

# Investigation of Carbon Footprints of Three Desalination Technologies: Reverse Osmosis (RO), Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED)

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## Abstract

Nowadays, the drinking water shortage is increasing, mainly due to rapid population growth, climate change, wasteful overuse of water, and pollution. Under the current circumstances, a quarter of the world's population will not have access to good quality drinking water. Thus, another solution must be adopted in areas with insufficient freshwater. One possible line is the desalination of seawater, one of the most practical solutions to solve the problem of drinking water shortage along the oil availability shore and continues to expand globally. Water produced may also be utilized for irrigation, reducing a region's reliance on imports, contributing to the local economy, and improving food supplies. However, this process is not a consequences-free procedure; it may cause several environmental and human health problems.

The three most applied desalination technologies are reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED). In this study, the emissions of greenhouse gases (GHGs) of drinking water produced from seawater using these three technologies with fossil and renewable energy sources were investigated based on two methods: life cycle assessment (LCA) using SimaPro life cycle analysis software and carbon footprints. As a result, RO technology has significantly lower CO<sub>2</sub> emissions than thermal technologies. The RO combined renewable energy is the most environmentally friendly; provides outstanding benefits in terms of human health and ecosystem quality. This technology may still evolve in the future to produce longer-lasting, cheaper membranes, and the energy requirements of this process are lower with applying modern energy recovery systems.

## Keywords

carbon footprint, life cycle assessment, desalination, reverse osmosis, multi-stage flash distillation, multi-effect distillation

## 1 Introduction

Economic and social development is supported by energy and water resources. Social and political pressure is mounting on industrial and residential developments that achieve "low carbon" and "water conservation" outcomes in the face of rising carbon dioxide emissions and climate change is getting worse and worse.

Among the causes of global disasters, climate change is the leading cause of natural disasters, extreme weather, food shortages, and ecosystem collapse [1–3]. A significant cause of climate change is an increase in the surface temperature of the earth (global warming), which is caused by an increase in greenhouse gas (GHG) concentrations. According to published data by NASA's Global Climate Change, the average global temperature on Earth has increased by at least

1.1 °C (1.9 °F) since 1880; the latest annual average anomaly in 2021 is 0.85 °C or 1.53 °F [4]. Six well-mixed GHGs were identified, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), dinitrogen oxide (N<sub>2</sub>O), hydrogen fluoride (HFC), perfluorocarbons (PFC), and sulfur hexafluoride (SF<sub>6</sub>), in which the most significant order comes from CO<sub>2</sub> emissions (76%), then followed by CH<sub>4</sub> (16%) and N<sub>2</sub>O (6%) [5]. On the other hand, the four most significant contributors to GHGs emissions are energy use in industry (24.2%), agriculture, forestry, and land use (18.4%), energy use in buildings (17.5%), and transportation (16.2%). Energy production of all types accounts for 73.2% of all emissions, including electricity, heat, and transport sources [6]. As shown in Fig. 1, global GHG emissions in 2016 were described by the source.

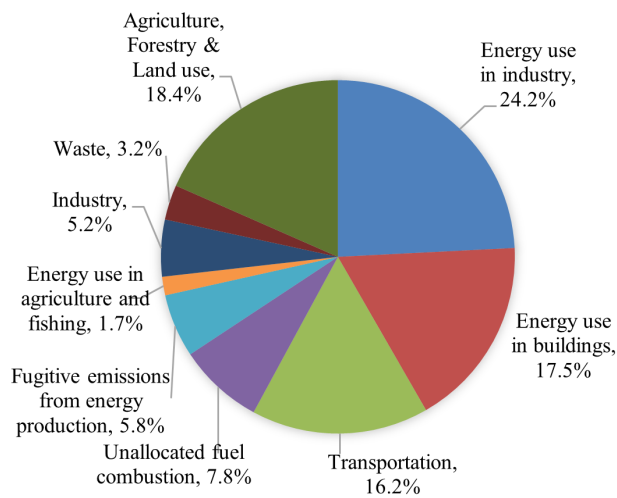


Fig. 1 Global greenhouse gas emissions by sector in 2016 [6]

Globally, GHGs are emitted at a rate of 50 billion tons per year. Carbon dioxide is the most significant of the greenhouse gases emitted by human activities, reaching 419 parts per million (ppm) in July 2022. It is accounted for about 80% of all GHGs emissions from human activities. The amount of atmospheric CO<sub>2</sub> has increased by 50% since the Industrial Revolution from the 18<sup>th</sup> century, it is now 150% higher than it was in 1750 [4]. The combustion of fossil fuels and cement production plays a significant role. Global carbon emissions must be dramatically reduced to prevent the worst effects of climate change.

Based on the growth rate of the world's population, only 60% of the world's water demand will be available to consume in 2030 [7]. It is also a worrying forecast because more than a billion people no longer have access to sufficient quantities and quality drinking water. One effective solution to the problem could be to achieve the desalination of seawater. The number and size of desalination

plants worldwide have grown by an average of 6.8% per year since 2010. As of February 2020, 16,876 installed desalination plants generate 97.2 million m<sup>3</sup> of freshwater per day globally [8].

Plants for desalinating urban water can be found all worldwide, although they are most prevalent in the Middle East and North Africa. The highest desalination capacity is found where crude oil is most readily available, as fossil fuels power most desalination plants today. About 55% of the world's total capacity for desalination is in Saudi Arabia, Kuwait, and Qatar. With 22% of the world's brine production, Saudi Arabia is the world's biggest producer. About 1.4 million m<sup>3</sup>/day is produced at Al-Jubail in Saudi Arabia, the largest desalination plant in the world [9]. Coastal desalination plants have also tended to be bigger than those on the mainland, with global desalination plants focusing on the coast.

The desalination process is based on extracting salt from seawater (as an aqueous salt solution) and utilizing of the resulting saltwater. It is typically done in two ways: either by distillation or thermal process and filtration or membrane. In desalination technologies, the multi-stage flash distillation (MSF), multi-effect distillation (MED), and reverse osmosis (RO) technologies are the three most used technologies. These properties are described in Table 1 [10–13].

The MSF process works because the saltwater is evaporated, and the water and salt can be separated. Evaporation takes place in numerous stages/effects (15–20 effects) in series-connected chambers under low pressure, causing the water to boil at a lower temperature. It is a procedure that is used in many countries to obtain sufficiently clean drinking water, with the added benefit of requiring few additions. However, if non-stainless steel is utilized, the corrosion phenomena are well-known. The water is

Table 1 Comparison of MSF, MED, RO desalination technologies [10–13]

	Thermal technology		Membrane technology
	MSF	MED	RO
Water type	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish
Operation temperature [°C]	90–110	70	Ambient
Typical unit size [m <sup>3</sup> /day]	50,000–70,000	5,000–15,000	24,000
Electrical energy consumption [kWh/m <sup>3</sup> ]	4–6	1.5–2.5	5–9
Thermal energy consumption [kJ/kg]	190–390	230–390	none
Electrical equivalent for thermal energy [kWh/m <sup>3</sup> ]	9.5–19.5	5–8.5	none
Total electric equivalent [kWh/m <sup>3</sup> ]	13.5–25.5	6.5–11	5–9
Maximum value of CO <sub>2</sub> emissions [kg CO <sub>2</sub> /m <sup>3</sup> ]	24	19.2	8.6
Distillate quality [ppm]	~10	~10	<500
Unit product cost [US \$/m <sup>3</sup> ]	0.52–1.75	0.52–1.01	0.52–0.56

evaporated at low pressure and then condensed on top of the chamber in the MED process, and the condensate released is used to heat the next chamber. Because of using the condensate, it has a lower energy requirement than the MSF process. It is capable of producing high-purity water. The RO process is based on the idea of reverse osmosis, in which saltwater is pushed through a semi-permeable membrane, leaving the salt behind. As opposed to osmosis, pressure is applied to the higher concentration solution, causing the solvent to flow toward the lower concentration solution. Consequently, clean water and salt concentration are produced. The benefit is that a large volume of clean water is recovered, the seawater utilized is of excellent quality, and it not only filters out the salt but also other hazardous chemicals.

Hybrid desalination systems combine thermal, and membrane desalination processes with at least one extra process: pretreatment of input water before desalination, brine treatment before disposal, or power generation. Like RO-MSF and RO-MED, hybrid systems have been applied at a large scale in electricity production and desalination plants, including Az-Zour in Kuwait, Fujairah I, and II in the UAE, and Ras Al-Khair in Saudi Arabia [14]. New commercial desalination plants have been equipped with the hybrid RO-MSF technology. The hybrid system has been viewed as a cost-effective alternative to standalone systems. Increased recovery rates and overall water quality can reduce stress and strain on energy consumption, scale, fouling, and the cost of production.

Desalination technology supplies people with drinking water in areas that would otherwise be scarce. Water produced can also be utilized for irrigation, such as in drought and arid regions, reducing a specific area's reliance on imports, contributing to the local economy, and improving food supplies [15, 16]. However, it has several environmental consequences, including high energy consumption, brine outflow, GHGs emissions, hazardous chemical emissions, and water intake activities. The significant effects are brine discharge, GHGs emissions, and excessive energy usage [17]. A brine solution's concentration is 1.6 to 2 times higher than seawater salinity (35 g/L), and its volume is enormous, affecting marine life and causing biological difficulties [18, 19]. Desalination facilities cause air pollution by emitting large amounts of flue gas and GHGs. Desalination needs a significant quantity of energy (see Table 1), which comes at a considerable expense.

## 2 Material and method

### 2.1 Carbon footprints

Carbon footprints are research methodologies that examine a product's whole life cycle, from raw ingredients to packaging, transportation, sale, and customer disposal or recycling. The difference between a life cycle analysis (LCA) and a carbon footprint is related to the impact categories. Carbon footprints are concentrated on a single category of environmental effect: the total amount of greenhouse gases (GHGs), in which carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and dinitrogen monoxide (N<sub>2</sub>O), are expressed in kilograms of CO<sub>2</sub>-equivalent. In this way, all GHGs can be expressed as one number, multiplying their total emissions by their global warming potential [20]. Meanwhile, an LCA considers further impact categories, such as human health, ecosystem quality, and resources.

During environmental impact evaluations, the carbon footprints of water resource projects have been underestimated. The carbon footprints are affected by various water extraction, transportation, and consumption operations. Water reuse and desalination generate greenhouse gas emissions from several sources: direct emissions from on-site sources, indirect emissions from off-site energy production, and other indirect emissions (e.g., chemicals, materials, fuels, etc.). In 2017, the world's total installed desalination capacity emitted around 76 million tons of CO<sub>2</sub> per year and could grow to 218 million tons by 2040 [21]. As Table 1, RO technologies emit much less CO<sub>2</sub> than thermal technologies. The pump in RO systems used 5–9 kWh/m<sup>3</sup> energy to overcome osmotic pressure, whereas the energy required for thermal technologies (6.5–28 kWh/m<sup>3</sup>) is higher. RO is typically the most fantastic energy-efficient technique. RO has a relatively small carbon footprint, and its environmental impact is negligible. However, the MSF and MED techniques have tremendous potential for improvement in the future, which will reduce carbon emissions. In UAE, during the production of the 1 m<sup>3</sup> of freshwater, the Carbon Footprints were 2.988 kg CO<sub>2</sub> for MSF desalination plants, 1.280 kg CO<sub>2</sub> for MED, and 2.562 kg CO<sub>2</sub> for RO [22]. Another study estimated that the Carbon Footprints of seawater RO desalination was 0.4–6.7 kg CO<sub>2</sub>/m<sup>3</sup>, that more significant than RO from brackish water (0.4–2.5 kg CO<sub>2</sub>/m<sup>3</sup>) and water reuse systems (0.1–2.4 kg CO<sub>2</sub>/m<sup>3</sup>) [23]. It is likely that the desalination of 1000 m<sup>3</sup> of seawater could release 6.7 tons of CO<sub>2</sub>. Seawater desalination facilities have a cumulative Carbon Footprint that can no longer be ignored as heroic global

efforts are underway to keep global warming below 1.5 °C as The United Nations Climate Change Conference in Glasgow (COP26) in 2022 was agreed [24]. Saudi Arabia has the most prominent global desalination capacity and the largest capacity plant, producing 1.4 million m<sup>3</sup>/day of drinking water. It is estimated that water production from desalination plants in Saudi Arabia will emit 6.5 million tons of CO<sub>2</sub> by 2040 [25]. Indicators such as those based on Carbon Footprints provide decision-makers with a means of identifying hot spots of emissions and determining the best way to reduce those emissions. As a result, these Carbon Footprint indicators can be used to drive sustainable desalination projects [26].

Several Carbon Footprints estimating tools have been established to calculate and analyze the CO<sub>2</sub>-equivalent of water reuse and desalination: LCA-based tools (e.g., SimaPro, Gabi, SiSOSTAQUA), Hybrid LCA-based tools (e.g., WEST, WWEST, WESTWeb), specific tools (e.g., Tampa Bay Water, Johnston tool), other related tools (e.g., CHEApet, Environment Agency Tool, Bridle and BSM2G tool, System Dynamics, GPS-X, mCO<sub>2</sub>, Carbon Accounting Workbook, BioWin 4.0 ...). These tools can be used to develop and utilize water resources not only economically, but also environmentally and socially in the future. To achieve "low carbon" development, using Carbon Footprints to develop and implement water resources is likely to expedite the process.

## 2.2 Life cycle assessment

Life cycle assessment (LCA) is a process to evaluate the environmental impacts of a particular product, service, or technology within a specified boundary. LCA is popularly known as a "cradle to grave" that examines all phases of the lifespan of a product, starting with the extraction of the raw materials and continuing through manufacture, distribution, usage, possibly recycling, and finally disposal [27]. According to ISO 14040:2006 [28] and ISO 14044:2006 [29] standards, Four stages of LCA are involved: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results [30].

Desalination LCA studies aim to evaluate the life cycle impacts of desalinated water generated by various desalination methods or facilities comprehensively. Boundary selection determines the desalination processes, affected geographic area, and relevant time horizon in an LCA study. The three desalination processes MSF, MED, RO combination with renewable energy sources in terms of climate change damage, CO<sub>2</sub> emission, or Carbon Footprints are compared in this study. However, the necessary energy and chemical needs in the operational phase are considered

only; the other phases were omitted because of a lack of data. As seen in Table 2, the analysis data is obtained from Saudi Arabia's desalination plant reported by the Federal Ministry for Environment, Nature Conservation and Nuclear Safety, Germany, in 2007 [31]. The functional unit is 1 m<sup>3</sup> of drinking water produced from the desalination plant. The IPCC 2013 GWP 100a V1.03 [32] is used in this study with the help of the SimaPro Life Cycle Analysis software version 9.1.1 [33]. The IPCC 2013 GWP 100a [32] method estimates greenhouse gas emissions in kilograms of CO<sub>2</sub>-equivalent based on their global warming potential (GWP) over a 100 year's time horizon provided by the Intergovernmental Panel on Climate Change (IPCC). With SimaPro version 9.1.1 [33], the results of the IPCC 2013 GWP 100a [32] method can be categorized into four categories: GHG emissions from fossil sources, biogenic carbon emissions, CO<sub>2</sub> uptake, and emissions from land transformation [33].

## 3 Results

Using of energy and raw materials in equipment manufacture accounts for most of a desalination plant's Carbon Footprint during construction. The primary CO<sub>2</sub>-equivalent value of the technologies has already been published by Thi et al. [34]. The Carbon Footprint of the construction stage is calculated in this study and classified into four impact categories based on how they impact the environment. According to the published journal article by Liu et al. in 2015, the estimated Carbon Footprint of the construction period was around 10% of the operation period [22]. The CO<sub>2</sub> emissions into the operation and maintenance phases were calculated based on the SimaPro program with the IPCC 2013 method, shown in Table 3 and Fig. 2. Overall, RO presents the lowest amount of pollution among the three desalination technologies, emitting CO<sub>2</sub> 3–4 times lower than MED and MSF. The two thermal technologies result in almost similar CO<sub>2</sub> emissions, whereby MSF is 1.2 times higher than MED, equivalent to about 3.3 kg CO<sub>2</sub>/m<sup>3</sup> drinking water.

As shown in Table 4, substances contribute a certain percentage to the total. Three major greenhouse gases contribute heavily to the Carbon Footprint of water products: carbon dioxide, methane, and dinitrogen monoxide. A significant amount of carbon dioxide is produced over the life cycle of three desalination technologies (between 95–96%). At the same time, there is a slight increase in dinitrogen monoxide production over methane production.

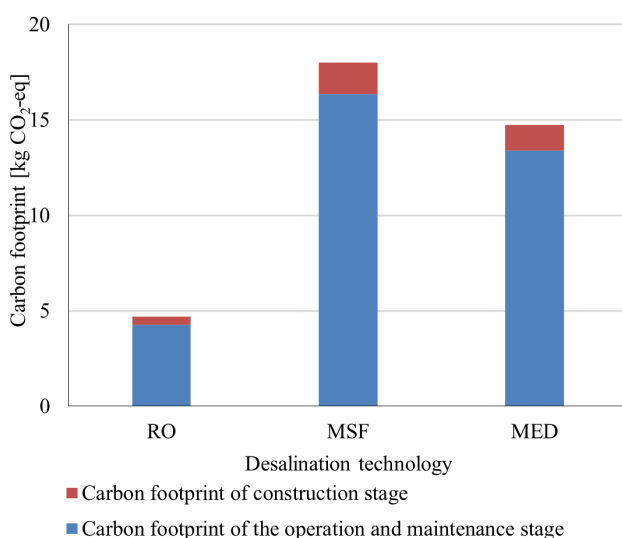
Carbon Footprints must take into account not only fossil fuel emissions but also biogenic emissions, land

**Table 2** A typical desalination plant inventory data to the production of one m<sup>3</sup> of drinking water [31]

		MSF	MED	RO	Unit	
In put	Seawater	10	9	3	m <sup>3</sup>	
	Heat energy	290	267.5	–	MJ	
	Electric energy	4	2	4	kWh	
	Disinfection	Chlorine	20.5	18.5	3.5	g
	Antiscalant	Phosphoric acid	–	27	6	g
		Sulfuric acid	20	–	195	g
	Dechlorination	Sodium bisulfate	–	18	9	g
	Antifoaming	Propylene glycol	1	0.9	–	g
	Coagulation	Aluminum chloride	–	–	6.75	g
		Ferric chloride	–	–	53.7	g
	Flocculation	Polyacrylamide	–	–	6.3	g
	Remineralization	Calcium hydroxide	0.5	0.5	0.5	g
	Chlorine		0.7	0.7	0.7	g
	Phosphoric acid		–	10	–	g
	Sulfuric acid		8	–	6	g
	Out put	Copper (from corrosion of structural materials)	0.03	20	–	mg
Propylene glycol		0.09	0.09	–	g	
Sodium chloride		45	45	45	kg	
Waste heat		73.4	114.2	–	MJ	

**Table 3** The Carbon Footprint of the desalination technology for production of 1 m<sup>3</sup> of drinking water based on IPCC 2013 GWP 100a method (\* has been published in [35])

Method	The carbon footprint of the operation and maintenance stages (kg CO <sub>2</sub> -eq)	The carbon footprint of the construction stage (kg CO <sub>2</sub> -eq)	Total carbon footprint (kg CO <sub>2</sub> -eq)
RO	4.279*	0.428	4.707
MSF	16.371*	1.637	18.008
MED	13.387*	1.339	14.726

**Fig. 2** The Carbon Footprints of the desalination technology in construction and operation-maintenance stages**Table 4** The percentage contribution of substances based on IPCC 2013 GWP 100a method

Substance	RO	MSF	MED
Carbon dioxide, fossil	94.7	96.4	96.5
Dinitrogen monoxide	0.974	1.2166	1.2452
Methane, fossil	0.199	0.192	0.195
Methane, biogenic	0.0132	0.00765	0.00756
Methane, bromotrifluoro, Halon 1301	0.00749	0.00829	0.00836
Sulfur hexafluoride	0.0151	0.00327	0.00331

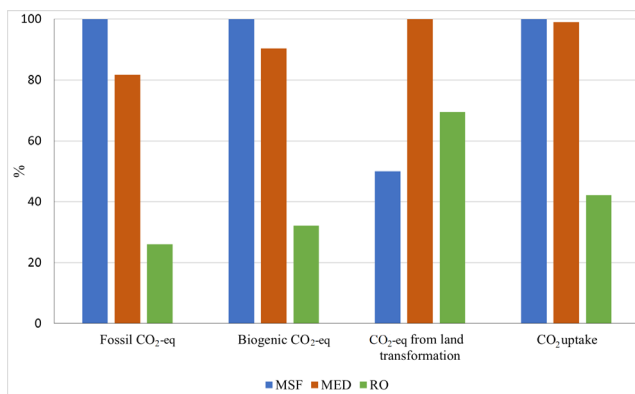
transformation, and carbon uptake. A detailed breakdown of each type of carbon emission is shown in Table 5 and is divided into percentages in Fig. 3. A significant amount of fossil carbon is emitted to the environment, accounting for 99.8%–99.9% of all impact categories. Among the four types of carbon emissions, MSF ranks first in fossil, biogenic, and uptake emissions, followed by MED and RO. The only indicator that reverses the situation is carbon from land transformation, where MED is the most important indicator, followed by MSF and RO. RO technology emits the least amount of CO<sub>2</sub>, reducing it by only 25–75% compared to thermal technology in all four cases.

The desalination process consumes significant energy and produces a significant amount of CO<sub>2</sub>. Recovering waste heat sources, applying high-efficiency generation technologies, and combining renewable energy sources are possible ways to reduce energy consumption. Desalination methods



**Table 5** The carbon emissions of the desalination technology [kg CO<sub>2</sub>-eq] (\* published in [35])

Impact category	MSF	MED	RO
Fossil CO <sub>2</sub> -eq	16.371*	13.387*	4.279*
Biogenic CO <sub>2</sub> -eq	0.0134	0.0121	0.00431
CO <sub>2</sub> -eq from land transformation	0.000233	0.000466	0.000324
CO <sub>2</sub> uptake	0.00725	0.00718	0.00306

**Fig. 3** The percentage of carbon emissions between three desalination technologies

that use renewable energy sources are a great strategy to minimize environmental effects while still producing fresh water in isolated, water-scarce, unfavorable, or unfeasible places with limited connection to the public electrical grid. Using alternative energy systems in desalination plants can help reduce costs and dependency on fossil fuels, as well as GHG emissions and local climate change impacts. Many desalination plants using solar, wind, or geothermal energy have been installed, but most are small. Since this energy is abundant and clean, it is the most popular and widely used in desalination worldwide. The sun's light and heat can produce power using modern technologies.

The Carbon Footprint of Siena (Italy) public tap water was analysed and calculated by Botto et al., which is  $1.35 \times 10^{-3}$  kg CO<sub>2</sub>-eq per 1.5 L drinking water [35]. In Table 6, the Carbon Footprint of desalination water in the operation stage with different energy sources is presented; the values shown in Table 6 are relative compared to the Carbon Footprint of 1 m<sup>3</sup> tap water, e.g., the CO<sub>2</sub> emission of desalination using solar energy with RO method is 0.17 times CO<sub>2</sub> emission of 1 m<sup>3</sup> tap water. Compared to conventional surface water treatment technologies, the desalination process using fossil energy releases 4.7–18.2 times more CO<sub>2</sub> emissions. To produce 1 m<sup>3</sup> of drinking water from desalination technology in the primary case (using energy or natural gas), the amount of CO<sub>2</sub> emitted into the environment is many times larger than tap water production from locally available

**Table 6** The Carbon Footprint of the desalination with renewable energy sources to produce 1 m<sup>3</sup> of drinking water based on the Carbon Footprint of tap water in Siena (Italy) [35]

Method	Basic fossil energy	Natural gas	Solar energy	Wind energy, on-shore	Wind energy, off-shore
RO	4.75	–	0.17	0.17	0.17
MSF	18.19	16.24	0.45	0.04	0.05
MED	14.87	13.07	0.45	0.08	0.07

water sources (springs, wells, and waterworks). A renewable energy source can be replaced fossil energies, thus significantly reducing CO<sub>2</sub> emissions, e.g., the CO<sub>2</sub> emission of desalination with MSF method is reduced from 18.19 to 0.04 times CO<sub>2</sub> emission of 1 m<sup>3</sup> tap water compared between basic fossil energy and wind energy on-shore. In general, it can also be said that all technology has improved regarding renewable energy sources, and wind energy was slightly most successful and environmentally friendly. There is no significant difference between on-shore and off-shore wind power plants. The combination of wind energy and MSF technology results is the most remarkable improvement, followed by MED and RO. Solar and wind power are the best solutions for saltwater desalination.

#### 4 Conclusion and discussions

An abundant seawater supply and rapid development of desalination technologies present great opportunities for managing current and future water scarcity problems. Although desalination plants are indisputably the most efficient globally, they are increasing their contribution to the world's Carbon Footprint. In this study, three technologies- RO, MSF, and MED- are compared with fossil fuels and renewable energy sources used in the processes. The Carbon Footprint in the construction stage of the desalination plant is approximately 10% of the operational stage. Overall, RO is the least polluting of the three desalination processes, emitting 3 to 4 times less CO<sub>2</sub> than MED and MSF. About 0.4 billion tons of CO<sub>2</sub>-equivalent will be emitted annually by desalination plants by 2050. The desalination process using fossil energy emits significantly more CO<sub>2</sub> than typical surface water treatment technology. The substitution of renewable energy sources for fossil fuels is considered effective in reducing CO<sub>2</sub> emissions. Wind energy is the most effective and low carbon emission of renewable energy sources to connect to a desalination system. It is recommended to use solar energy if there are inadequate wind resources. The excellent efficiency is achieved through the combination of wind energy and

thermal desalination. It is possible to reduce 99.7% of CO<sub>2</sub> emissions into the environment with wind and MSF technologies combined. Followed by MED, which reduces CO<sub>2</sub> emissions by 99.5%, and lastly, RO reduces CO<sub>2</sub> emissions by only 96.5%. Thus, as the planet undergoes an ongoing desalination revolution, it appears that ensuring clean energy is critical for carbon neutrality.

The MSF and MED processes can be well-established technologies, and a significant improvement is not expected, unlike the RO technologies, which still have much room for improvement. RO is dominating the desalination market globally, with this trend intensifying. Nevertheless, RO membrane processes are frequently plagued by fouling/deposition problems, and their effective lifespan is only about 5–7 years. The next generation of desalination systems will focus on improving energy conservation, optimizing processes and equipment, improving current limitations of thermal desalination processes, and combining renewable energies. A reliable and efficient desalination plant powered by renewable energy is necessary for sustainable development. The principal advantage of combining renewable energies is their lower emissions; However, the investment costs are high, and the availability of these energy sources is seasonal rather than continuous.

## References

- [1] Lóránt, B., Tardy, G. M. "Current Status of Biological Biogas Upgrading Technologies", *Periodica Polytechnica Chemical Engineering*, 66(3), pp. 465–481, 2022. <https://doi.org/10.3311/PPch.19537>
- [2] Adeyemo, O., Ja'afaru, M., Abdulkadir, S., Salihu, A. "Saccharification and Fermentation of Cellulolytic Agricultural Biomass to Bioethanol using Locally Isolated *Aspergillus niger* S48 and *Kluyveromyces* sp. Y2, respectively", *Periodica Polytechnica Chemical Engineering*, 65(4), pp. 505–516, 2021. <https://doi.org/10.3311/PPch.17900>
- [3] Groniewsky, A., Kustán, R., Imre, A. "Efficiency Increase of Biological Methanation based Power-to-Methane Technology Using Waste Heat Recovery with Organic Rankine Cycle", *Periodica Polytechnica Chemical Engineering*, 66(4), pp. 596–608, 2022. <https://doi.org/10.3311/PPch.20428>
- [4] NASA Global Climate Change "Carbon dioxide", [online] Available at: <https://climate.nasa.gov/> [Accessed: 15 October 2022]
- [5] Intergovernmental Panel on Climate Change "Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report", Cambridge University Press, 2015. ISBN 9781107415416 <https://doi.org/10.1017/CBO9781107415416>
- [6] Ritchie, H., Roser, M., Rosado, P. "CO<sub>2</sub> and Greenhouse Gas Emissions", *Our World in Data*, Aug. 2020. [online] Available at: <https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions> [Accessed: 15 October 2022]
- [7] Feria-Díaz, J. J., López-Méndez, M. C., Rodríguez-Miranda, J. P., Sandoval-Herazo, L. C., Correa-Mahecha, F. "Commercial Thermal Technologies for Desalination of Water from Renewable Energies: A State of the Art Review", *Processes*, 9(2), 262, 2021. <https://doi.org/10.3390/pr9020262>
- [8] Eke, J., Yusuf, A., Giwa, A., Sodiq, A. "The global status of desalination: An assessment of current desalination technologies, plants and capacity", *Desalination*, 495, 114633, 2020. <https://doi.org/10.1016/j.desal.2020.114633>
- [9] Acciona, S. A., Veolia, SUEZ, Abengoa, Ferrovial, S. A. "Global Desalination Market by Regions, Technology, Application, Company, Analysis, Forecast", *Research and Markets*, Dublin, Ireland, Rep. 5308262, 2021.
- [10] Washahi, M. A., Gopinath, A. S. "Techno Economical Feasibility Analysis of Solar Powered RO Desalination in Sultanate of Oman", In: 2017 9th IEEE-GCC Conference and Exhibition (GCCCE), Manama, Bahrain, 2017, pp. 1–9. <https://doi.org/10.1109/IEEEGCC.2017.8448195>
- [11] Cherif, H., Belhadj, J. "Chapter 15 – Environmental Life Cycle Analysis of Water Desalination Processes", In: Gude, V. G. (ed.) *Sustainable Desalination Handbook: Plant Selection, Design and Implementation*, Butterworth-Heinemann, 2018, pp. 527–559. ISBN 978-0-12-809240-8 <https://doi.org/10.1016/B978-0-12-809240-8.00015-0>

- [12] Abdelkareem, M. A., El Haj Assad, M., Sayed, E. T., Soudan, B. "Recent progress in the use of renewable energy sources to power water desalination plants", *Desalination*, 435, pp. 97–113, 2018.  
<https://doi.org/10.1016/j.desal.2017.11.018>
- [13] Al-Karaghoul, A., Kazmerski, L. L. "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes", *Renewable and Sustainable Energy Reviews*, 24, pp. 343–356, 2013.  
<https://doi.org/10.1016/j.rser.2012.12.064>
- [14] Al Bloushi, A., Giwa, A., Mezher, T., Hasan, S. W. "Chapter 3 – Environmental Impact and Technoeconomic Analysis of Hybrid MSF/RO Desalination: The Case Study of Al Taweelah A2 Plant", In: Gude, V. G. (ed.) *Sustainable Desalination Handbook: Plant Selection, Design and Implementation*, Butterworth-Heinemann, 2018, pp. 55–97. ISBN 978-0-12-809240-8  
<https://doi.org/10.1016/B978-0-12-809240-8.00003-4>
- [15] Martínez-Alvarez, V., González-Ortega, M. J., Martín-Gorriz, B., Soto-García, M., Maestre-Valero, J. F. "14 – Seawater desalination for crop irrigation – Current status and perspectives", In: Gude, V. G. (ed.) *Emerging Technologies for Sustainable Desalination Handbook*, Butterworth-Heinemann, 2018, pp. 461–492. ISBN 978-0-12-815818-0  
<https://doi.org/10.1016/B978-0-12-815818-0.00014-X>
- [16] Suwaileh, W., Johnson, D., Hilal, N. "Membrane desalination and water re-use for agriculture: State of the art and future outlook", *Desalination*, 491, 114559, 2020.  
<https://doi.org/10.1016/j.desal.2020.114559>
- [17] Elsaid, K., Sayed, E. T., Abdelkareem, M. A., Mahmoud, M. S., Ramadan, M., Olabi, A. G. "Environmental impact of emerging desalination technologies: A preliminary evaluation", *Journal of Environmental Chemical Engineering*, 8(5), 104099, 2020.  
<https://doi.org/10.1016/j.jece.2020.104099>
- [18] Kim, D. H. "A review of desalting process techniques and economic analysis of the recovery of salts from retentates", *Desalination*, 270(1-3), pp. 1–8, 2011.  
<https://doi.org/10.1016/j.desal.2010.12.041>
- [19] Panagopoulos, A., Haralambous, K.-J. "Environmental impacts of desalination and brine treatment – Challenges and mitigation measures", *Marine Pollution Bulletin*, 161, 111773, 2020.  
<https://doi.org/10.1016/j.marpolbul.2020.111773>
- [20] Saleh, L., al Zaabi, M., Mezher, T. "Estimating the social carbon costs from power and desalination productions in UAE", *Renewable and Sustainable Energy Reviews*, 114, 109284, 2019.  
<https://doi.org/10.1016/j.rser.2019.109284>
- [21] Shahzad, M. W., Burhan, M., Ang, L., Ng, K. C. "Energy-water-environment nexus underpinning future desalination sustainability", *Desalination*, 413, pp. 52–64, 2017.  
<https://doi.org/10.1016/j.desal.2017.03.009>
- [22] Liu, J., Chen, S., Wang, H., Chen, X. "Calculation of Carbon Footprints for Water Diversion and Desalination Projects", *Energy Procedia*, 75, pp. 2483–2494, 2015.  
<https://doi.org/10.1016/j.egypro.2015.07.239>
- [23] Cornejo, P. K., Santana, M. V. E., Hokanson, D. R., Mihelcic, J. R., Zhang, Q. "Carbon footprint of water reuse and desalination: a review of greenhouse gas emissions and estimation tools", *Journal of Water Reuse and Desalination*, 4(4), pp. 238–252, 2014.  
<https://doi.org/10.2166/wrd.2014.058>
- [24] United Nation Climate Change. "The UN Climate Change Conference in Glasgow (COP26)", [online] Available at: <https://washmatters.wateraid.org/blog> [Accessed: 15 October 2022]
- [25] Alnajdi, O., Wu, Y., Kaiser Calautit, J. "Toward a Sustainable Decentralized Water Supply: Review of Adsorption Desorption Desalination (ADD) and Current Technologies: Saudi Arabia (SA) as a Case Study", *Water*, 12(4), 1111, 2020.  
<https://doi.org/10.3390/w12041111>
- [26] Ghani, L. A., Ali, N., Nazaran, I. S., Hanafiah, M. M., Yatim, N. I. "Carbon Footprint-Energy Detection for Desalination Small Plant Adaptation Response", *Energies*, 14(21), 7135, 2021.  
<https://doi.org/10.3390/en14217135>
- [27] Wrisberg, N., de Haes, H. A. U., Triebswetter, U., Eder, P., Clift, R. (eds.) "Analytical Tools for Environmental Design and Management in a Systems Perspective: The Combined Use of Analytical Tools", Springer, 2002. ISBN 978-1-4020-0453-7  
<https://doi.org/10.1007/978-94-010-0456-5>
- [28] International Organization for Standardization "ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework", International Organization for Standardization, Geneva, Switzerland.
- [29] International Organization for Standardization "ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines", International Organization for Standardization, Geneva, Switzerland.
- [30] Aziz, N. I. H. A., Hanafiah, M. M. "Application of life cycle assessment for desalination: Progress, challenges and future directions", *Environmental Pollution*, 268, 115948, 2021.  
<https://doi.org/10.1016/j.envpol.2020.115948>
- [31] AQUA-CSP "Concentrating Solar Power for Seawater Desalination", Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Bonn, Germany, Final Report, 2007. [online] Available at: <https://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/aqua-csp/AQUA-CSP-Full-Report-Final.pdf> [Accessed: 15 October 2022]
- [32] Intergovernmental Panel on Climate Change (IPCC) "Intergovernmental Panel on Climate Change's Fifth Assessment Report", Intergovernmental Panel on Climate Change, Geneva, Switzerland, Rep. AR5, 2013. [online]. Available at: <http://www.ipcc.ch/> [Accessed: 27 July 2021]
- [33] SimaPro "SimaPro Life Cycle Analysis (9.1.1)" [computer program] Available at: <https://simapro.com/> [Accessed: 27 July 2022]
- [34] Do Thi, H. T., Pasztor, T., Fozzer, D., Manenti, F., Toth, A. J. "Comparison of Desalination Technologies Using Renewable Energy Sources with Life Cycle, PESTLE, and Multi-Criteria Decision Analyses", *Water*, 13(21), 3023, 2021.  
<https://doi.org/10.3390/w13213023>
- [35] Botto, S., Niccolucci, V., Rugani, B., Nicolardi, V., Bastianoni, S., Gaggi, C. "Towards lower carbon footprint patterns of consumption: The case of drinking water in Italy", *Environmental Science & Policy*, 14(4), pp. 388–395, 2011.  
<https://doi.org/10.1016/j.envsci.2011.01.004>