Periodica Polytechnica Chemical Engineering, 67(1), pp. 41–48, 2023

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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Received: 27 July 2022, Accepted: 24 October 2022, Published online: 09 January 2023

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_2 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_2), methane (CH_4), dinitrogen oxide (N_2O), hydrogen fluoride (HFC), perfluorocarbons (PFC), and sulfur hexafluoride (SF_6), in which the most significant order comes from CO_2 emissions (76%), then followed by CH_4 (16%) and N_2O (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.

Cite this article as: Do Thi, H. T., Toth, A. J. "Investigation of Carbon Footprints of Three Desalination Technologies: Reverse Osmosis (RO), Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED)", Periodica Polytechnica Chemical Engineering, 67(1), pp. 41–48, 2023. https://doi.org/10.3311/PPch.20901

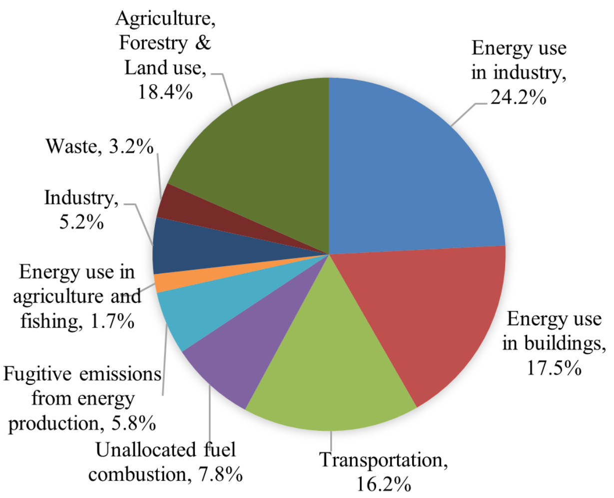

Fig. 1 Global greenhouse gas emissions by sector in 2016 [6]

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_2 has increased by 50% since the Industrial Revolution from the 18th 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^3 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^3/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 is 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^3/day]	50,000–70,000	5,000–15,000	24,000
Electrical energy consumption [kWh/m^3]	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^3]	9.5–19.5	5–8.5	none
Total electric equivalent [kWh/m^3]	13.5–25.5	6.5–11	5–9
Maximum value of CO_2 emissions [kg CO_2/m^3]	24	19.2	8.6
Distillate quality [ppm]	~10	~10	<500
Unit product cost [US $/m^3]	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_2), methane (CH_4), and dinitrogen monoxide (N_2O), are expressed in kilograms of CO_2-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_2 per year and could grow to 218 million tons by 2040 [21]. As Table 1, RO technologies emit much less CO_2 than thermal technologies. The pump in RO systems used 5–9 kWh/m^3 energy to overcome osmotic pressure, whereas the energy required for thermal technologies (6.5–28 kWh/m^3) 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^3 of freshwater, the Carbon Footprints were 2.988 kg CO_2 for MSF desalination plants, 1.280 kg CO_2 for MED, and 2.562 kg CO_2 for RO [22]. Another study estimated that the Carbon Footprints of seawater RO desalination was 0.4–6.7 kg CO_2/m^3, that more significant than RO from brackish water (0.4–2.5 kg CO_2/m^3) and water reuse systems (0.1–2.4 kg CO_2/m^3) [23]. It is likely that the desalination of 1000 m^3 of seawater could release 6.7 tons of CO_2. 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^3/day of drinking water. It is estimated that water production from desalination plants in Saudi Arabia will emit 6.5 million tons of CO_2 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_2-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_2, 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_2 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^3 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_2-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_2 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_2-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_2 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_2 3–4 times lower than MED and MSF. The two thermal technologies result in almost similar CO_2 emissions, whereby MSF is 1.2 times higher than MED, equivalent to about 3.3 kg CO_2/m^3 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^3 of drinking water [31]

			MSF	MED	RO	Unit
In put	Seawater		10	9	3	m^3
	Heat energy		290	267.5	–	MJ
	Electric energy		4	2	4	kWh
	Disinfection	Chlorine	20.5	18.5	3.5	g
	Antiscaling	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
Out put	Chlorine		0.7	0.7	0.7	g
	Phosphoric acid		–	10	–	g
	Sulfuric acid		8	–	6	g
	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^3 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_2-eq)	The carbon footprint of the construction stage (kg CO_2-eq)	Total carbon footprint (kg CO_2-eq)
RO	4.279*	0.428	4.707
MSF	16.371*	1.637	18.008
MED	13.387*	1.339	14.726

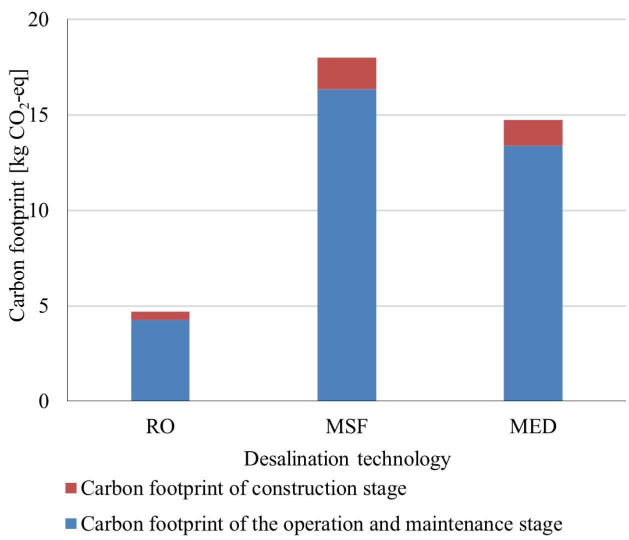

Fig. 2 The Carbon Footprints of the desalination technology in construction and operation-maintenance stages

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_2, 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_2. 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_2-eq] (* published in [35])

Impact category	MSF	MED	RO
Fossil CO_2-eq	16.371*	13.387*	4.279*
Biogenic CO_2-eq	0.0134	0.0121	0.00431
CO_2-eq from land transformation	0.000233	0.000466	0.000324
CO_2 uptake	0.00725	0.00718	0.00306

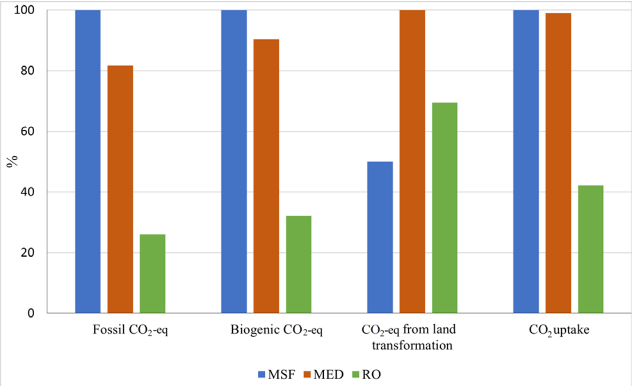

Fig. 3 The percentage of carbon emissions between three desalination technologies

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 1.35×10^{-3} kg CO_2-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^3 tap water, e.g., the CO_2 emission of desalination using solar energy with RO method is 0.17 times CO_2 emission of 1 m^3 tap water. Compared to conventional surface water treatment technologies, the desalination process using fossil energy releases 4.7–18.2 times more CO_2 emissions. To produce 1 m^3 of drinking water from desalination technology in the primary case (using energy or natural gas), the amount of CO_2 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^3 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_2 emissions, e.g., the CO_2 emission of desalination with MSF method is reduced from 18.19 to 0.04 times CO_2 emission of 1 m^3 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_2 than MED and MSF. About 0.4 billion tons of CO_2-equivalent will be emitted annually by desalination plants by 2050. The desalination process using fossil energy emits significantly more CO_2 than typical surface water treatment technology. The substitution of renewable energy sources for fossil fuels is considered effective in reducing CO_2 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_2 emissions into the environment with wind and MSF technologies combined. Followed by MED, which reduces CO_2 emissions by 99.5%, and lastly, RO reduces CO_2 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. Renewable energy plants have a significantly shorter life than conventional plants. It is worth noting that we cannot rely solely on renewables due to the unresolved energy storage problem. Combining waste heat and/or renewable energy can produce economic and environmental benefits by eliminating or reducing fuel and energy inputs. As a result, the production costs will be reduced, as will the greenhouse gas emissions from fuel consumption.

Acknowledgement
This publication was supported by NTP-NFTÖ-21-B-0014 National Talent Program of the Cabinet Office of the Prime Minister, MEC 140699, OTKA 128543 and OTKA 131586. The research was supported by the EU LIFE program, LIFE-CLIMCOOP project (LIFE19 CCA/HU/001320). The research reported in this paper and carried out at the Budapest University of Technology and Economics has been supported by the National Research Development and Innovation Fund (TKP2020 National Challenges Subprogram, Grant No. BME-NC) based on the charter of bolster issued by the National Research Development and Innovation Office under the auspices of the Ministry for Innovation and Technology.

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