Economic Feasibility of Solar-Powered Reverse Osmosis Water Desalination: A Comparative Systemic Review

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Abstract

Due to disparities in the allocation of rainwater and drought, extreme exploitation of groundwater reservoirs has depleted water supplies in many locations. In addition, improper disposal of domestic and industrial waste leads to poor drainage and deterioration of water quality. According to studies, desalination methods are an effective solution for treating sea and brackish water and making it usable in daily life. Solar-powered desalination has recently received a great deal of attention around the world. Previously, most experimental studies focused on the use of solar energy in traditional desalination methods such as multistage flash and multi-effect distillation. Desalination with reverse osmosis has become popular due membrane technology improvement and benefits like high recovery ratios and low energy consumption. This article aims to comparatively and systematically review the economic feasibility of the use of solar photovoltaic reverse osmosis in desalination in Morocco and the Middle East and North Africa (MENA) region.

Highlights

- The Middle East and North African (MENA) countries are advantageously located in the sunbelt region.
- Desalination is the solution to the scarcity of freashwater in the mostly arid MENA region.
- Increasing energy prices and climate change concerns imply a need for a sustainable and green solution.
- Solar-powered desalination technology is both cost-effective and environmentally friendly.
- Solar-powered reverse osmosis is more economically feasible and less polluting than other rechnologies.

1. Introduction

Due to the inequality in the allotment of rainwater and the drought, existing water reserves are diminishing. On the other hand, improper disposal of household and industrial waste leads to exploitation of groundwater resources (Randhawa, 2002) As freshwater supplies are minimal to meet the main needs of the population and saltwater is not ideal for many applications, the desalination of salt water (seawater) is a positive approach to meet the requirements (Adams et al., 2002).

Desalination is currently separated into two categories, namely physical procedures that comprise reverse osmosis (RO) and chemical processes, including a zero valet iron technique (ZVI) (Antia, 2016). During the physical process, salt and water are physically separated. By using the least energy, it is referred to as “minimum thermodynamic energy of separation (MTES)”, and efforts to reduce energy use in MTES are only worthwhile if they are also economically beneficial (Antia, 2016; Cottier et al., 2010).

One of the best and gold standard desalination techniques is RO (Wang et al., 2018), which uses high-grade energy to purify water through by removing salt and other impurities using semi-permeable mebranes (Charcosset, 2009). On the other hand, thermal desalination techniques use heat, often to evaporate and condense water to purify it (Mittelman et al., 2007). The heat required to evaporate seawater makes specific energy consumption (SEC) used in the thermal desalination higher than that of the RO process (Chae & Kim, 2017). Furthermore, thermal desalination uses low-grade energy, which is difficult to regulate due to its rapid dissipation (Ranjan & Kaushik, 2013; Warsinger et al., 2015). However, the SEC of RO desalination remains substantial, accounting for most expenses. Therefore, solar-powered RO systems have been introduced to further minimize the energy costs and environmental carbon footprints of RO desalination units.

Most studies and reviews done on renewable energy usage in water treatment have studied or reported on particular plants, evaluated economics aspects of particular systems and particular energy source. There is evidence of economic benefits of renewable energy, in particular solar energy, in desalination processes but there is a lack of a comparative research to evaluate the economic practicality of desalination using renewable energy in perspective of each country's or location's uniqueness. As every country, including Morocco and other Middle East and North Africa (MENA) countries, adopt renewable evergy and desalination systems, there is no data on what systems and energy sources are more economically viable than the others in the MENA region, which systems worked better in some countries than others and why and what differentiates the use of particulatar technologies between MENA countries.

This paper is the first to presents a comparatively systematical review photovoltaic-reverse osmosis (PV-RO) desalination powered by solar energy sources in Morocco and the MENA region, focusing on the economic feasibility of RO systems and other desalination technologies comparing economic aspects desalination technologies powered by solar energy sources in Morocco and MENA countries.

2. Methodology

This review included studies focusing on the economic feasibility of reverse osmosis desalination systems powered by solar energy and other desalination technologies comparing economic aspects of solar energy use to power desalination technologies in Morocco and other Middle-East and North Africa (MENA) countries.

2.1. Data Sources

We searched for relevant studies by using a database of ScienceDirect, PubMed, EBSCOhost, Mendeley, and Scopus. During article searching, we combined these relevant keywords: "desalination", "reverse osmosis", "water", "energy", "membrane-based technologies", "thermal desalination", "component", "cost analysis", and "solar energy", "renewable energy, desalination technologies, "desalination economics". We also searched the references of relevant articles to obtain more studies.

2.2. Inclusion Criteria

All research that contained or met the goals and objectives were included. We included studies: (i) investigating the economic aspects of desalination technologies, (ii) published as articles in English, (iii) whose full text is available, (iv) original research studies, (v) review and meta-analysis articles. We excluded books, theses, comments, and conference presentations were excluded from the study.

2.3. Study Selection

A total of 1251 articles were considered pre-eligible. Titles, keywords, abstract and full text were used to shortlist them according to inclusion criteria, and duplicates were removed.

2.4. Data extraction and quality assessment

The extracted data included the study’s title, year of publication, journal and authors. Data were organized in a Microsoft excel sheet and we did further processing, and fixed errors.

3. Results

Of 1123 articles identified from the ScienceDirect, PubMed, EBSCOhost, Mendeley, and Scopus databases, 128 articles were from other websites, organization and citation searching. After selection, 51 articles were selected from the databases and 3 articles from other sources, making 54 articles (Fig. 1).

3.1. Article characteristics

This review collected 11 articles reporting about Morocco, 13 articles reporting about the Middle East and North Africa (MENA), 9 articles focusing only on the Middle East, including Morocco and 16 articles reporting about individual MENA countries. The country most represented in the MENA region, apart from Morocco, was Saudi Arabia, with 5 articles.

Of the articles reviewed, 35 explored the use of solar energy in desalination and 22 explored renewable energy as a whole, including solar energy. Most, 38 articles reported more or less about the economic aspects of desalination, and 14 of them specifically performed economic analysis, cost analysis or cost feasibility analysis of renewable energy-powered desalination systems. The majority, 34 reviewed articles, studied reverse osmosis technology used in desalination with or without including other technologies. Table 1 shows the details of the selected articles.

Table 1
Articles included in this systematic review

No.	Title	PY	Journal	Ref.
1	Hybrid renewable energy systems for desalination	2020	Applied Water Science	(Esmaeilion, 2020)
2	Global applicability of solar desalination	2016	Renewable Energy	(Pugsley et al., 2016)
3	Technical and economic assessment of photovoltaic-driven desalination systems	2010	Renewable Energy	(Al-Karaghouli et al., 2010)
4	Desalination projects economic feasibility: A standardization of cost determinants	2017	Renewable and Sustainable Energy Reviews	(Pinto & Marques, 2017)
5	A comprehensive techno-economical review of indirect solar desalination	2011	Renewable and Sustainable Energy Reviews	(Ali et al., 2011)
6	Remineralization of Reverse Osmosis (RO)-desalted water for a Moroccan desalination plant: optimization and cost evaluation of the lime saturator post	2012	Desalination	(El Azhar et al., 2012)
7	Distributed generation of freshwater through reverse osmosis desalination units by using various energy sources, techno-economic feasibility study	2020	Desalination and water treatment	(Meratizamana & Godarzib, 2007)
8	A levelized cost analysis for solar-energy-powered sea water desalination in the Emirate of Abu Dhabi	2019	Sustainability (Switzerland)	(Kaya et al., 2019)
9	Comparison of desalination technologies using renewable energy sources with life cycle, pestle, and multi-criteria decision analyses	2021	Water (Switzerland)	(Do Thi et al., 2021)
10	Desalination of Morocco and presentation of design and operation of the Laayoune seawater reverse osmosis plant	2000	Desalination	(Zidouri, 2000)
11	Impact of solar energy cost on water production cost of seawater desalination plants in Egypt	2008	Energy Policy	(Lamei et al., 2008)
12	Concentrating solar power for seawater desalination in the Middle East and North Africa	2008	Desalination	(Trieb & Müller-Steinhagen, 2008)
13	Future sustainable water desalination technologies for the Saudi Arabia: A review	2012	Renewable and Sustainable Energy Reviews	(El-Ghonemy, 2012)

PY: Publication year

No.	Title	PY	Journal	Ref.
14	Cost effectiveness of conventionally and solar powered monovalent selective electrodialysis for seawater desalination in greenhouses	2021	Applied Energy	(Ahdab et al., 2021)
15	Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability	2013	Desalination	(Ghaffour et al., 2013)
16	Nanofiltration and reverse osmosis membrane for nitrate removal: performance study and economic evaluation	2021	Moroccan Journal of Chemistry	(Touir et al., 2021)
17	Solar-Powered Reverse Osmosis Desalination	2022	Journal of Physics: Conference Series	(Shukla et al., 2022)
18	Energy, exergy, and thermo-economic analysis of renewable energy-driven polygeneration systems for sustainable desalination	2021	Processes	(Khoshgoftar Manesh & Onishi, 2021)
19	Application of solar energy in water treatment processes: A review. Desalination	2018	Desalination	(Zhang et al., 2018)
20	Design and economic evaluation of solar-powered hybrid multi effect and reverse osmosis system for seawater desalination	2019	Desalination	(Filippini et al., 2019)
21	Brackish Water Desalination using Reverse Osmosis and Capacitive Deionization at the Water-Energy Nexus	2020	Water Research	(Pan et al., 2020)
22	Techno-economic feasibility of a solar-powered reverse osmosis desalination system integrated with lithium battery energy storag	2019	Desalination and Water Treatment	(Meratizamana & Godarzib, 2007)
23	Environmental and economic assessment of the combination of desalination powered by renewable energies in Morocco	2019		(Rechreche, 2019)
24	PV and CSP solar technologies & desalination: economic analysis	2016	Desalination and Water Treatment	(Darwish, 2015)
25	Hybrid renewable energy/hybrid desalination potentials for remote areas: Selected cases studied in Egypt	2021	RSC Advances	(Kashyout et al., 2021)
26	Design and Simulation of a Solar Energy System for Desalination of Brackish Water	2019	Environmental and Climate Technologies	(Ennasri et al., 2019)
27	Techno-economic feasibility of solar based desalination through reverse osmosis	2020	Desalination	(Ghafoor et al., 2020)

PY: Publication year

No.	Title	PY	Journal	Ref.
28	Economic analysis of wind-powered desalination in the south of Morocco	2004	Desalination	(Zejli et al., 2004)
29	The challenges of reverse osmosis desalination: solutions in Jordan	2020	Water International	(Walschot et al., 2020)
30	The state of desalination and brine production: A global outlook	2019	Science of the Total Environment	(Jones et al., 2019)
31	Solar Dome Integration as Technical New in Water Desalination: Case Study Morocco Region Rabat-Kenitra	2021		(Lachhab et al., 2021)
32	Main Technical and Economic Guidelines to Implement Wind/Solar-Powered Reverse-Osmosis Desalination Systems	2022	Processes	(Subiela-Ortín et al., 2022)
33	A Roadmap for Renewable Energy in the Middle East and North Africa	2014	Oxford Institute for Energy Studies	(El-Katiri, 2014)
34	Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco	2020	Desalination	(Kettani & Bandelier, 2020)
35	Desalination experience in Morocco	2001	Desalination	(Tahri, 2001)
36	Desalination as an alternative to alleviate water scarcity and a climate change adaptation option in the MENA region	2020	Konrad-Adenauer-Stiftung	(Kharraz, 2020)
37	Promotion of Solar Desalination in the MENA Region	2006	Middle East Desalination Centre, Muscat, Oman	(Quteishat & Abu-Arabi, 2006)
38	Energy and economic analysis of evaporative vacuum easy desalination system with brine tank	2020	Journal of Thermal Analysis and Calorimetry	(Kariman et al., 2020)
39	Optimization of Renewable Energy Power System for Small Scale Brackish Reverse Osmosis Desalination Unit and a Tourism Motel in Egypt	2012	Smart Grid and Renewable Energy	(Fahmy et al., 2012)
40	Evaluating the economic viability of solar-powered desalination: Saudi Arabia as a case study	2016	International Journal of Water Resources Development	(Keulertz & Woertz, 2015)
41	Thermo-economic Assessment of the Possible Desalination Processes for the Second Block of Bushehr Nuclear Power Plant	2019	E3S Web of Conferences	(Sadeghi et al., 2019)

PY: Publication year

No.	Title	PY	Journal	Ref.
42	Feasibility design of an optimized desalinator assisted only by solar energy. Case: Saudi Arabia	2021	Preprints	(Biain, 2021)
43	Water desalination technologies utilizing conventional and renewable energy sources	2014	International Journal of Low-Carbon Technologies	(Yadav et al., 2014)
44	Renewable energy desalination: an emerging solution to close the water gap in MENA	2013	Desalination Updates	(Bank, 2012)
45	Optimum design of PV-RO system solar-powered sea water desalination without storage in Saudi Arabia (Case study)	2021	International Journal of Smart Grid and Clean Energy	(Al-Shail & Ordoñez, 2019)
46	Combined concentrated solar power plant with low-temperature multi-effect distillation	2020	Energy Exploration and Exploitation	(Al-Addous et al., 2020)
47	Desalination in Morocco: Status and prospects	2021	Desalination and Water Treatment	(El-Ghzizel et al., 2021)
48	Techno-economic analysis of a stand-alone solar desalination plant at variable load conditions	2018	Applied Thermal Engineering	(Laissaoui et al., 2018)
49	Is renewable-energy desalination technology coming of age in the MENA region	2017		(ClimaSouth, 2017)
50	indirect-solar-desalination-value-engineering-and-cost-benefit-analysis	2015	International Journal of Electrical and Computer Engineering	(Rachid et al., 2015)
51	Economic Feasibility of Small Scale Solar Powered RO Desalination for Brackish/Saline Groundwater in Arid Regions	2017	International Journal of Water Resources and Arid Environments	(Dawoud, 2017)
52	the Economics and Performance of Desalination Plants	2009	Water and Wastewater Treatment Technologies	(El-Nashar, 2009)
53	Solar-driven desalination with reverse osmosis: The state of the art	2009	Desalination and Water Treatment	(Ghermandi & Messalem, 2009)
54	Solar-thermal powered desalination: Its significant challenges and potential	2015	Renewable and Sustainable Energy Reviews	(Reif & Alhalabi, 2015)

PY: Publication year

3.2. Desalination process

Desalination is a generic terminology for extracting salt from water to produce freshwater, defined as having a salt content of < 1000 mg/L (Micale et al., 2009), making unusable waters suitable for humans, livestock, agricultural, and several other uses (Beltrán & Koo-Oshima, 2006). Due to increased demand for freshwater, climate change, and drought, conventional water resources are fully depleted, and desalination is becoming more popular (Hindiyeh et al., 2021). The traditional desalination method, which often involves fossil fuels, requires a large amount of energy, making the process costly (Semiat, 2008). Therefore, different coupling options are emerging between desalination technologies and renewable energy sources, focusing on cost reduction and environmental protection (Fig. 2) (Curto et al., 2021).

Multi-effect distillation is a multiple stage process. In each stage, the feed water is heated and the steam flows into tubes of the next stage (effect), with more heating and evaporation. The vapors are then condensed in desalinated water (Adams et al., 2002; El-Nashar et al., 2008).

3.2.1. Electrodialysis

Electrodialysis (ED) is a membrane-based salt-flushing process using electrical field to treat brackish water or wastewater with low salinity (Krishna, 2004).

An economic analysis of the ED process powered by fuel and PV showed that the cost of the PV-powerd process is 30% higher than the fuel-based process (Abraham & Luthra, 2011).

3.2.2. Desalination with Reverse Osmosis

RO is the second leading desalination technology with low SEC. This process is based on reverse osmosis, which is the movement of water from a low concentrated area to a high concentrated area through a semipermeable membrane. Only molecules the diameter of water molecules may flow through the tiny holes in the membrane, helping to remove all types of pollutants. Solar-driven RO plants have advantages over the traditional desalination process and other solar-driven technologies, such as high recovery ratio and low energy consumption (Ali et al., 2011). Solar photovoltaic energy that powers this process process is useful for producing drinking water in remote locations where power grid links are inexistent or unstable (Alnaimat et al., 2018).

3.3. Comparison of economic aspects of water desalination technologies in Morocco and other MENA countries

In Morocco, the Khenifra plant uses conventional and reverse osmosis (RO) systems, producing 36,290 m^3/day of freshwater (Boulahfaa et al., 2020). The RO technique using solar energy has been reported as the best alternative, as it is low cost and sustainable in the treatment of brackish water widely available in Morocco (El Azhar et al., 2012; Ennasri et al., 2019; Zidouri, 2000). With the growing adoption of renewable energy, renewable energy desalination plants, including solar-powered plants, have been installed, and

Morocco has adopted PV renewable energy sources in some desalination plants (Ennasri et al., 2019). In addition, solar-powered desalination systems have been reported to reduce the economic burden usually paused by desalination energy supplies. Morroco and other countries in the Mediterranean region have abundant sunshine, but also, due to their arid climate, they have limited water sources, making the use of a solar-powered desalination system the most reliable solution (Ahdab et al., 2021; Touir et al., 2021; Walschot et al., 2020).

Morocco has adopted membrane-based desalination systems such as RO (brackish and seawater) and ED (brackish water) (Ennasri et al., 2019; Quteishat & Abu-Arabi, 2006). However, RO requires less energy, lower capital cost and greater capacity (12,000 m^3/day) (Ennasri et al., 2019), than ED. Solar power supplies used for RO desalination cut cost in Morocco by cutting fuel imports, generating electricity for both desalination plants and other activities, and reducing carbon emissions. When comparing RO powered by wind and vapour compression (VC), two systems used for desalination in southern Morocco, Zejli et al. reported that RO used relatively less energy, reflecting lower cost (Table 2) (Zejli et al., 2004). For example, the water cost of VC was higher. However, the overall costs were lower for wind-powered VC and RO compared to grid-powered systems. They also reported that VC was used only with desalination units without the need for pretreatment.

Table 2
Comparison of RO and VC (Zejli et al., 2004)

	RO	**VC**
Desalination units	5	2
Water production, m^3/h	10	25
Water production, m^3/d	1200	1200
SEC (seawater), kWh / m3	5	15
Power, kW	250	750
Energy consumption, megawatt hour (MWh) / year	2190	6570
Lifetime, years	20	20
RO: Reverse Osmosis; VC: Vapor Compression		

The RO technology of the Chtouka Ait Baha plant in Morocco uses SEC of 4kWh/m^3 and the fixed water cost of about \$1/m^3 on average is affordable. Furthermore, this study and other studies indicated that solar energy is cost-effective when used in RO desalination plants (Kaya et al., 2019; Kettani & Bandelier, 2020). Compared to other MENA countries, the water cost of \$1/m^3 is higher than the cost in those countries in general where desalinated water costs \$0.5/m^3 with RO and except for thermal systems where the water cost is $1/m^3 for the desalination of MSF and MED in many MENA countries. This aligns with the reported thermal system being more expensive in Morocco, too (Quteishat & Abu-Arabi, 2006). Regarding energy consumption, 4kWh/m^3 is higher than 3.5kWh/m^3 on average in Abu Dhabi and 3 kWh/m^3 in Egypt (Kaya et al., 2019; Lamei et al., 2008). In general, studies comparing solar MED and RO (PV-RO) plants found that the solar RO system is more environmentally benign and cost-effective than the solar MED system (El-Nashar et al., 2008). However, for large-scale capacities greater than 1000 m^3/day, a solar-driven MED plant was reported to be more cost-effective than a PV-RO plant (Boulahfaa et al., 2020; Ennasri et al., 2019; Ghafoor et al., 2020; Quteishat & Abu-Arabi, 2006).

In the context of Morocco, solar PV energy was feasible and cheaper than concentrated solar power (CSP) due to the complexity of building the high voltage line infrastructure from the desert, which drives costs higher. It is suggested that building many CSP driven RO plants would make building a CPS line cheaper and provide RO plants with the CSP advantage of storing heat at a lower cost. Meanwhile, studies have shown that the best alternative is to combine grid and solar energy when only solar power supply is not adequate (Filippini et al., 2019; Kettani & Bandelier, 2020). On the other hand, the CSP-powered plant's economic feasibility in Jordan is challenged by subsidized water tariffs up to 80% lower cost than the actual cost, making it economically unviable to run (Al-Addous et al., 2020). A reduction of 16% in subsidies on water tariffs would make solar-powered RO economically viable, attracting more adoption and more benefits (Rachid et al., 2015; Trieb & Müller-Steinhagen, 2008).

On the other hand, compared to other MENA countries, solar energy supply is favored over other renewable energy sources due to both sunlight availability and different water salinity, especially in countries bordering the Mediterranean Sea. The CSP in these countries generates both heat and electricity as in Morocco, but in countries bordering the Red and Mediterranean Seas, CSP-RO desalinated water costs $1.52-1.74 / m3 less than $1.97–2.08 from MED powered by CSP, which is a thermal process (Bank, 2012). Using CSP thermal energy sources is cheaper than using thermal energy directly operating the desalination system (Darwish, 2015).

On the contrary, a study on a pilot plant in Ouarzazate, Morocco, with concentrated photovoltaic panels and vanadium flow batteries showed decreased plant performance and a 50% cost increase, but with an 81% reduction in carbon emissions from 7440 to 23825 tons of CO_2 emissions eliminated compared to fossil powered plants (Biain, 2021). The long-term economic benefits of renewable energy for the powering of desalination plants were attributed to the benefits of lower carbon emissions (El-Ghzizel et al., 2021; Rechreche, 2019; Shatat & Riffat, 2014). Meanwhile, another study on integrated solar dome desalination found that it is efficient and profitable due to the abundance of sunshine throughout the year in Morocco and other MENA countries (Khoshgoftar Manesh & Onishi, 2021; Lachhab et al., 2021). Regenerative energy-powered RO desalination systems were found to be economically and environmentally beneficial in Saudi Arabia, leading other MENA countries to desalination to obtain freshwater (Al-Shail & Ordoñez, 2019; Do Thi et al., 2021).

Membrane-based desalination systems are favored over thermal systems because they can be adapted to water quality, produce higher capacity, and have lower capital and operational costs (Reif & Alhalabi, 2015). Therefore, Morocco has been adopting more and more RO systems to solve its water supply shortage, using more versatile systems to supply all regions (Table 3) (El-Ghzizel et al., 2021).

Table 3
Characteristics of desalination technologies in Morocco (El-Ghzizel et al., 2021)

City	Technology	Nature of water	Production capacity	Year of commissioning	
			(m3/d)		
Tarfaya	ED	Brack water	75	1976	(replaced by other units, 2001)
	RO	Brack water	800	2001	
	MED – VCD: Vapor	Seawater	250	1977	(replaced by units realized in 1995 and 2005)
Boujdour	Compression distillation				
	Reverse osmosis	Seawater	3,700	1995–2005–2011	
Laâyoune	Reverse osmosis	Seawater	26,000	1995–2005–2010	
Tan Tan	Reverse osmosis	Brack water	12,000	2003–2014	
Akhfenir	Reverse osmosis	Seawater	860	2011	
Tagounite	Reverse osmosis	Brack water	400	2008	
Khenifra	Reverse osmosis	Brack water	30,000	2012	
Dakhla	Reverse osmosis	Brack water	17,280	2015	
Khouribga	Reverse osmosis	Brack water	30,000	2019	

RO: Reverse Osmosis; ED: Electrodistillation; MED: Multi-Effect Distillation; VCD: Vapor Compression Distillation

Solar-powered thermal desalination is cheaper than solar RO in countries of the Gulf Cooperation Council (GCC) where the salinity of the water is high (Bank, 2012). Since RO systems use high-grade energy and are power-hungry, the measures taken, including solar energy, have yielded a significant energy cost reduction of up to 43% per m^3. In addition to increasing fuel prices, solar energy has become more feasible and preferred in addition to wind energy. Renewable energy is a sustainable solution to the RO disadvantage of higher carbon emissions due to higher energy consumption. However, solar-powered desalination plants have been proven to be cost-effective in remote areas with limited traditional electricity supplies (El-Ghzizel et al., 2021), where RO systems drain more electricity (Lachhab et al., 2021; Pan et al., 2020). Like in remote Moroccan areas, solar-powered desalination in MENA countries solves challenges associated with traditional energy and ways of transport of water while reducing associated costs (Kashyout et al., 2021; Quteishat & Abu-Arabi, 2006). Combining different systems, either various renewable energy sources or conventional energy with renewable energy is more economically and environmentally beneficial than purely fossil-powered desalination or water transport from other locations (Kashyout et al., 2021).PV-wind hybrid desalination system is cost-effective in remote areas because it is energy efficient and results in lower net cost in small scale plants, common in remote areas (Dawoud, 2017; Fahmy et al., 2012; Shahzad et al., 2018).

More evidence on the profitability of solar-powered desalination has shown that it depends on area specificities and desalination scale studies. For example, nuclear and solar energy, when used for small-scale desalination processes, are not cost-effective, but when used for large-scale desalination, they are economically feasible and cost-effective (Sadeghi et al., 2019; Tahri, 2001). Higher investment costs favor large-scale facilities that require a general low cost compared to traditional fuel-driven desalination plants. This indicates that solar-powered options will be viable in the coming years (Dawoud, 2017; El-Nashar, 2009; Zhang et al., 2018).

More recent evidence showed that solar energy usage in desalination leads to lower water costs and that solar-powered RO desalination plants significantly cost lower when subsidies are applied or not (Esmaeilion, 2020; Kharraz, 2020). As Morocco has committed to significantly reducing its greenhouse gas footprints, the use of renewable energy together with conventional energy in water treatment plants accelerates this achievement.

In the Arab Gulf countries, the thermal desalination process has been widely favored over solar RO because of higher salinity that damages membranes in RO systems, fouling and scaling and lower energy costs in the region (Ali et al., 2011; El-Ghonemy, 2012). On the contrary, in North Africa, RO is widely used in desalination primarily because the salinity of the water is favorable (Figs. 3 and 4) (Kharraz, 2020).

Despite recent advances in RO technologies that solve most technical problems, MENA countries still face challenges in adopting solar powered systems due to the increased technology and investment costs for solar power facilities. That overshadows the lower operating and maintenance costs of these systems (Ghermandi & Messalem, 2009; Keulertz & Woertz, 2015; Quteishat & Abu-Arabi, 2006), as they result in higher water costs compared to conventional energy (Do Thi et al., 2021). This evidence is the same as what was reported in studies from Morocco in particular. Similarly, in Iran, when comparing the grid, diesel engines and PV solar panels, RO powered by gas engines was more economical than solar-powered RO due to high water salinity increasing the SEC. However, solar energy will be economical,, as carbon emission taxes will increase,, making solar energy sources economically feasible alternatives (Lamei et al., 2008; Meratizamana & Godarzib, 2007). However, solar energy will be economical since the emission penalty cost of fossil fuel-powered units will increase the costs of those units and make the solar system economically feasible (Lamei et al., 2008; Meratizamana & Godarzib, 2007).

Another challenge is brine production, which makes management and disposal both costly and environmentally hazardous. New strategies for safe disposal will reduce costs and save the environment (Jones et al., 2019).

During the last decades, the solar energy cost has been decreasing. With more countries committing to adopting renewable energy and fuel prices, it is expected that the demand for solar energy will increase, and mass production will reduce the cost and make it affordable and profitable (Pugsley et al., 2016; Quteishat & Abu-Arabi, 2006).

In the MENA region, especially in countries like Morocco that import energy, solar energy is cheaper than conventional fuel-derived energy. When used extensively in desalination, it is profitable considering the prices of fuel on the international market (El-Katiri, 2014).

As in Morocco, wind energy cost in MENA countries is lower than fuel cost and benefits are expected to increase in the long-term with the reduction of air pollution, increased fuel prices in the future and improved climate (El-Katiri, 2014; Pinto & Marques, 2017; Shukla et al., 2022). Another study revealed that solar-powered RO has a return period of under 5 years to economically be profitable (Meratizamana & Godarzib, 2007; Pugsley et al., 2016), which is more than 2.7 times longer than the 1.83-year payback period for the solar-powered RO estimated in Pakistan (Ghafoor et al., 2020).

The largest plants in the MENA region are located in Saudi Arabia, followed by the United Arab Emirates (UAE) (Table 4). The largest plant (Al Shuaiba) has the lowest water cost of 0.56/m^3, which is lower than $1 (0.98–1.14 $/$m^3$)/$m^3$ of the largest Moroccan plant, the Chtouka desalination plant, but similar to the cost of Magtaa plant in Algeria (Kharraz, 2020).

Table 4
The MENA region's largest desalination plants (in operation): The KSA and the UAE (Kharraz, 2020)

Location	m^3/d	Process	Feedwater	Year	Cost (USD)
Al Jubail, KSA	800,000	MED	SW	2007	0.827/m³
Al Shuaiba 3, KSA	880,000	MSF	SW	2009	0.57/m³
Jebel Ali M Plant, UAE	636,440	MSF	SW	2013	EPC cost: $1.07 billion
Soreq, Israel	540,000	RO	SW	2013	0.585/m³
Magtaa, Algeria	500,000	RO	SW	2014	0.56/m³
Ras Al-Khair, KSA	1,025,000	RO	N/A	2016	-
Ras Al-Khair, KSA	728,000	MSF	SW	2016	EPC cost: $4.2 billion
Yanbu 3, KSA	550,000	MSF	SW	2017	EPC cost: $1 bn

KSA: Kingdom of Saudi Arabia; MSF: Multi-stage Flash; USD: United States Dollar; MED: Multi-Effect Distillation; EPC: Engineering, Procurement and Construction; SW: Seawater; N/A: Non-applicable.

Furthermore, RO systems powered by gas engines in Iran result in a water cost range of $0.89 to 0.92 / m3 (Meratizamana & Godarzib, 2007), still lower than in Morocco. This indicates that the Moroccan plant is still expensive compared to plants in the MENA region. Despite the difference in cost, only the Algeria plant is based on RO technology, while the Al Shuaiba plant is based on MSF technology.

Another difference is in capacity, where the capacity for Al Shuaiba plant is 880,000 m^3, for Magtaa plant is 500,000 m^3 / day and for Chtouka plant it is 275,000 m^3/day. Therefore, the Magtaa plant and Al Shuaiba plant cost almost two times and three times less than the Moroccan largest plant, respectively. Desalination systems tend to be more cost-feasible in large-scale plants. The RO in small scale desalination plants leads to up to a 50% increase in cost compared to large scale seawater desalination plants (Ghaffour et al., 2013; Tahri, 2001). Other factors contributing to the difference in cost are subsidies, currency exchange, cost calculation methods used (Ghafoor et al., 2020), and the resulting electricity prices (Kariman et al., 2020).

Despite the relatively high investment costs for the use of for the use of for the use of renewable energy in the treatment of treatment of treatment of water in MENA, the reduction of the cost of reduction of the cost of reduction of the cost of PV modules in recent decades provides an attractive option (Fig. 5) (Al-Karaghouli et al., 2010; Kharraz, 2020). In many MENA countries, including Morocco, coupling solar energy with desalination or combining solar, thermal, and electrical grid energy in desalination processes improved energy efficiency and reduced cost.

In Abu Dhabi, 90% of seawater desalination is by MSF and MED, which are energy inefficient and more polluting. The cost analysis of the powering of RO systems with solar energy concluded that when solar photovoltaic systems are used to power RO desalination facilities, they reduce the SEC by about 10%, resulting in a reduced total cost of water (Kaya et al., 2019). Hybrid RO and CSP are more economical than PV-RO because thermal storage of CSP improves the performance of the RO unit with low water costs, similar to a fossil-powered RO unit (Laissaoui et al., 2018).

4. Discussion

4.1. The Energy Cost of Desalination

Energy is the main driver of the cost of the desalination process (Kariman et al., 2020). SEC is based on desalination technology and plant design parameters. It is also affected by ambient conditions such as temperature and feed water composition. As we have found out in our review, energy has been the main driver of costs in both Morocco and MENA countries, and costs were different depending on many factors specific to each country (Ghermandi & Messalem, 2009; Napoli & Rioux, 2016; Quteishat & Abu-Arabi, 2006). Countries have explored inexpensive energy resources to meet their desalination process needs. One example is building desalination plants close to thermal power plants since the saltwater must be evaporated with heat. Consequently, the waste heat generated by the desalination facility as a by-product during electricity production can be recovered and used in thermal power plants. In addition, the cost of desalinated water depends on location, ambient conditions, operational and maintenance costs, and environmental costs associated with CO_2 emissions (Lapuente 2012) and subsidies (Al-Addous et al., 2020; Ghaffour et al., 2013). As we have seen, the cost of cost of water was influenced by subsidies in Jordan, making the cost of desalination of the cost of desalination of water using renewable energy uncompetitive compared to the the water of other sources, making the method economically uncompetitive not because it is expensive but because subsidies provide a cheaper alternative. Some articles revealed that renewable energy-powered renewable energy-powered desalination systems are economical in large-scale desalination plants. The solar-powered large-scale RO systems can lower the cost by $0.37 to $0.74/m^3 (Sadeghi et al., 2019). On the other hand, large-scale desalination is expensive, and water costs about twice as much as it does in a typical river or lake water purification operation (2011). Morocco and other MENA countries have adopted hybridisation for cost reduction such as Solar-Wind hybrid desalination used in Morocco. This hybrid was reported to be more cost-effective by other studies outside Morocco (Bourouni et al., 2011; Gallardo-Vázquez et al., 2019). In 2003, a photovoltaic and wind-coupled RO plant was established in Greece for seawater desalination, and its energy requirement was reported to be 3.96 kWp of PV panels and 900 Wp of wind turbine. When a 44.4 kWh battery was linked to PV and wind turbine systems, the energy consumption became 16.5 kWh/m^3 with a capacity of 3.12 m3 / day. The estimated cost range of water was 23–27$/m^3 (Fahmy et al., 2012; Lachhab et al., 2021).

In addition to combining different energy sources, hybrids of different systems can also reduce the specific energy consumption (SEC). Studies have been conducted with the mixture of RO and other membranes and showed various advantages of hybrid systems, such as decreased individual energy usage, improved RO membrane lifespan, improved performance, reliability, and general reduction of costs (Obotey Ezugbe & Rathilal, 2020).

4.2. Economic evaluation of desalination with solar-driven reverse osmosis

Reviewed articles showed that the current technology of solar RO systems in the MENA region is not cost-effective in small-scale settings in general and cannot be applied everywhere due to different factors, including water salinity (Kashyout et al., 2021; Kharraz, 2020; Rachid et al., 2015; Zejli et al., 2004). However, it remains an efficient and inexpensive approach to water management problems for small units in areas with limited electricity supplies (Rahimi et al., 2021). However, in these areas, costs depend on the conditions of the sun and the conditions of the water (Mohamed et al., 2008).

4.3. Capital Expenses

One of the significant challenges MENA countries face in installing RO desalination systems powered by solar power powered by solar power is the high investment costs of this new technology,, which costs too much to appreciate the the benefits (Ghermandi & Messalem, 2009; Napoli & Rioux, 2016). Capital expenses for the solar PV-RO plant include hardware costs (on equipment and materials) and other capital costs. Therefore, it depends on customer choices, such as selecting types of equipment and site characteristics, including feed water, desalinated water quality, and regulations. The cost of solar PV-RO depends highly on the availability of solar energy and feed water solute required for desalination in a given region. However, batteries must be taken into account while designing a water treatment system. The photovoltaic / battery network is projected to account for 25% of the overall capital investment in the facility, while the water treatment plant (RO, cartridge filters and UV disinfection) is anticipated to account for more than 50% (Helal et al., 2008). Many researchers have reported that using batteries to extend normal operating times is more economical than generating more water at peak hours (Sauer et al., 2012). Increased operational demands may allow for battery storage, and cloud occurrences can induce fast fluctuations in power generation, resulting in frequent pump performance variations. These drastic changes in flow and pressure may affect water quality and damage membranes (Pan et al., 2020; Reif & Alhalabi, 2015). The initial, operational, and end of life cost of a solar-derived RO plant is shown in Table 4.

Table 4
Initial, operational, and end of life cost of a solar derived RO plant

Type of cost	% of initial costs	USD
System Balance and Miscellaneous	60.9%	6,252,000
Development	0.18%	18,382
Feasibility study	0.22%	22,466
Power system (PV modules)	38.5%	3,960,000
Inverter Replacement Costs	After 5 years	720,000
Engineering	0.16%	16,339
Operation and Maintenance (O&M)	After one year	20,000
End-of-project life	10%	(1,021,200)
USD: United States Dollar; PV: Photovoltaic		

4.4. Economic aspects of a solar-powered PV-RO System

For a PV-RO system, the cost of water output per unit is influenced by several variables, including recovery ratio, the expense of equipment/ machinery, hybridization configuration, government subsidies, interest rate, labor costs, etc. Therefore, solar RO costs can be significantly reduced by acting on those factors.

- **Developing more economic PV cells**

Even if photovoltaic modules cost about 60% less than in the 1990s, solar cells that are both more inexpensive and more efficient can be made using nanotechnology (Ushasree et al., 2019)

- **Design of a battery-less photovoltaic system**

Due to the increased inner deterioration at high temperatures, the battery performance, charging, and discharge phase reduces the average battery lifespan in cold and warm places. This decreases the water flow produced and a subsequent increase in the device's total cost. Because the battery performance is typically 75–80%, approximately 20–25% extra PV is necessary to maintain a constant supply. Therefore, battery-less photovoltaic systems are the sustainable solution

- **Employing Energy Recovery Device**

The Energy Recovery Device (ERD) helps conserve power at a controlled pressure that can be passed immediately to the feed water. It contributes to the reduction of the implementation price of the device. It uses the extracted energy to increase the water pressure (Helal et al., 2008), conserving up to 57% of absolute power relative to non-recovery devices, with 95% effectiveness. Seawater desalination experiments showed high performance, versatility in service, and cost reduction of ERD systems (Elasaad et al., 2015; Subiela-Ortín et al., 2022).

4.5. Prospects of the Solar-Powered RO Desalination System

New RO technology to make "fouling-resistant" membranes and make RO capable of desalinating water with high salinity would be vital in cost reduction. Besides this, using fossil fuels and other non-green energy sources might increase the emission of greenhouse gases and lead to climate change. Fossil fuel prices are expected to continue to rise, making it economically unfeasible for countries that import energy, such as Morocco. As MENA countries become more industrialized, their energy demand and their carbon emission footprints will increase with their expenses for energy and water supply and for tackilng climate change impacts. The potential of its location under the sun under the sun and its commitment to reduce carbon emissions make solar energy-powered desalination systems the only sustainable solution. Considering the arid climate in these countries with freshwater scarcity, there is an increasing need to treatwastewater, seawater and brackish water for satisfying the increasing demand (Maftouh et al., 2022; Quteishat & Abu-Arabi, 2006).

All of these point to the expected incsease in the installation of solar-powered desalination plants in the MENA region and increased investments to aquire more advanaced energy and cost-efficient technologies. Solar power RO desalination systems should be promoted and subsidized to become a massively adopted system, focusing on their potential benefits and removing barriers to their installation (Ali et al., 2011). Proper site analysis, including the water storage or salinity issue, available resources (electricity, gas reservoirs, solar energy), and the requirement of desalinization plants (small or large), should be performed in the area that needs freshwater. This will allow the introduction of area-specific efficient, and cost-effective desalination methods.

5. Conclusion

In regions where only seawater or brackish water is a source of drinking water, desalination systems can be used to provide drinking water. Several technologies have been established, and many more research and development methods for desalination are being explored. With increasing freshwater demand and climate change worldwide, solar-powered RO systems present preferred alternatives to fossil-fueled desalination systems and other water purification methods. Countries located in the subbelt region like Morocco and other countries in the Middle East and Africa are benefited by using solar energy in desalination. This review comparatively explored the economic aspects of solar energy sources in desalination methods and other energy sources in Morocco and other MENA countries.

The higher investment costs of solar-powered desalination methods remain challenging for Morocco and other MENA countries. This review showed that desalinated water cost in Morocco is higher than the costs in other MENA countries, but different factors, including subsidies in some MENA countries, influence the water costs. RO systems are more cost-effective in MENA countries with lower water salinity, which explains why North African countries use RO systems more than GCC countries where water salinity is higher, preferring thermal systems. Renewable energy use in desalination has been shown to be economically feasible according to the specific needs and water conditions of each country. In general, solar RO is cost-effective, efficient, reliable and environmentally safe. Their benefits are expected to align with the future global direction of climate protection. Despite benefits and increasing trends toward the solar-driven RO process, its adoption in desalination plants worldwide is still limited. This indicates the need for more efforts and extensive research exploring the barriers and providing solutions to ensure that all potential benefits are unlocked for freshwater accessibility worldwide.

Declarations

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Figures

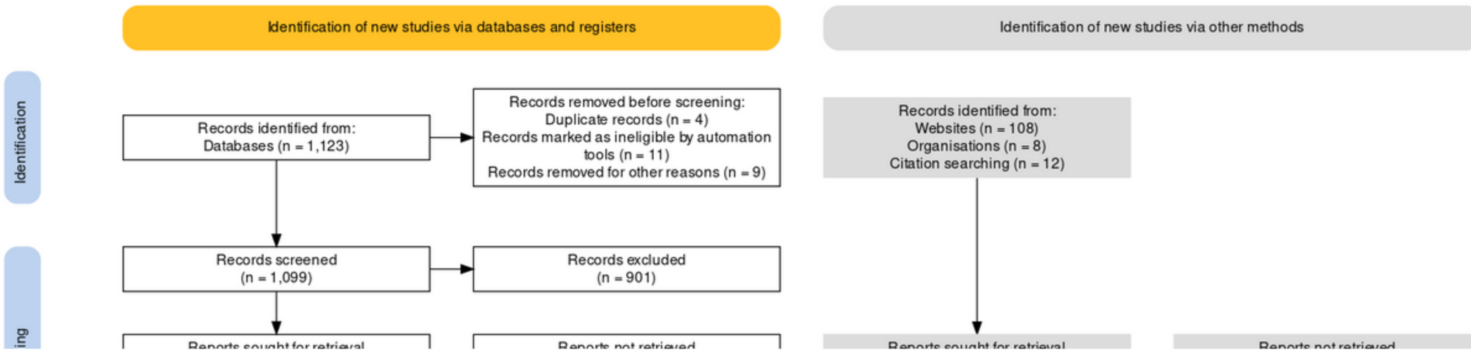

Figure 1

Flowchart for detaling identification and selection of articles

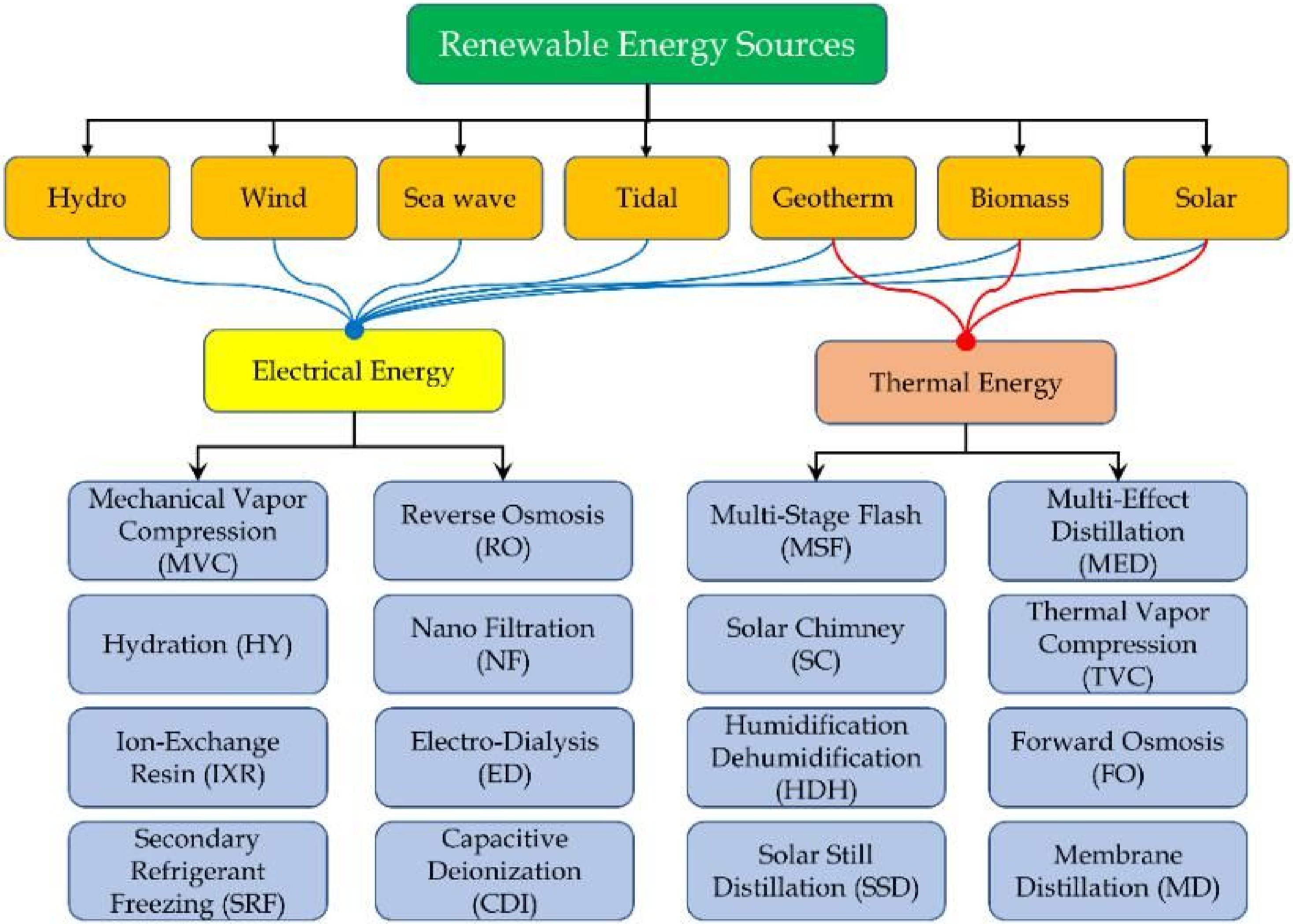

Figure 2

Coupling options between desalination technologies and renewable energy sources (Curto et al., 2021)

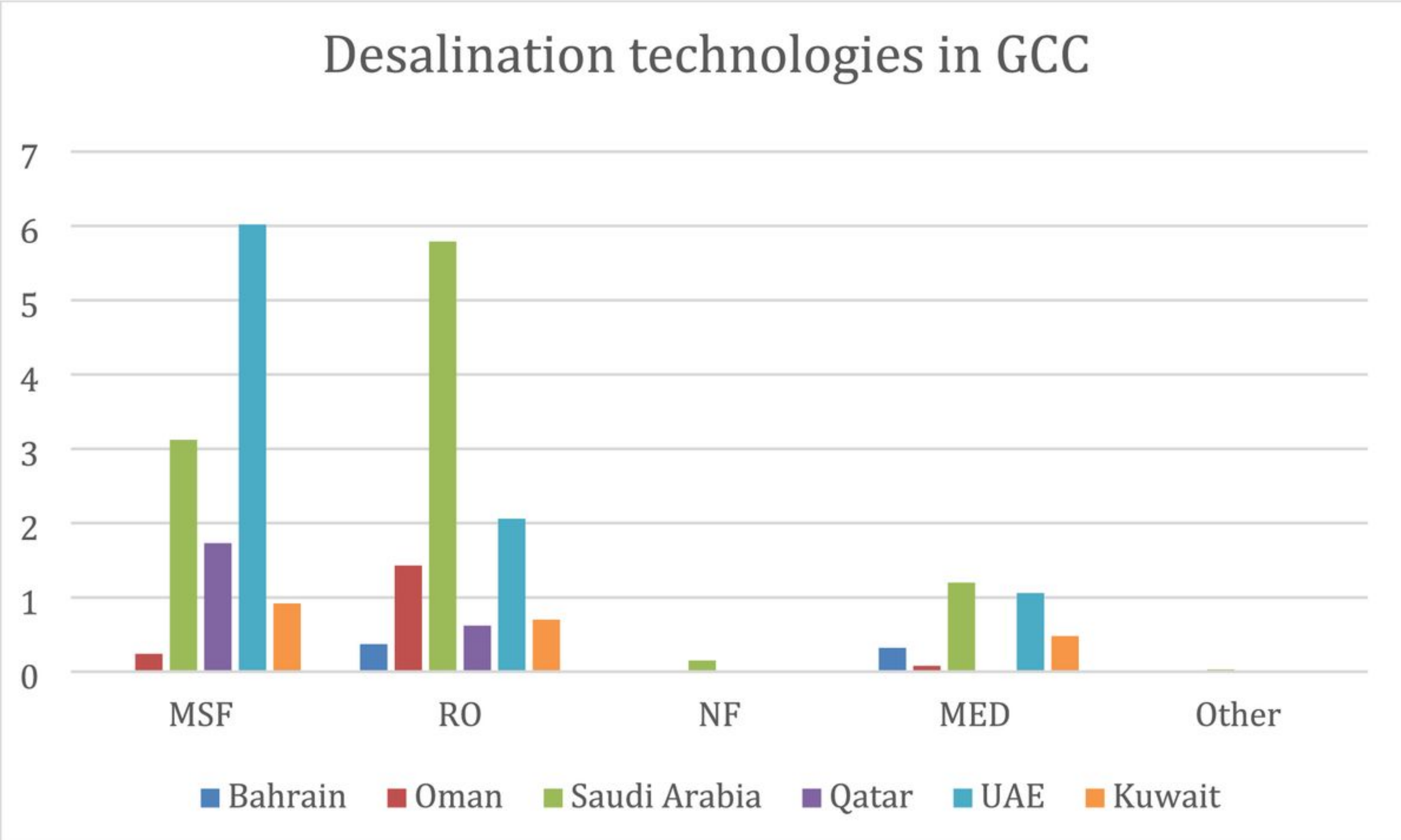

Figure 3

Desalination technologies (Capacity in Mm^3/day) in countries of the GCC (Kharraz, 2020)

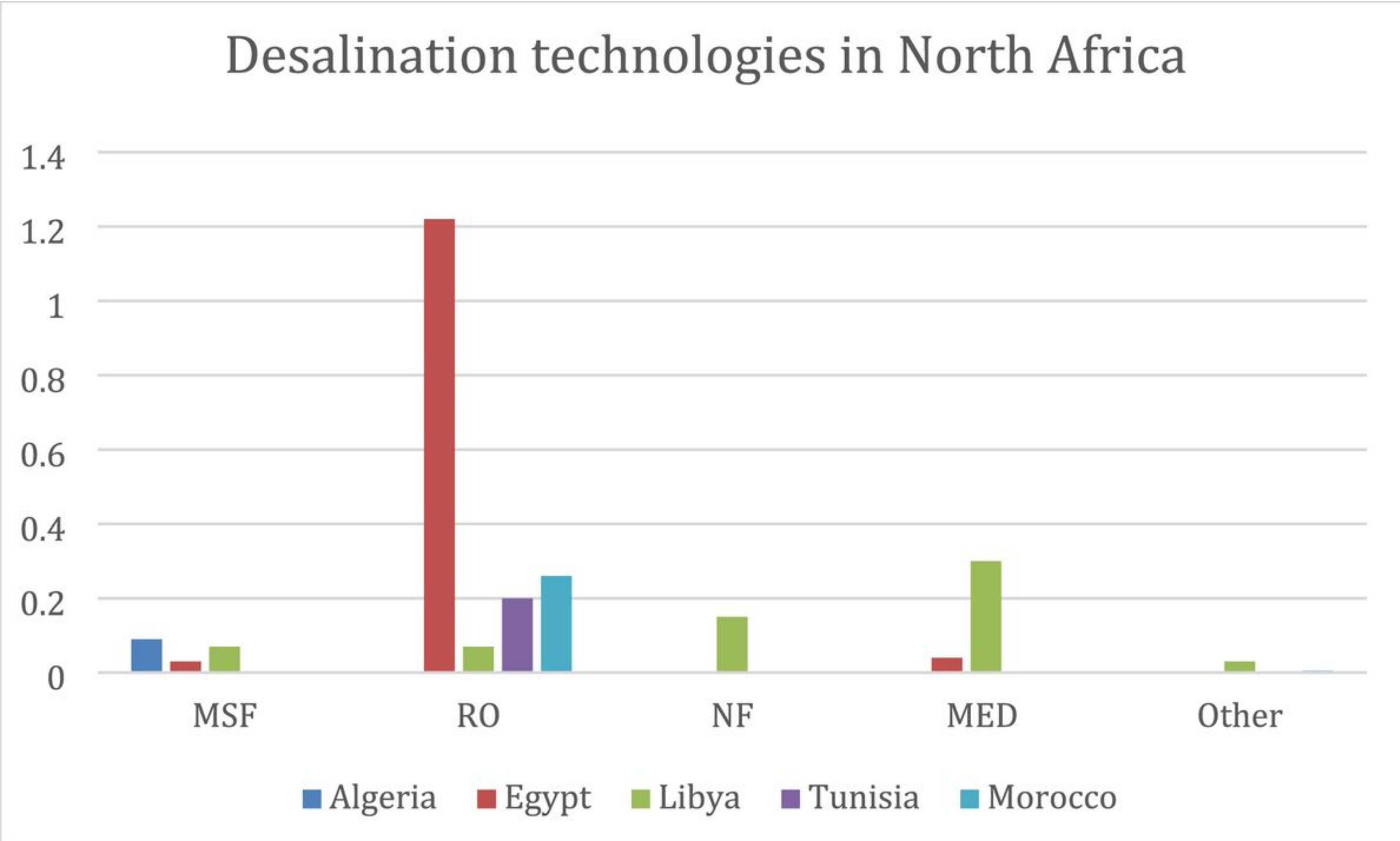

Figure 4

Desalination technologies (Capacity in Mm^3/day) in North African countries (Kharraz, 2020)

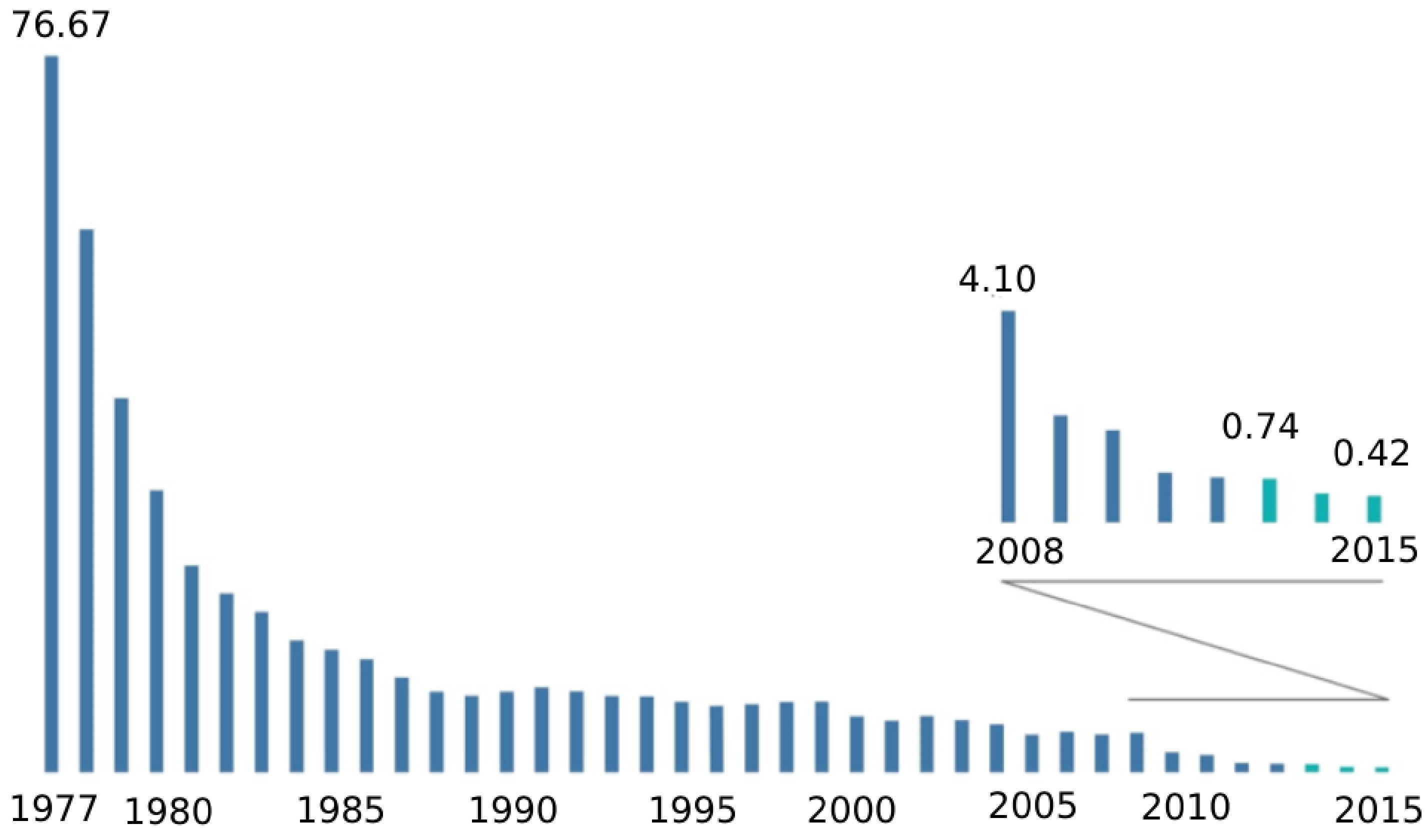

Figure 5

Price of PV modules: 1977 – 2015 (USD/watt) (Kharraz, 2020)