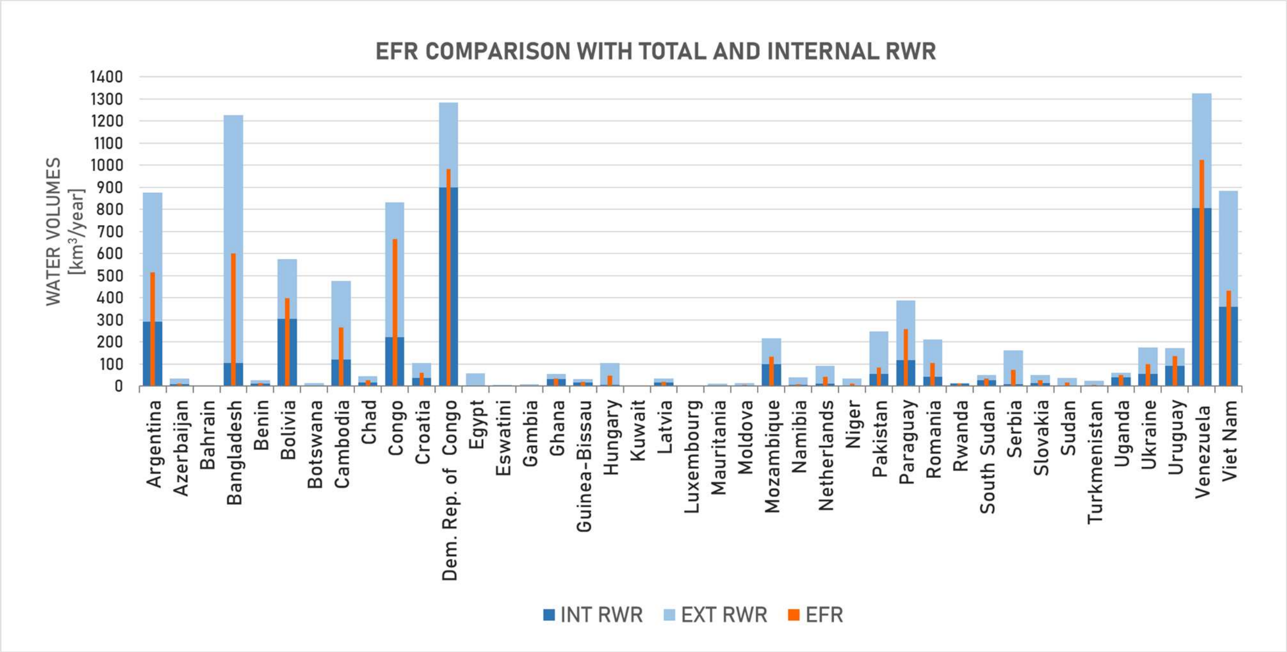
For Libya, the ratio has also been assumed equal to the Jordan one, because the closest countries, Algeria and Egypt, have significantly different ratios (39% and 5%, respectively). Additionally, Libya shares similar environmental conditions with the Arabian Peninsula and Jordan.

The AVLB values are evaluated by subtracting the EFR are subtracted from the RWR_{TOT} provided by AQUASTAT. This is because, as previously mentioned, the total renewable water resources account for the flow reserved by upstream and/or downstream countries through formal or informal agreements or treaties. Therefore, it is not necessary to consider only the internal water resources and avoiding the external one, and consequently calculate AVLB as $RWR_{INT} – EFR$.

Furthermore, there are 41 countries that, in the actual situation, have environmental flow requirements which are higher than the amount of internal renewable water resources, therefore they would be in BWS even without a water demand. The values of RWR_{INT}, RWR_{EXTT}, RWR_{TOT}, and EFR of these 41 countries are shown graphically in the graphs 3a and 3b.



Graph 3a: EFR and RWR_{TOT} comparison for countries with EFR > internal RWR



Graph 3b: EFR and RWR_{TOT} comparison for countries with EFR > internal RWR – focus on countries with total RWR < 100 km3/year

AVLB evaluation - AQUASTAT withdrawal definition issue

Another problem with the calculation of the AVLB values is actually related to the AQUASTAT withdrawal data (the USE values). Total water withdrawal is defined in the AQUASTAT glossary simply as the "Annual quantity of water withdrawn for agricultural, industrial and municipal purposes".

However, in the 'term detail' section there is also the following remark:

1. [Total water withdrawal] = [Municipal water withdrawal] + [Industrial water withdrawal] + [Agricultural water withdrawal]. It can include water from renewable freshwater resources, as well as water from over-abstraction of renewable groundwater or withdrawal from fossil groundwater, direct use of agricultural drainage water, direct use of (treated) wastewater, and desalinated water.

Therefore, the values considered as uses do not only comprehend the consumption of conventional water, being it renewable or not, but also include non-conventional sources, such as desalinated water and treated wastewater, as well as non-consumptive uses, like the direct use of agricultural drainage water.

The non-conventional water direct uses are defined, according to AQUASTAT, as:

- Direct use of agricultural drainage water: agricultural drainage water is water withdrawn for agriculture but not consumed and then returned.
- Direct use of non-treated municipal wastewater for irrigation purposes: municipal wastewater applied artificially (irrigation) and directly (i.e. with no or little prior dilution with fresh water during most of the year) on land to assist the growth of crops and fruit trees
- Direct use of treated municipal wastewater for irrigation purposes: treated municipal wastewater applied artificially (irrigation) and directly (i.e. with no or little prior dilution with freshwater during most of the year) on land to assist the growth of crops and fruit trees.
- Desalinated water produced: water produced annually by desalination of brackish or salt water. It is estimated annually on the basis of the total capacity of water desalination installations.

Since the evaluation of each country's situation relies on the combination of their DEM, USE, and AVLB values, it is crucial to consistently compare these three parameters. Indeed, by comparing these values, this study primarily aims to understand which countries can meet their water demand with the renewable water resources available to them, whether this demand is currently being met, and if it is done in a sustainable way.

For instance, when comparing water use and demand, considering only conventional water resources (whether renewable or not) would be misleading.

In many cases, this approach would suggest that demand is unmet, while in reality it is often fulfilled through alternative sources such as desalination or treated municipal wastewater. Therefore, in this comparison, water use values should align with the withdrawal values reported by AQUASTAT.

However, when assessing the relationship between water use and availability, it would not be possible to accurately determine when the consumption is unsustainable simply by considering AVLB = TOT RWR – EFR.

This is because withdrawals comprehend also non-consumptive activities, where water is eventually returned to the environment, as well as non-conventional resources, which are not accounted for in total RWR values. So, sometimes use could be higher than availability, but this does not necessarily mean that it is unsustainable, because the amount of conventional water resources alone could be lower than AVLB.

In the end, to determine whether USE is sustainable, both AVLB and USE must account for the same types of water resources, either only conventional ones or both conventional and non-conventional.

However, since USE includes non-conventional resources to allow a fair comparison with demand, availability must also incorporate them to ensure consistency.

AVLB values are so evaluated as the result of the following calculation:

- If municipal treated wastewater reused > municipal treated wastewater reused for agriculture:
  $AVLB_{TOT} = RWR_{TOT} + W_{DRAINAGE} + WW_{T} + WW_{NOT\ T\ FOR\ AGRI} + W_{DESAL} - EFR$
- If municipal treated wastewater reused for agriculture > municipal treated wastewater reused:
  $AVLB_{TOT} = RWR_{TOT} + W_{DRAINAGE} + WW_{T\ FOR\ AGRI} + WW_{NOT\ T\ FOR\ AGRI} + W_{DESAL} - EFR$

Where:

- RWR_{TOT} = total renewable water resources
- EFR = Environmental Flow Requirements
- $W_{DRAINAGE}$ = direct use of agricultural drainage water
- WW_{T} = direct use of treated municipal wastewater
- $WW_{T\ FOR\ AGRI}$ = direct use of treated municipal wastewater for irrigation purposes
- $WW_{NOT\ T\ FOR\ AGRI}$ = direct use of non-treated municipal wastewater for irrigation purposes
- W_{DESAL} = desalinated water produced

Every component of the equation refers to 2020, is expressed in km^3/year and has been downloaded from AQUASTAT.

The assessment of total renewable water availability depends on the values of $WW_{T\ FOR\ AGRI}$ and WW_{T}. If WWT is either unavailable or lower than $WW_{T\ FOR\ AGRI}$, it is excluded from the calculation, as it is assumed that it inherently includes $WW_{T\ FOR\ AGRI}$ and therefore cannot be lower.

For the same reason if $WW_{T} > WW_{T\ FOR\ AGRI}$, only WW_{T} is considered in the evaluation to avoid counting $WW_{T\ FOR\ AGRI}$ twice.

Sectorial differences

Fortunately, the AQUASTAT dataset provides not only the total water withdrawal values but also sector-specific withdrawal data for agriculture, municipal, and industrial use. Since DEM values were calculated as the sum of demand across different sectors, the comparison between DEM and USE can also be conducted at a sectoral scale. This analysis revealed that, in many cases, the overall assessment based on total USE and DEM does not represent the situation of the three sectors, as total demand may appear satisfied while in one or more sectors it is not. To make a complete comparison for each sector, sectorial AVLB values are also required. However, these are not provided by AQUASTAT. Therefore, sectorial AVLB values were estimated as follows:

$$\mathrm{AVLB_{AGRI}} = (\mathrm{RWR_{TOT}} - \mathrm{EFR}) \cdot \frac{\text{DEM AGRI}}{\text{DEM TOT}} + \mathrm{W_{DRAINAGE}} + \mathrm{WW_{T\ FOR\ AGRI}} + \mathrm{WW_{NOT\ T\ FOR\ AGRI}} + \mathrm{W_{DESAL}} \cdot 0.018$$

- When municipal treated wastewater reused > municipal treated wastewater reused for agriculture:

$$\mathrm{AVLB_{MUN}} = (\mathrm{RWR_{TOT}} - \mathrm{EFR}) \cdot \frac{\text{DEM MUN}}{\text{DEM TOT}} + (\mathrm{WW_{T}} - \mathrm{WW_{T\ FOR\ AGRI}}) \cdot \frac{\text{DEM MUN}}{\text{DEM MUN+D} \quad \text{IND}} + \mathrm{W_{DESAL}} \cdot 0.6225$$

$$\mathrm{AVLB_{IND}} = (\mathrm{RWR_{TOT}} - \mathrm{EFR}) \cdot \frac{\text{DEM IND}}{\text{DEM TOT}} + (\mathrm{WW_{T}} - \mathrm{WW_{T\ FOR\ AGRI}}) \cdot \frac{\text{DEM IND}}{\text{DEM MUN+DEM IND}} + \mathrm{W_{DESAL}} \cdot 0.35$$

- When municipal treated wastewater reused for agriculture > municipal treated wastewater reused:

$$\mathrm{AVLB_{MUN}} = (\mathrm{RWR_{TOT}} - \mathrm{EFR}) \cdot \frac{\text{DEM MUN}}{\text{DEM TOT}} + \mathrm{W_{DESAL}} \cdot 0.6225$$

$$\mathrm{AVLB_{IND}} = (\mathrm{RWR_{TOT}} - \mathrm{EFR}) \cdot \frac{\text{DEM IND}}{\text{DEM TOT}} + \mathrm{W_{DESAL}} \cdot 0.35$$

Where:

- DEM = water demand
- 0.018 = average fraction of desalinated water used for agricultural purposes
- 0.6225 = average fraction of desalinated water used for municipal purposes
- 0.35 = average fraction of desalinated water used for industrial purposes

While water availability for agriculture remains unchanged regardless of missing or inconsistent downloaded data, availability for the industrial and municipal sectors varies depending on the values of $\mathrm{WW_{T\ FOR\ AGRI}}$ and $\mathrm{WW_{T}}$. In some cases, only one of these values is missing, or due to an error, $\mathrm{WW_{T\ FOR\ AGRI}}$ is reported as higher than $\mathrm{WW_{T}}$, which is illogical since, as explained before, $\mathrm{WW_{T}}$ includes $\mathrm{WW_{T\ FOR\ AGRI}}$.

In such cases, the $\mathrm{WW_{T}}$ value is not considered. However, when $\mathrm{WW_{T}} \geq \mathrm{WW_{T\ FOR\ AGRI}}$, the difference between these two values is allocated to both municipal and industrial water availability.

Similar to $\mathrm{AVLB_{TOT}}$, which is allocated among the three availability categories based on each sector's share of total water demand, the difference between total treated municipal wastewater and the portion used for agriculture has been distributed between the municipal and industrial sectors in proportion to their respective shares of the combined demand.

EVALUATION OF DESALINATED WATER REQUIREMENTS

As previously explained, each country's situation has been assessed under three different scenarios, corresponding to three distinct EFR values and, consequently, three levels of renewable water availability.
Furthermore, since total and sectoral water demand and use are available, and the sectorial RWR availabilities have been estimated, it is possible to evaluate each country's situation globally and for each of the three sectors, resulting in four different scenarios.
Considering the three EFR values and the sectoral scenarios, this results in a total of 12 possible combinations, meaning that for each country, 12 different analyses have been conducted. Consequently, in each of these 12 scenarios, countries have been classified into one of the six previously defined categories based on their water use, demand, and availability values.

The study assesses the desalinated water volumes needed and its associated energy requirements only for countries experiencing blue water scarcity, so those where, even when considering both conventional and non-conventional water sources, renewable water availability is lower than water demand.
Desalination is an energy-intensive process, requiring significant amounts of power to produce freshwater. Therefore, the study considers its implementation only in countries where it is strictly necessary, so where demand cannot be met sustainably due to limited renewable water availability, rather than as a response to overexploitation or economic constraints.

For the same reasons desalination was considered only for countries facing BWS, the volume of water to be desalinated was calculated solely to address the gap between water demand and availability. Specifically, in each of the three EFR scenarios, it is assumed that all available renewable water resources are fully utilized. As a result, desalination is strictly required only to increase water availability to meet demand.

Therefore, the hypotheses for the three different combinations are as follows:

- **DEM > AVLB > USE**: use is increased to fully exploit all available renewable water resources.
- **USE > DEM > AVLB** and **DEM > USE > AVLB**: withdrawal decreased to a sustainable value.

However, when quantifying the volumes of water to be desalinated, another important aspect must be considered: the efficiency of the existing water distribution system.
When this efficiency is below 100%, even by fully utilizing all available renewable water resources the deficit relative to the water demand is no longer equal to the gap between demand and availability, because part of the availability is lost during transportation. For this reason, the volume of water required for desalination is calculated as $\text{DEM} - \text{AVLB} \cdot \eta$, where η represents the efficiency of the water distribution system.

The results are therefore presented as the volumes of desalinated water required to meet water demand, varying with the efficiency of the distribution network, across a range of efficiencies from 50% to 100%, in each of the 12 scenarios analyzed.

EVALUATION OF ENERGY REQUIREMENTS FOR DESALINATION

The energy required to produce the additional water needed to achieve sustainable demand was estimated using a simple approach: for each country, the same energy consumption per cubic meter of desalinated water was assumed. Therefore, the energy requirements for desalination will be directly proportional to the desalinated water requirements values.

Since all desalination plants are considered to use reverse osmosis systems, energy requirement has been assumed of 3 kWh/m³ has been used. While newer technologies can achieve lower values, around 2.7 kWh/m³ or less, this estimate represents a scenario where the most advanced systems may not be in place.
However, it still assumes efficient membrane-based desalination, like modern plants with an overall good energy performance.

EVALUATION OF PHOTOVOLTAIC AND AGRIVOLTAIC AREAS REQUIREMENTS FOR ENERGY PRODUCTION

To assess the land requirements for photovoltaic and agrivoltaics systems to meet energy demands, it is essential to determine the average solar energy production per unit of area in each country.
To estimate this, data was first obtained from the Global Solar Atlas (GSA) on the long-term average of daily totals of potential photovoltaic electricity production (PV_{OUT}), measured in kWh/kW_P.
These values cover the period from 1994, 1999, 2005, 2007, or 2018 (depending on the region) up to 2023.
The downloaded data provides an assessment of the average daily photovoltaic energy output per kWp of installed capacity. Specifically, the GSA evaluates these values for a ground-mounted photovoltaic power plant equipped with crystalline silicon (c-Si) modules.
These modules are assumed to be installed at the optimal tilt angle to maximize monthly energy production.

However, to estimate the spatial requirements for each kWh of solar energy produced in each country, it is also necessary to determine the area occupied per kW_P of installed capacity.

The study *"Outdoor performance analysis of different PV panel types"* by E. Elibol et al. analyzes the performance of three types of photovoltaic panel systems: 24 amorphous silicon thin-film panels (a-Si), each with a capacity of 100 W; 11 polycrystalline panels, each with a capacity of 240 W; and 10 monocrystalline panels, each with a capacity of 235 W.
For each panel type, the occupied area is known, allowing for the calculation of the area/power ratio (m^2/ kW_P).

These ratios are 15.7 m^2/ kW_P for a-Si panels, 6.8 m^2/ kW_P for monocrystalline c-Si panels, and 6.5 m^2/ kW_P for polycrystalline c-Si panels.

Since GSA does not specify which type of c-Si panels it assumes in its assessment of daily energy production, monocrystalline panels are considered in this analysis.
This helps to prevent overestimating panel performance while ensuring accuracy, as the difference between monocrystalline and polycrystalline panels is just 0.3 m^2/ kW_P.

In the end, photovoltaic spatial requirements for solar energy production are calculated or each country as:

$AREA_{PV} = (DEM - AVLB \cdot \eta) \cdot 3\ kWh/m^3 \cdot (PV_{OUT} \cdot 365)^{-1} \cdot 6.8\ m^2/kW_P$

Where:

- $(DEM - AVLB \cdot \eta)$ is the annual desalinated water requirement [m^3 / year]
- 3 kWh/m^3 is the energy requirement for each cubic meter of desalinated water produced
- $(PV_{OUT} \cdot 365)$ is the annual solar energy produced per kW_P of installed capacity [kWh / (year · kW_P)]
- 6.8 m^2/kW_P is the area/power ratio for monocrystalline c-Si panels

Subsequently, the areas requirements have been estimated under the assumption that the energy is produced with agrivoltaics systems, where agricultural activities coexist with solar energy production on the same land.

When using an agrivoltaics system to generate the energy needed for desalination, a larger land area must be considered. Unlike conventional photovoltaic systems, agrivoltaics installations require significantly wider spacing between panel rows to ensure sufficient sunlight reaches the crops below.
This spacing allows for efficient energy production while minimizing the impact on agricultural productivity.

For agrivoltaics systems, a maximum coverage of 40% of solar panels relative to the total area has been assumed. This ratio is taken from the French regulatory framework on agrivoltaics, and it is one of the three main criteria in the framework that must be met to ensure the principle of non-competition between agricultural activities and energy production.
In fact, the second criterion is related to agricultural productivity, that allows the implementation of agrivoltaics only if the agricultural yield is at least 90% of that observed without the integration of solar panels.

Since it has been assumed that only 40% of the agrivoltaics area is dedicated to electricity production, the relationship between photovoltaic area ($AREA_{PV}$) and agrivoltaics area ($AREA_{AV}$) is expressed as:

$AREA_{PV} = AREA_{AV} \cdot 0.4$

Therefore, the agrivoltaics areas requirements to produce the solar energy needed for desalination have been simply evaluated as:

$AREA_{AV} = AREA_{PV} / 0.4 = 2.5 \cdot AREA_{PV}$

As a result, the spatial requirements for agrivoltaics systems are directly proportional to those for photovoltaic systems.

EVALUATION OF THE FRACTION OF AV AREAS REQUIREMENTS RELATIVE TO TOTAL RAINFED CROPLAND SUITABLE FOR CONVERSION

Once the agrivoltaics areas required for desalinated water production have been calculated for each country, the next step was to determine if each country in BWS has sufficient available space for agrivoltaics implementation, and, if so, how much of this space should be converted to agrivoltaics use.
This is a critical phase of the study, as it determines if preventing BWS scenarios by utilizing renewable energy produced with agrivoltaics is feasible or not.

The dataset related to the article *"Global land-water competition and synergy between solar energy and agriculture"* by N. Galli et al. provides data on globally non-irrigated croplands suitable for conversion to agrivoltaics.
In total, the dataset includes nine different scenarios, depending on the following two factors:

- Yield variation threshold: rainfed croplands where the conversion to agrivoltaics results in a yield that is at least 80%, 90%, or 100% of the standard yield.
- Radiation conditions: Agrivoltaics radiation considered 50%, 70%, or 90% of the standard radiation levels.

All three scenarios related to the first factor were considered in order to observe the spatial availabilities differences depending on whether the areas involve a yield loss of 20%, 10%, or no yield loss at all.
In the latter case, the rainfed areas suitable for conversion will likely be smaller (or at most equal) compared to those considered when yield losses are assumed.
Regarding the radiation conditions, only the scenarios with 70% of the standard radiation were examined. This allows for an analysis of intermediate scenarios for this factor.

Overall, the agrivoltaics area requirements were compared to three different convertible areas values, depending on the following scenarios considered:

- Agrivoltaics radiation = 70% of standard radiation, yield at least 80% of the standard yield.
- Agrivoltaics radiation = 70% of standard radiation, yield at least 90% of the standard yield.
- Agrivoltaics radiation = 70% of standard radiation, yield equal to the standard yield.

As mentioned earlier, there are 12 scenarios related to the desalinated water volume requirements, which result from the combinations of the three different EFRs and the three sectors, along with the total situation. Therefore, there are also 12 results for each country regarding energy and spatial requirements, evaluated as $AREA_{AV}/AREA_{RAINF\ AV\ CONV}$, where $AREA_{RAINF\ AV\ CONV}$ = total rainfed cropland convertible to AV.

However, since three different values of rainfed land convertible to agrivoltaics were considered, there will be 9 different ratios between the required and available areas for each sector, depending on the EFRs and the considered convertible area.
Consequently, 36 scenarios have been analyzed (9 for each of the three sectors and the total situation).

The final step in this study involved again a comparison between the spatial requirements for agrivoltaics and the availability of non-irrigated areas suitable for conversion. However, in this case, only those areas that are currently in BWS were considered.

To determine these values, results from the dataset related to "Global Agricultural Economic Water Scarcity" study by M. C. Rulli et al. were used.
Specifically, the data on the number of months each cropland worldwide currently experiences BWS were utilized.

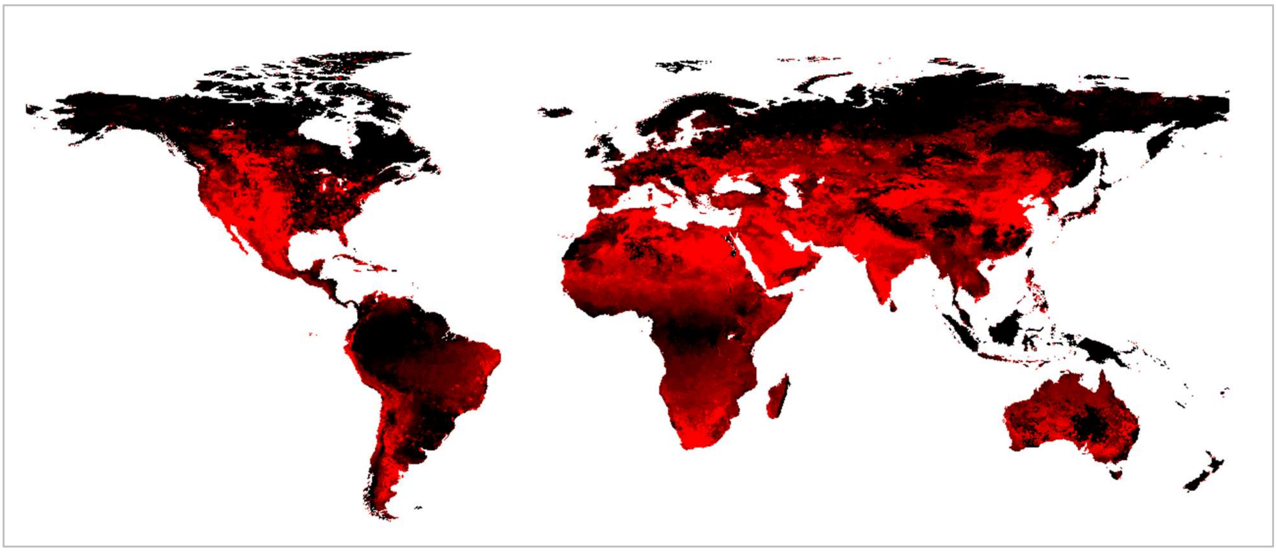


Figure 6: Areas in BWS from 0 months/year (black) to 12 months/year (bright red) [M.C. Rulli et al., 2020]

With these data, along with those from the study by Galli et al., it was possible to assess, through QGIS, the values of rainfed agricultural areas suitable for conversion to agrivoltaics are currently in BWS, country by country, considering the variation in the number of months of BWS experienced annually.

For each of the three previously considered cropland, with varying assumed yield losses, the number of areas that are in BWS for at least 1 month, 3 months, and 6 months per year was calculated.

Naturally, the greater the number of months per year considered, the smaller the extent of the non-irrigated agricultural area that is suitable for conversion in BWS.
Therefore, for the same assumed yield loss, the rainfed areas suitable for conversion in BWS for 6 months per year will clearly be smaller than those for just 1 month per year.

Overall, each of the 12 results related to agrivoltaics spatial requirements was compared with 9 different convertible areas in BWS, depending on the assumed yield loss and the number of months per year in BWS, resulting in a total of 108 ratios between required and available areas.

RESULTS

DESALINATED WATER REQUIREMENTS

The countries that, from a global perspective and considering actual EFR, are in a BWS situation are Libya, Saudi Arabia and Yemen. Among these, only Yemen has a water use lower than the demand, but still unsustainable (DEM > USE > AVLB), while Libya and Saudi Arabia are in a USE > DEM > AVLB situation (Graph 4).

Considering EFR of 60% (Graph 5a and 5b), Algeria, Egypt, Jordan and Pakistan join Libya and Saudi Arabia. Also Palestine, in this scenario is in BWS, but in a AVLB > USE situation. Therefore, Palestine globally has lower RWR than its demand, which is not satisfied by the USE, but its current water withdrawal is sustainable. Finally, assuming 80% EFR (Graph 6a, 6b and 6c), the number of countries in BWS rises to 15.

In this scenario, 13 countries are in a USE > DEM > AVLB type of BWS (Iran, Israel, Morocco, Sudan, Tunisia, Turkmenistan, Uzbekistan plus the 5 in this situation in the 60% scenario) while only Yemen and Palestine are in a DEM > USE > AVLB situation. Therefore, the Palestine water use would be unsustainable considering EFR of 80%.

The results confirm what was expected: as environmental flow requirements increase, the number of countries experiencing BWS rises significantly. Specifically, there are 3 countries in BWS under the current scenario, while this number increases to 8 and 15 when EFR is set at 60% and 80% of total renewable water resources, respectively. As EFR values change, so does a country's AVLB, which in turn affects the impact of water distribution system efficiency on the volume of desalinated water required.

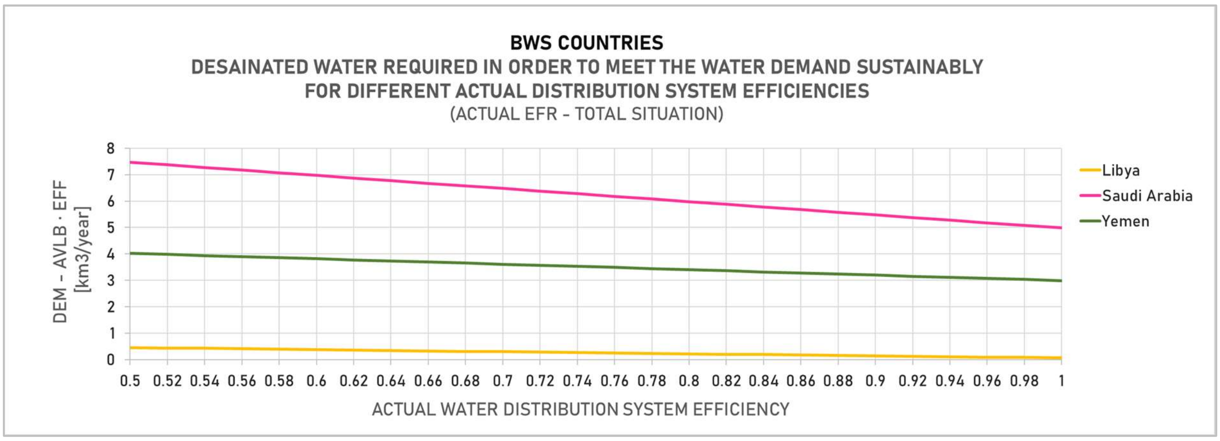
For example, in Pakistan, the efficiency of the water network significantly reduces the need for desalinated water, depending on whether EFR is set at 60% or 80%.

With an EFR of 60%, the desalination requirement decreases from approximately 52 to 4 km³/year when network efficiency improves from 50% to 98% (graph 5a). When considering an EFR of 80%, the need for desalination drops from about 75 km³/year to 52 km³/year for the same efficiency levels (graph 6a).

This highlights that, in Pakistan, limiting water consumption to only 20% of available renewable resources (thus avoiding a water stress situation) would result in a water deficit of approximately 53 km³/year, even with a highly efficient distribution network. However, if the goal were to avoid severe water scarcity by consuming up to 40% of available renewable water resources, the deficit would shrink to 4 km³/year with a 98% efficient network and around 2.5 km³/year with a fully efficient (100%) network.

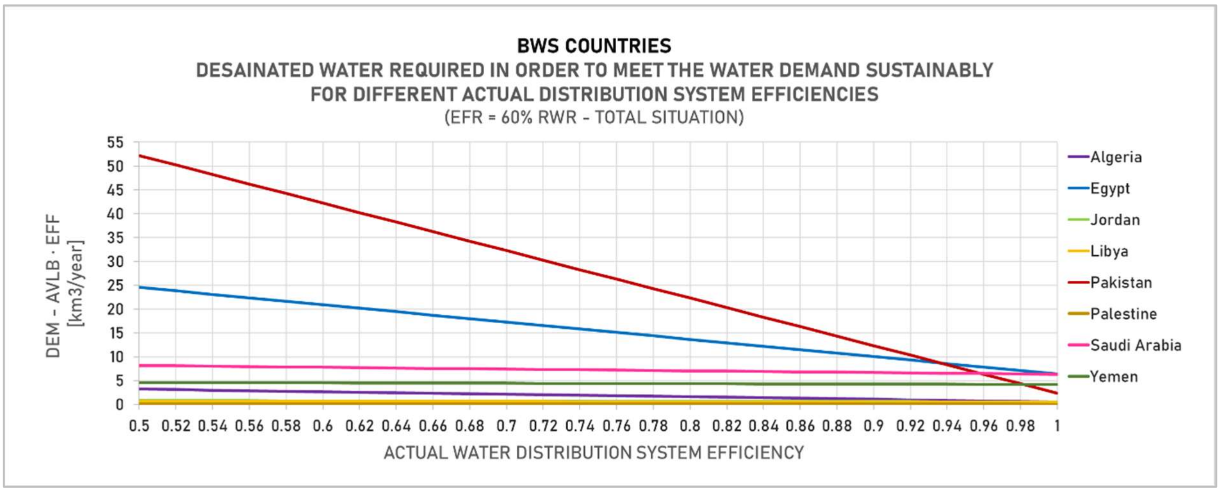
These results stem from the fact that Pakistan's water demand is approximately 102 km³/year, while its available water resources are around 50 km³/year with an EFR of 80% and 100 km³/year with an EFR of 60%. As a result, the gap between demand and availability is 52 km³/year in the first scenario, whereas it shrinks to just 2 km³/year in the second. However, even in this more favorable case, a decrease in distribution network efficiency would significantly increase the water demand deficit.

TOTAL SITUATION – ACTUAL EFR

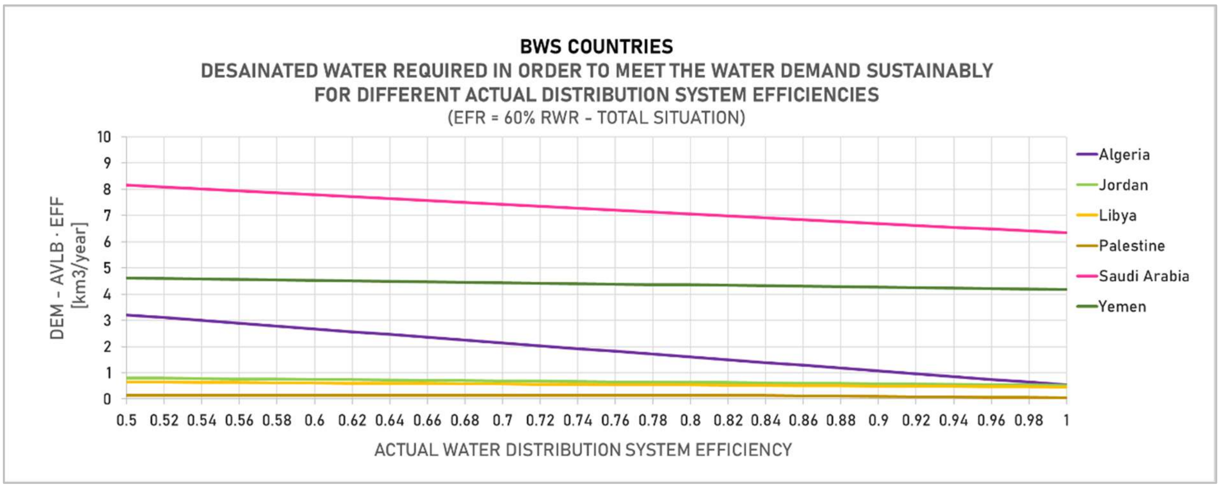


Graph 4: BWS countries desalinated water need for different efficiencies (Total situation – Actual EFR)

TOTAL SITUATION - 60% EFR

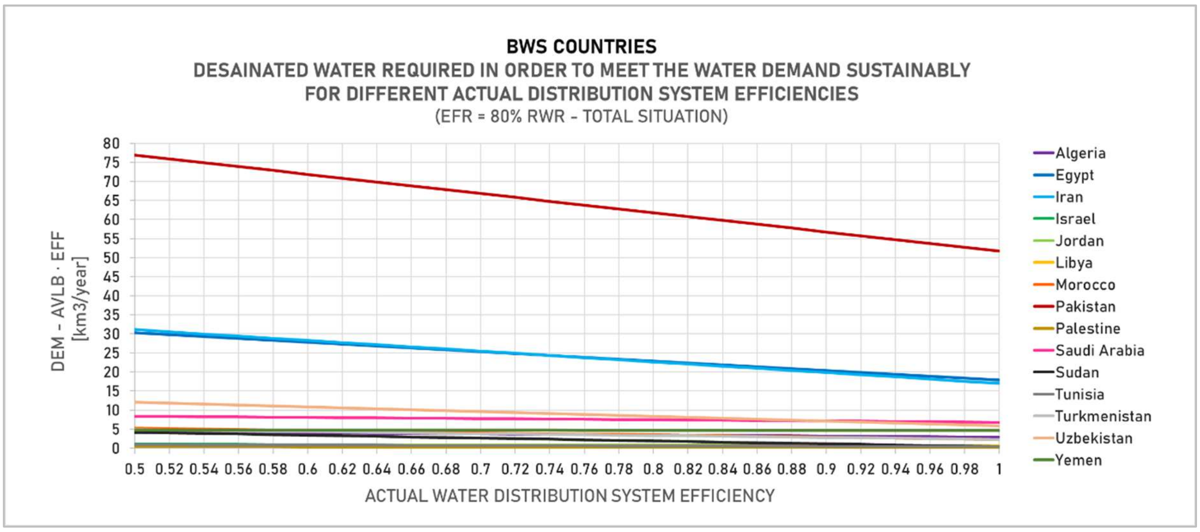


Graph 5a: BWS countries desalinated water need for different efficiencies (Total situation – 60% EFR)

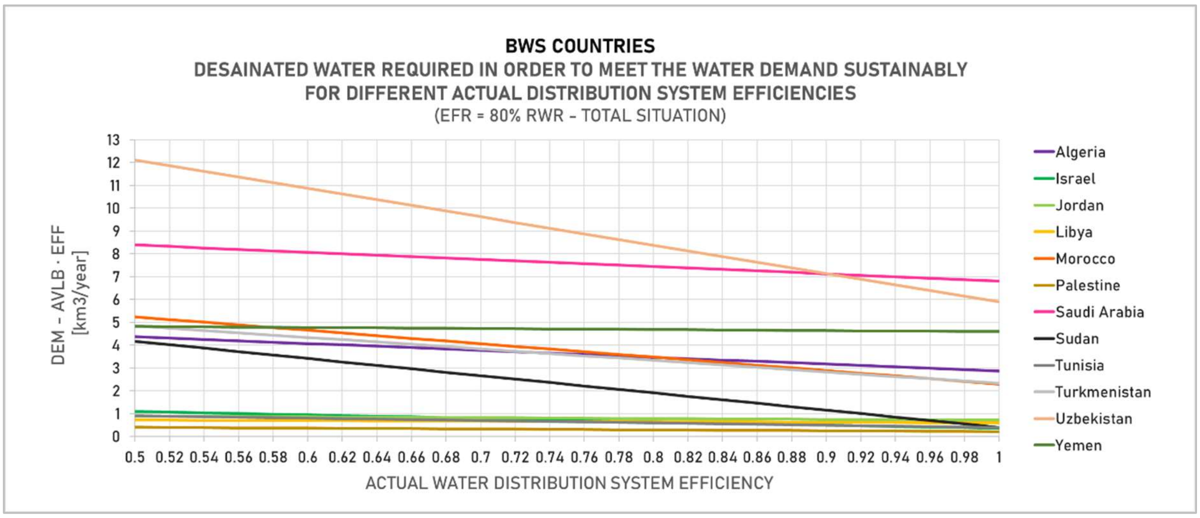


Graph 5b: Algeria, Jordan, Libya, Palestine, Saudi Arabia and Yemen desalinated water need for different efficiencies (Total situation – 60% EFR)

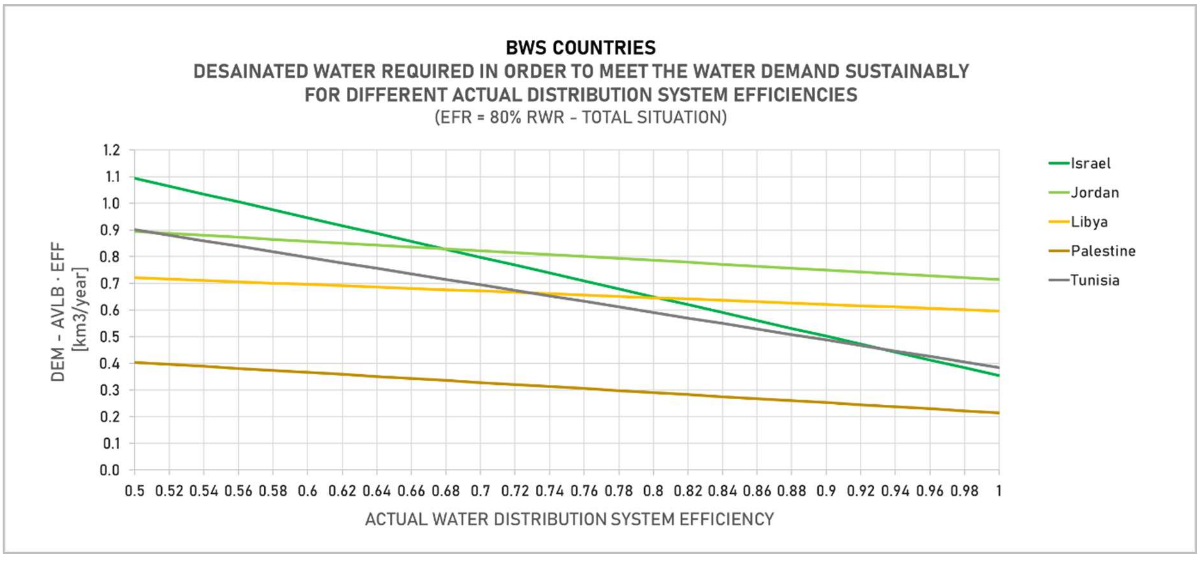
TOTAL SITUATION - 80% EFR



Graph 6a: BWS countries desalinated water need for different efficiencies (Total situation – 80% EFR)



Graph 6b: Algeria, Israel, Jordan, Libya, Morocco, Palestine, Saudi Arabia, Sudan, Tunisia, Turkmenistan, Uzbekistan and Yemen desalinated water need for different efficiencies (Total situation – 80% EFR)



Graph 6c: Israel, Jordan, Libya, Palestine and, Tunisia desalinated water need for different efficiencies (Total situation – 80% EFR)

As previously explained, both conventional and non-conventional water sources are considered in this analysis when evaluating water availability and use. To assess how each country's situation changes depending on the types of water resources considered, availability and use values are adjusted based on whether non-conventional resources are considered and which ones of them.

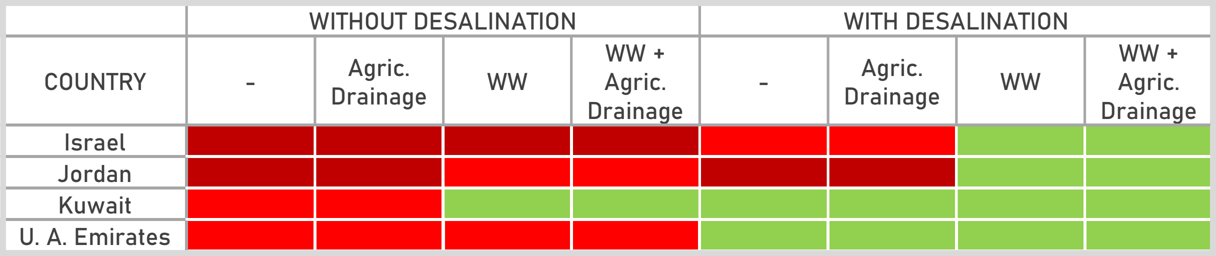
Alongside conventional sources, three types of non-conventional water resources have been added to total renewable water availability: desalinated water, direct use of agricultural drainage, and municipal wastewater (treated and untreated).

Based on the type of water source included and the possible combinations, a total of eight scenarios can be evaluated for each EFR level:

- One scenario considering only conventional resources,
- One including both conventional and all non-conventional resources,
- Six scenarios based on different combinations of water from desalination, agricultural drainage, and municipal wastewater.

The results are shown in tables 1, 2 and 3, each one representing the country's changes in the situation for the EFR considered.

Table 1: countries' situation changes according to different water sources - actual EFR



	WITHOUT DESALINATION				WITH DESALINATION			
COUNTRY	-	Agric. Drainage	WW	WW + Agric. Drainage	-	Agric. Drainage	WW	WW + Agric. Drainage
Israel	🟤	🟤	🟤	🟤	🔴	🔴	🟢	🟢
Jordan	🟤	🟤	🔴	🔴	🟤	🟤	🟢	🟢
Kuwait	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
U. A. Emirates	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🟢

Where:

🟢 = USE > AVLB > DEM (Overexploitation)

🔴 = USE > AVLB > DEM (BWS with demand satisfaction)

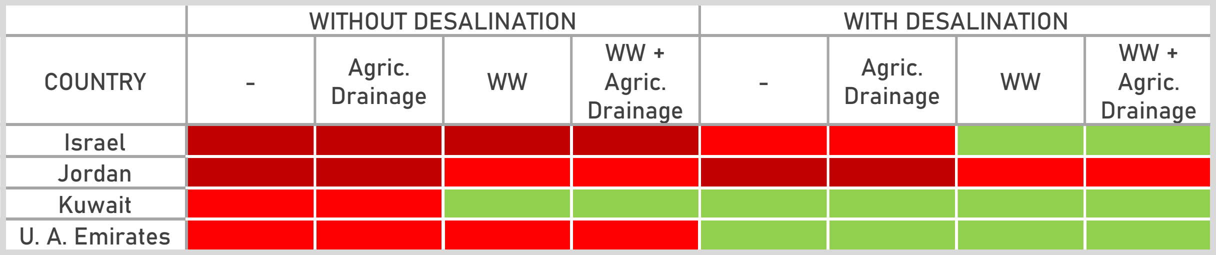
🟤 = DEM > USE > AVLB (BWS worse scenario)

Under the current EFR scenario (*Table 1*), four countries would fall into BWS if one or more non-conventional water sources were unavailable, joining then Libya, Saudi Arabia, and Yemen, which are in BWS even considering the non-conventional sources.

Specifically, Israel, Jordan, and the United Arab Emirates would experience BWS if desalinated water were not considered. Moreover, Israel and Jordan would remain in BWS even if, in addition to desalinated water, they did not utilize treated municipal wastewater.

Kuwait, on the other hand, would fall into BWS if both desalinated water and treated municipal wastewater were excluded from total renewable water availability.

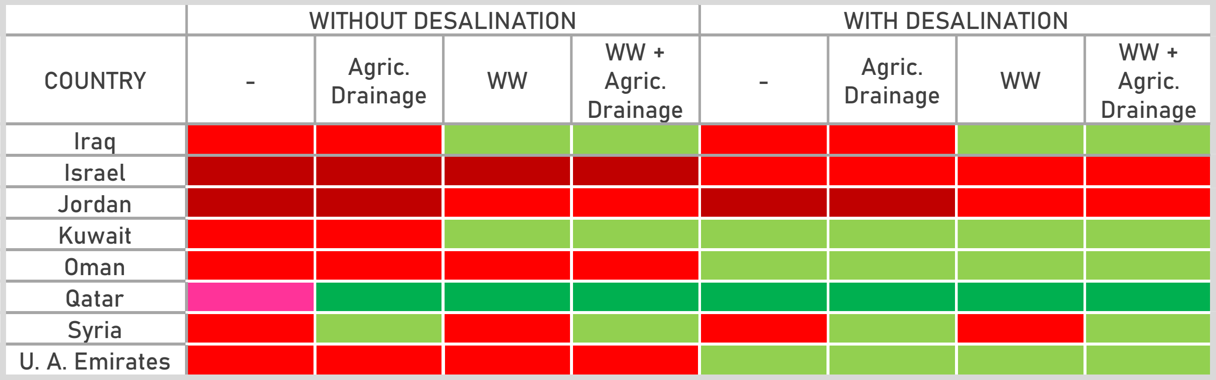
Table 2: countries' situation changes according to different water sources - EFR 60%



	WITHOUT DESALINATION				WITH DESALINATION			
COUNTRY	-	Agric. Drainage	WW	WW + Agric. Drainage	-	Agric. Drainage	WW	WW + Agric. Drainage
Israel	🟫	🟫	🟫	🟫	🟥	🟥	🟩	🟩
Jordan	🟫	🟫	🟥	🟥	🟫	🟫	🟥	🟥
Kuwait	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
U. A. Emirates	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩

In the 60% EFR scenario, the countries that have at least one combination of water sources placing them in BWS remain the same as in the current scenario, with most showing similar variations depending on the types of water sources considered. The only exception is Kuwait, which, in this case, falls into BWS even when all types of non-conventional water sources are included.

Table 3: countries' situation changes according to different water sources - EFR 80%



	WITHOUT DESALINATION				WITH DESALINATION			
COUNTRY	-	Agric. Drainage	WW	WW + Agric. Drainage	-	Agric. Drainage	WW	WW + Agric. Drainage
Iraq	🟥	🟥	🟩	🟩	🟥	🟥	🟩	🟩
Israel	🟫	🟫	🟫	🟫	🟥	🟥	🟥	🟥
Jordan	🟫	🟫	🟥	🟥	🟫	🟫	🟥	🟥
Kuwait	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
Oman	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩
Qatar	🟣	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Syria	🟥	🟩	🟥	🟩	🟥	🟩	🟥	🟩
U. A. Emirates	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩

Where:

🟢 = AVLB > USE > DEM (Sustainable situation)

🟣 = DEM > AVLB > USE (BWS with possible improvements)

In the 80% EFR scenario, the number of countries with at least one combination of water sources leading to BWS doubles compared to the previous scenarios, increasing from 4 to 8. Among these 8 countries, only Israel and Jordan remain in BWS even when all types of non-conventional water sources are included. As a result, they are the only ones represented in graphs 6a, 6b, and 6c.

United Arab Emirates and Oman rely exclusively on desalination to avoid BWS, while in Syria agricultural drainage plays a crucial role in ensuring that renewable water availability exceeds demand.

Qatar, unlike the other countries, can achieve an optimal AVLB > USE > DEM situation with any of the non-conventional water sources. However, if it were to rely solely on conventional resources, it would not only fall into BWS but also face an unmet total water demand.

Finally, Iraq presents an interesting case, as its renewable water availability surpasses demand specifically due to the use of municipal wastewater. However, according to AQUASTAT data, most of the municipal wastewater used in Iraq is untreated (1.03 km³/year untreated wastewater, 0.005 km³/year treated).

This means that Iraq avoids falling into BWS primarily due to its reliance on untreated municipal wastewater.

Agricultural sector

Again, the considered EFR reflect on the number of countries in BWS and their typology of BWS.
For example, assuming the actual EFR (Graphs 7a and 7b), six countries are in BWS, while considering 60% EFR and 80% EFR the number rises to 10 and 17, respectively.

Also, while considering the actual EFR Israel and Jordan are in a DEM > AVLB > USE situation, for 60% EFR (and consequently also for 80% EFR) the USE exceeds the AVLB, and the two middle east countries end up in a DEM > USE > AVLB situation. Considering actual EFR, only Yemen is in this BWS status.

In both the 60% and 80% scenario, all the other countries in BWS have a demand satisfied (therefore unsustainable withdrawal), except for Palestine which has a sustainable use (DEM > AVLB > USE)

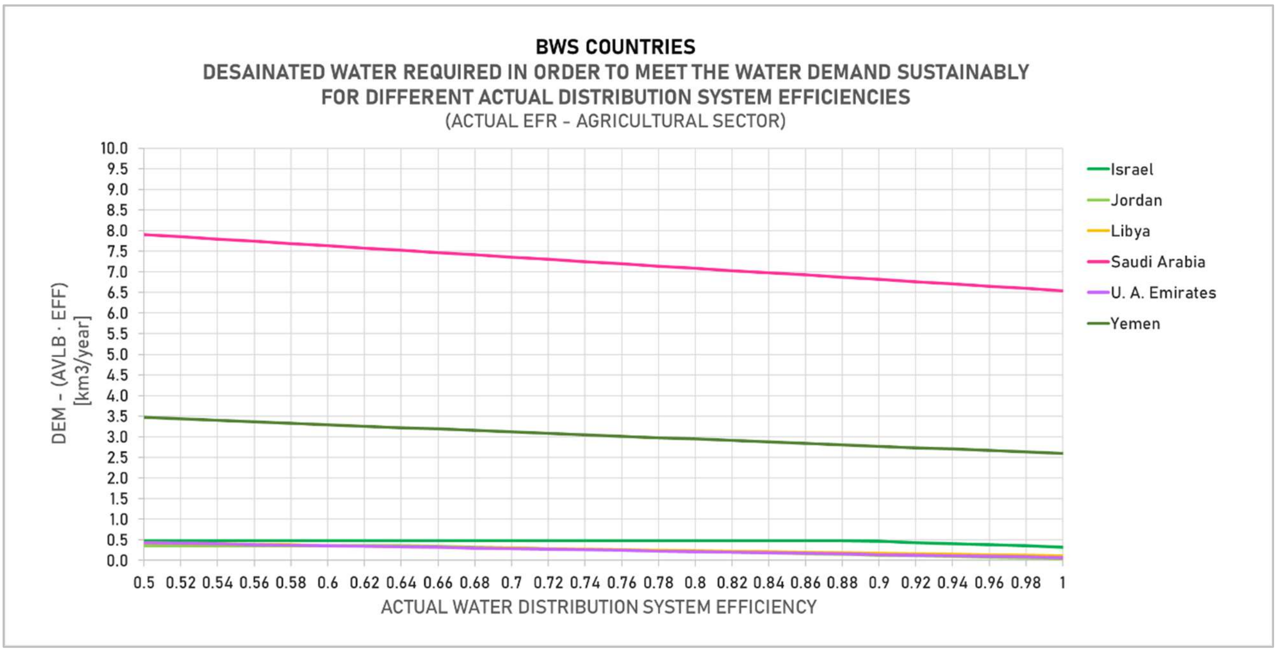
The results for the agricultural sector show clear differences compared to the total situation previously presented, starting with the number of countries experiencing BWS.

In the actual EFR scenario, Israel, Jordan, and the United Arab Emirates are added to the list of BWS countries alongside Libya, Saudi Arabia, and Yemen, the latter three already being in BWS in the total situation.
In the 60% EFR scenario, only Israel and the U. A. Emirates fall into BWS despite not being in this condition in the total situation. Similarly, in the 80% EFR scenario, this applies to Oman and, once again, to the Emirates.
These differences indicate that in every EFR scenario, U. A. Emirates have an overall RWR availability that exceeds total water demand, while in the agricultural sector, availability is always lower than its respective demand.
As a result, in each EFR scenario, at least one of the industrial or municipal sectors must have a water demand lower than its respective availability.

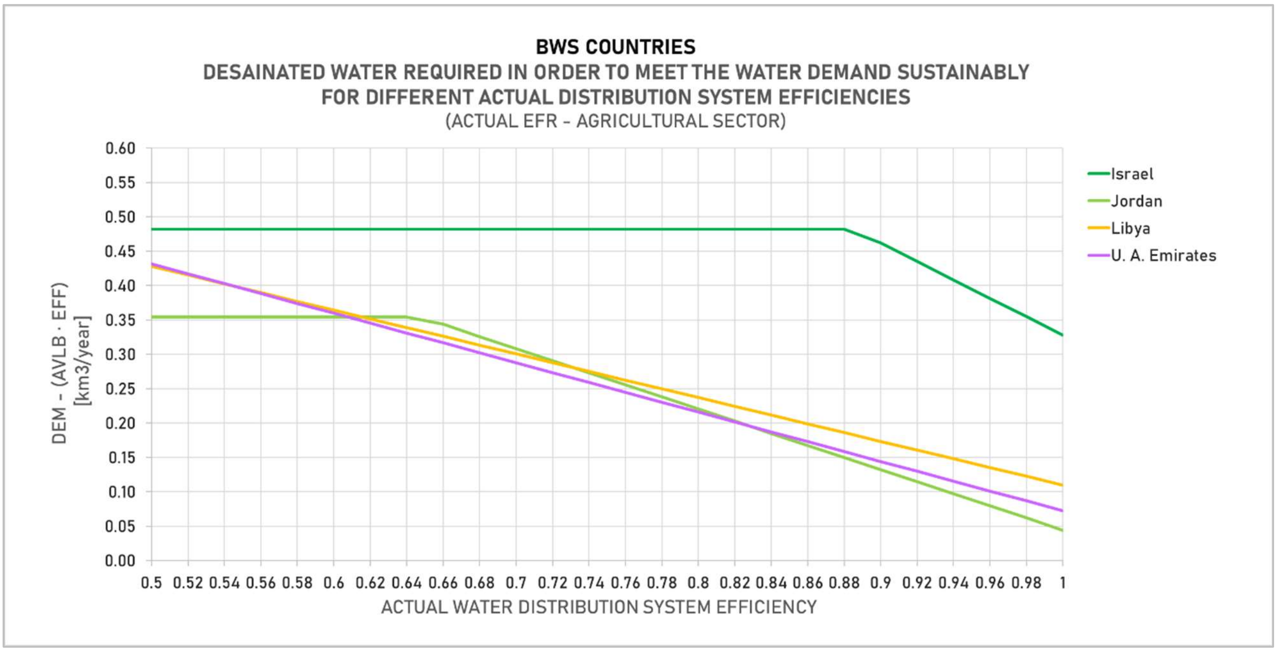
Another difference respect to the graphs illustrating the total situation is the behavior of certain curves as efficiency varies, particularly those of Israel and Jordan in graph 7b and Palestine in graph 9c. In these cases, the water volume to produce is constant below a certain efficiency threshold.
This occurs because Israel and Jordan (under actual EFR) and Palestine (under 60% and 80% EFR) are in a the BWS type DEM > AVLB > USE, the only one that does not involve RWR overexploitation.

For countries in this specific BWS condition, it is assumed that they cannot desalinate more than what would be required for an efficiency level where $\eta \cdot \text{AVLB} = \text{USE}$.
Indeed, exceeding this threshold would imply producing more desalinated water than the one needed to fill the DEM - USE gap, but, as previously stated, in BWS countries all AVLB is assumed to be fully utilized.
Therefore, for these countries, desalination needs vary in an efficiency range between 100% and USE/AVLB ratio, because below this value they should produce a water volume larger than DEM – USE difference.

ACTUAL EFR

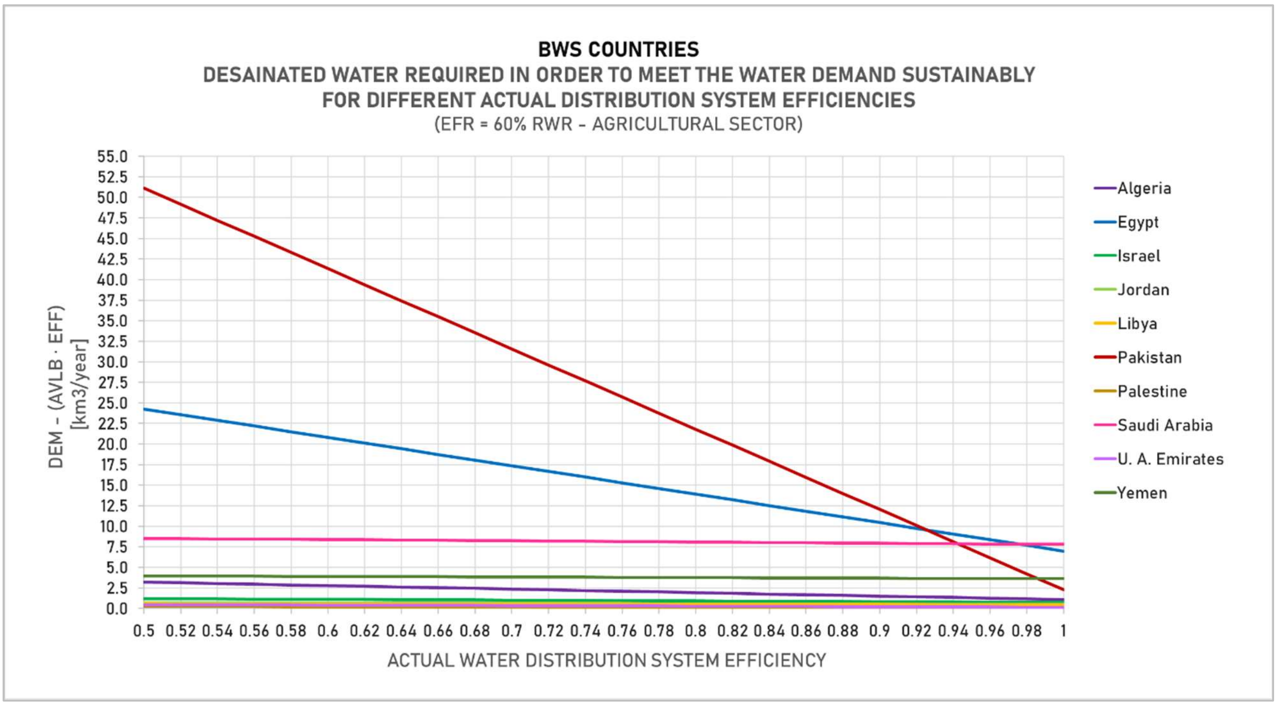


Graph 7a: BWS countries desalinated water need for different efficiencies (Agricultural sector – Actual EFR)

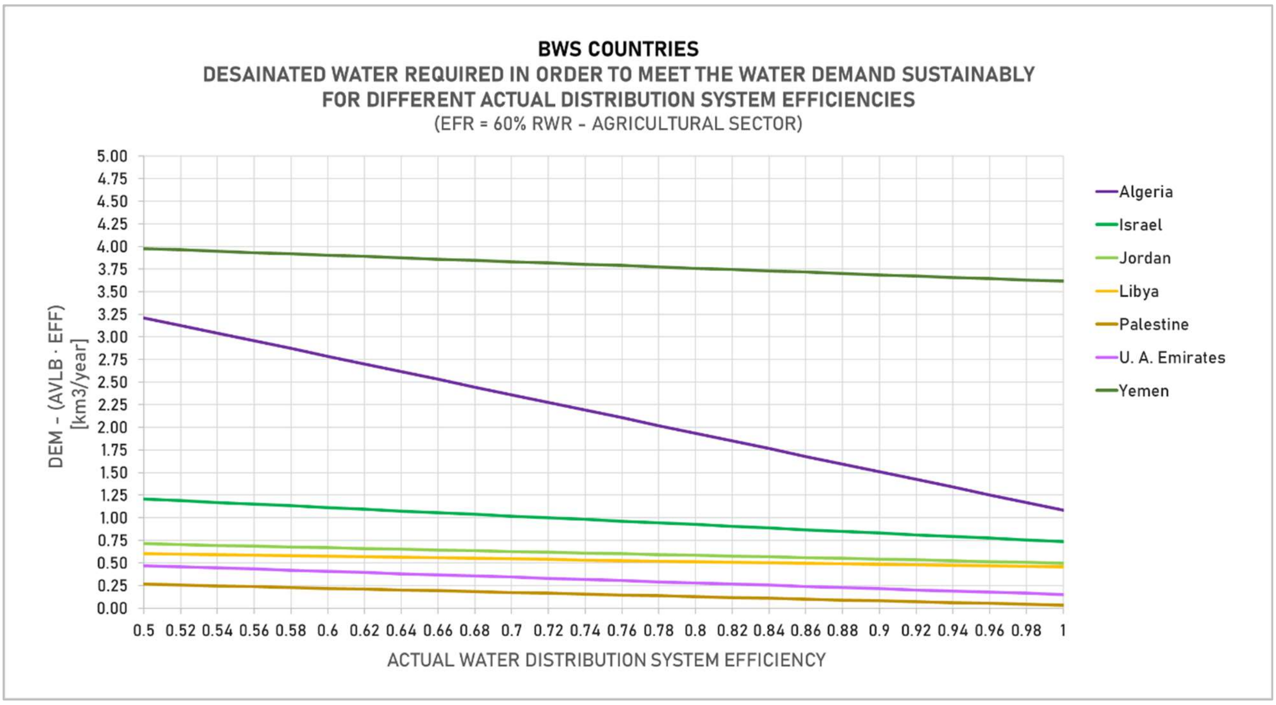


Graph 7b: Israel, Jordan, Libya, U. A. Emirates desalinated water need for different efficiencies (Agricultural sector – Actual EFR)

60% EFR

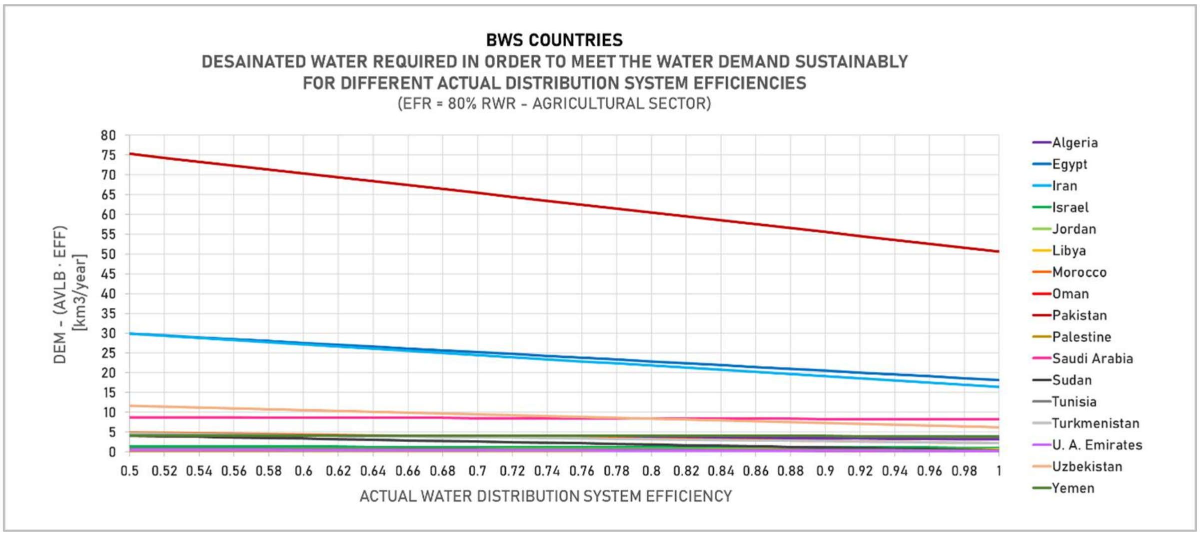


Graph 8a: BWS countries desalinated water need for different efficiencies (Agricultural Sector – 60% EFR)

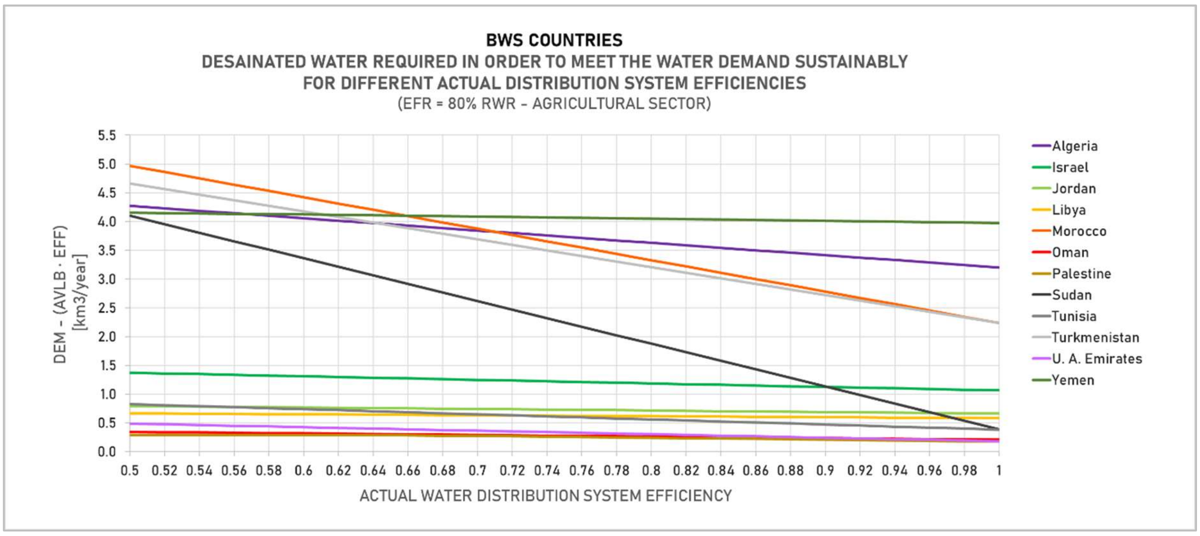


Graph 8b: Algeria, Israel, Jordan, Libya, Palestine, U. A. Emirates and Yemen desalinated water need for different efficiencies (Agricultural Sector – 60% EFR)

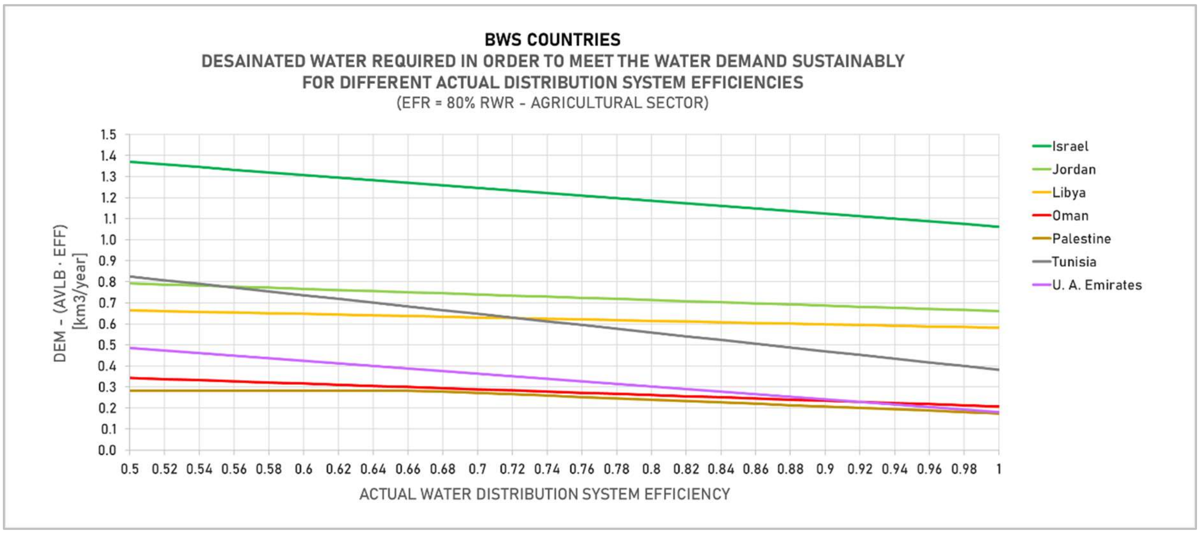
80% EFR



Graph 9a: BWS countries desalinated water need for different efficiencies (Agricultural Sector – 80% EFR)



Graph 9b: Algeria, Israel, Jordan, Libya, Morocco, Oman, Palestine, Sudan, Tunisia, Turkmenistan, U. A. Emirates and Yemen desalinated water need for different efficiencies (Agricultural Sector – 80% EFR)



Graph 9c: Israel, Jordan, Libya, Oman, Palestine, Tunisia and U. A. Emirates desalinated water need for different efficiencies (Agricultural Sector – 80% EFR)

Municipal sector

For the actual EFR (graph 10), only Yemen is in BWS and, again in a DEM > USE > AVLB typology of BWS. Considering higher EFR, obviously the number of countries in BWS increases again: four in the 60% scenario and nine in the 80% scenario.
However, for each EFR considered Yemen is the only country with a demand not satisfied, while the others are in a USE > AVLB > DEM situation.

The municipal sector shows significant differences both in the number of BWS countries and in the volumes of desalinated water required compared to the agricultural sector and the overall situation.
Indeed, in the actual EFR scenario only Yemen is in BWS, while globally also Libya and Saudi Arabia are in this condition.

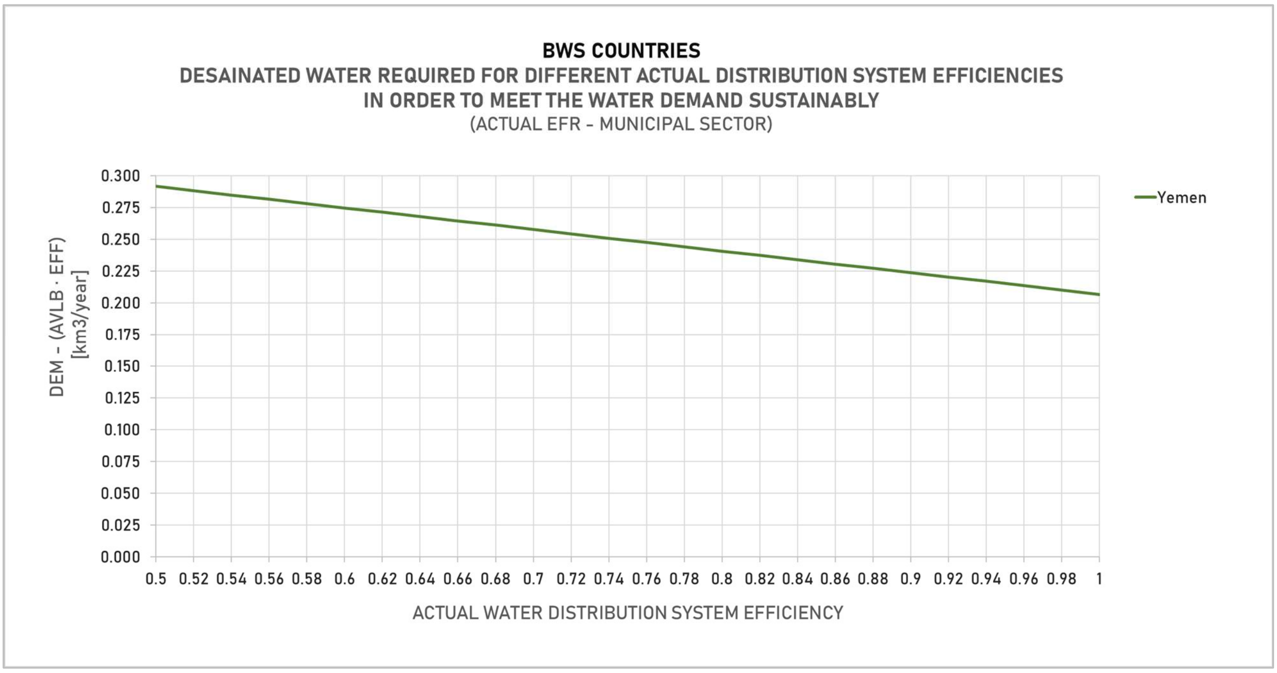
In the actual EFR scenario, only Yemen is classified as BWS, whereas, at the global level, Libya and Saudi Arabia are also in this condition.
In the 60% EFR scenario, Jordan, Pakistan, and Palestine join Yemen in experiencing BWS, whereas, for the same EFR, the total and agricultural situations include 8 and 10 BWS countries, respectively.
At 80% EFR, Iran, Iraq, Morocco, Sudan, and Turkmenistan are also in BWS. Among them, Iraq is the only country not classified as BWS in either the total or agricultural scenarios.
This is because, as previously mentioned, Iraq uses more than 1 km³/year of untreated municipal wastewater for irrigation purposes, which increases RWR availability beyond both total and agricultural water demand.

In this sector, there are no DEM > AVLB > USE cases in any EFR scenario, indicating that all BWS countries are already fully utilizing their available RWR to meet municipal demand.
Moreover, every country is currently satisfying its municipal demand except for Yemen, which remains the only country in a DEM > USE > AVLB situation across all EFR scenarios.

In general, the volumes of desalinated water required to sustainably meet municipal demand are significantly lower than those calculated for agriculture. In that case, desalination needs exceed 10 km³ per year, as seen in the 80% EFR scenario for Egypt, Iran, and Pakistan, which require 18.2, 16.5, and 50.6 km³/year, respectively, even with 100% distribution efficiency.

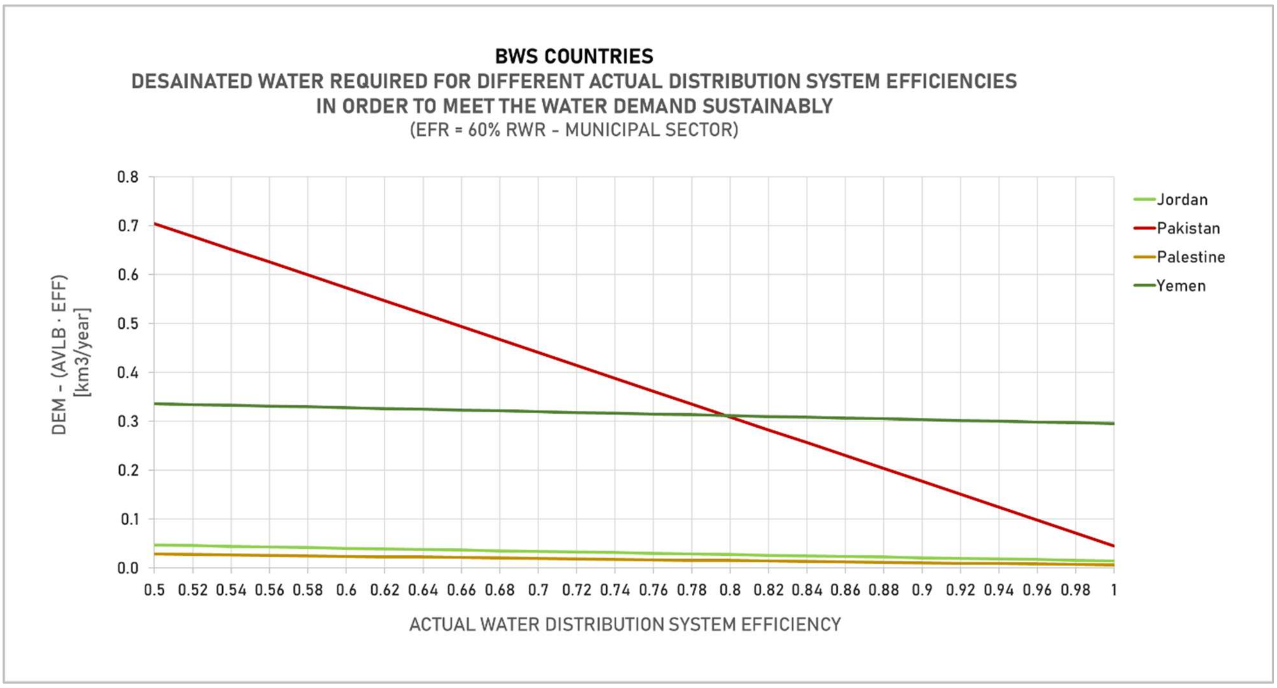
In contrast, for the municipal sector, the highest desalination requirement is for Pakistan in the 80% EFR scenario, reaching just over 1 km³/year for an efficiency equal to 50% and 0.7 km³/year for efficiency = 100%.
As for Yemen, the only country that does not meet its municipal demand, desalination needs would range from approximately 0.35 km³/year in the worst-case scenario (80% EFR and 50% efficiency) to 0.21 km³/year in the best-case scenario (actual EFR and 100% efficiency).
In the agricultural sector, Yemen's desalination requirements are significantly higher, ranging from 2.6 km³/year in the best case to 4.2 km³/year in the worst case.

ACTUAL EFR



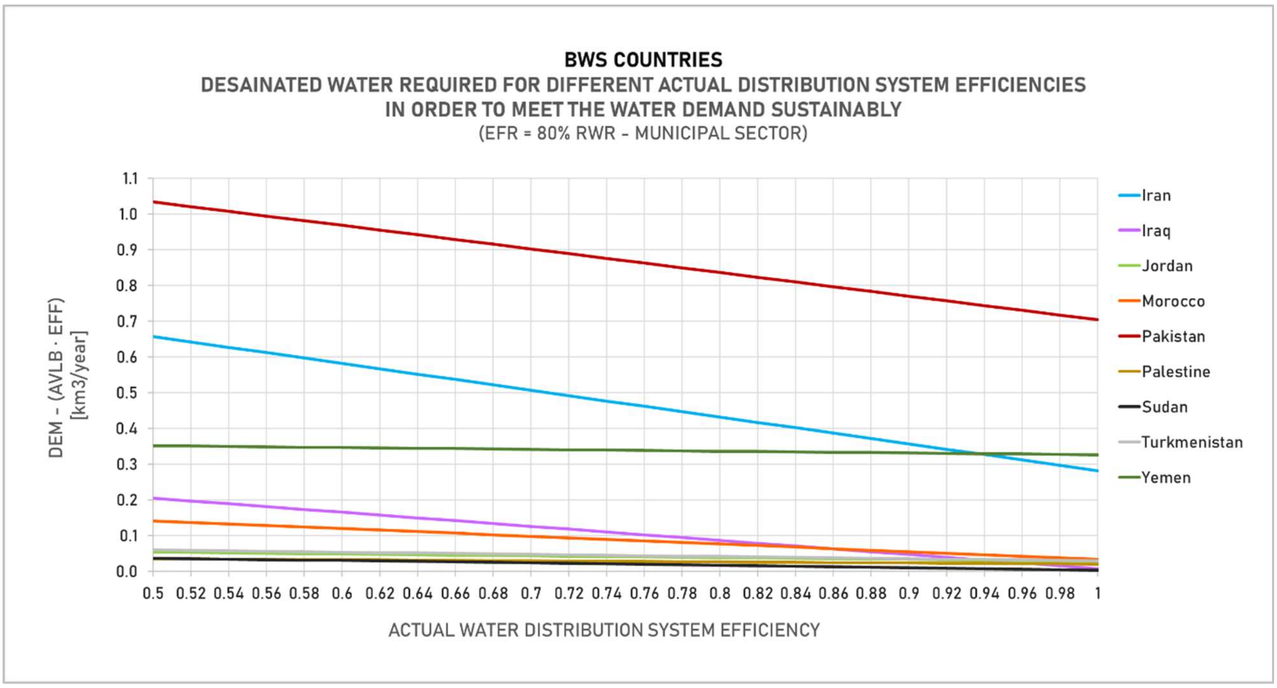
Graph 10: BWS countries desalinated water need for different efficiencies (Municipal Sector - Actual EFR)

60% EFR

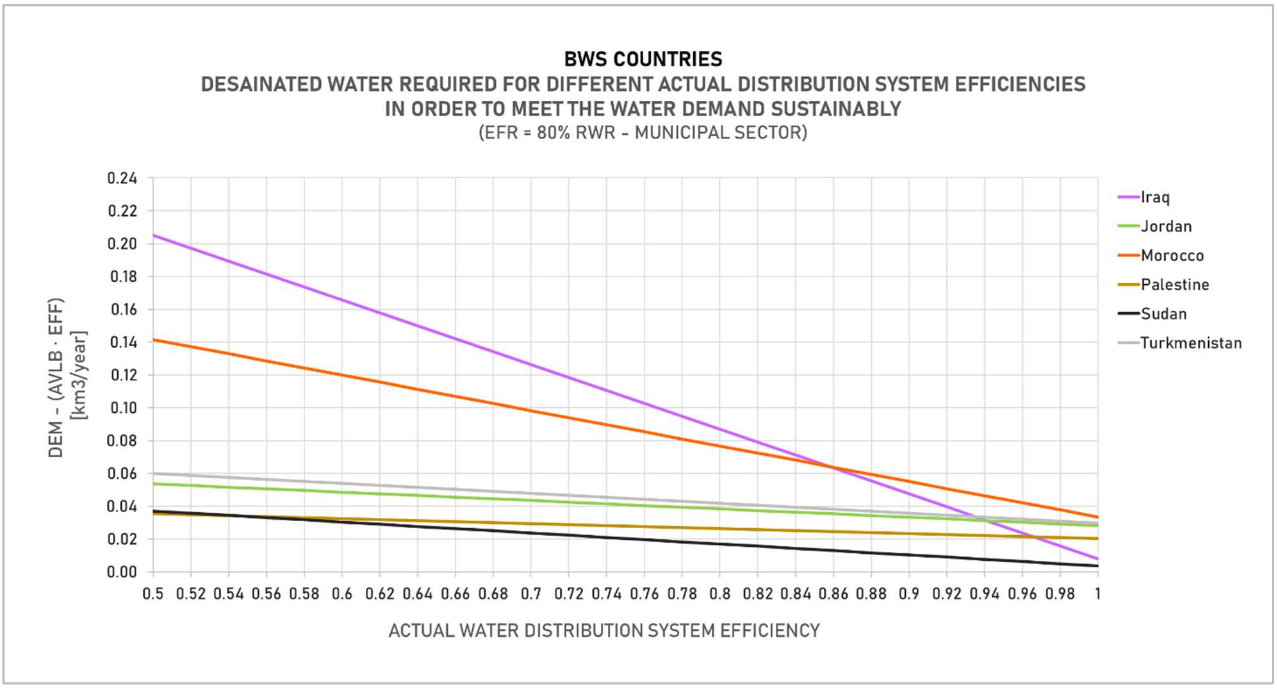


Graph 11: BWS countries desalinated water need for different efficiencies (Municipal Sector – 60% EFR)

80% EFR



Graph 12a: BWS countries desalinated water need for different efficiencies (Municipal Sector – 80% EFR)



Graph 12b: Iraq, Jordan, Morocco, Palestine, Sudan and Turkmenistan desalinated water need for different efficiencies (Municipal Sector – 80% EFR)

Industrial sector

Similarly to the municipal sector, the industrial sector also requires significantly lower desalinated water volumes compared to agriculture, and fewer countries fall into BWS across different EFR scenarios.
For actual EFR (graph 13), Yemen is once again the only country in BWS. However, unlike the previously analyzed cases, it is not in a state of overexploitation but in a DEM > AVLB > USE condition.

Considering EFR equal to 60% of total RWR (graphs 14a and 14b), Jordan and Palestine join Yemen in the DEM > AVLB > USE situation, while Libya and Pakistan satisfy their water demands by overexploiting their AVLB. Therefore, in the 60% scenario no country is in a DEM > USE > AVLB situation, which is qualitatively the worst one.

For 80% EFR (graphs 15a and 15b), Yemen and Palestine shift into the DEM > USE > AVLB category, which characterizes also Morocco, that for lower EFR does not even result in BWS situation.

Jordan withdrawal is still sustainable in this scenario (DEM > AVLB > USE), like the one of Tunisia that, similarly to Morocco, is not included in the BWS countries for actual and 60% EFR. Together with Libya and Pakistan, in the 80% scenario also Iran, Iraq, Sudan and Turkmenistan fall in the USE > DEM > AVLB condition.

Iraq presence among BWS countries for 80% EFR further highlighting how the use of untreated municipal wastewater for irrigation prevents it from appearing among BWS countries in the total and agricultural situation.

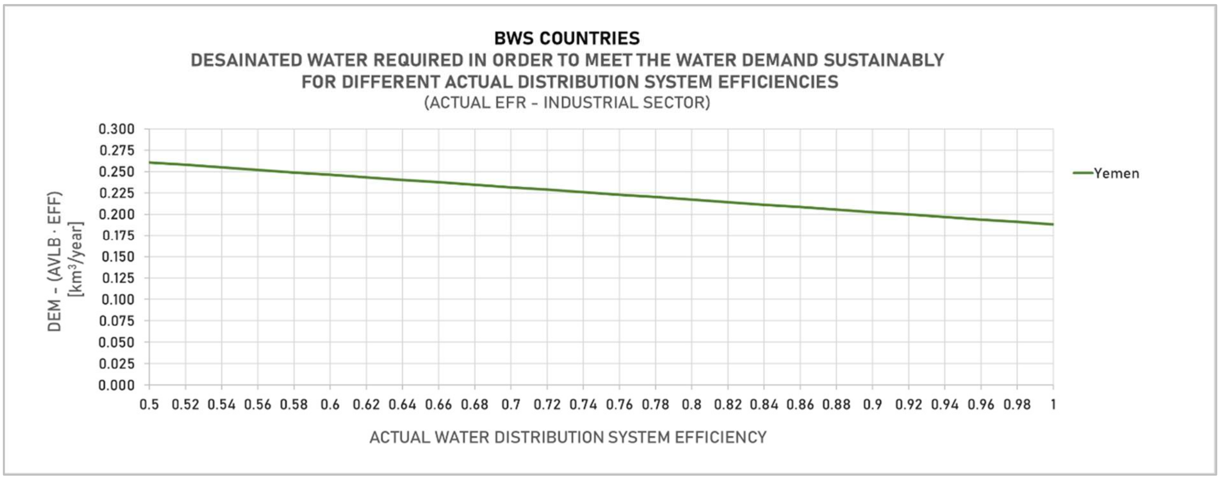
As observed in the agricultural sector graphs, the industrial sector graphs also show cases where, below a certain efficiency threshold, the amount of desalinated water required does not increase.
This occurs in Jordan, Palestine, and Yemen at 60% EFR and in Jordan and Tunisia at 80% EFR, all of which are in a DEM > AVLB > USE situation.

For example, Jordan has a DEM of $70 \cdot 10^6$ m^3/year, a USE of $37 \cdot 10^6$ m^3/year, and an AVLB of $57 \cdot 10^6$ m^3/year for the 60% EFR scenario, which decreases to $45 \cdot 10^6$ m^3/year at 80% EFR.
As a result, the maximum amount of water that should be produced through desalination is determined by the DEM-USE difference, which equals $70 - 37 = 33 \cdot 10^6$ m^3/year.

This threshold is reached in the 60% EFR scenario when the water distribution system efficiency (η) is equal to USE/AVLB = $37/57 \approx 65\%$.
Indeed, for an efficiency of 64%, the required desalinated water volume would be:
$\mathrm{DEM} - (\mathrm{AVLB}_{60\%} \cdot 0.64) = 70 - (57 \cdot 0.64) = 33.5 \cdot 10^6$ m^3/year, which exceeds the DEM-USE gap.

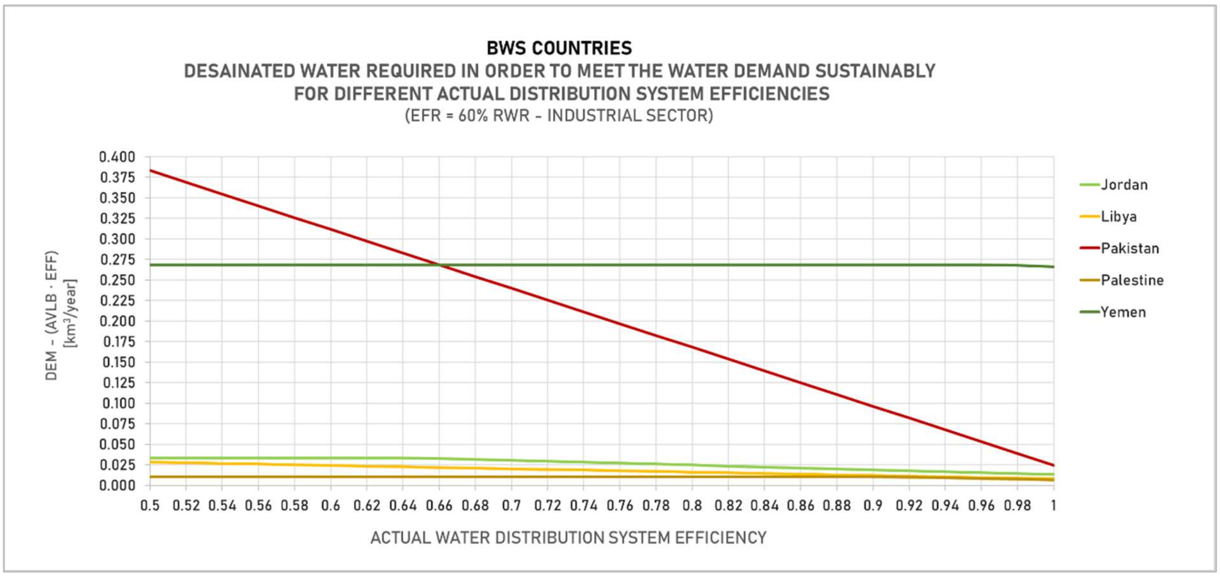
In the 80% EFR scenario, the threshold is reached at an efficiency of $37/45 \approx 82.2\%$. In this case:
$\mathrm{DEM} - (\mathrm{AVLB}_{80\%} \cdot 0.822) = 70 - (45 \cdot 0.822) = \mathrm{DEM} - \mathrm{USE} = 33 \cdot 10^6$ m^3/year.

ACTUAL EFR

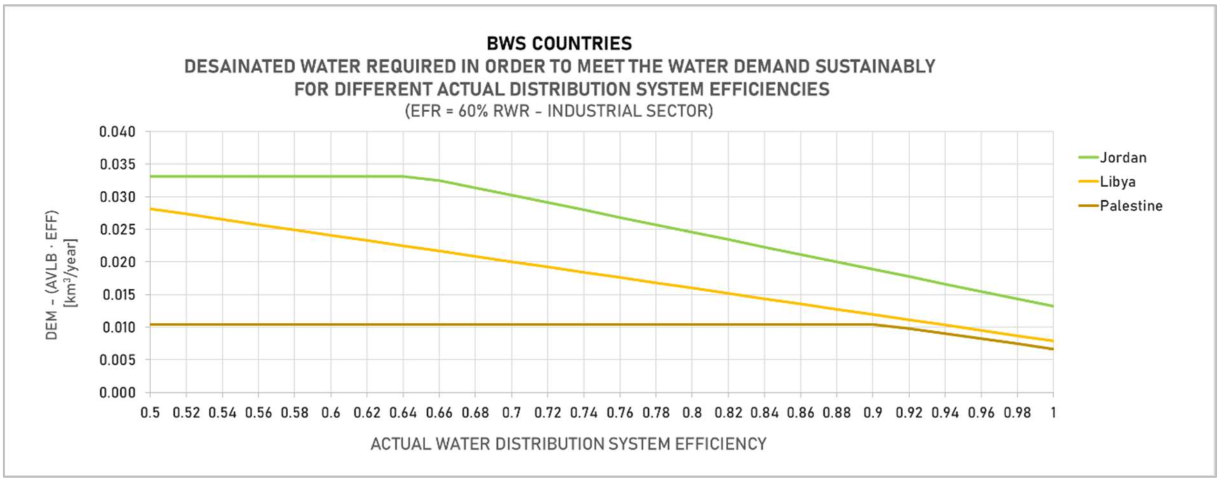


Graph 13: BWS countries desalinated water need for different efficiencies (Industrial Sector - Actual EFR)

60% EFR

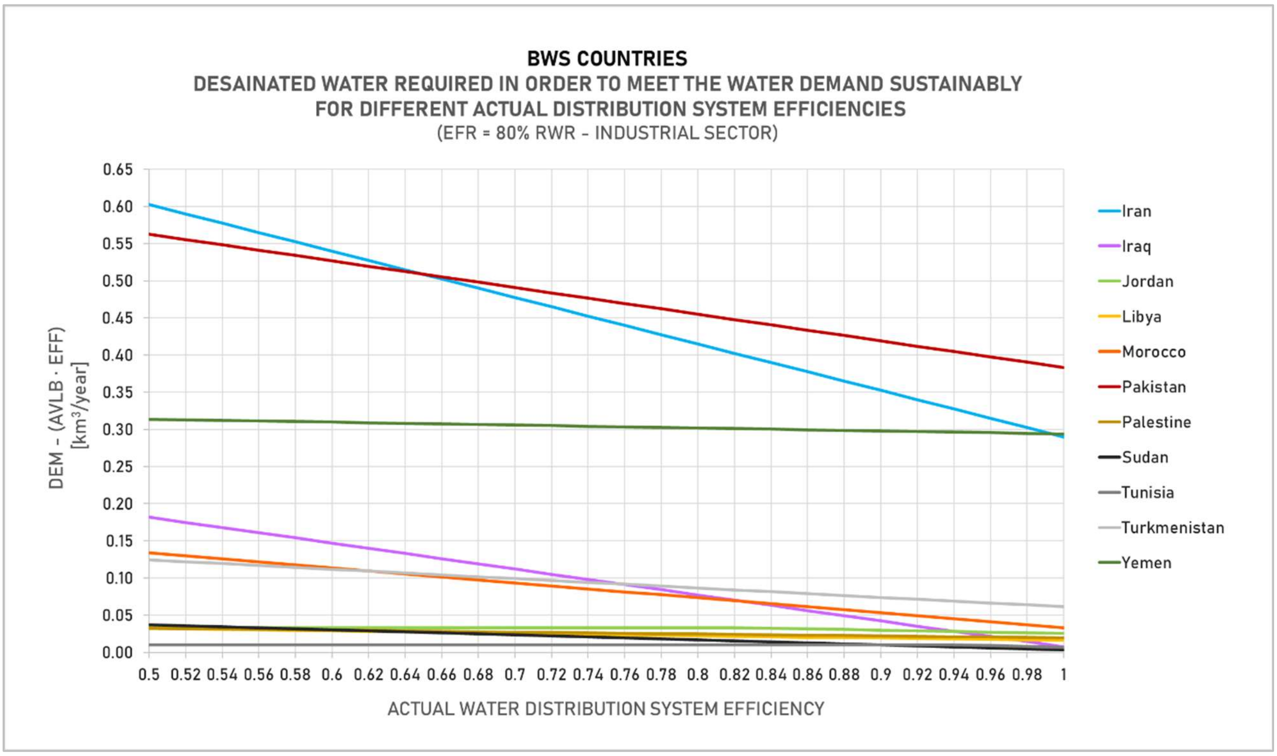


Graph 14a: BWS countries desalinated water need for different efficiencies (Industrial Sector – 60% EFR)

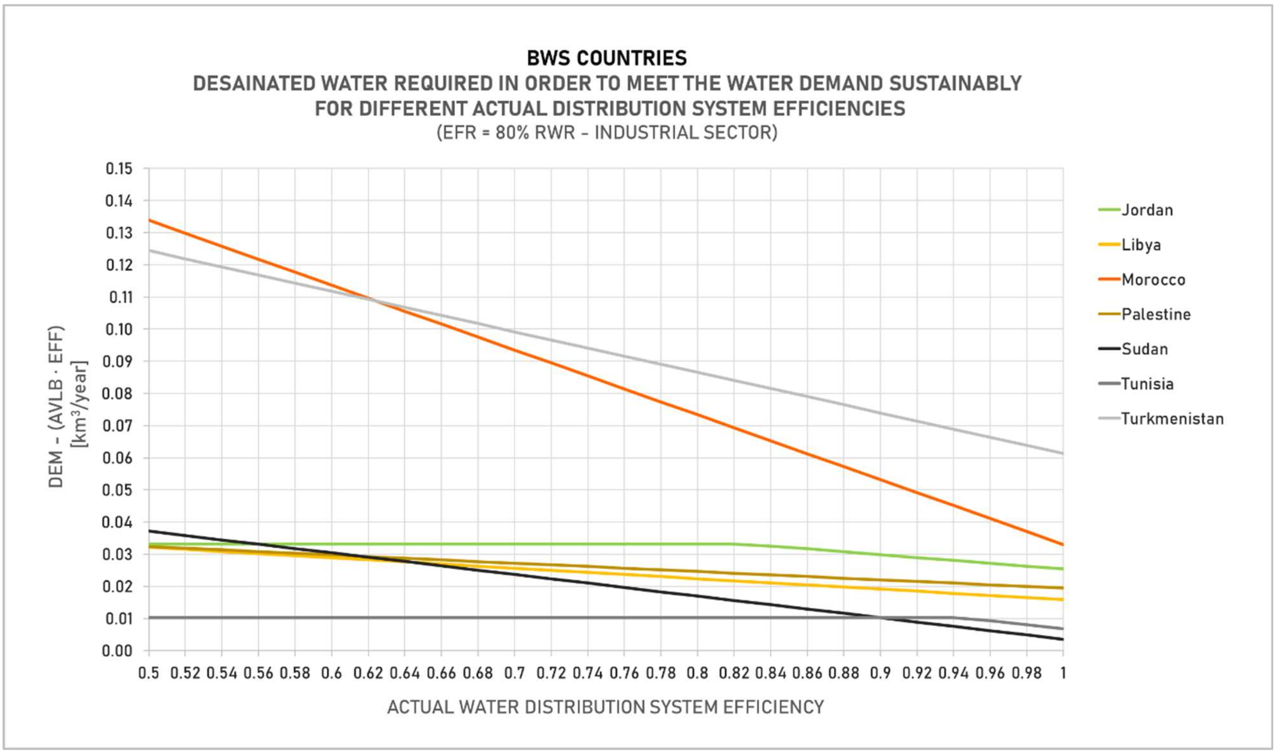


Graph 14b: Jordan, Libya and Palestine desalinated water need for different efficiencies (Industrial Sector – 60% EFR)

80% EFR



Graph 15a: BWS countries desalinated water need for different efficiencies (Industrial Sector – 80% EFR)



Graph 15b: Jordan, Libya, Morocco, Palestine, Sudan, Tunisia and Turkmenistan desalinated water need for different efficiencies (Industrial Sector – 80% EFR)

ENERGY REQUIREMENTS FOR DESALINATION

The trends of energy demand for desalinated water production closely follows the previously shown trend of desalinated water demand.
This similarity is due to the fact that energy requirements have been calculated by simply multiplying the volume of desalinated water to be produced by the energy requirement for producing 1 m^3 of desalinated water, which has been assumed to be 3 kWh.

Since energy demand is directly proportional to the volume of water that needs to be produced, results have been presented only for the global scenario and the municipal sector of the various countries in the BWS situation. The reason for focusing on the municipal sector among the three is that the volumes of desalinated water required for agriculture are roughly comparable to the ones for the total situation (up to several tens of billions of cubic meters per year), while the volumes needed in the industrial sector are on a much smaller scale, similar to that of the municipal sector (several hundred million cubic meters per year).

Additionally, the results of the municipal sector are shown because it is the only one that includes direct human consumption, making it the top priority for increasing RWR availability to ensure a sustainable supply.

TOTAL SITUATION

Given the direct proportionality between these results and the volume of water to be produced, Pakistan, as the country with the highest desalinated water demand in the 80% scenario, also has the largest energy requirements (Graph 18a). Specifically, its energy consumption is around $230 \cdot 10^9$ kWh/year for water distribution system efficiency of 50% efficiency and $155 \cdot 10^9$ kWh/year for 100% efficiency.

In the 60% EFR scenario (Graph 18b), for efficiencies above 98%, Saudi Arabia, Yemen, and Egypt would need to produce larger volumes of desalinated water than Pakistan, resulting in higher energy demands.
In particular, for Egypt, energy consumption surpasses that of Pakistan for efficiencies above 94%, while for Saudi Arabia, it surpasses the one of Pakistan for efficiencies above 96%.

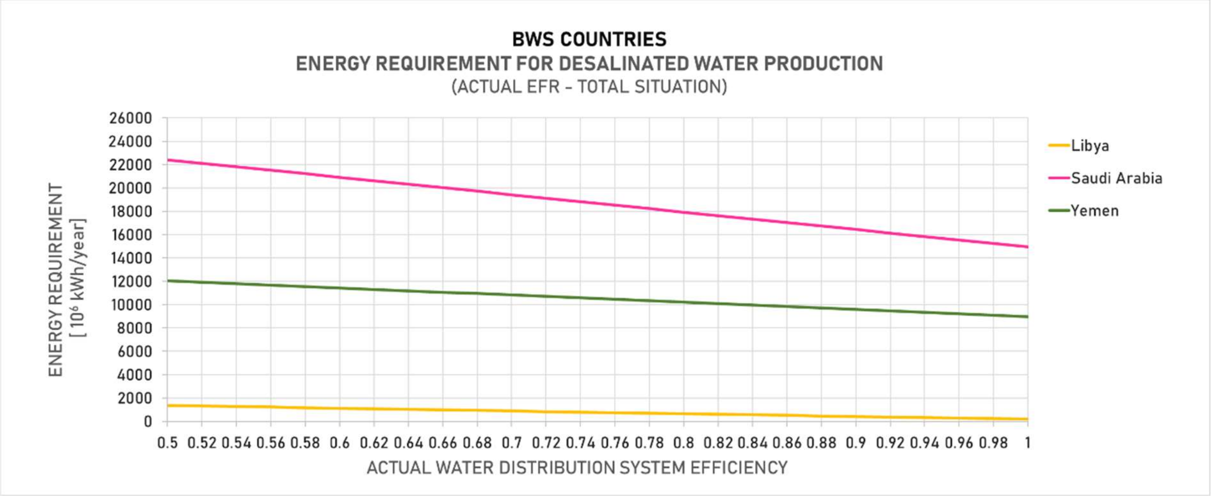
MUNICIPAL SECTOR

Regarding the municipal sector, energy requirements are shown only for Yemen, as it is the only country included in the BWS for this specific scenario. These values range from a minimum of 620 million to a maximum of 875 million kWh/year.

In the 60% EFR scenario, Pakistan has the highest energy demands for efficiencies below 80%, while Yemen has the highest requirements for efficiencies above this threshold.

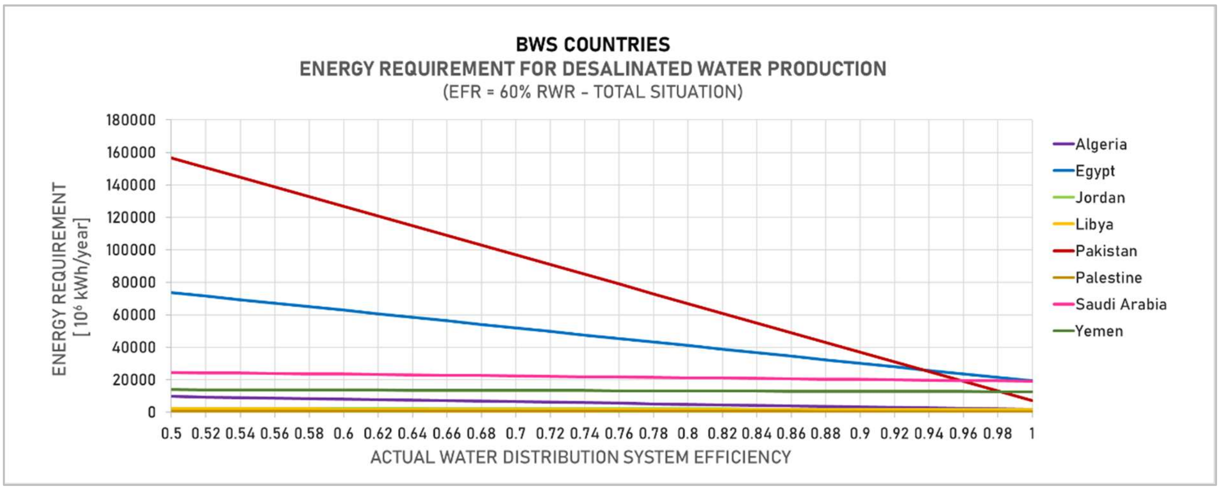
Finally, in the 80% EFR scenario, Pakistan has the highest energy demands across all assumed efficiency levels, followed by Iran and Yemen for efficiencies below 94%, with the order reversing above this threshold.
In this EFR scenario, Pakistan energy requirements range between 2.1 and 3.1 billion kWh/year, which are approximately two orders of magnitude lower than those estimated for the global situation.

TOTAL SITUATION – ACTUAL EFR

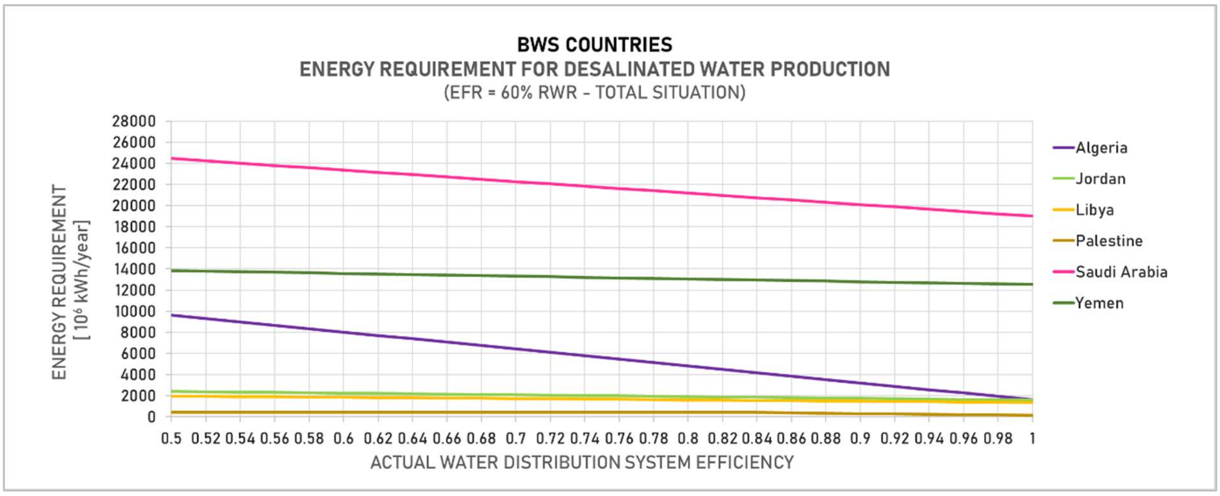


Graph 16: BWS countries energy requirements for desalination (Total Situation – Actual EFR)

TOTAL SITUATION – 60% EFR

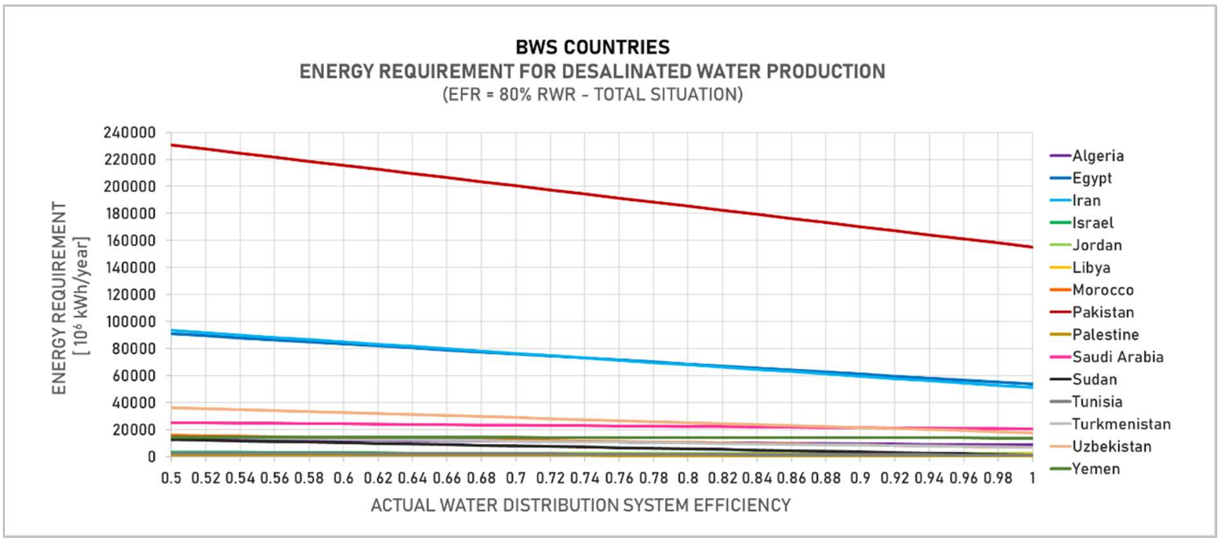


Graph 17a: BWS countries energy requirements for desalination (Total Situation – 60% EFR)

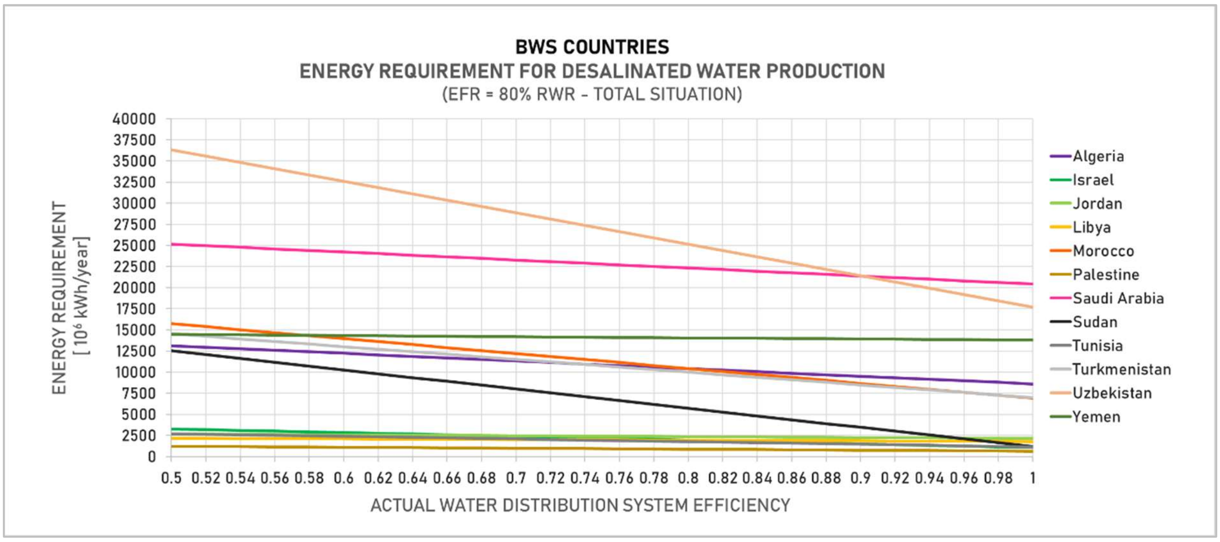


Graph 17b: Algeria, Jordan, Libya, Palestine, Saudi Arabia, Yemen energy requirements for desalination (Total Situation – 60% EFR)

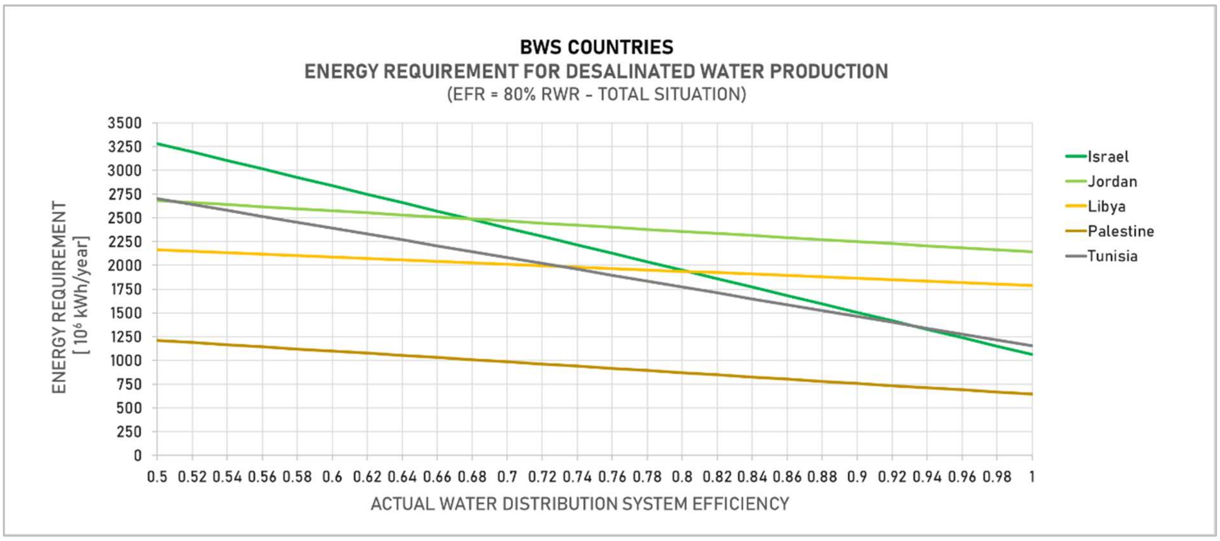
TOTAL SITUATION – 80% EFR



Graph 18a: BWS countries energy requirements for desalination (Total Situation – 80% EFR)

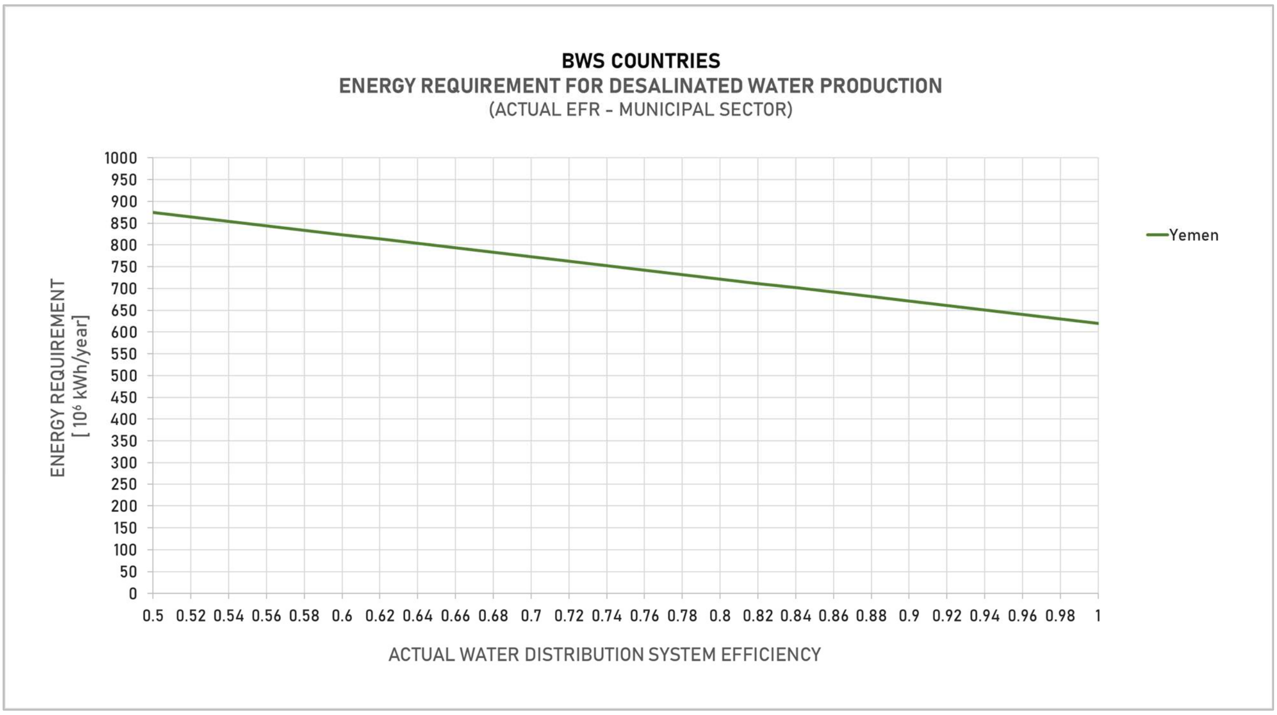


Graph 18b: Algeria, Israel, Jordan, Libya, Morocco, Palestine, Saudi Arabia, Sudan, Tunisia, Turkmenistan, Uzbekistan and Yemen energy requirements for desalination (Total Situation – 80% EFR)



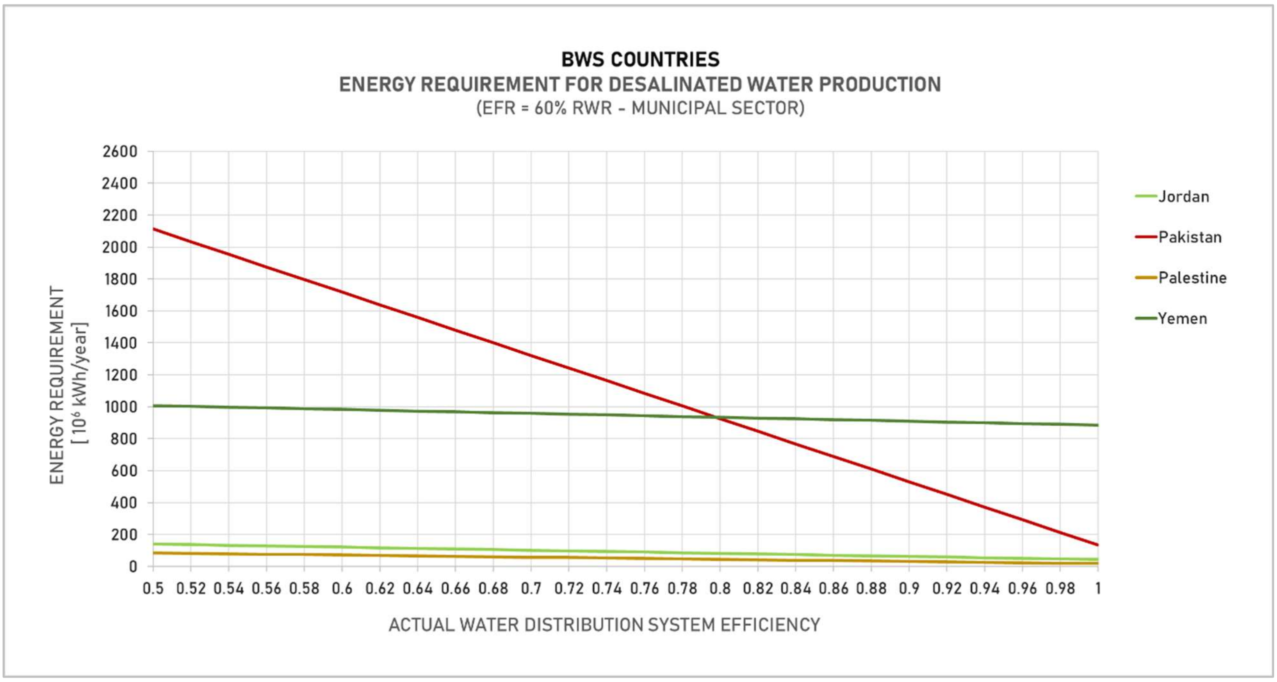
Graph 18c: Israel, Jordan, Libya, Palestine, and Tunisia energy requirements for desalination (Total Situation – 80% EFR)

MUNICIPAL SECTOR – ACTUAL EFR



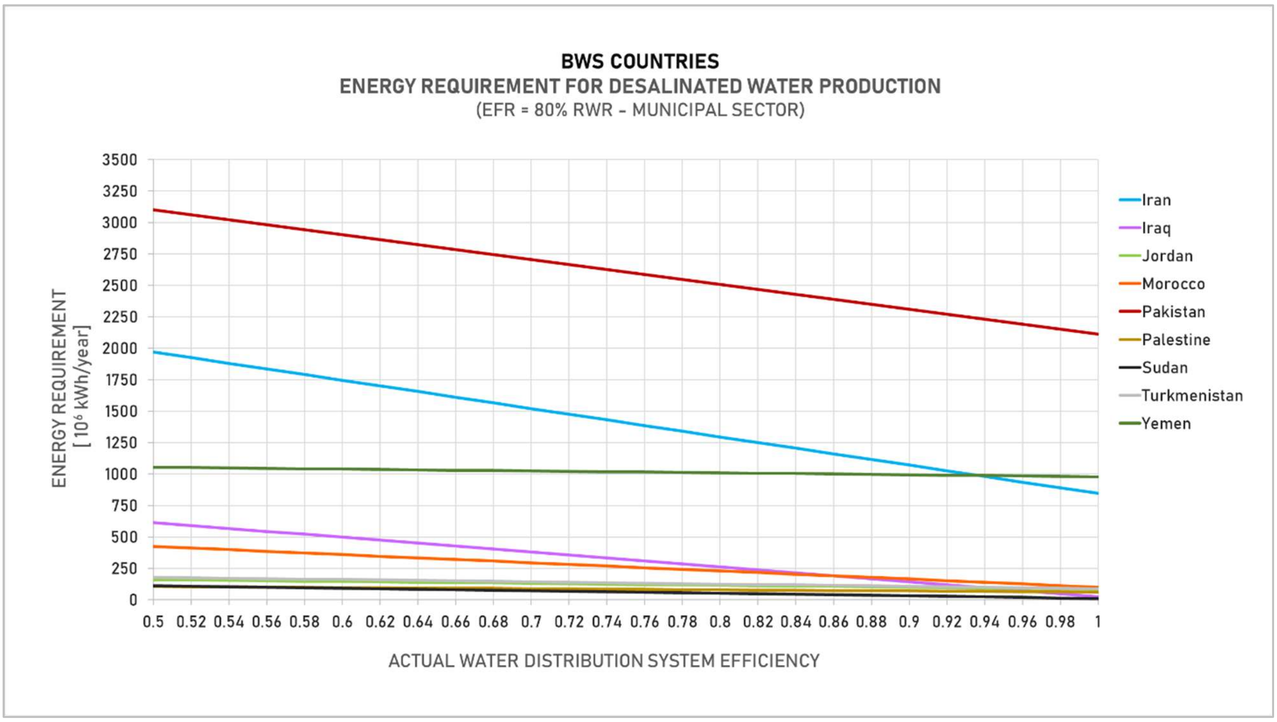
Graph 19: BWS countries energy requirements for desalination (Municipal Sector – Actual EFR)

MUNICIPAL SECTOR – 60% EFR

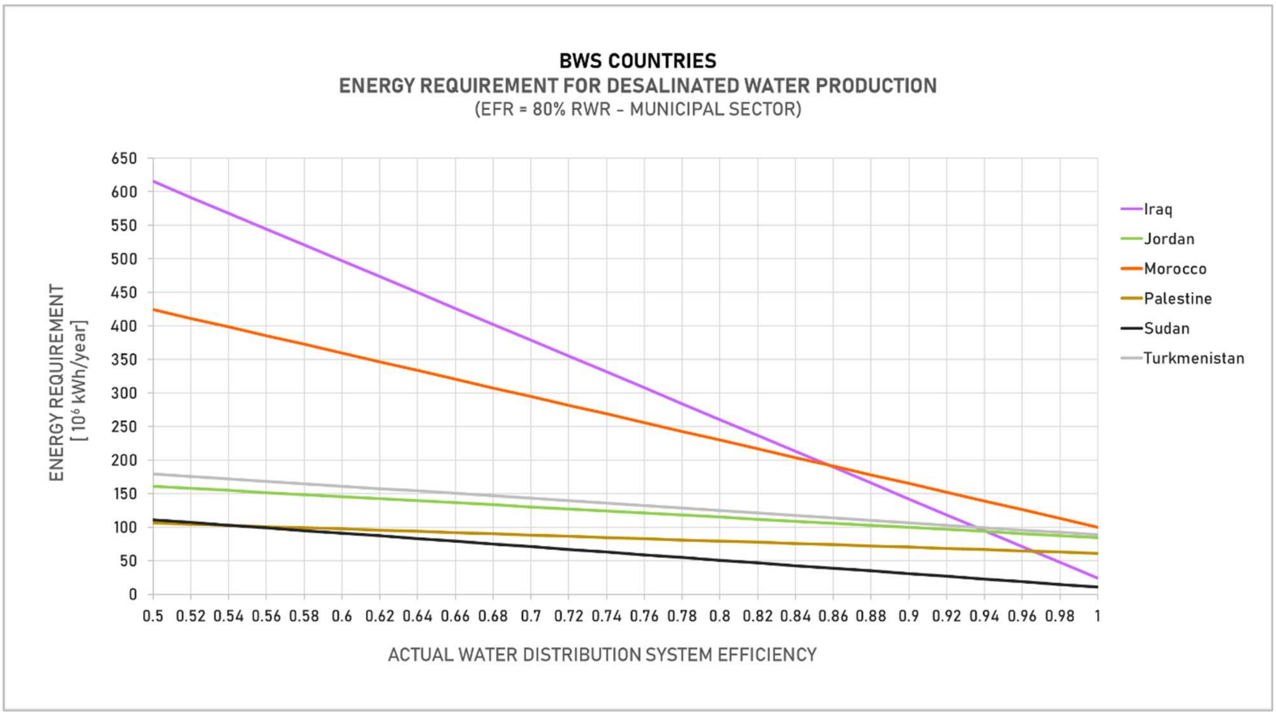


Graph 20: BWS countries energy requirements for desalination (Municipal Sector – 60% EFR)

MUNICIPAL SECTOR – 80% EFR



Graph 21a: BWS countries energy requirements for desalination (Municipal Sector – 80% EFR)

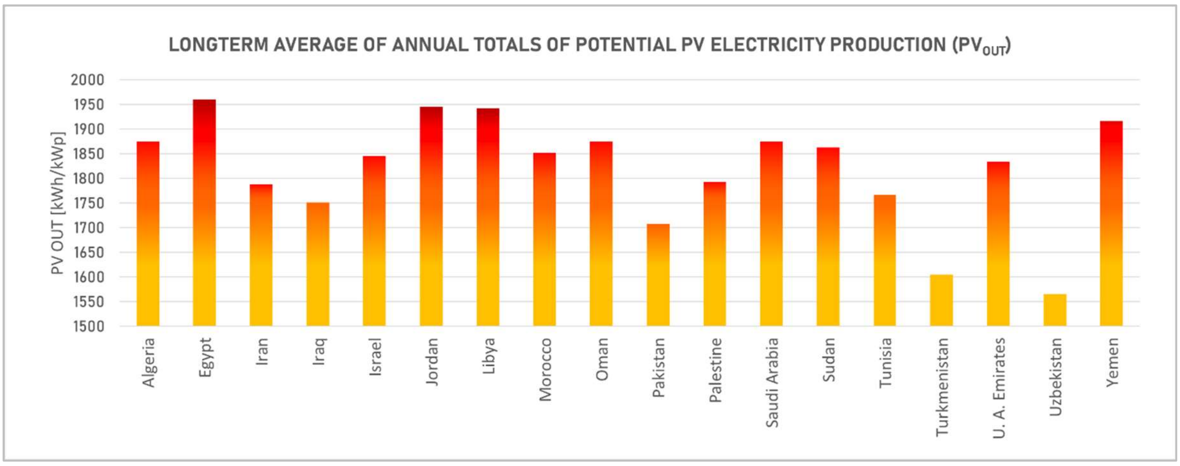


Graph 21b: Iraq, Jordan, Morocco, Palestine, Sudan and Turkmenistan energy requirements for desalination (Municipal Sector – 80% EFR)

AGRIVOLTAICS AREAS REQUIREMENTS FOR ENERGY PRODUCTION

The results are presented only for agrivoltaics spatial requirements, as photovoltaic areas are directly proportional, representing only 40% of the agrivoltaics area. Similarly to energy requirements, agrivoltaics results are shown only for the total scenario and the municipal sector.

However, these results are not directly proportional to desalinated water demand, as they depend also on solar irradiation, which varies by country.



Graph 22: Annual solar energy production per kW$_P$ of installed capacity for each country in BWS in at least one scenario

For example, Egypt, Jordan, Libya, and Yemen have an annual photovoltaic productivity exceeding 1900 kWh/kW$_P$, while Pakistan, Turkmenistan, and Uzbekistan have a productivity below 1750 kWh/kW$_P$ per year (Graph 22). Naturally, the higher the energy generation per kW$_P$ installed, the lower the agrivoltaics space required to produce the energy needed for desalination.

As a result, Egypt, Jordan, Libya, and Yemen have lower agrivoltaics space requirements relative to their own energy needs compared to Pakistan, Turkmenistan, and Uzbekistan, where the required area is proportionally larger in relation to their energy demand.

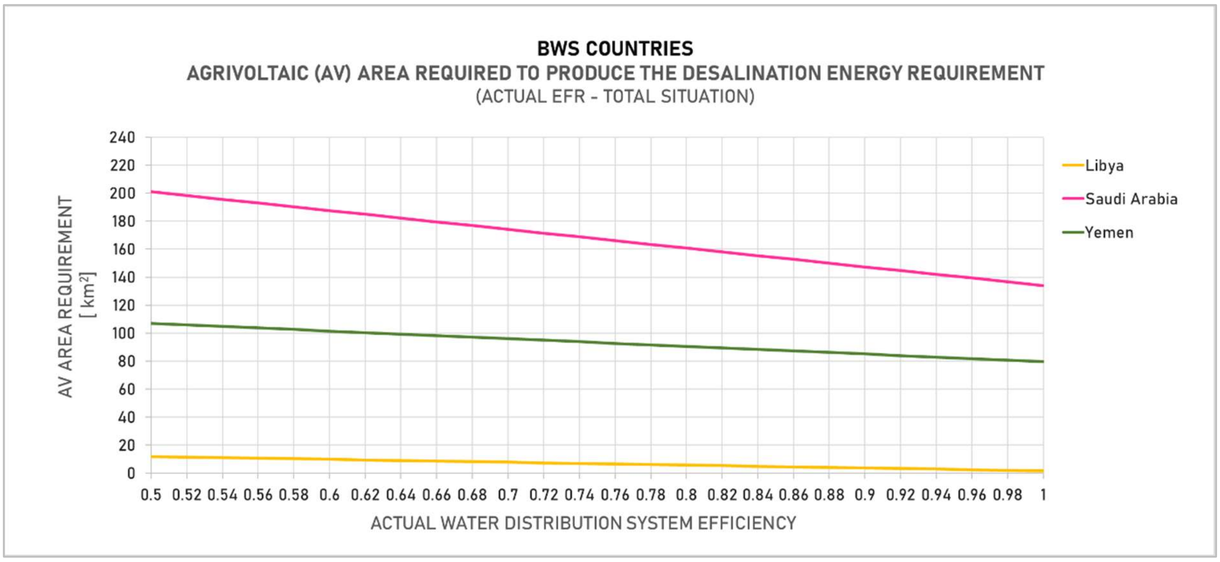
However, as shown in Graphs 25a and 25b, under the total scenario with 80% EFR, Egypt still has a higher absolute spatial requirement than Turkmenistan and Uzbekistan.

There are cases where energy productivity affects the ranking of countries with the highest requirements.

For example, while Graph 18b (total situation, 80% EFR) shows that Uzbekistan has lower energy requirements than Saudi Arabia for efficiencies above 90%, Graph 25b shows that, for the same scenario, Uzbekistan has always higher spatial requirements than Saudi Arabia, regardless of the efficiency level.

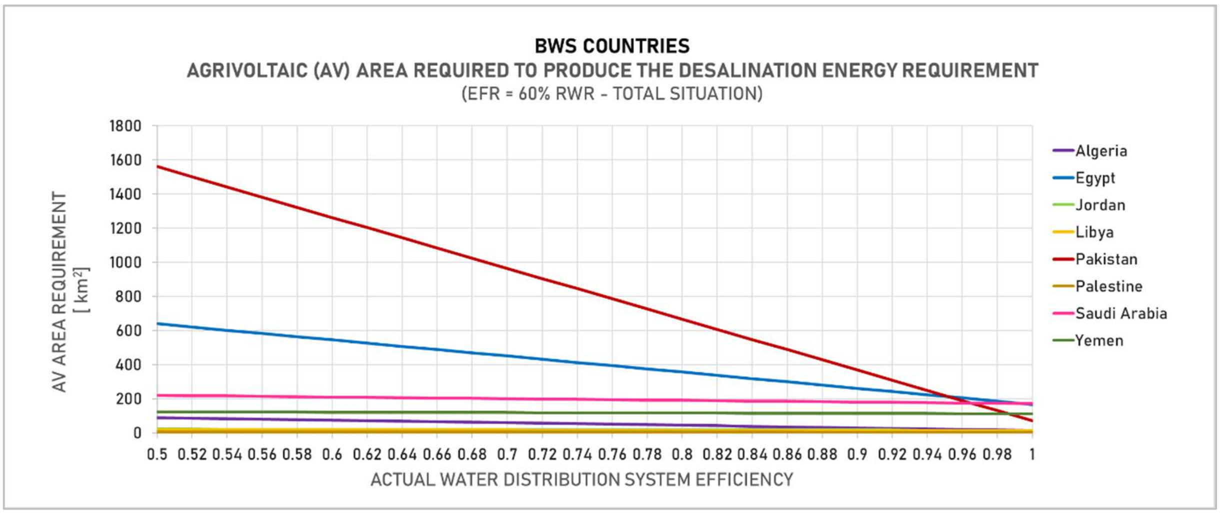
This is because Uzbekistan has an average annual solar energy productivity of 1565 kWh/kW$_P$ (the lowest among the countries in graph 22), while the one of Saudi Arabia is 1896 kWh/ kW$_P$.

TOTAL SITUATION – ACTUAL EFR

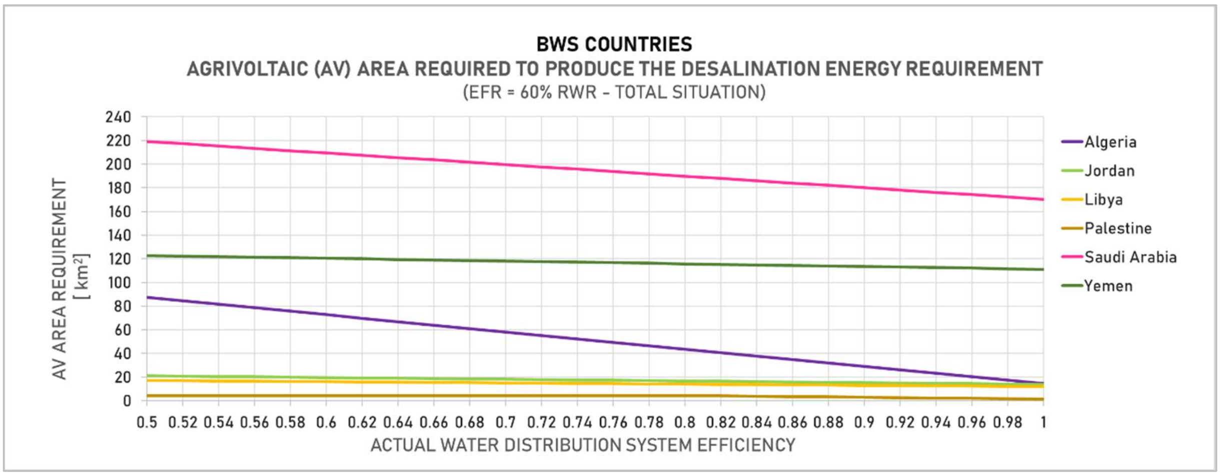


Graph 23: BWS countries AV area requirements for desalination (Total Situation – Actual EFR)

TOTAL SITUATION – 60% EFR

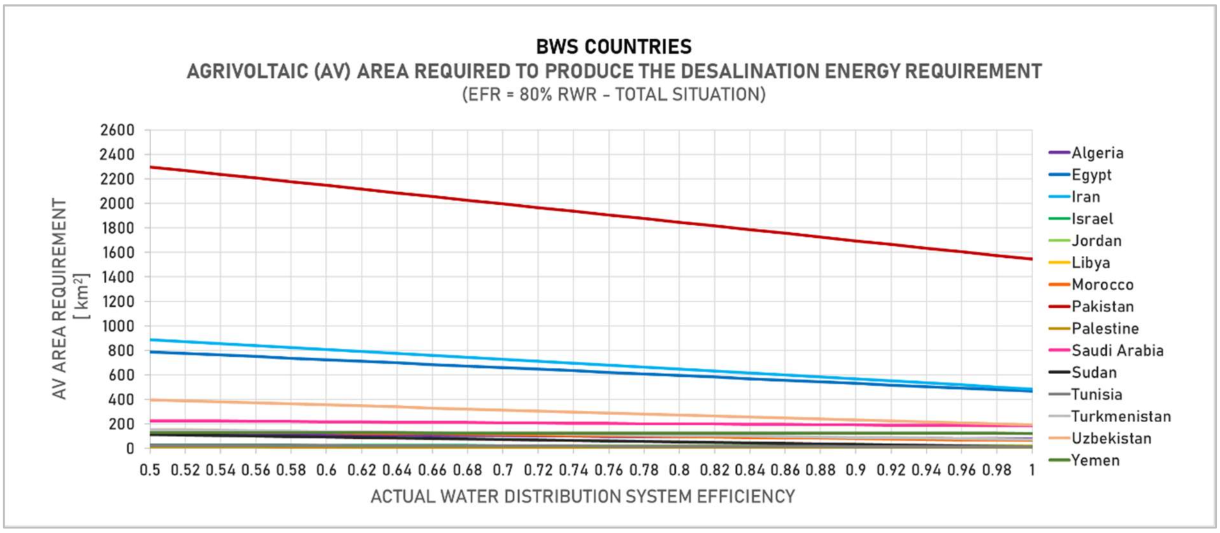


Graph 24a: BWS countries AV area requirements for desalination (Total Situation – 60% EFR)

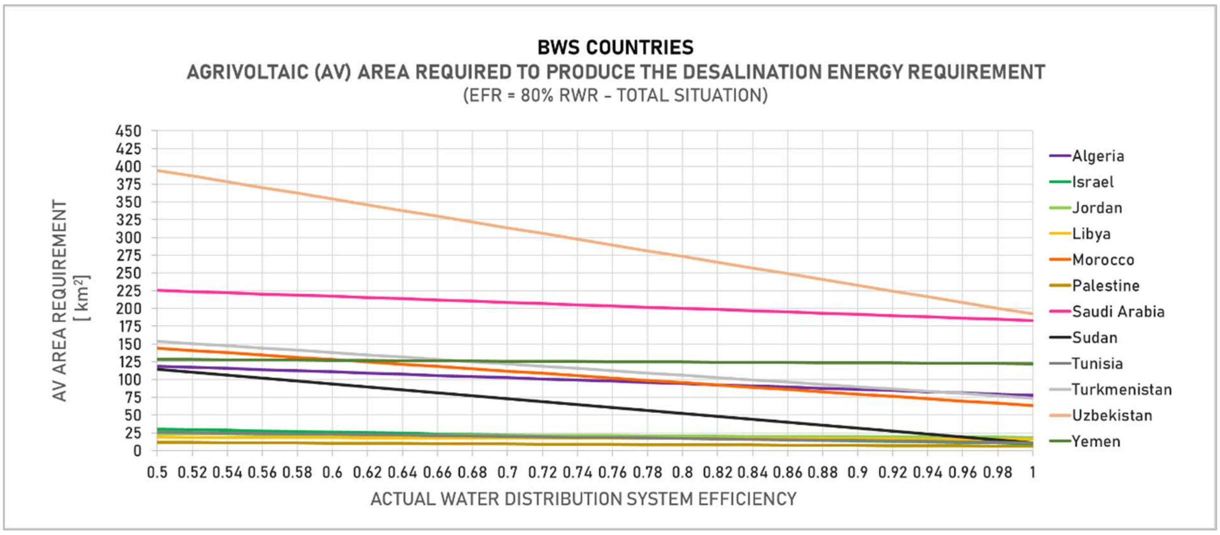


Graph 24b: Algeria, Jordan, Libya, Palestine, Saudi Arabia, Yemen energy requirements for desalination (Total Situation – 60% EFR)

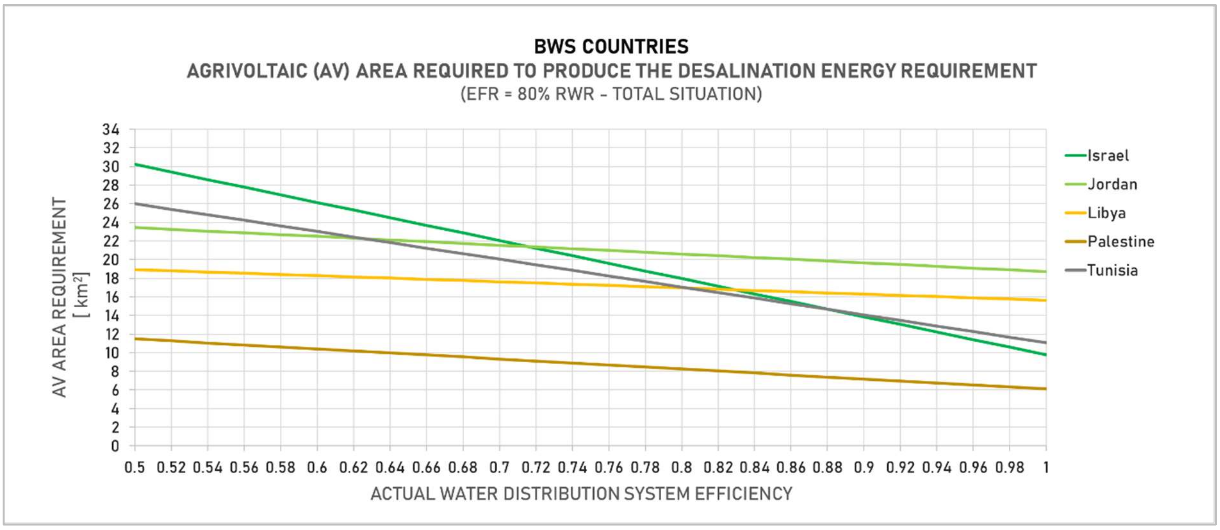
TOTAL SITUATION – 80% EFR



Graph 25a: BWS countries AV area requirements for desalination (Total Situation – 80% EFR)



Graph 25b: Algeria, Israel, Jordan, Libya, Morocco, Palestine, Saudi Arabia, Sudan, Tunisia, Turkmenistan, Uzbekistan and Yemen AV area requirements for desalination (Total Situation – 80% EFR)



Graph 25c: Israel, Jordan, Libya, Palestine, and Tunisia AV area requirements for desalination (Total Situation – 80% EFR)

Regarding the municipal sector, the agrivoltaics (and of course photovoltaic) areas required for energy production are naturally significantly smaller compared to those estimated for the total scenario.

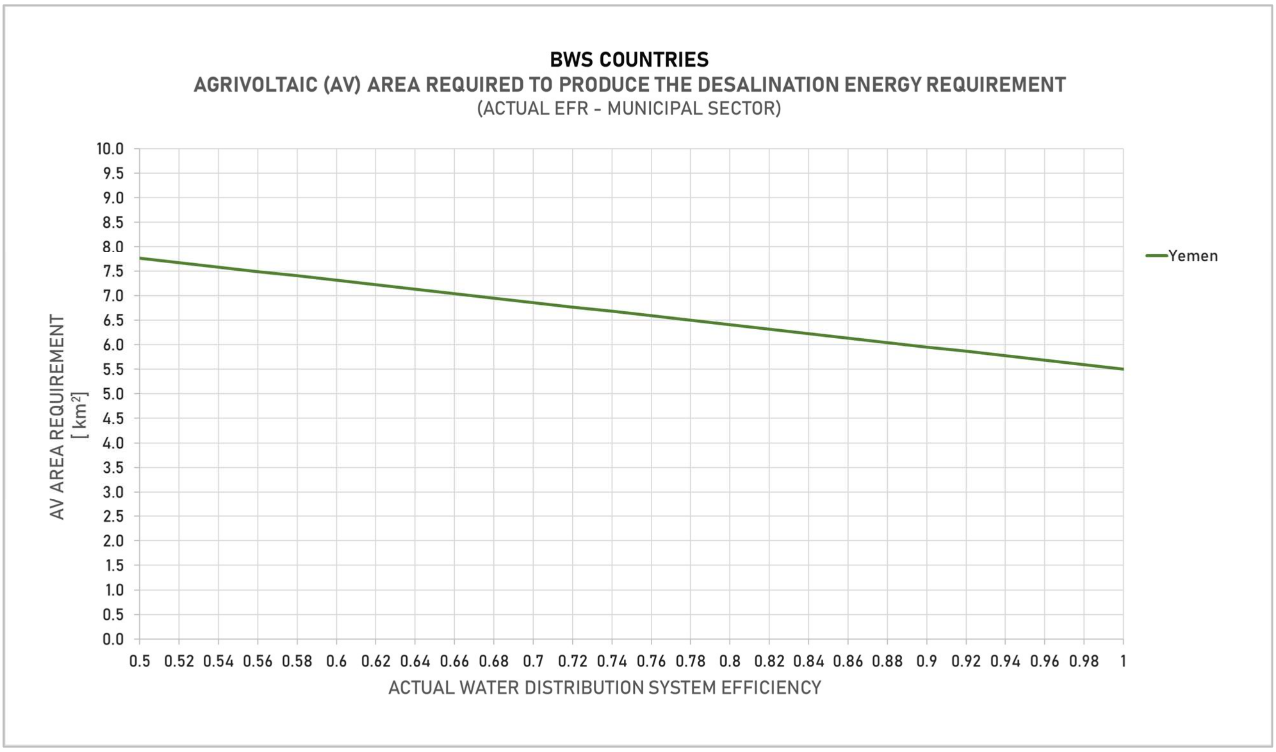
Considering actual EFR values, for the municipal sector Yemen, the only country in BWS, would require an agrivoltaics area ranging from 7.76 to 5.5 km², values that would increase to 8.94-7.85 under the 60% scenario (Graph 27) and to 9.35-8.69 km² under the 80% EFR scenario (Graph 28a).

The influence of the available solar energy in each country can be seen also in the municipal sector: for example, for the 60% EFR scenario, Pakistan has higher energy requirements than Yemen for efficiencies below approximately 79.5% (Graph 20), but higher spatial requirements than Yemen for efficiencies below about 83% (Graph 27).
Once again, the threshold efficiency varies depending on the criteria being compared, whether energy requirements or spatial requirements, due to differences in the average energy production per installed kW_P.

Overall, for 80% EFR, Pakistan is the country with highest requirements, both in the municipal sector (from 31 to 21 km² depending on efficiency) and in the total scenario (from 2296 to 1544 km²).
For water distribution efficiencies below 97%, Iran follows Pakistan in terms of AV spatial requirements. However, above this threshold, Yemen has the second-highest values with lower spatial requirements.
Regarding energy requirements, the threshold efficiency for both Yemen and Iran is around 94%.

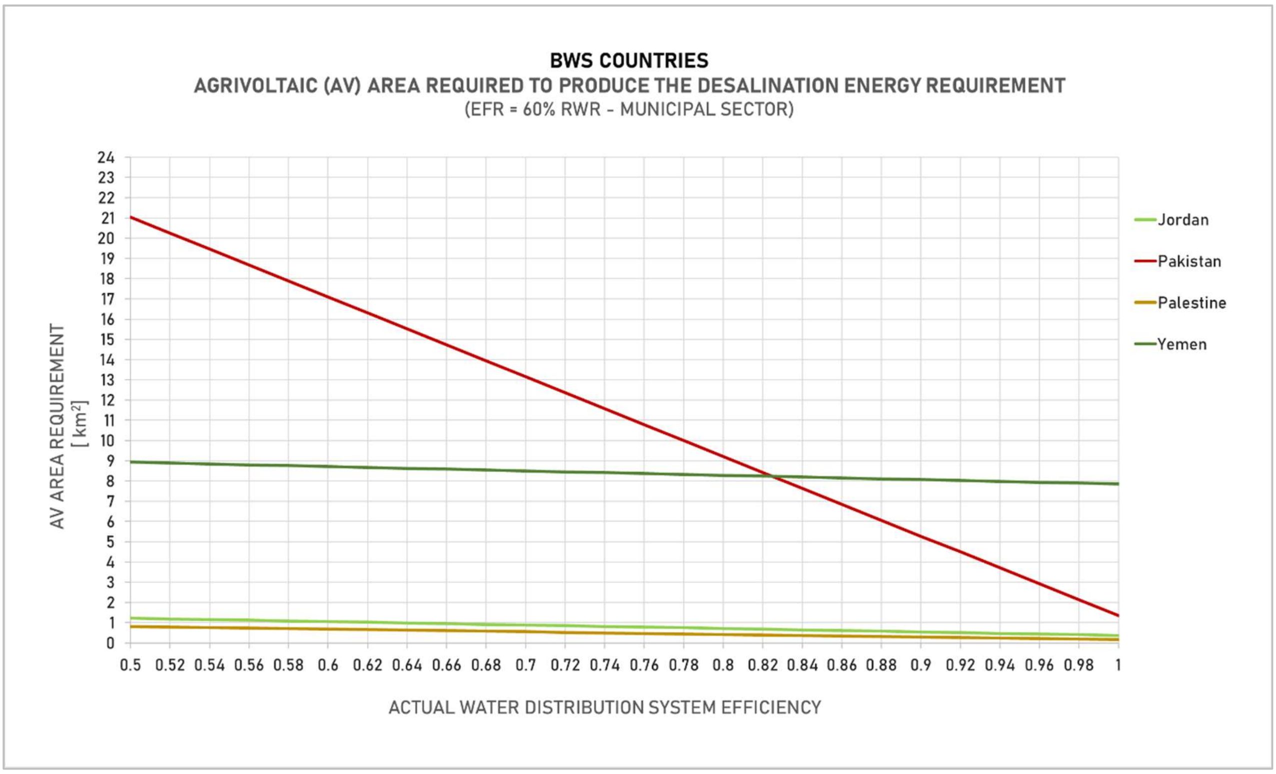
Indeed, in graph 22 it can be observed that Yemen has an average annual potential PV electricity production of 1916.4 kWh/ kW_P, while the one of Iran is around 1787.8 kWh/ kW_P

MUNICIPAL SECTOR – ACTUAL EFR



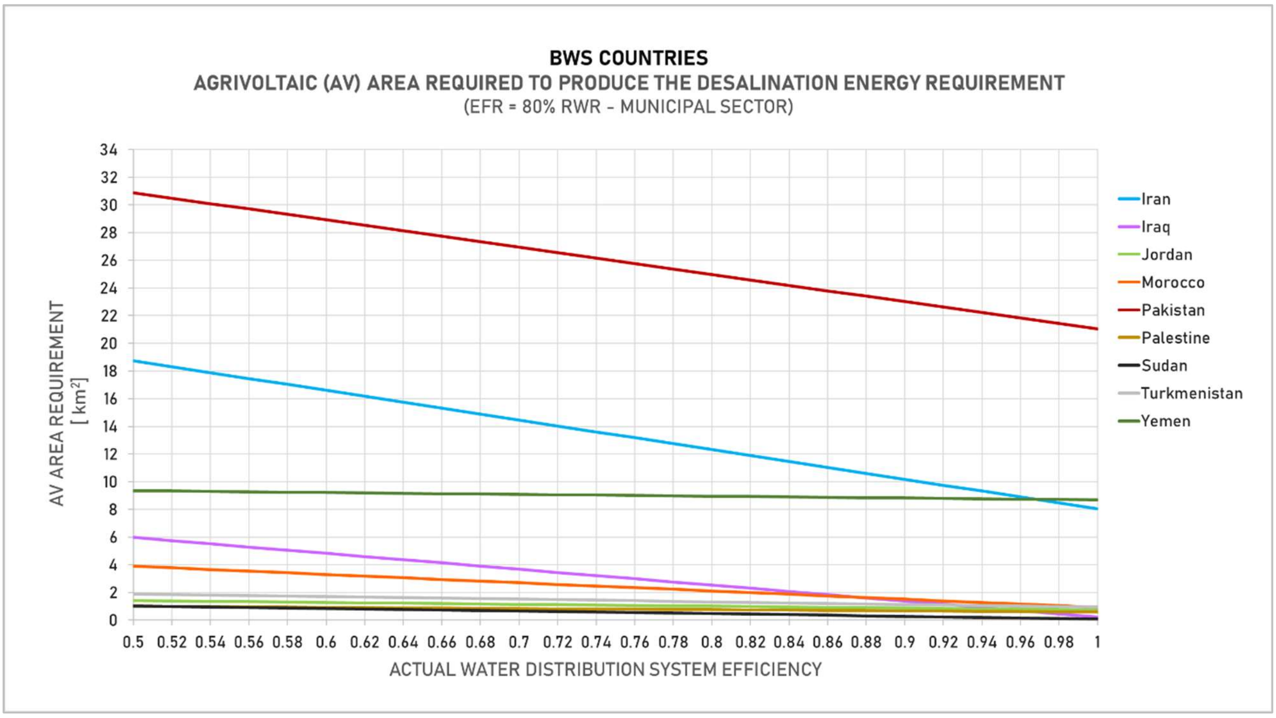
Graph 26: BWS countries AV area requirements for desalination (Municipal Sector – Actual EFR)

MUNICIPAL SECTOR – 60% EFR

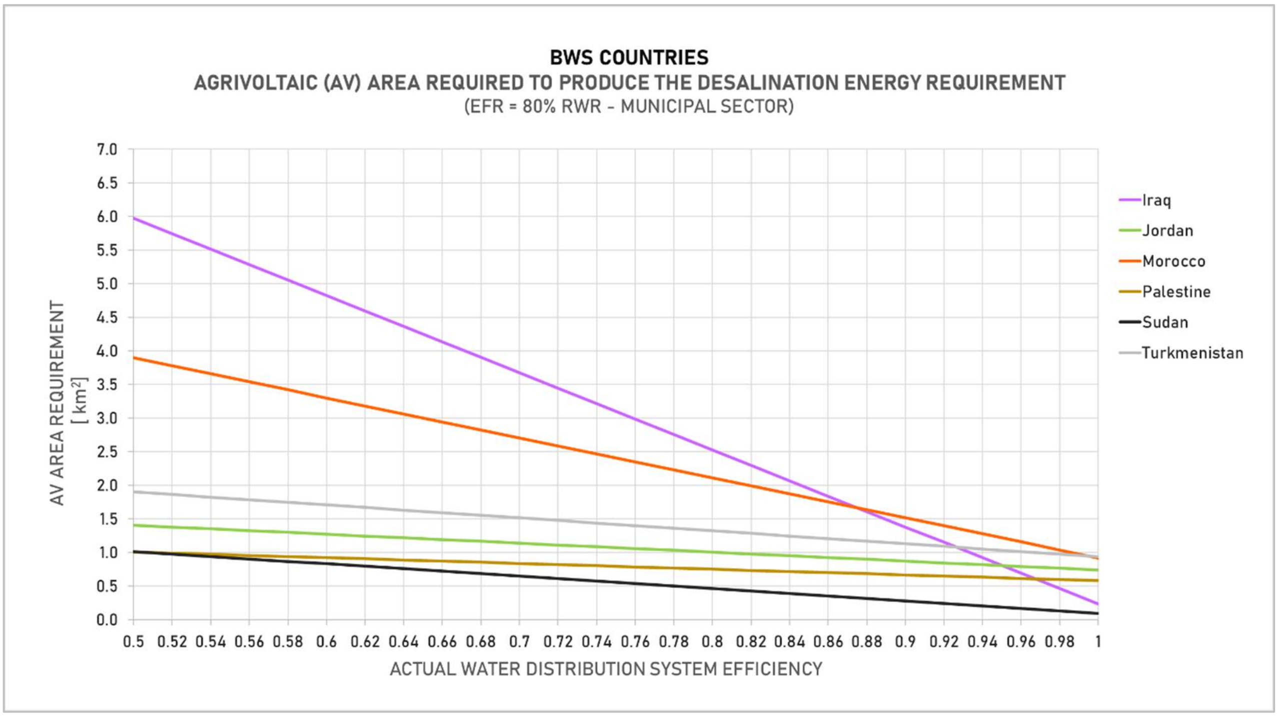


Graph 27: BWS countries AV area requirements for desalination (Municipal Sector – 60% EFR)

MUNICIPAL SECTOR – 80% EFR



Graph 28a: BWS countries AV area requirements for desalination (Municipal Sector – 80% EFR)



Graph 28b: Iraq, Jordan, Morocco, Palestine, Sudan and Turkmenistan AV area requirements for desalination (Municipal Sector – 80% EFR)

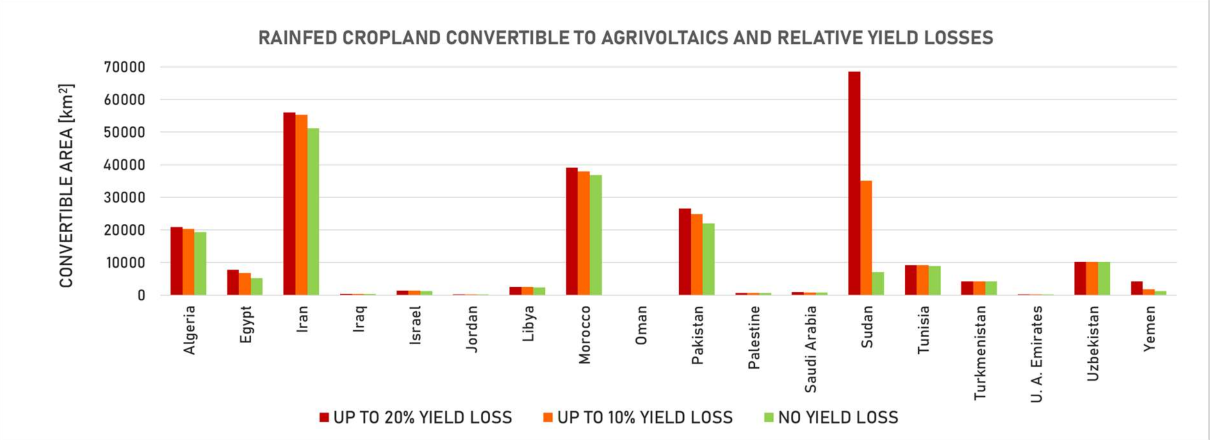
COMPARISON OF AGRIVOLTAICS AREAS REQUIREMENTS WITH TOTAL RAINFED CROPLAND SUITABLE FOR CONVERSION TO AGRIVOLTAIC

Given the multitude of scenarios for this analysis, which are totally 36 (considering the three sectors plus the total situation, three different EFR values, and three AV convertible areas), only the results related to the municipal sector are presented.

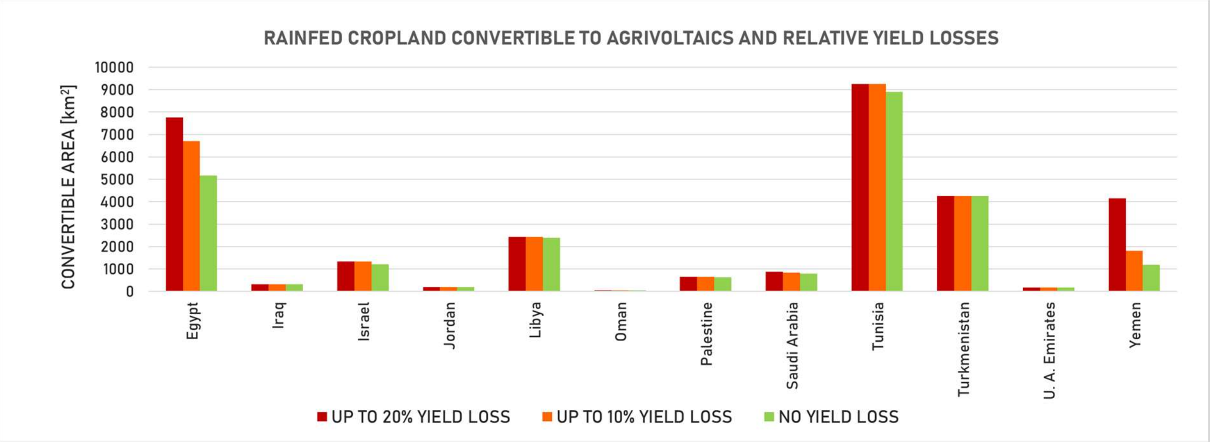
Consequently, nine specific scenarios are shown for this sector, each one resulting from the combination of the three EFR values with the three AV-convertible area levels, which reflect varying crop loss assumptions.

Graphs 29a and 29b illustrate the non-irrigated areas that can be converted to agrivoltaics for each country experiencing BWS in at least one scenario. As expected, the available convertible area decreases as the allowed yield loss is reduced. Among the countries facing BWS in at least one municipal sector scenario (Iran, Iraq, Jordan, Morocco, Pakistan, Palestine, Sudan, Turkmenistan, and Yemen) significant differences between the three areas are mainly observed for Sudan and Yemen. In these two cases, the areas convertible with up to a 20% yield loss are more than twice those under a maximum 10% yield loss.

Iran, Morocco, and Pakistan also show little variations between the three areas, while in Iraq, Jordan, Palestine, and Turkmenistan, the differences are almost negligible.



Graph 29a: total rainfed cropland convertible to agrivoltaics and relative yield losses (BWS countries)



Graph 29b: total rainfed cropland convertible to agrivoltaics and relative yield losses (BWS countries with convertible areas < 10^4km^2)

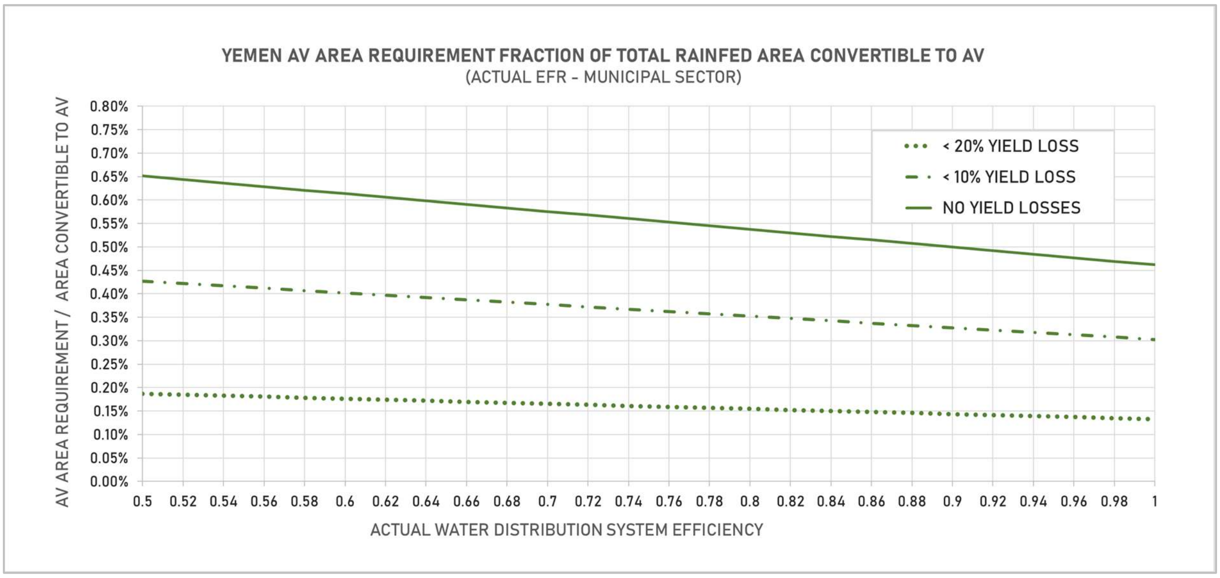
The differences between the three convertible area scenarios have a significant impact on the results. In Yemen and Sudan, for a given EFR, the fraction of agrivoltaics area required relative to the available convertible area varies considerably depending on the assumed yield loss. In contrast, for Iraq, Jordan, Palestine, and Turkmenistan, this variation is minimal.

The influence of yield loss assumptions is clear in Graphs 31a, 31b, and 31c. While Iran, Pakistan, and Palestine show minor differences in the ratio of required agrivoltaics area to convertible area across the three yield loss scenarios, for Yemen there is a substantial change (even considering actual EFR, in graph 30).
In particular, in the scenario allowing up to a 20% yield loss (Graph 31a), Yemen's ratio remains lower than the one of Jordan for every efficiency level. However, in the scenario where no yield loss is considered in converted areas (Graph 31c), Yemen's ratio surpasses that of Jordan across all water distribution system performances.

In Graphs 32a, 32b, and 32c, referred to 80% EFR, Yemen results show variations like the ones of the 60% EFR scenario. However, while significant differences should be observable also for Sudan in Graphs 32d, 32e, and 32f, they are almost imperceptible due to the vast difference between the required agrivoltaics area and the rainfed areas convertible to AV.
Only in the scenario with zero yield loss (Graph 32f) there is a notable variation, where Sudan's values exceed those of Morocco, while for yield losses up to 10% and 20%, they are lower.

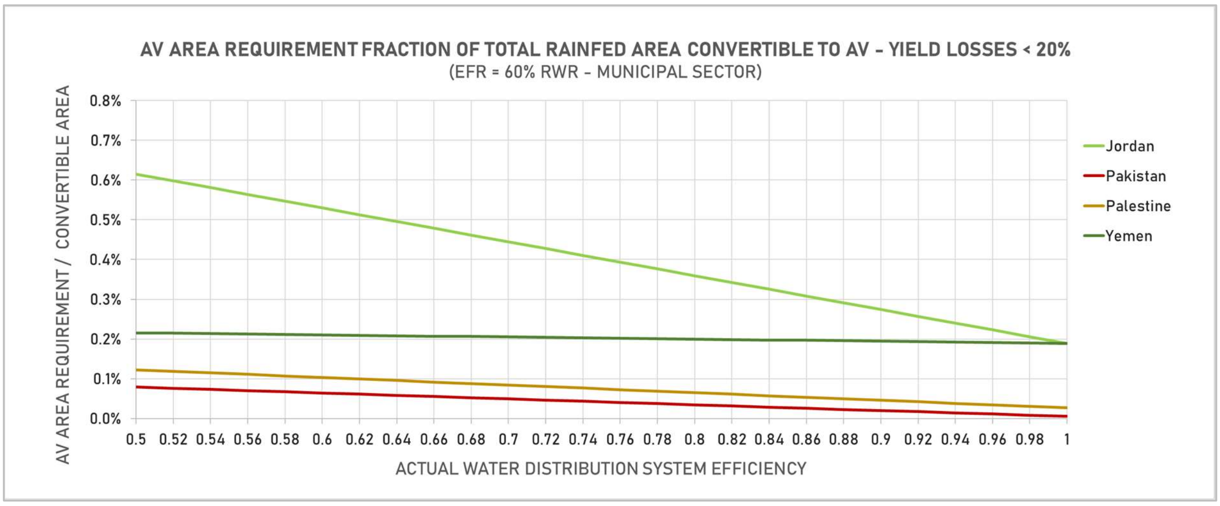
Indeed, while Sudan's agrivoltaics area requirements range from approximately 1 km² to 0.1 km² depending on the assumed efficiency, the convertible AV areas are around 68,000 km², 35,000 km², and 7,000 km² for yield losses of up to 20%, 10%, and zero, respectively.
Therefore, even considering the smallest convertible area and 50% efficiency, the required area would still account for only 0.014% of the available convertible non-irrigated cropland.

MUNICIPAL SECTOR – ACTUAL EFR

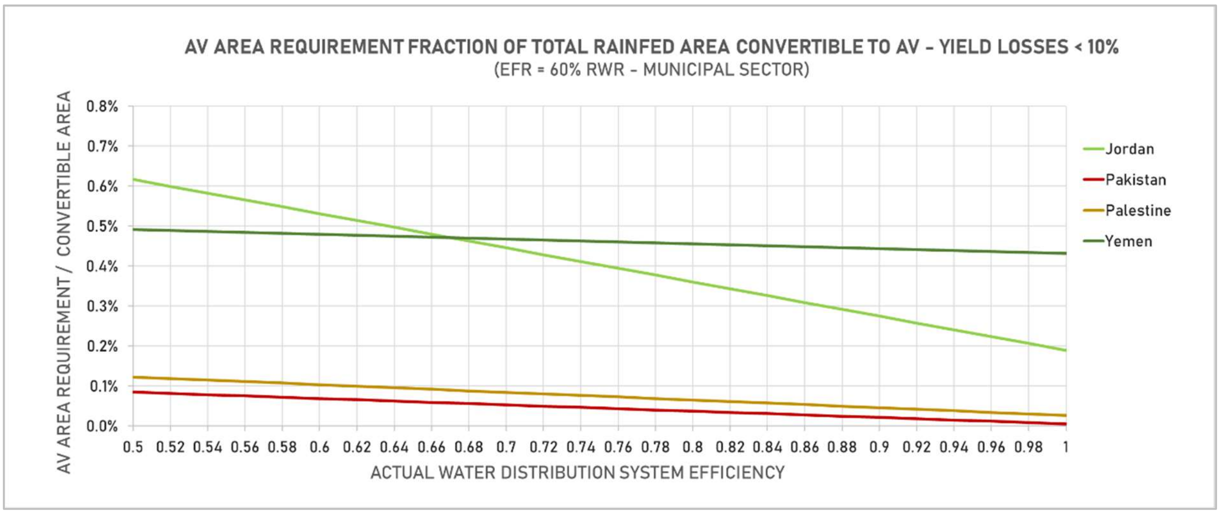


Graph 30: Yemen AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – Actual EFR)

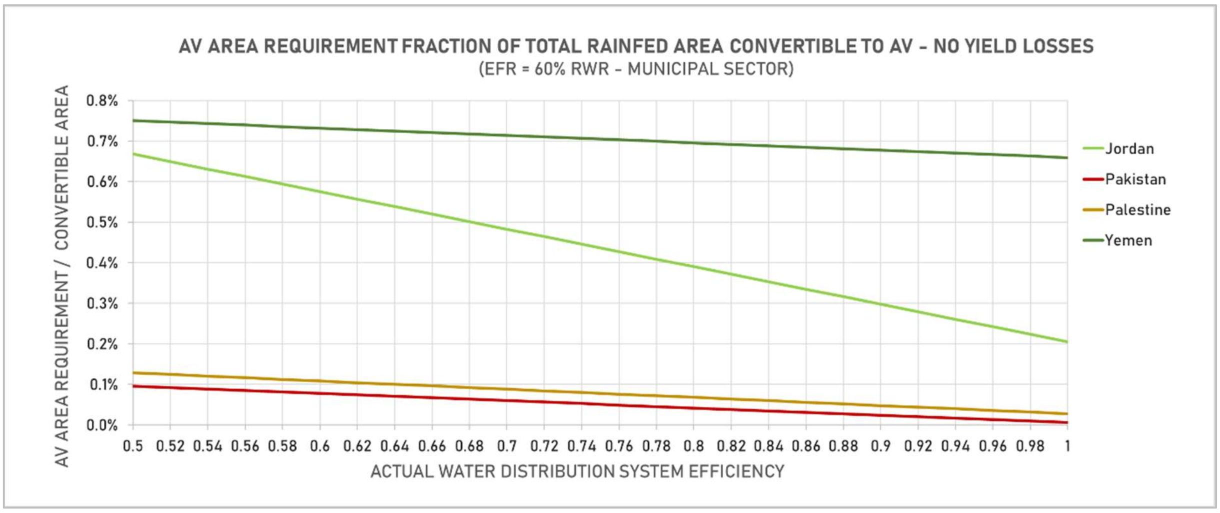
MUNICIPAL SECTOR – 60% EFR



Graph 31a: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 60% EFR – up to 20% yield losses)

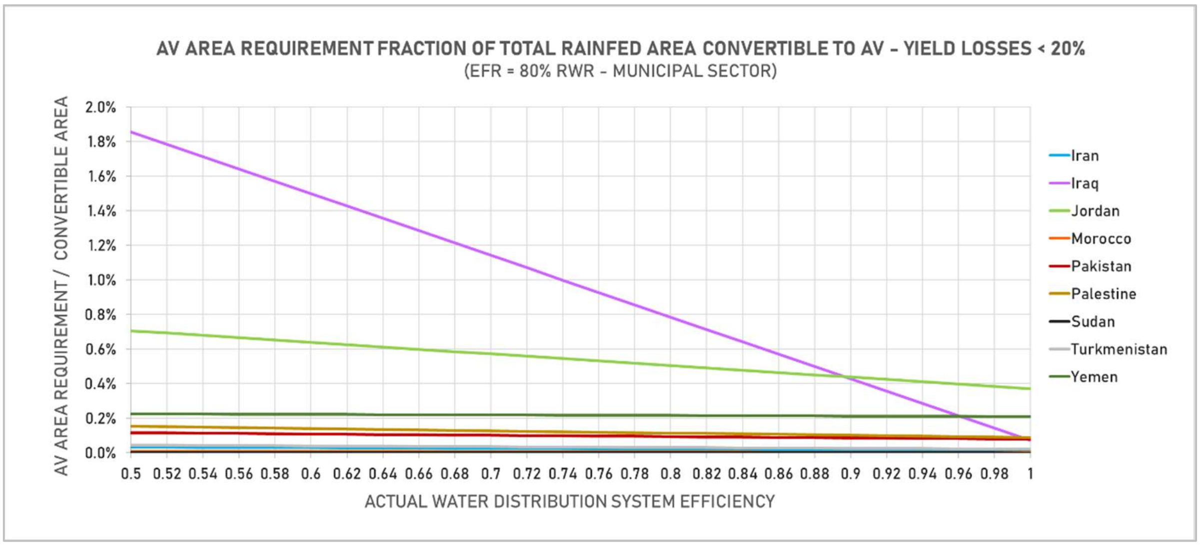


Graph 31b: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 60% EFR – up to 10% yield losses)

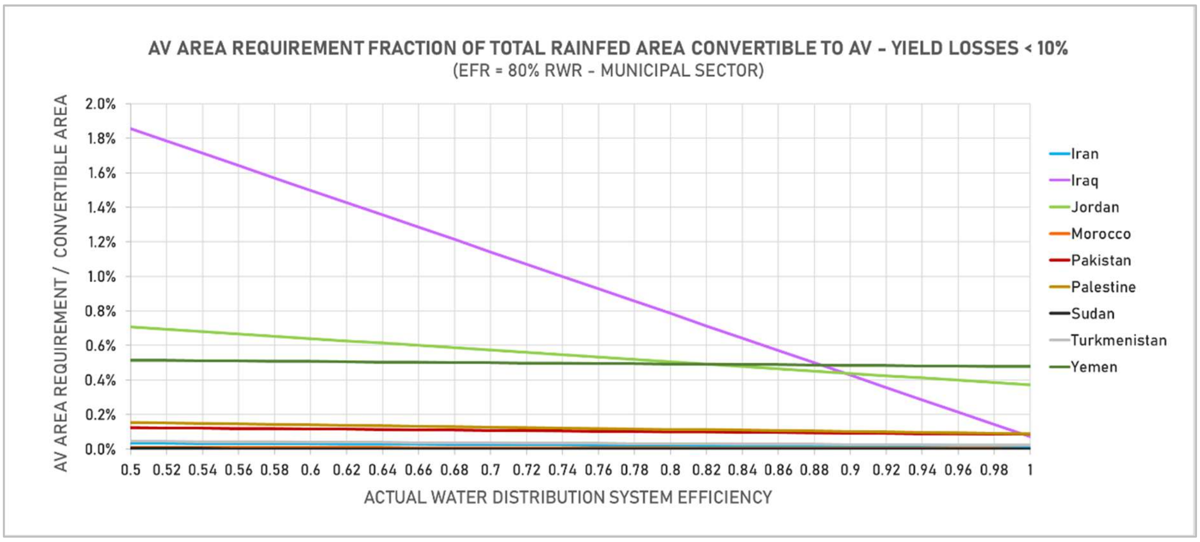


Graph 31c: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 60% EFR – No Yield losses)

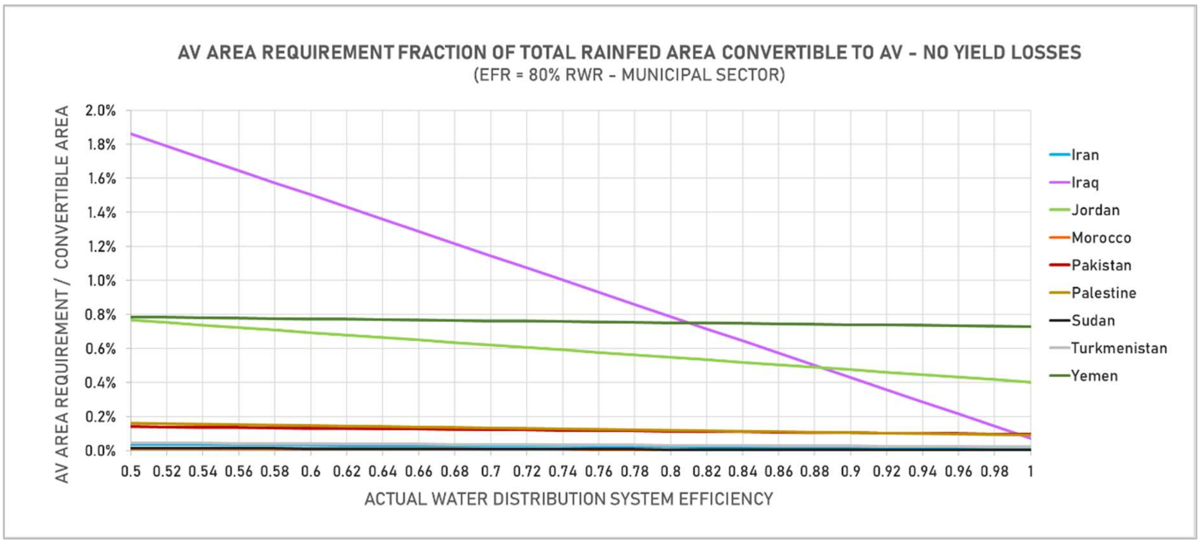
MUNICIPAL SECTOR – 80% EFR



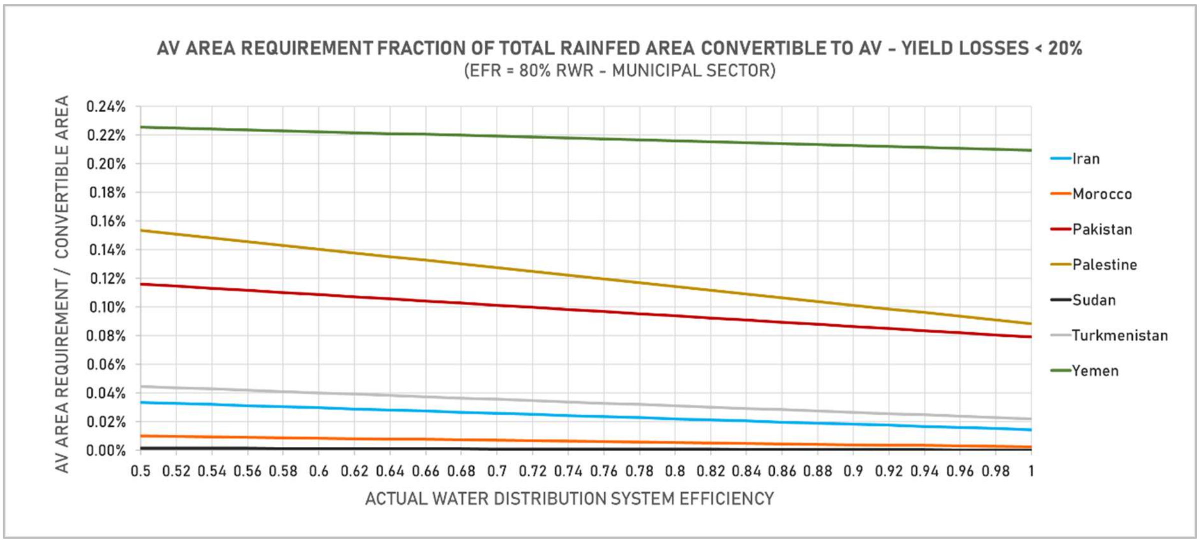
Graph 32a: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – up to 20% yield losses)



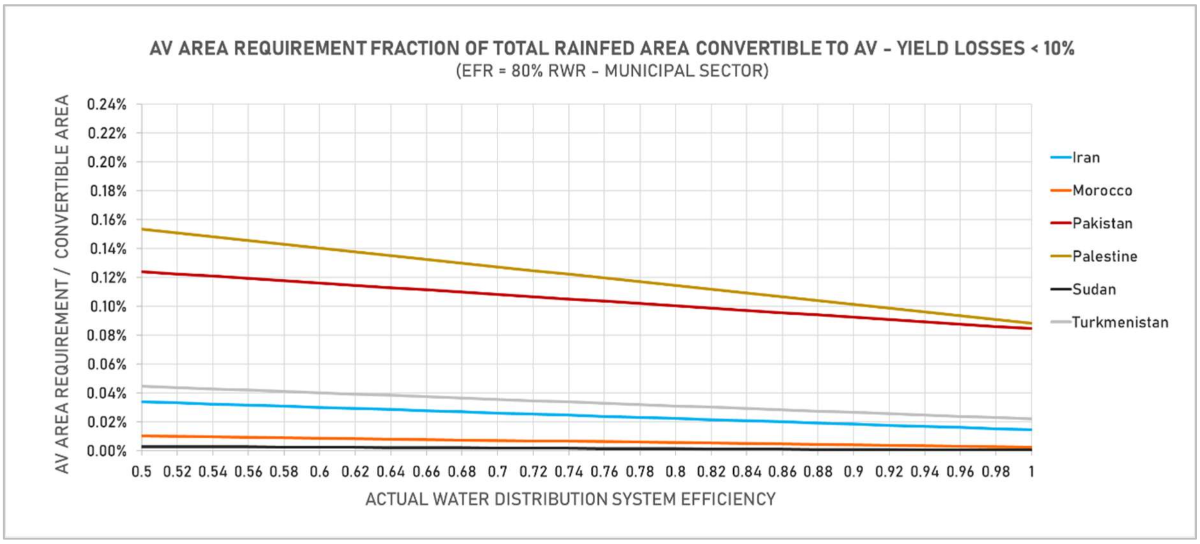
Graph 32b: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – up to 10% yield losses)



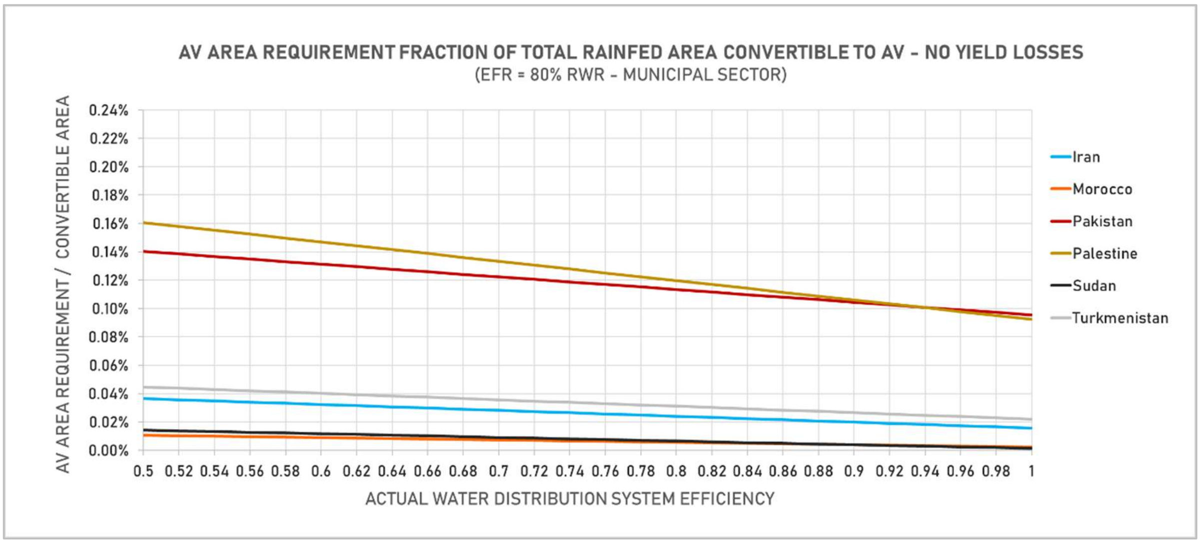
Graph 32c: BWS countries AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – No yield losses)



Graph 32d: Iran, Morocco, Pakistan, Palestine, Sudan, Turkmenistan and Yemen AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – up to 20% yield losses)



Graph 32e: Iran, Morocco, Pakistan, Palestine, Sudan and Yemen AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – up to 10% yield losses)

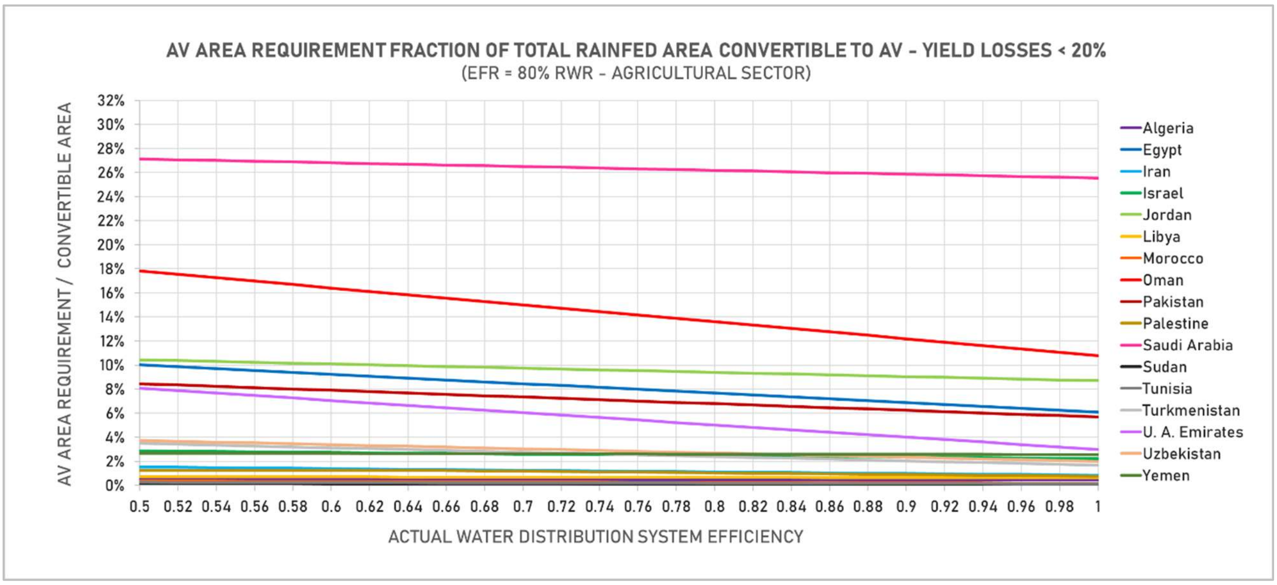


Graph 32f: Iran, Morocco, Pakistan, Palestine, Sudan and Yemen AV area requirement fraction of rainfed area convertible to AV (Municipal Sector – 80% EFR – No yield losses)

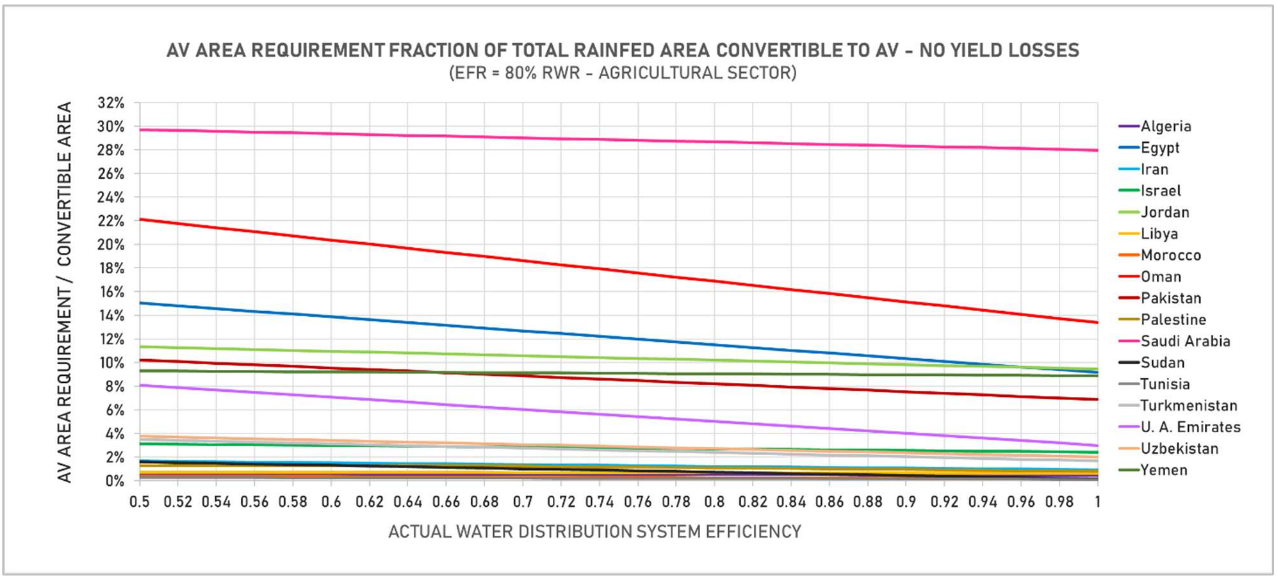
By analyzing these results, it can be concluded that the agrivoltaics areas required to sustainably meet municipal water demand are significantly smaller than the rainfed areas that can be converted to agrivoltaics. The highest observed value is approximately 1.85%, relative to Iraq at 50% efficiency in Graph 32c, which considers 80% EFR and non-irrigated areas convertible without yield losses.

At 100% efficiency, the highest ratio is found in the same graph for Yemen, that reach approximately 0.75%. This means that the agrivoltaics areas needed would amount to less than one-hundredth of the total rainfed land that could be converted without any yield loss.

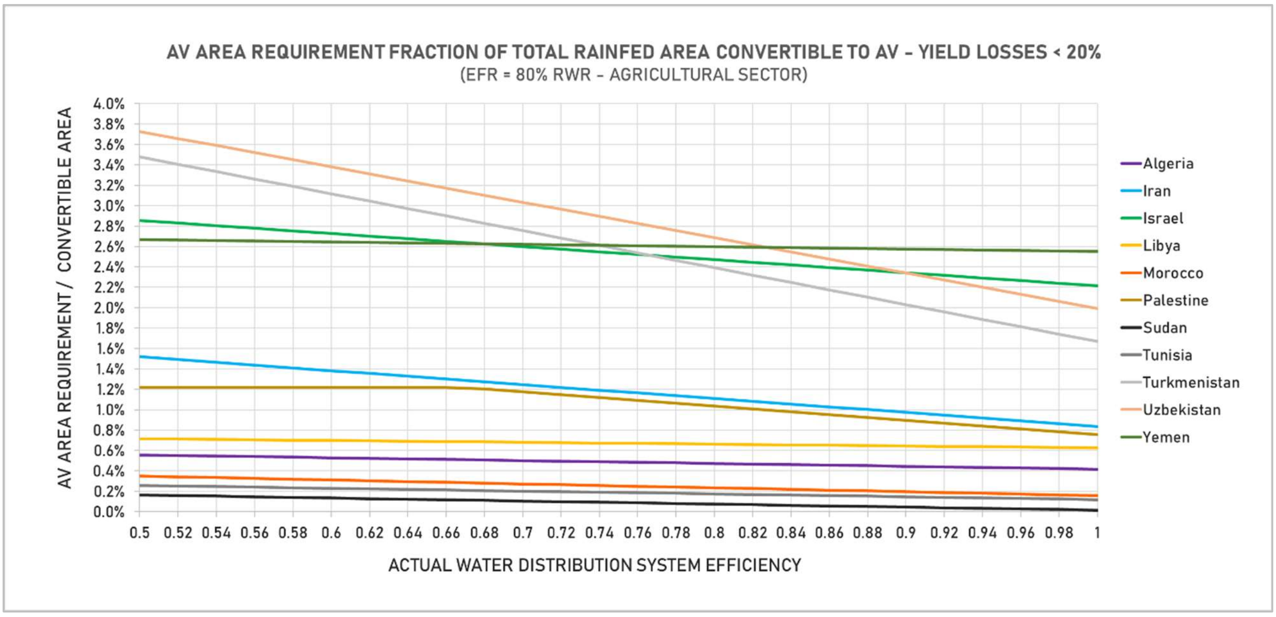
Obviously, in the agricultural sector, where desalinated water demand is significantly higher than in the municipal sector, the agrivoltaics areas required are substantially larger. Consequently, the ratios of these required areas to the rainfed cropland convertible are also considerably higher.



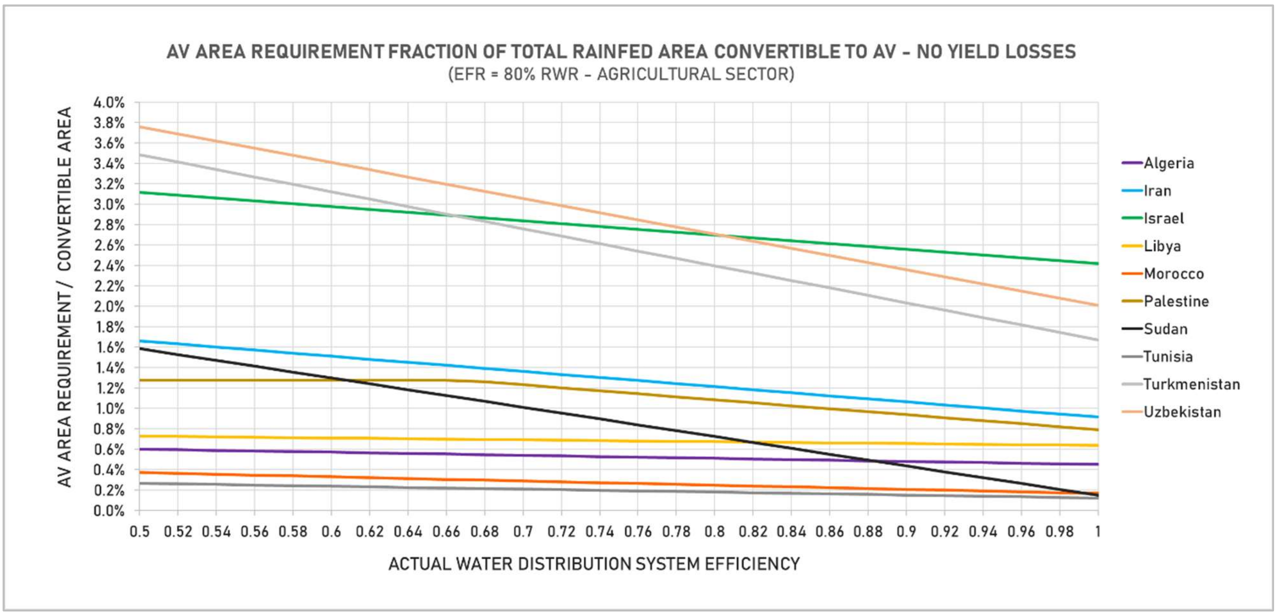
Graph 33a: BWS countries AV area requirement fraction of rainfed area convertible to AV (Agricultural Sector – 80% EFR – up to 20% yield losses)



Graph 33b: BWS countries AV area requirement fraction of rainfed area convertible to AV (Agricultural Sector – 80% EFR – No yield losses)



Graph 33c: Algeria, Iran, Israel, Libya, Morocco, Palestine, Sudan, Tunisia, Turkmenistan, Uzbekistan and Yemen AV area requirement fraction of rainfed area convertible to AV (Agricultural Sector – 80% EFR – up to 20% yield losses)



Graph 33d: Algeria, Iran, Israel, Libya, Morocco, Palestine, Sudan, Tunisia, Turkmenistan and Uzbekistan AV area requirement fraction of rainfed area convertible to AV (Agricultural Sector – 80% EFR – up to 20% yield losses)

Graphs 33a, 33b, 33c, and 33d present the results for the agricultural sector under the 80% EFR scenario, comparing areas convertible with up to 20% yield loss (Graphs 33a and 33c) and those convertible without yield loss (Graphs 33b and 33d).

Overall, the results shown for the agricultural sector are significantly higher compared to the ones observed in the municipal sector, where the highest estimated value is around 1.8%.
In the agricultural sector, the highest values are the ones relative to Saudi Arabia, where the agrivoltaics area required would account for 27–26% of the total convertible land where up to 20% yield loss is allowed (graph 33a), and 30–28% when only considering areas where conversion does not lead to yield reduction (graph 33b).

Furthermore, these graphs show again how the choice of convertible areas affects the results for certain countries. In Graphs 33a and 33b, for example, the ratios for Egypt vary significantly depending on whether only areas with no yield loss from conversion are considered or if areas with up to a 20% yield loss are included.

Specifically, the values range from about 6–10% (depending on the assumed water distribution efficiency) when considering areas with conversion-related yield losses (Graph 33a) to approximately 10–15% when considering areas without yield losses (Graph 33b).

Notable differences can be observed also in the results for Oman, which range from 10–18% in the graph 33a to 13.5–22% in the graph 33b.
These ratios, among the highest reported, result from the fact that even if agrivoltaics area requirements of Oman are not particularly high compared to other nations (ranging from 5.6 to 9.3 km²), the rainfed areas available for conversion are very limited, as shown in Graph 29b.
Consequently, even a little difference in these areas leads to significant variations in the three ratios evaluated. Specifically, Oman has only 51.9, 46.7, and 41.8 km² of non-irrigated areas convertible to agrivoltaics, corresponding to conversion related yield losses of up to 20%, 10%, and zero, respectively.

For Sudan, there are notable differences between the results in Graphs 33c and 33d.
These differences are harder to see in the municipal sector due to the large gap between the required agrivoltaics area and the three convertible areas.
In particular, the ratios range from 0.02-0.16% in Graph 33c to 0.15-1.59% in Graph 33d where, for efficiencies below 82%, they surpass those of Libya, Algeria, Turkmenistan, and Uzbekistan.

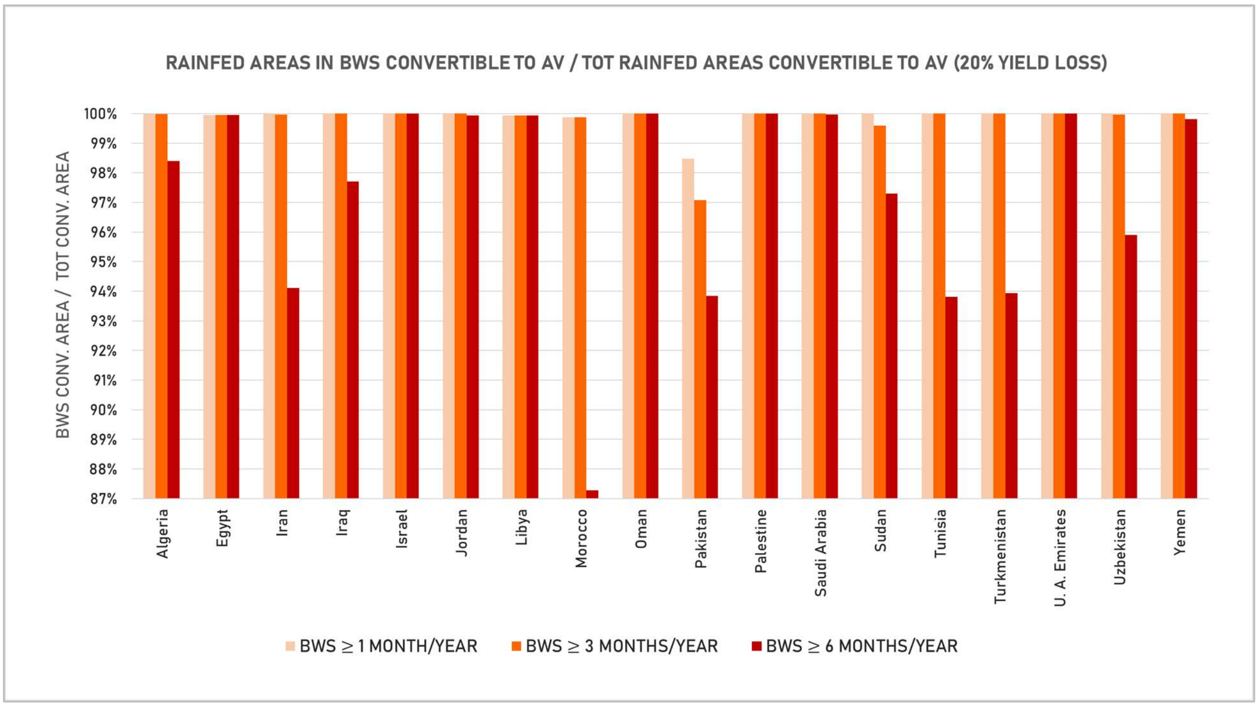
COMPARISON OF AGRIVOLTAICS AREAS REQUIREMENTS WITH RAINFED CROPLAND SUITABLE FOR AGRIVOLTAICS CURRENTLY IN BWS

Graphs 34a, 34b, and 34c show the proportion of non-irrigated cropland convertible to agrivoltaics that experience BWS for at least 1, 3, and 6 months per year, relative to the total convertible rainfed areas.
The results are shown for each type of convertible area considered previously: areas where agrivoltaics conversion leads to a yield loss of no more than 20%, no more than 10%, and no yield loss at all.

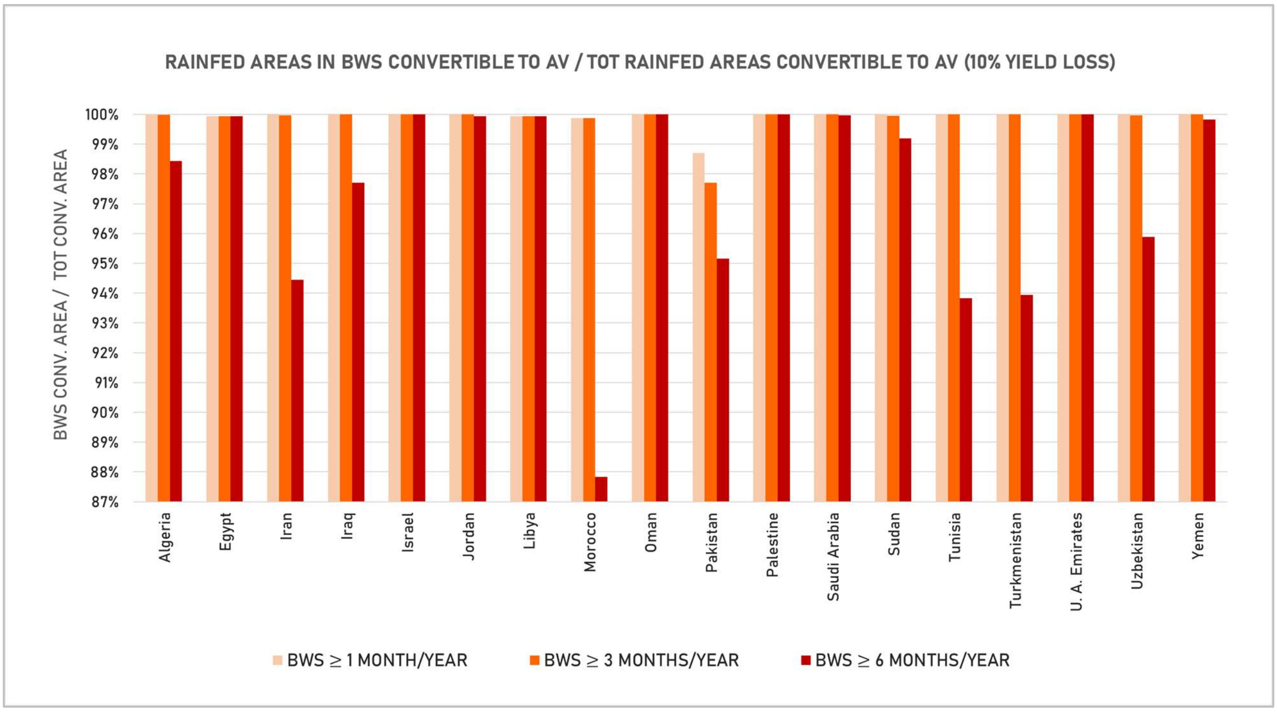
Except for Pakistan, nearly 100% of the rainfed areas suitable for agrivoltaics conversion experience BWS for at least three months per year, regardless of the assumed yield loss.

In Pakistan, more than 98% of the convertible areas are in BWS for at least one month per year, percentage that increase to 99% when considering only areas where conversion does not imply yield losses (Graph 34c). Moreover, 97%, 97.7%, and 98.2% of Pakistan convertible lands experience BWS for at least three months per year for yield loss of 20%, 10%, and none, respectively.

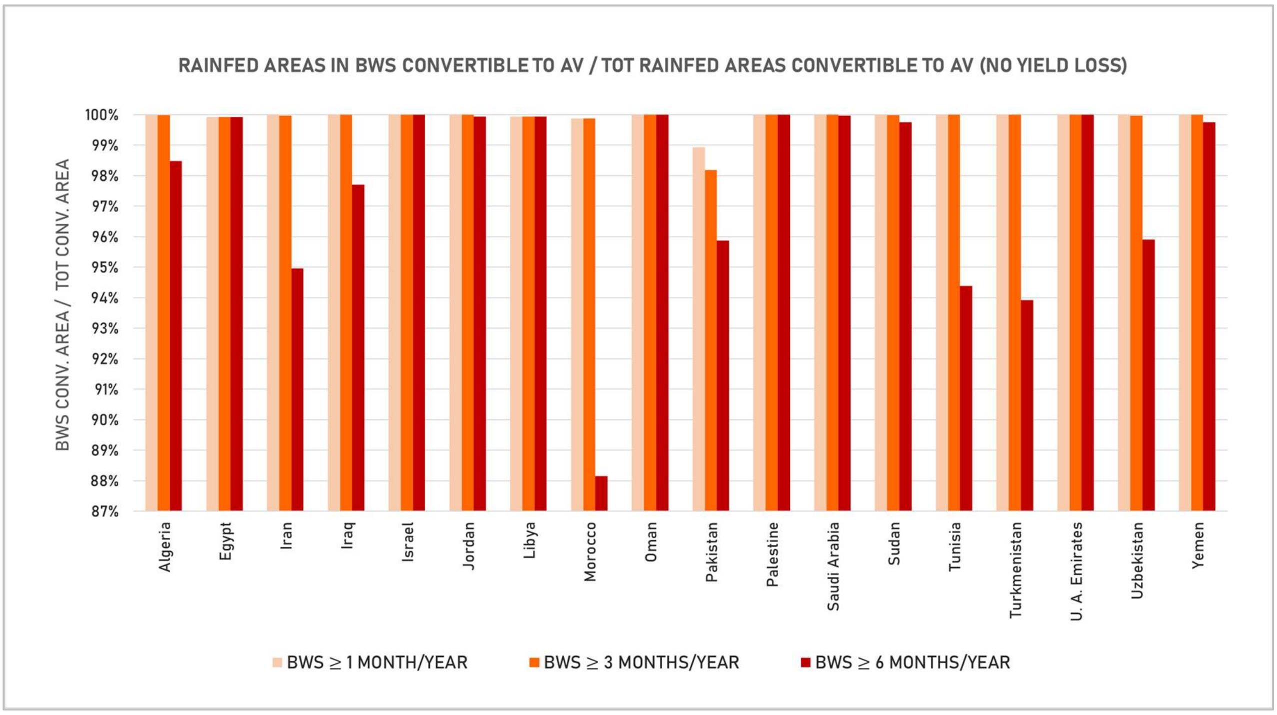
When looking at areas experiencing BWS for at least six months per year, these percentages decline, especially in Morocco, where the share of convertible areas in BWS for at least half the year falls below 90% of the total convertible land but remains above 87%.
In particular, the fractions of convertible areas in more than 6 months/year BWS respect to the total are around 87.3%, 87.8% and 88.2% considering up to 20%, 10% and none yield losses, respectively.



Graph 34a: rainfed areas in BWS convertible to AV compared to total areas suitable for conversion (up to 20% yield losses)



Graph 34b: rainfed areas in BWS convertible to AV compared to total areas suitable for conversion (up to 10% yield losses)



Graph 34c: rainfed areas in BWS convertible to AV compared to total areas suitable for conversion (no yield losses)

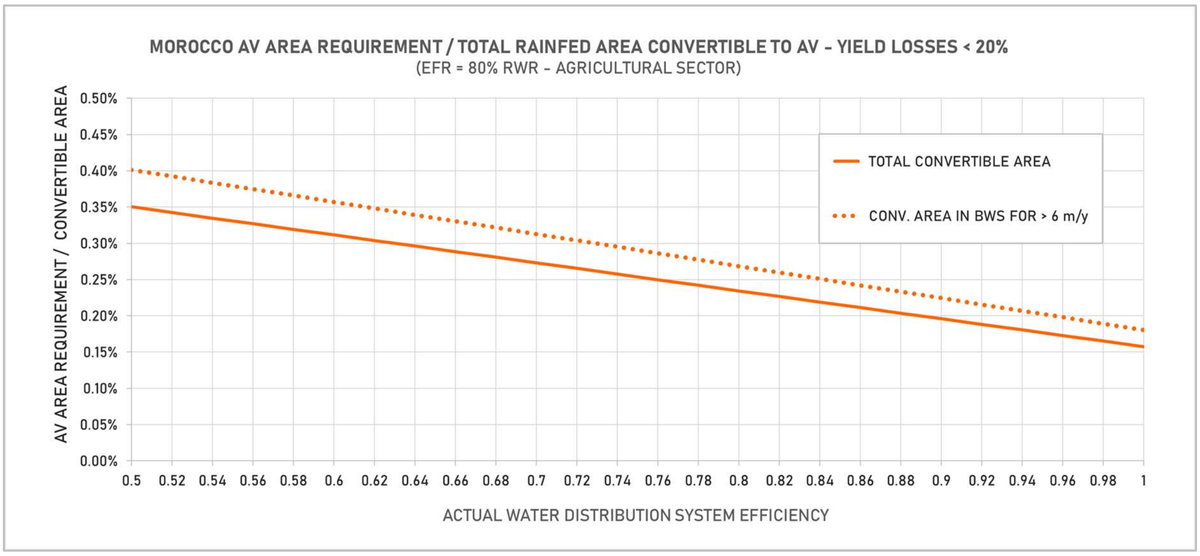
Overall, except for Morocco, countries experiencing BWS in at least one scenario have at least 93% of their non-irrigated convertible cropland under BWS for six months per year. This percentage rises to almost 100% for Egypt, Israel, Jordan, Libya, Oman, Palestine, Saudi Arabia, U. A. Emirates and Yemen, for each yield loss considered. As a result, the ratios between the agrivoltaics areas required for desalination and the rainfed areas in BWS suitable for agrivoltaics remain almost identical to those previously shown, regardless of the number of months per year under BWS considered or the assumed yield loss due to land conversion.

Graphs 35 and 36 illustrate how, for Morocco and Pakistan, the ratio between the required agrivoltaics area and the available convertible land changes depending on whether the total convertible land is considered or only the areas experiencing BWS for at least six months per year.

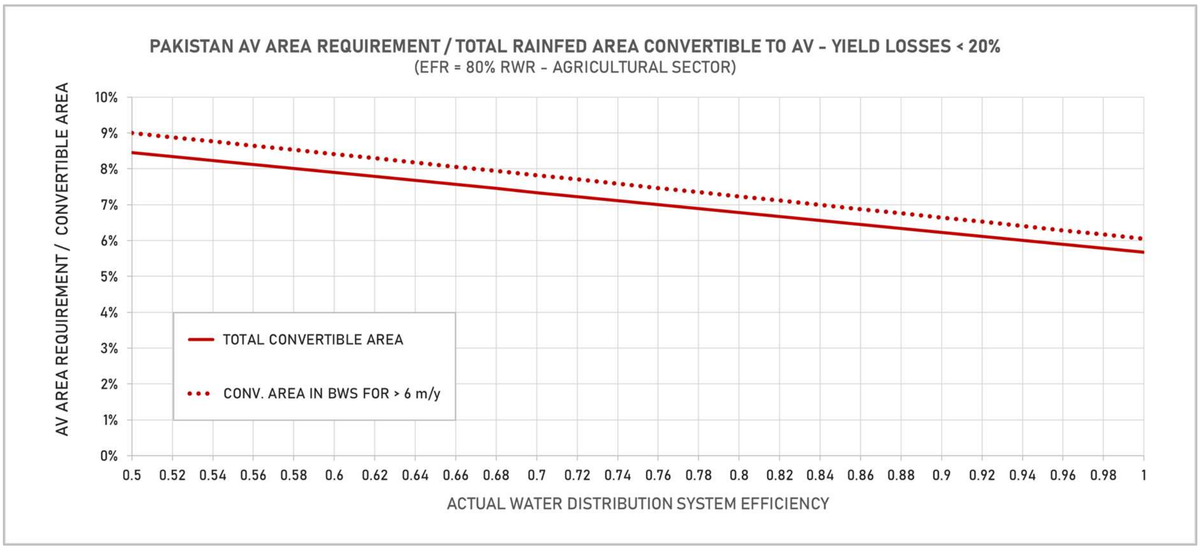
These two countries are specifically highlighted due to distinct characteristics:

- Morocco shows the most significant variation in available land under BWS for at least six months.
- Pakistan, among the countries with highest agrivoltaics requirements/convertible land ratio (Graph 33a) is the only one also showing substantial differences in convertible land in BWS depending on the duration of water stress considered (Graph 34a).

As a result, the impact on the ratios when comparing total convertible land to only BWS-affected land is particularly notable in these two cases, while other countries do not show significant changes.



Graph 35: Morocco AV area requirement fraction of total convertible area and of total convertible area in BWS (Agricultural Sector – 80% EFR – up to 20% yield losses – BWS ≥ 6 months per year)



Graph 36: Pakistan AV area requirement fraction of total convertible area and of total convertible area in BWS (Agricultural Sector – 80% EFR – up to 20% yield losses – BWS ≥ 6 months per year)

DISCUSSION

This study offers a holistic perspective, interconnecting water security, the necessary annual water production for each country, and the associated energy and photovoltaic and agrivoltaics area requirements. However, the analysis is subject to certain issues related to the extent and location of BWS countries and to various assumptions and simplifications often driven by data constraints.

ISSUES RELATED TO WATER SUPPLY FOR DESALINATION

It is important to note that for some of the countries in BWS, even if land availability allows for renewable-energy-powered desalination, significant challenges may arise in the production of desalinated water.
A clear example is Uzbekistan, which lies several dozen kilometers from the Caspian Sea, the closest among the major saltwater bodies. Beyond this, the closest alternatives would be the Black Sea and the Persian Gulf, both several hundred kilometers away from the country.

For Uzbekistan, this distance presents not only a major challenge in transporting water from the sources to the country's territory but also a significant issue related to brine disposal.
As previously highlighted, brine production amounts to approximately 1–1.5 times the volume of desalinated water produced. If Uzbekistan relies on the Caspian Sea water, surface water discharge, the most economically viable disposal method, would be highly discouraged. Given that the Caspian is a closed water body, continuous brine discharge could lead to a steady increase in its salinity, posing serious environmental risks.
Clearly, Turkmenistan, which borders the Caspian Sea, would face a similar problem to Uzbekistan regarding brine disposal. However, unlike its neighboring country, Turkmenistan does not face issues with accessing saline water sources.

Other countries that would encounter challenges with desalinated water supply are Jordan and Iraq. This is not because they lack access to the sea, but because the portion of their territory bordering salty water bodies is limited to a small area relative to the size of the country.
Jordan, for example, has direct access to the sea only along a stretch of coastline on the Gulf of Aqaba, located to the east of the Sinai region. This stretch is just about 20 km long, and it borders to the east with Israel and to the south with Saudi Arabia. Clearly, this is a very small and peripheral part of the country.

Similarly, Iraq has access to the sea only in a narrow stretch in the southeast, on the Persian Gulf. This roughly 20 km section borders Kuwait to the southwest and Iran to the northeast and is more than 500 km away from the capital, Baghdad.

These areas are not only extremely small compared to the total surface area of the two countries, but they are also geographically much closer to the Mediterranean than to the countries' own sea access points.
For instance, Amman, the capital of Jordan, is only 105 km from the Mediterranean, while it is more than 280 km from the Gulf of Aqaba.

In the end, from a practical perspective, Jordan and Iraq, as well as Uzbekistan and Turkmenistan (if it does not rely on Caspian Sea water), would need to find a way to build desalination plants outside their own territories. This would require the construction of a distribution network that, in part, would have to pass through other countries between the plant and their own borders.

Another alternative could be purchasing desalinated water directly from countries with more extensive access to the sea or ocean. However, the same issue of transporting water to their own territories would still arise.

In both cases, it is crucial to consider that if the destination takes place outside a country's borders, the associated energy production must also be relocated near the plant, and so in another country. This would significantly increase the spatial requirements for photovoltaic installations within a territory that would then need to meet both its own energy demands and, at least partially, those of other countries.

If a country lacks sufficient land suitable for agrivoltaics conversion to meet the energy demands of both its own water production and that of neighboring nations, it could optimize energy production spatially by generating part of the required electricity through agrivoltaics systems and the remainder through traditional photovoltaic installations.

In general, the common problem that BWS countries share is the distribution of the water produced throughout their territory. The further inland a country extends, the greater the logistical and infrastructural efforts required to transport desalinated water across vast distances. A prime example of this issue is Algeria, where some regions are nearly 2,000 km away from the Mediterranean.

One possible approach to mitigate this challenge is to maximize the use of available renewable water resources in inland areas, while prioritizing desalinated water in regions closer to the coast.
Naturally, if bringing RWR to areas far from the coast would imply moving water over hundreds of kilometers from the source, there would be the same problem of desalinated water transportation.

However, in most BWS-affected countries, most of the population is concentrated along the coast, meaning that a large share of the desalinated water produced will likely be consumed near the reverse osmosis plants, at least for municipal use.

In a broader sense, a key aspect to explore in future research is the spatial proximity between water demand and desalinated water availability. While inland areas may face significant logistical challenges, many of the countries analyzed in this study have population centers near coastal areas, where desalination plants are expected to be located.

Therefore, future studies could examine how population distribution influences the feasibility and necessity of large-scale water transportation. This would provide a more precise assessment of whether desalination can effectively meet national water demands while minimizing distribution constraints.

TOTAL AND SECTORIAL SITUATION DISCREPANCIES

An important consideration arises when comparing sector-specific scenarios with total scenarios
Indeed, while considering the total water demand, use, and availability of a country might initially seem an oversimplification, it actually shows how, in many cases, better management of available resources could prevent issues within specific sectors.

To provide a concrete example, Saudi Arabia, which is in BWS only in the agricultural sector as well as in the total scenario, has a water demand gap of approximately 8.25 km³ in the agricultural sector. However, when considering the total demand and availability, this gap reduces to 6.81 km³ (both values for EFR of 80%).
In some cases, it might even be unnecessary to produce desalinated water by looking at the total situation (beyond volumes currently produced), as seen in the cases of Iraq, Oman, and U.A. Emirates in the 80% EFR scenario. These three countries are not in BWS in their total water scenario, but only in the agricultural sector for Oman and the UAE, and in the industrial and municipal sectors for Iraq.
Therefore, with proper distribution of water availability, these countries could avoid a BWS situation in all three sectors and, as a result, in their overall water balance.

Of course, the results obtained strongly depend on how sectoral water availability is assessed. As previously mentioned, sector-specific water availabilities were estimated using data from AQUASTAT. Indeed, national-scale sectoral water availabilities are not provided by the dataset, so total water availability was proportionally distributed among sectors based on their respective demands. Additionally, non-conventional water sources were added to the availabilities. In particular, desalinated water has been allocated according to global sectoral usage patterns.
This approach was necessary because, although AQUASTAT theoretically reports to have the sectorial fractions of total desalinated water, the values are not available.

As a result, sectorial AVLB are not rigidly pre-defined, but they are assumed mainly to be proportional to the demands and the desalinated components align with global averages.
It is therefore crucial to recognize that countries classified as being in BWS in only one or two sectors, and those with a sectorial water deficit greater than their total deficit (Saudi Arabia), may be in these situations due to the methodology used to assess sectoral water availability.

Nevertheless, discrepancies between total and sector-specific situations are observed also when comparing demands and uses, which are known in each sector: for instance, for 80% EFR, Israel and Jordan show a total water use exceeding their total water demand.
However, when looking at the agricultural sector (and industrial in Jordan case), the situation is reversed.
This suggests that, even if the sectorial results obtained are strongly influenced by the availabilities evaluation method, differences between total and sectors situations could take place also when comparing demands with availabilities.

Consequently, BWS conditions could emerge in specific sectors even if the country does not experience an overall water deficit.

In any case, analyzing the total water balance provides a more optimistic perspective, allowing for the assessment of whether a country, with better water resource management, could avoid BWS altogether or, at the very least, reduce the need for desalination compared to what sector-specific calculations would suggest.

TEMPORAL AND SPATIAL RESOLUTION

The AVLB and USE values provided by AQUASTAT, which, together with demand, were used to classify each country's situation, are given on an annual and national scale.

Therefore, this study, both at the sectoral and total level, was conducted on the same scale, disregarding potential differences within a country's territory and variations across different months of the year.

Regarding spatial simplification, its relevance depends on the size and homogeneity of a country's territory. The smaller and more homogeneous a country is, the less significant this simplification becomes.

However, for large nations, this factor is far from negligible. Even in Italy, there are substantial disparities in water availability and demand, with over 16% of the population concentrated in Lombardy region alone. For countries like Russia, Canada, the USA, China, Brazil, Australia, and India, assuming that water availability is evenly distributed in line with demand is clearly unrealistic.

For instance, in the United States, the renewable water resources available in Washington state, the wettest state in the country, cannot be optimally redistributed across the entire U.S. territory.

Moreover, this study does not account for any geographical barriers that might further constrain water distribution within each country.

The impact of using annual-scale data can be observed by comparing the results obtained with those shown in Figure 6, which refers to the 2020 study "*Global Agricultural Economic Water Scarcity*". In this case, availability, demand, and use in the agricultural sector are analyzed by month and at a much more detailed spatial scale than the national level.

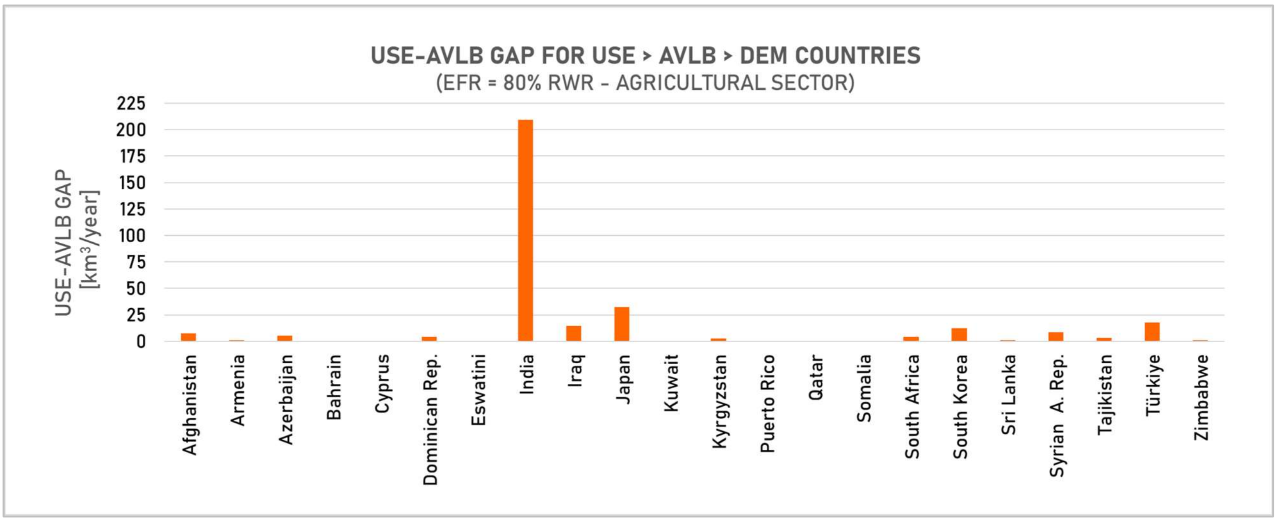
In the 2020 paper it is reported that 68% of croplands experience BWS for at least one month per year, 37% for at least five months, and, more broadly, 56% of blue water used in irrigation is not sustainable. Furthermore, it highlights that 2.23 billion people currently rely on unsustainable blue water use.

However, the same study concludes that, when summing availability, demand, and use over an annual scale, sustainable food production could increase by $1.57 \cdot 10^{15}$ kcal per year compared to the monthly scale, equivalent to feeding approximately 1.28 billion more people.

This suggests that, with adequate water storage to retain rainfall within national territories, and more generally, with the ability to access annual water resources at any time of the year, BWS issues could be significantly mitigated. Indeed, it is reasonable to assume that areas experiencing BWS for just one or two months per year would not be classified as such when considering an annual balance.

A clear example of the difference between the monthly and the simplified annual scale analyses is India. In the study by M.C. Rulli et al., maps visually depict the world's cropland areas under BWS (as well as Green and Economic Water Scarcity) on a month-by-month basis. Except for July, August, and September, most of the Indian territory is in BWS for the remaining nine months of the year.

However, in the annual-scale calculations of this desalination study, India does not experience BWS in the agricultural sector, even when considering an 80% EFR.
In fact, with a 60% EFR, India is in the optimal situation where AVLB > USE > DEM. At 80% EFR, however, use exceeds availability, making water consumption considerably unsustainable, as illustrated in the following graph:



Graph 37: USE-AVLB gaps for countries in a USE > AVLB > DEM Situation (Agricultural Sector – 80% EFR)

Although in this study India is not classified as a country in BWS, at 80% EFR, it would still consume over 200 km³ more per year than its available renewable water resources.
India's annual RWR is estimated at 478.5 km³, while its water withdrawals amount to 688 km³.
Meanwhile, its agricultural water demand is 307.8 km³, meaning that when considering the country's total annual water availability, it can more than meet its demand.
However, this would require a water storage system capable of efficiently managing resources throughout the year and across all regions of India.
Such high water use relative to availability is, at least in part, a sign that India does not fully exploit its renewable water resources, leading to unsustainable withdrawals to meet agricultural demand.

In any case, analyzing the USE, DEM, and AVLB combinations for each country on an annual and national scale is a simplification entirely consistent with the purpose of this study. Indeed, desalination, as highlighted multiple times, is a relatively extreme solution strategy, where water is generated at high energy and economic costs, as well as significant expenses related to the disposal of brine waste.

Therefore, desalination should not be seen as a solution for BWS situations that occur only for a few months of the year or affect only a limited part of a country. Instead, it should be considered as a last-resort strategy in cases where national water availability cannot sustainably meet demand under any circumstances.

For example, if a given city experiences municipal BWS for three months per year, but its total annual RWR exceeds its annual municipal water demand, desalination would be the wrong solution. In such cases, the appropriate strategy would be to store excess water during the nine months when availability exceeds demand, so it can be used during the three critical months.
Similarly, if a country is not experiencing BWS at a national level but faces localized scarcity in specific areas, the solution should not be to implement desalination to address the problem in that region. Instead, better management of existing national water resources should be prioritized.

USE-DEM COMPARISON ISSUE

Another limitation is the absence of data on the efficiency of the water distribution system, both in terms of overall analysis and sector-specific situations.
Countries have been classified based on whether they meet their water demand solely by comparing withdrawal and demand values: if the former exceeds the latter, the country's demand is considered met.

However, having withdrawals larger than demands does not necessarily mean that the demand is actually satisfied: it only indicates that a higher quantity of water is extracted than what is required.
Unfortunately, without information on water distribution systems, it is not guaranteed that the withdrawn water, once it reaches the point of consumption, is sufficient to meet the demand. There may be losses during transport, resulting in a greater amount of water being lost than the difference between USE and DEM, meaning that the demand might not be satisfied.

Hence, due to the lack of data on distribution network efficiency, it has been assumed for simplicity that in cases where withdrawals exceed demand, the efficiency is sufficient to meet the latter.
However, this assumption does not affect the core analysis, as it concerns the comparison between water use and demand rather than the balance between demand and availability, which is the relationship that determines whether a country is experiencing blue water scarcity and, consequently, whether it must implement desalination technology to meet its demand.
Indeed, if demand is not met despite withdrawals exceeding it, the issue could be resolved by simply improving the existing distribution network and increasing its efficiency.

SUMMARY

What can be confidently concluded from the results is that any country experiencing BWS in even a single sector, even when considering the highest EFRs, has sufficient rainfed cropland that can be converted to agrivoltaics to produce the solar energy required to desalinate enough water per year.

As a result, these countries could increase their annual renewable water resources and achieve sustainable water demand by relying on agrivoltaics systems implemented in BWS areas.

This could be done even when considering only convertible non-irrigated areas that experience six or more months of BWS per year, where the conversion does not lead to yield losses.

It is also important to highlight that these conclusions are valid even by assuming a water distribution network efficiency of only 50%, hence even when half of the available RWR, which are considered fully withdrawn, are lost during transport.

Moreover, if the latest-generation reverse osmosis desalination systems and c-Si polycrystalline panels were considered, these conclusions would be even more robust.

In fact, the percentage of areas that would need to be converted to AV, relative to the rainfed areas that can be converted, would be even lower when accounting for advanced reverse osmosis systems, which, as mentioned earlier, could require 2.7 kWh per cubic meter of water produced or less. assumed.

Similarly, using polycrystalline panels instead of monocrystalline ones, which require 0.3 m^2 less per kW_P installed, would further optimize land use efficiency.

Therefore, since the agrivoltaics land requirements were estimated as:

$$AREA_{AV} = ((DEM - AVLB \cdot \eta) \cdot 3\ kWh/m^3 \cdot (PV_{OUT} \cdot 365)^{-1} \cdot 6.8\ m^2/kW_P) / 0.4$$

Considering different technologies, the AV area needed, compared to those previously calculated, would be:

- 90% when assuming more efficient desalination plants (2.7/3 = 0.9)
- 95.6% when assuming polycrystalline panels (6.5/6.8 = 0.956)

Hence, by combining the use of latest-generation reverse osmosis systems and polycrystalline panels, the land area required would be reduced to just 86.04% (0.9 × 0.956) of the previously estimated values.

However, the fact that all countries have sufficient areas to produce the necessary energy through agrivoltaics does not mean that implementing photovoltaic or agrivoltaics systems is an easy task.

Naturally, when considering only municipal demand, the spatial requirements for agrivoltaics are relatively modest. As mentioned earlier, the maximum case occurs for Pakistan, assuming an EFR of 80%, which requires an area ranging between 21 and 31 km^2 (equivalent to 2100–3100 hectares).

This range would be reduced to between 18 and 27 km^2 if more modern desalination plants and polycrystalline photovoltaic panels are used.

It is also important to note that only 40% of this area is occupied by photovoltaic panels.
Therefore, the photovoltaic area required for Pakistan would range between 8.4 and 12.4 km², considering the assumptions of the study.
However, when considering total RWR availability and demand, which includes also industrial and, especially, agricultural demand (significantly the higher one), the space required for agrivoltaics would be between 1550 and 2300 km².
If conventional photovoltaic plants are used, the required area would drop to between 620 and 920 km².
For context, Pakistan occupies a total area of about 882,000 km², meaning that implementing agrivoltaics would cover at least 0.17% of the territory, whereas using only photovoltaic systems would cover 0.07%.

Other countries that, under the same scenario, would need at least 200 km² of agrivoltaics systems (about twice the area of Paris) are: Saudi Arabia, Uzbekistan, Egypt, and Iran. For these countries, implementing desalination powered entirely by agrivoltaics would indeed be a challenging task.

Regarding the conversion of rainfed agricultural areas, Saudi Arabia would require the highest proportion of its available non-irrigated land suitable for agrivoltaics (AV) implementation. To prevent yield losses associated with conversion, the country would need to convert between 23.1% and 28.5% of its rainfed cropland. In contrast, Pakistan, despite having the highest spatial requirements, would only need to convert between 7% and 10.4% of its available non-irrigated land suitable for AV, assuming no yield losses.

Other countries that would need to implement AV on at least 10% of their suitable rainfed cropland (without conversion losses) to meet total demand include Egypt, Jordan, and Yemen. However, for the municipal sector with an EFR of 80%, these proportions are always below 2% for each country in BWS in this sector. Specifically, Pakistan's proportion falls between 0.1% and 0.14%.

Of course, as mentioned in the discussion chapter, relying on desalination is a challenging option for some countries due to their geographic constraints.
This is particularly true for Iraq and Jordan, but even more so for Turkmenistan and Uzbekistan. The closest saltwater source for the latter two is the Caspian Sea, a closed body of water where desalination could lead to significant brine discharge issues.

While Jordan and Iraq do have access to open saltwater sources, their coastal areas are extremely limited (only a few kilometers in length) making it difficult to allocate sufficient space for large-scale desalination plants.
However, in these countries there are enough AV-convertible rainfed cropland to generate the energy required for desalination.
As a result, they can use agrivoltaics to produce the necessary energy and supply it to the desalination plants built outside their national territories.

Another important aspect highlighted by this study is the significant impact of respecting EFR that prevent water stress situations on the water availability of different countries.
Globally, considering current EFR, only Libya, Saudi Arabia, and Yemen are classified as experiencing BWS. These are all countries where EFR were assumed to be equal to just 4% of their total available renewable water resources. On the other hand, when EFR are considered at levels that prevent water stress, the number of countries in BWS rises to 15.
Even when considering conditions of water stress (but not severe water stress, meaning EFR between 60% and 80%), Algeria, Egypt, Jordan, Pakistan, and Palestine would be in BWS (in the total situation).

In any case, even under the most stringent EFR assumptions, all countries facing BWS are in the MENA region (Middle East and North Africa), except for Pakistan, Sudan, Turkmenistan and Uzbekistan, which still border this region. These countries are predominantly arid and desertic, with limited annual precipitation and in some cases lacking significant rivers or lakes (Saudi Arabia), but they all have abundant solar irradiation.

Therefore, for these nations, solar-powered desalination, whether through photovoltaic or agrivoltaics systems, represents a major opportunity to sustainably meet water demands without exacerbating water stress.
Despite their limited natural water resources, they are in the ideal location to generate the freshwater they need by exploiting renewable energy, avoiding reliance on fossil fuels.

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