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Review

Toward a Sustainable Decentralized Water Supply: Review of Adsorption Desorption Desalination (ADD) and Current Technologies: Saudi Arabia (SA) as a Case Study

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Abstract: Several regions are confronting a severe scarcity of fresh water due to the gap between supply and demand. They strive to bridge that gap by depleting nonrenewable water aquifers and expanding centralized energy-intensive desalination technologies. Continuing to adopt the same unsustainable approach could deplete the water aquifers and increase the consumption of fossil fuel and the ecological impact on air, water, and land. However, the traditional paradigm of centralized desalination systems could be shifted by increasing the utilization of renewable distributed generation, which can be coupled with emerging desalination technology such as adsorption desorption desalination (ADD), which has autonomous and resilient attributes that can contribute to the sustainability of decentralized fresh water supply in the future. In this work, three commercialized desalination technologies were reviewed and compared with emerging ones to explore the most economically and environmentally efficient systems within the context of decentralized water production. The well-known configurations of ADD were evaluated and compared with sea water reverse osmosis (SWRO), which is recognized as the principal commercialized desalination technology worldwide. The quantitative case study methodology was used by investigating four centralized seawater desalination plants in Saudi Arabia (SA) with their associated pipeline systems from the energy consumption point of view to determine the applicability of implementing ADD technology in SA and similar arid areas. The study reveals that adopting decentralized ADD technology coupled with renewable energy sources could reduce the specific energy consumption from 4 kWh/m^3 to less than 1.38 kWh/m^3. Combining reduced energy consumption from desalination plants and elimination of supply pipelines could potentially result in a significant reduction in energy consumption and carbon emissions. Finally, the study may be useful for researchers working on enhancing ADD processes, as well as technology users who would like to implement the most efficient ADD configurations. Additionally, it may initiate a direction of utilizing the results of original critical reviews as a methodology to develop the applied technologies.

Keywords: decentralized; desalination technologies; adsorption desorption desalination (ADD); specific energy consumption

1. Introduction

The Middle East (ME) region is profoundly deprived of natural drinking water resources. It is classified as one of the most severe water stress areas globally, with an 88% criticality ratio (the ratio of average annual water withdrawals to water availability) compared to 5% in Central Africa and 25% globally (excluding Greenland and Antarctica) [1]. In arid and semi-arid regions, where maximum yearly precipitation is in the range of 200–250 mm and 250–600 mm, respectively, the evaporation rate is more than the precipitation rate and affordable fresh water is very scarce [2]. Water scarcity is being faced by most ME countries, where many cities and villages suffer from a lack of fresh water. The Kingdom of Saudi Arabia (SA), one of the ME countries, was chosen as the case study for many reasons. It is one of the largest arid countries without any rivers or lakes and has a low rate of rainfall. It is located in the arid zone, with an evaporation rate of 0.368 m/year, and the temperature is expected to increase from 1.8 °C to 4.1 °C by 2050 [3]. At the same time, its population increased from 4.3 million in 1962 to 32.6 million in 2019, at an annual growth rate of 2.52%, and is expected to reach 56 million by 2050 [4]. The total annual water consumption in SA is around 24 billion cubic meters, distributed among the agriculture sector (88%), domestic sector (9%), and industrial activities (3%) [5]. SA has the third highest domestic per capita water consumption of 100–350 L/capita/day (L/cap/d) for the urbanized region and 10–20 L/cap/day for rural areas [6]. By 2025, local fresh water demand could reach 8.5 million cubic meters per day (Mm^3/day), while it was around 6.8 Mm^3/day in 2010. Water insufficiency occurs due to the imbalance between the high fresh water consumption rate and the low annual rainfall rate, which ranges between 70 mm and 130 mm [7].

The primary sources of water supply in SA are as follows: (i) Underground nonrenewable water, with six major nonrenewable aquifers in the north, middle, east, and southeast providing a water supply of around 19 billion cubic meters (Bm^3) per year. The estimated storage capacity of these aquifers decreased from 500 billion cubic meters in 1984 to 289.1 billion cubic meters in 1996. The proven reserve in 2013 was found to be 428.4 billion cubic meters [5]. (ii) Surface renewable water, accumulated from the intermittent rainfall on the west and southwest mountains. The annual recharge quantity is around 10% of the annual total consumption, which does not exceed 2 Bm^3/y [5,8]. (iii) Seawater desalination, a process driven by thermal or electrical energy by which fresh or potable water is separated from the sea or brackish water [9]. It contributes 2.4 Bm^3/y, 61% of the domestic water demand, playing a significant role in SA's fresh water supply. Further expansion of existing seawater desalination technologies has unavoidable negative economic and environmental impacts on the sea, air, and land [1]. The costs associated with water production and transmission are higher compared to the cost of treating regular surface water or fresh underground water available near the demand zones [10], as shown in Table 1. (iv) Wastewater reuse and reclamation, which contributes to the demand–supply balance for agricultural and industrial use.

Table 1. Energy used for different feed sources.

Water Supply Alternative	Energy Use (kWh/m^3)	Reference
Minimum energy of separation (seawater at 35,000 ppm)	0.9	[1]
Conventional treatment of surface water	0.2–0.4	[2]
Brackish water desalination	0.5–2.5	[3]
* SWRO desalination	3–4 [a]	[3]

* SWRO, sea water reverse osmosis, [a] with energy recovery.

Analyzing the sustainability of the aforementioned sources of water supply shows that underground and surface water resources are not sustainable for the water supply in SA due to the increase in water extraction rates, the low recharge rate, and the geological distribution of aquifers across the country. It cannot meet all of the country's demands.

On the other hand, expanding centralized energy-intensive conventional desalination technologies increases fossil fuel consumption, which will increase the economic and environmental challenges. Continuing the existing water management strategy could deplete water aquifers within 25 years or even less [4] and increase domestic oil consumption. Finally, wastewater reuse still requires more investment in infrastructure; then it can contribute to the demand–supply balance for agricultural and industrial use. Therefore, seawater and brackish water desalination technologies could be considered as the most sustainable sources of fresh water supply, provided that the high energy consumption and harmful environmental impacts have been resolved.

Several interdependent factors affect the issue of sustainable water supply. These include the selection of desalination technology, decentralization of production systems, energy and environmental requirements, availability of solar energy, and aquifer abstraction and recharging rates, which have to be investigated within the context of temporal and spatial dimensions of the water shortage issue. Previous studies [5–7] investigated sustainable desalination technologies in different regions, but there is a lack of work identifying the interdependencies among factors. Additionally, there is no demonstration of the potential of an integrated decentralized low-energy desalination system.

To address this, the present study focuses on selecting the desalination technology, taking into consideration energy and environmental issues. Many papers have reviewed commercial and/or emerging desalination technologies from different aspects [5–8], but there is no review on the advancements of ADD systems and issues and challenges faced by the sector. It is also common in the literature to investigate the ADD process as a dual-purpose technology, i.e., for cooling and water production. Therefore, ADD was reviewed and compared economically and environmentally with sea water reverse osmosis (SWRO), one of the leading commercialized desalination technologies in the world today. A comprehensive review of the available configurations of ADD was conducted, focusing on specific energy consumption (SEC) and specific daily water production (SDWP). Finally, two specific ADD configurations were selected to be used in the proposed framework.

Using SA as a case study, the study demonstrates an integrated system solution by adapting the selected configuration of ADD powered by solar energy to the four main centralized water systems in the region. Small and medium-size decentralized water production systems were proposed to eliminate the need to construct massive water transmission pipelines, which could reduce the water levelized cost and environmental impact. A predetermined aquifer abstraction rate proportional to the recharging rate of each aquifer was used as the main constraint to control the amount of supply from the groundwater.

2. Issues of Sustainable Desalination Technologies in Saudi Arabia

SA released the 2030 projection plan to increase its installed capacity during the period 2018 to 2030, which includes decommissioning plants that reach their anticipated design life expectancy, as shown in Table 2. Concurrently, more energy-efficient desalination plants will be commissioned. The daily water production and types of technologies employed in desalination plants in 2017 reveal that around 4 million cubic meters are produced daily using desalination technologies such as multi-stage flashing (MSF), multi-effect desalination (MED), and SWRO; 77.5% of the current seawater production is produced by MSF, 20.5% by RO, and 2% by MED–thermal vapor compression (TVC) plants. The high energy consumption of existing desalination technologies and transmission of water via pipelines remain among the main issues of the sector. While water production processes and technologies have experienced rapid advances in recent years, resulting in a dramatic reduction in energy consumption [1], the existing processes of seawater desalination are energy-intensive due to the irreversibility within various system components, such as in the evaporator of MSF and MED, due to vaporization, and in the pressurized membrane in SWRO [11].

This can be determined from the universal performance ratio (UPR), which is based on the primary energy of all existing commercialized desalination technologies, including SWRO, with UPR = 86, while its thermal index limit is 828, which means that the conventional technology is operating at less than 12% of the thermal index limit [10]. The primary energy consumption of MSF per cubic meter of production in kWh/m^3 is 14 and 8.6 for MED with a performance ratio of 11.5, and for SWRO, it is 4.5 kWh/m^3 according to the latest power and desalination plant in Saudi Arabia powered by a combined cycle power plant, with efficiency of 52.3% [12]. Table 2 shows data on the contribution of desalination technology and the production and efficiency of each technology. Figure 1 illustrates efficiency as consumption of barrel of oil equivalent (BOE). MSF, MED, and SWRO, respectively, can produce 61, 101, and 148 m^3 of water product per BOE.

Table 2. Projected decommission and commission plan in Saudi Arabia (SA), 2018 to 2030. SWCC, Saline Water Conversion Corporation; MSF, multi-stage flashing.

Year	Plants to Be Decommissioned		Plants to Be Commissioned	
	Plant Name	Capacity (m^3/d)	Plant Name	Capacity (m^3/d)
2018	Khafji Yanbu-I MSF Jeddah-IV MSF	22,070 71,790 191,680	Yanbu III Jeddah-4	550,000 400,000
2019	Haql-SWRO Duba-SWRO Jubail-I MSF Jubail-II MSF	5405 5647 130,000 869,800	Haql-3 Duba-4 Alwajh-4	9000 9000 9000
2020			Jubail-3 Rabigh-3 Yanbu-4 Ummluj-4	1,100,000 600,000 450,000 18,000
2025	Shoaibah-I MSF Shoqaiq-I MSF Khobar-I MSF Khobar-II MSF	141,880 86,272 145,829 205,568	Shoaiba-4 Shuqaiq-3 Al-Khobar-4	1,000,000 325,000 775,000
2030	Jeddah-I SWRO Jeddah-II SWRO Yanbu-II MSF Shoaibah-II Yanbu SWRO	60,783 59,080 110,243 388,045 121,523	Jeddah-5 Rabig-4 Ras Al-Khair Yanbu-5	400,000 600,000 1,000,000 400,000

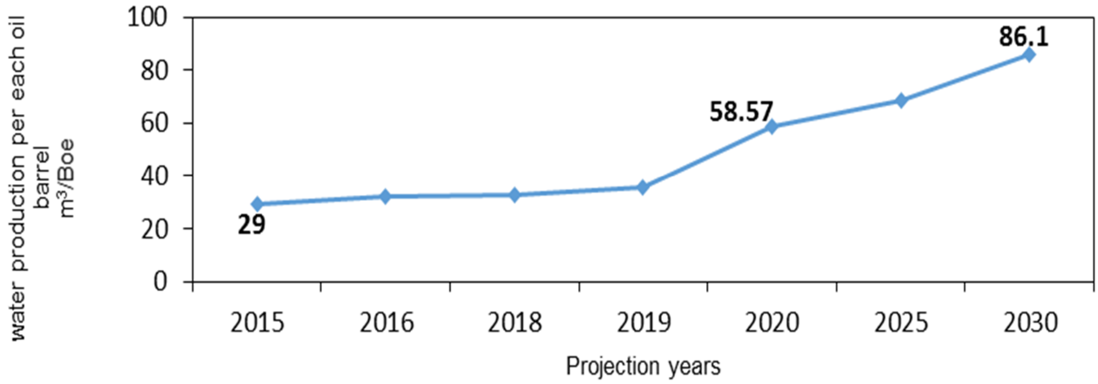

Figure 1. Fuel consumption for water production in the 2030 projection plan.

These numbers depend on the efficiency of the power plant and the salinity of the feed water [12]. As shown in the same figure, the productivity of each barrel of oil will increase three times by the year 2030, due to the installation of more efficient desalination technology, which is SWRO as per the plan. Nevertheless, the huge gap between the thermal index and the efficiency of the current desalination technology encourages researchers to exert more effort on enhancing the existing technologies and developing new ones.

As shown in Figure 2, based on the above data, installation of SWRO technology will increase fourfold by 2030 per the SWCC plan, while MSF will decrease, and MED will have a 10% share. Despite their relatively low thermal efficiency, MSF and, more recently, MED technologies still have advantages in Saudi and Gulf Cooperation Council (GCC) markets due to the availability of cheap energy and the synergy of cogeneration of water and electricity.

In 2017, the largest plant was commissioned with a capacity of 1.025 million cubic meters daily (Mm^3/day). The plant is 70% MSF and 30% SWRO, coupled with a combined cycle power plant with a total thermal efficiency of about 54%. At the same time, the Yanbu cogeneration plant uses MSF with a capacity of 0.55 Mm^3/day. Additionally, MED with a capacity of 90,000 m^3/day was commissioned in

2018 at the Shuaiba plant in Saudi. This trend can be attributed to the availability of a low-cost steam process at steam or combined-cycle power plants fired by natural gas or fossil fuels such as heavy or crude fuel oil. In 2014, the cogeneration plants in SA were reported to consume approximately 1.5 million barrels of oil daily for both water and electricity production; equivalently, this is about 15% of the total daily oil production of Saudi Arabia. Given SA's projected GDP and population growth in the coming decades, predicted domestic oil consumption is expected to exceed oil production capacity by 2040 [10].

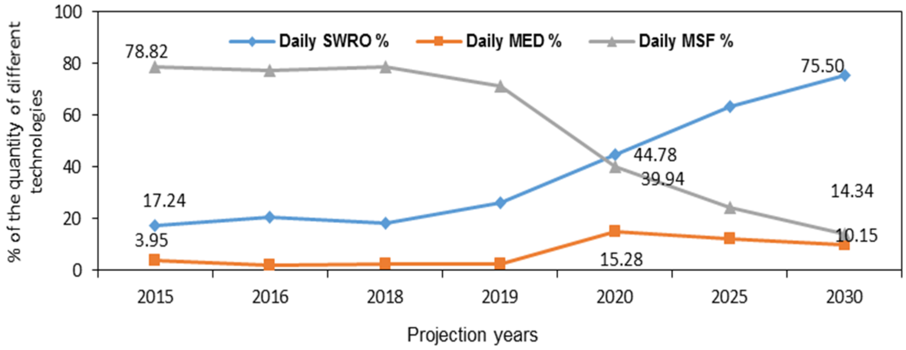

Figure 2. Trend of expected desalination technologies in the 2030 projection plan. MED, multi-effect desalination.

The second main issue with the existing desalination technologies is the centralization of the plants. These technologies are unsustainable solutions to meet the future water demand in SA, particularly for low-income rural and remote communities. They utilize the economy of scale advantage, which is considered as the main driver and hence deemed as a standard option in the planning of water system expansion. It is driven by reducing the levelized production cost and increasing control of the water quality [13]. Nevertheless, this option leads to the construction of massive transmission pipelines with pumping stations and electrical substations to transfer water to inland cities, which consumes more electricity than the production process itself. For example, the Shoqaiq desalination plant supplies 100,000 m^3/day to the city of Abha and many small towns and villages up to an elevation of 2084 m above sea level and a distance of 105 km. According to the calculation in Equation (1), it was found that the daily energy required for pumping water to terminal cities is 1510 MWh or 342,014 BOE yearly (considering 5.8 GJ/BOE), and the cost of power for the Shoqaiq pipeline is about USD 26 million (USD 75/BOE), in addition to producing 180,000 tons of CO_2 yearly. However, using decentralized energy-efficient desalination plants could eliminate the issue.

$$\text{Power} = \dot{Q} * \rho * g * \frac{H_{Total}}{\eta_{pump}} \text{ W} \tag{1}$$

where $\dot{Q}$ is water flow in m^3/s, ρ is water density in kg/m^3, g is gravity in m/s^2, H_{Total} is the vertical horizontal head in m, and η is pump efficiency. Figure 3 shows the energy consumption and CO_2 emissions for the four main pipelines supplying the four main cities. It shows that the pipelines of Shuqaiq and Jubail supply water to Abha and Riyadh, respectively, and consume twice the energy used in production due to the height of Abha city and the length and high flow rate of the Jubail–Riyadh pipeline (400 km, 500,000 m^3/day).

While the Shoaibah desalination plant pipeline supplies water to Makkah and consumes the same energy as production due to the short distance and lower elevation of Makkah (90 km, 240 m), the Yanbu pipeline consumes 8.51 kWh/m^3, which is twice the energy consumed in production because of the moderate distance and elevation compared to the other pipelines (162 km, 620 m).

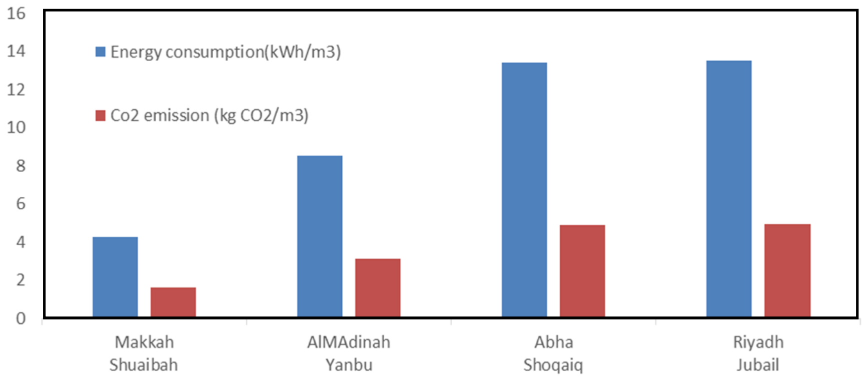

Figure 3. Energy consumption and emission of main pipelines in SA.

The yearly cost of energy for the four water supply pipelines is more than USD 0.347 billion, considering USD 75 per barrel of oil equivalent. In addition to that, the pipelines are expected to emit more than 2.73 million tons of CO_2 equivalent yearly. Hence, building such pipelines and their components further increases the environmental and cost issues [14].

The third issue is the environmental impact of existing desalination technologies. Environmental analysis shows that total installed desalination capacity in the world emits around 76 million tons (Mt) of CO_2 per year, and it is projected to grow to 218 million tons by 2040 [15]. The environmental impact of business as usual (BAU) in the desalination industry also includes aspects related to air, land, and seawater pollution. The CO_2 equivalent emissions due to water production from desalination plants in Saudi Arabia is estimated to reach 6.5 million tons of CO_2 in 2040, which represents around 3% of global emissions.

Low freshwater cost and environmental impact targets could be achieved by investigating and controlling the water production and transmission cost elements and increasing the utilization of renewable energy sources. In SA, emerging decentralized solar-powered desalination technology is suggested to replace existing installations [16]. The water production and transmission cost elements can be classified into installation capital cost, operation and maintenance cost, and energy cost. It essentially depends on the plant size, the type of process, and the location of the plant [17]. On the other hand, water, air, and land pollution generated by desalination technologies depends on the process used and the location of the plant. In coastal and inland plants, pollution of seawater and land where disposal of rejected brine is concentrated is the main problem. For thermal desalination processes (MSF and MED), air pollution also arises from fuel combustion in the form of carbon, nitrogen, and sulphur oxides and unburned hydrocarbons [18]. Desalination plants are considered to be the second largest source of pollution after the oil sector in GCC countries, as reported by [19]. Figure 4 shows available water resources, such as the Red Sea and Arabian Gulf, the six main underground aquifers, and the main centralized desalination plants.

All the water resources are connected via pipelines to the demand zones. It is clear that the intensity of solar irradiation, the mass population in the main cities and small cities (fewer than 5000 inhabitants) across each zone, and the aquifers lay in the same location. These water supply and demand elements can be utilized to reduce the cost and environmental impact. For instance, zone 1 in the southwest of the country comprises the following three water resources: Shoqaiq desalination plant, Wajid water aquifer, and surface water collected in the Baish Dam. The desalination plant and dam water connect in the pipeline to transfer water to Abha and 35 other small towns in the mountains. Energy consumption and CO_2 emissions are 8.51 kWh/m^3 and 3.12 kg CO_2/m^3, respectively. The same situation can be observed for zone 3, where Riyadh and other medium and small towns receive fresh water from Jubail and Ras Al-Khair power and desalination plant (RAK), with values of 13.5 kWh/m^3 and 4.96 kg CO_2/m^3. Could the aquifers available in that zone be utilized to reduce the transmission cost? Cost and emissions can be reduced by using low-energy desalination technology coupled with solar energy instead of fossil fuel and installing decentralized plants along the two coasts to supply the coastal cities or aquifers to supply the inland cities, in lieu of constructing new pipelines.

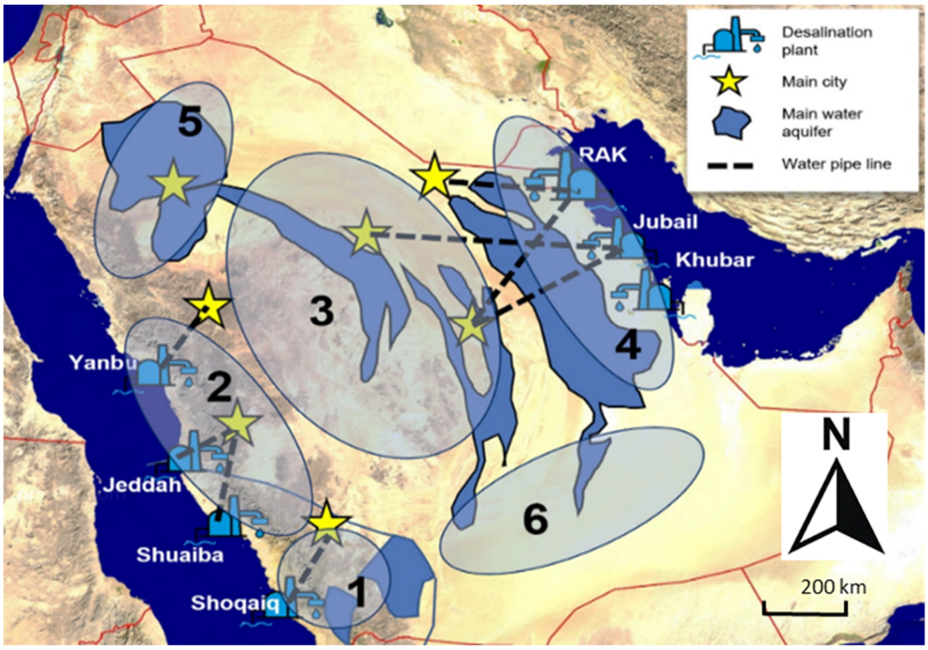

Figure 4. Water resources and main demand zones in SA.

As the average irradiation in SA is 2200 kWh/m^2 yearly [20], solar energy in the six zones, as shown in Figure 4, represents a huge resource and could be a promising solution to supply the energy required for desalination in isolated rural communities, such as most of the small towns in zones 1 and 3 [21]. In the last two decades, there has been remarkable development in a variety of solar-assisted thermal applications in an attempt to resolve the high energy consumption. It has been found that solar energy technology is suitable for incorporation into different desalination processes at a reasonable cost wherever a proper water source is available. However, the main disadvantage is the intermittent supply of energy, which requires a storage system or hybridization with a complementary system to overcome this drawback [22,23]. Considering the mentioned issues and with the target of reducing water cost compared to natural surface fresh water and minimizing the impact of these processes on the environment, emerging decentralized solar-powered desalination technology can be proposed to replace the existing installations in SA.

3. Seawater Desalination Technologies

The existing desalination technologies can be classified into two categories based on the form of energy used, namely thermal energy and electricity driven processes. The former includes multi-effect distillation (MED) thermal vapor compression (MED–TVC), multi-stage flash (MSF), humidification–dehumidification (HDH), adsorption desorption desalination (ADD), and membrane distillation (MD). The latter include mechanical vapor compression (MVC), reverse osmosis (RO), electro-dialysis reversal (EDR), and ion exchange (IEX) [24].

Among the current desalination technologies, six dominate, representing more than 90% of the capacity today. These processes can also be categorized into two groups: mature and in commercial operation [25], and not in common use and either still in research phase or at pilot plant scale. The main commercialized desalination technologies are reverse osmosis (RO), multi-stage flashing (MSF) with brine recycling (MSF–BR), multi-effect, thermal/mechanical vapor compression desalination (MED–TVC/MED–MVC), electro-dialysis (ED)/reverse electro-dialysis, freezing desalination (FD), and ion exchange (IEX). There are mainly nine emerging desalination technologies under investigation:

humidification/dehumidification (HDH), forward osmosis (FO), membrane distillation (MD), capacitive deionization (CDI), pervaporation (PV), microbial (MBD), ion concentration–polarization (ICP), clathrate hydrates (CH), and adsorption desorption desalination (ADD) with a pilot plant of 100 m^3/day built recently in SA by [26].

More enhancements of desalination technologies are still under major development. For membrane-based technologies, innovative biomimetic membranes and carbon nanotubes or graphene-based products have shown promise, with superior performance in terms of water permeability and salt rejection. All are still under development. Several thermal-based technologies have also been developed recently. Microbial desalination cells have shown considerable improvement in both salt removal capacity and water recovery. However, to date, only small-scale evaluation of the process has been carried out [27]. Three main commercialized desalination technologies are currently dominating worldwide, with collectively more than 90% of the total installed capacity. They are SWRO (65%), MSF (21%), and MED (7%) [28].

Table 3 shows a comparison of energy consumption, environmental impact in terms of quantity of CO_2 emissions, and decentralization capability for different unit capacities of various desalination technologies. It shows that SWRO has the lowest energy consumption, the lowest CO2 emissions and the applicability of decentralization with the lowest installation cost, which explains its broad acceptance worldwide. However, all are far from the level of energy consumed in the treatment of surface water, which does not exceed 0.2 kWh/m^3, as shown in Table 1.

Table 3. Energy consumption and CO_2 emissions for desalination technologies. TVC, thermal vapor compression.

Item	MSF/Unit	MED–TVC/Unit	SWRO/Skid	Comments
Typical unit size (m^3/day)	50,000–92,000	10,000–90,000	100–40,000	Commercial unit size for SWCC plants
Capital cost (\$/m^3/day) [15]	1598	1860	1313	
Minimum electrical energy consumption (kWh/m^3) [29]	2.5	2	4–6	Thermal plant efficiency 30% SWRO with energy recovery
Thermal energy consumption (kWh/m^3) [29]	15.83	12.2	None	Thermal plant efficiency 30%
Equivalent energy consumption (kWh/m^3)	18.33	14.2	None	
CO_2 (kg/m^3) [15]	15.6–25	7–17.6	1.7–2.8	
Decentralization	–	–	✔	MSF and MED not app. due to economy of scale

Table 4 summaries the advantages, disadvantages, and energy consumption of 16 commercialized and emerging desalination technologies. Most of the emerging technologies have lower energy consumption than commercialized ones except ion-concentration polarization. Emerging technologies are continuously being developed to overcome the drawbacks of the existing technologies. Although the development of most of the existing commercialized desalination technologies occurred in the last 50 years, several environmental and economic challenges need to be resolved, such as CO_2 emissions and high levelized cost [3]. It is an industrial fact that SWRO has the lowest specific energy consumption among them. However, ADD specific electrical energy consumption is lower than SWRO by around 60%, and it utilizes low-grade, waste, or renewable thermal energy [5].

From Table 4, three commercialized (SWRO, MSF, and MED) and two emerging (ADD and IEX) technologies are selected and compared in Figure 5.

Table 4. Review of advantages and disadvantages of commercialized and emerging desalination technologies.

Technology	Advantages	Drawbacks	Energy Cons. kWh/m^3
SWRO [16]	• Relatively lower investment cost • No cooling water flow • Simple operation and fast startup • High footprint/production capacity • 30–60% recovery • Removal of contaminants other than salts achieved • Modular design	• Higher costs for chemical and membrane replacement • Weak to feed water quality changes • Adequate pretreatment a necessity • Membranes susceptible to biofouling • Mechanical failures due to high-pressure operation possible • Appropriately trained and qualified personnel recommended • Minimum membrane life expectancy around 5–7 years	2.5–5 [5]
Multi-stage flashing (MSF) [25,30,31]	• Large-capacity designs • Proven, reliable technology with long operating life • Flashing rather than boiling reduces incidence of scaling • Minimal pretreatment of feed water required • High-quality product water • Plant process and cost independent of salinity level • Heat energy can be sourced by combining with power generation	• Huge capital investment required • Energy-intensive process • Larger footprint required • Corrosion problems if materials of lesser quality used • Slow startup rates (hours) • Maintenance often requires entire plant to shut down • High level of technical knowledge required • Recovery ratio low	Electrical 2.5–4; thermal 57.14 [32]
Multi-effect desalination (MED) [31]	• Minimal pretreatment of feed water required • Very reliable process with minimal requirements for operational staff • Tolerates normal levels of suspended and biological matter • Heat energy can be sourced by combining with power generation • Very high-quality product water	• High energy consumption • High capital and operational cost • High-quality materials required as process is susceptible to corrosion • Product water requires cooling and blending prior to being used for potable water needs	Electrical 1.5–2; thermal 43.2 [5]
Sea water reverse osmosis (SWRO) [33–35]	• Relatively low energy consumption • Well commercialized • Depends on electrical energy only	• Depends on pretreatment system • Uses different chemicals • Needs advanced controlling system	3–4 [36]

Table 4. *Cont*.

Technology	Advantages	Drawbacks	Energy Cons. kWh/m^3
Electro-dialysis reversal (EDR) [37,38]	• Energy usage proportional to salts removed not volume treated • Higher membrane life of 7–10 years • Operational at low to moderate pressure	• Only suitable for feed water up to 12,000 mg/L TDS • Periodic cleaning of membranes required • Leaks may occur in membrane stacks • Bacterial contaminants not removed by system and post-treatment required for potable water	2.036.6–8.7 [32]
Ion exchange (IEX) [39]	• Only electrical energy used • Can remove boron efficiently	• Low concentration salts • Not commercialized for seawater	
Membrane distillation [40]	• No applied pressure • Rejection capacity is high • Low operating temperatures under vacuum • Plastic material can be utilized to avoid corrosion • Feed salt concentrations have little effect on performance • Waste heat, solar energy, and geothermal can be used	• Under bench-scale or pilot-scale studies • No membranes and modules designed specifically for MD • Fouling of membranes when membrane is wet • Requires pretreatment of feed water source	43 without waste heat [41] 10.3 with waste heat 1 electrical energy [42]
Humidification–dehumidification [43,44]	• Simple operation and maintenance • High rejection capacity • Lower operating temperatures compared to conventional thermal desalination • Ideal for small-scale remote applications when combined with solar energy	• Requires waste heat or renewable energy source for cost-effective desalination • Large footprint requirement due to humidifier and dehumidifier chambers • Optimization of carrier gas flow rate and feed water type is essential	(300–500) or 120 with modified configuration [40]
Pervaporation [45]	• Absence of applied pressure • High rejection capacity • Lower operating temperatures • High feed salinity	• Low flux • Performance depends on selection of membrane material • Lack of pilot scale or demonstration scale data	Energy required for pumping is 2 [45,46]
Microbial desalination [47–49]	• Absence of applied pressure • Absence of external electricity source	• Low efficiency • Requires a carbon source; bench-scale studies have been performed	0.16 produced energy/m^3 of saline water [50]

Table 4. *Cont.*

Technology	Advantages	Drawbacks	Energy Cons. kWh/m^3
Capacitive-deionization technologies [51]	• Absence of applied pressure • High rejection of salt • More efficient for low salinity feed water sources (TDS < 15,000 mg/L)	• Efficiency of electrodes for salt • Separation requires optimization • Limited data available for seawater desalination	1.96 [52]; 1.8 [40] 0.1–2.03 [53]
Ion-concentration polarization [32]	• Absence of applied pressure • Absence of membranes and fouling • High rejection of salt and microorganisms • Efficient for small-scale desalination modules • Can be operated using battery power in remote locations	• Limited data available • Applicable only for small-scale systems • Scaling of microchannel due to hardness ions could be an issue	3.5 [54]
Clathrate hydrates [55,56]	• Low pressure requirements • High rejection of salt	• Process has not been evaluated on a continuous basis • Separation of hydrates from brine requires optimization • Elimination of salt molecules from hydrate cages	Estimated to be significantly lower than RO process due to absence of feed pressure requirement
Forward osmosis [57,58]	• Low or no hydraulic pressure • High rejection of wide range of contaminants • Lower membrane fouling propensity than pressure-driven membrane processes • Low fouling and energy consumption	• Depends on draw solute's chemical properties and physical structure • Regeneration of draw solutes from diluted draw solutions and production of clean water might be energy-intensive • Low performance FO membranes	1.3–1.5 [59]
Adsorption desorption desalination (ADD)	• Low energy consumption • Utilization of low-temperature heat source or solar heat • Stationary operation without moving parts • Production of two effects, distillation and cooling • No limitation on feed water TDS • Up to 100% rejection	• Requires waste heat or renewable energy source for cost-effective desalination • Data available only for pilot or demonstration scale projects	1.38 [12]

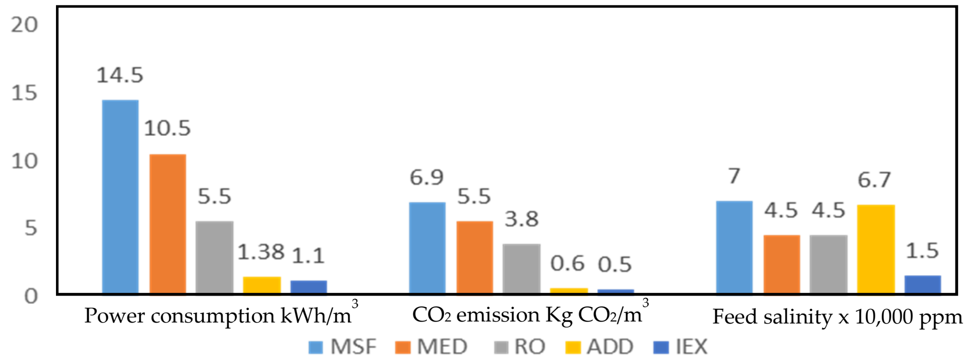

Figure 5. Comparison among desalination technologies with main operational parameters [60].

SWRO can be considered to be the best technology compared to MSF and MED based on power consumption, emissions, and feed water salinity. At the same time, IEX has lower energy consumption and emissions but limited feed salinity. It is limited to brackish water with low salinity only. ADD has the advantage in terms of power consumption, CO_2 emissions, and feed salinity compared to the others [60]. Thus, among the commercialized and emerging desalination processes, ADD can be considered as one of the most promising. It has great potential due to its high performance compared to other thermal processes; in [61] it was reported that ADD energy consumption did not exceed 1.38 kWh/m^3 with a unit water cost of \$0.457/m^3 for a plant of 1000 m^3/day, which is less than the benchmarked SWRO energy consumption of 4.5 kWh/m^3 and unit water cost of \$0.5/m^3. Additionally, an 85% reduction in the CO_2 footprint could be attained.

ADD has several advantages compared to the other methods, complying with cost and environmental requirements. It operates at low-grade energy and low temperature. The maximum temperature could be in the range of 85 °C. Operating the system at low temperature reduces exposure to corrosion and fouling problems due to the use of low saline water temperature. Additionally, ADD has low maintenance and operation costs due to the absence of moving parts and simple design [62,63]. In addition, it produces two products at the same time, namely potable water from the condenser, and chilled water in the evaporator. At the same time, it can prevent any possible bio-contamination in the produced water. Because of its low electrical energy consumption and ability to utilize renewable or waste energy sources, it generates a small carbon footprint. The advantages of ADD have been evaluated and proven across many published papers [64,65], and a pilot plant with a capacity of 100 m^3/day was recently built in Saudi. However, more study and optimization are required to allow commercialization of the technology.

On the other hand, ADD has its drawbacks, such as the intermittent working principle, which reduces the water production rate. This drawback can be overcome using a multi-bed system and addressing the need to maintain the system under high vacuum to facilitate the adsorption process, which can be considered as a manufacturing and fabrication problem rather than a process problem. Additionally, it needs more attention in the design of the bed heat exchanger, which can be optimized by a thorough numerical and experimental investigation of different bed aspects [66–70]. The system scalability has not yet been tested. This issue can be partially overcome by using a hybrid between ADD and commercialized desalination technologies such as SWRO–ADD and MED–ADD.

Hence, ADD may play a significant role in supplying water to inland households directly from high brackish water aquifers, and seawater to inland and coastal households. It may be considered as a practical, inexpensive, and environmentally friendly method of desalinating saline and brackish water to produce potable water for industrial, residential, and agricultural applications, and could be one of the candidates for future decentralized desalination.

4. Adsorption Desorption Desalination

The adsorption–desorption process is a physical and/or chemical surface phenomenon where the molecules/atoms of a substance (the adsorbate) are attracted to and retained on the surface of a solid or liquid material (the adsorbent), resulting in a higher concentration of the molecules/atoms on the surface. It has been used as a separation process for mixtures like seawater solution into two streams [71,72]. The adsorption–desorption process has been deployed in many applications such as separation processes, air-conditioning, and brackish water desalination. It involves the physical uptake of water vapor on the surface of the adsorbent such as silica gel, zeolite, or activated carbon. The adsorbent's characteristics play a vital role in the adsorption process. Adsorbents are classified based on the adsorption process as physical, chemical, and composite adsorbents. Physical adsorbents are usually porous materials with different pore sizes. They adsorb adsorbates (refrigerant/vapor) by an intermolecular force called the Van der Waals force. They retain their original properties after removing adsorbates by adding heat during the desorption process.

One of the essential characteristics of adsorbent materials such as silica gel and zeolite is the ability to have continuous uptake of adsorbate up to the saturation limit of the adsorbent. Silica gel, for example, with an approximate specific surface area of 650 m^2/g, can adsorb water vapor up to 35–40% of its dry mass [73]. This advantage lets the physical adsorbent be commonly used in desalting.

The adsorption process can be described by equilibrium, heat, and kinetics. The adsorption equilibrium is the maximum amount of adsorbate that can be adsorbed at a given pressure of adsorbate and temperature of adsorbent. Adsorption equilibrium at a constant adsorbent temperature is called the adsorption isotherm. A summary of the main adsorption isotherm models used in the ADD model are listed in Table 5. Different theories used to explain the adsorption isotherm include Henry's law, Langmuir's theory, Gibbs' theory, and the adsorption potential theory [74].

Table 5. Main adsorption isotherm models.

Isotherm	Nonlinear Form	Linear Form	Reference
Langmuir	$q_e = \frac{Q_0 b C_e}{1+bC_e}$	$\frac{C_e}{Q_e} = \frac{1}{bQ_0} + \frac{C_e}{Q_0}$	[75]
Freundlich	$q_e = K_F * C_e^{\frac{1}{n}}$	$log q_e = log K_F + \frac{1}{n} log C_e$	[76]
Tempkin	$q_e = \frac{RT}{b_T} ln A_T C_e$	$q_e = \frac{RT}{b_T} ln A_T + \left(\frac{RT}{b_T}\right) ln C_e$	[77]
Dubinin–Radushkevich	$q_e = (q_s) exp\left(-k_{ad}\epsilon^2\right)$	$ln(q_e) = ln(q_s) - K_{ad}\epsilon^2$	[78]
Dubinin–Astakhov	$q^* = q^0 * \exp\left\{-\left[\frac{RT}{E} * in\left(\frac{P_0}{P}\right)\right]^n\right\}$		[79,80]
Toth	$q_e = \frac{K_T C_e}{(a_T+C_e)^{\frac{1}{t}}}$	$ln\left(\frac{q_e}{K_T}\right) = ln(C_e) - \frac{1}{t} ln(a_T + C_e)$	[81]
BET	$q_e = \frac{q_s C_{BET} C_e}{(C_s - C_e)\left[1+(C_{BET}-1)\left(\frac{C_e}{C_s}\right)\right]}$	$\frac{C_e}{q_e(C_s-C_e)} = \frac{1}{q_s C_{BET}} + \frac{C_{BET}-1}{q_s C_{BET}} \frac{C_e}{C_s}$	[82]

The first empirical isothermal models were suggested in [81]. After 10 years, Langmuir theoretically derived the monolayer isotherm model. Brunauer, Emmett, and Teller (BET) proposed the monolayer adsorption amount [82]. BET theory, despite many restrictions, was the first attempt to create a universal theory of physical adsorption. Both Langmuir and BET theories originated from one common assumption, which is the existence of an interfacial geometric surface on a mono- or multilayer when adsorption takes place. Thus, the surface area of the adsorbent is the main geometric parameter. Theoretical, empirical, and semi-empirical models have been used to model the amount of adsorbate adsorbed on the surface of the adsorbent [83]. Adsorption is an exothermic process, and the heat of adsorption can be calculated from Equation (2); it depends mainly on the characteristics of the adsorbent and adsorbate in addition to temperature, pressure, and the concentration of the adsorbate, while desorption is an endothermic process that depends on the same parameters [71].

$$Q_{ads/des} = h_{fg} + E\left\{-\ln\left(\frac{q}{q_m}\right)\right\}^{\frac{1}{n}} + T \times v_g\left(\frac{dp}{dT}\right)_g \tag{2}$$

where h_{fg} is latent heat, q_m is the maximum capacity of the adsorbent, E is activation energy, v_g is the volume of the gas phase of the adsorbate, and n is an isotherm model constant [79]. Adsorption kinetics is the rate at which the adsorbate is adsorbed on the surface of the adsorbent.

The transient amount is commonly calculated from the adsorption equilibrium and kinetics data, and is given by the linear driving force (*LDF*) equation [79]:

$$\frac{dq}{dt} = \frac{15D_{s0}\exp\left(\frac{E}{RT}\right)}{R_p^2}\,(q^* - q) \tag{3}$$

where q^* and q are the adsorbed amount at equilibrium conditions and the transient amount, respectively, D_{s0} is a diffusivity factor of the adsorbate in the adsorbent, R is the universal gas constant, and R_p^2 is the average radius of the adsorbent molecule [79]. Most physical adsorbents suffer from low adsorption kinetics and hence low cyclic flow rate. The operation of the ADD cycle can be sub-categorized into the evaporation–adsorption process and the desorption–condensation process.

As illustrated in Figure 6, the standard configuration of ADD consists of three main components, namely the evaporator, condenser, and adsorbent/desorbent beds. The adsorber bed is filled with adsorbents (silica gel) and equipped with heat exchangers.

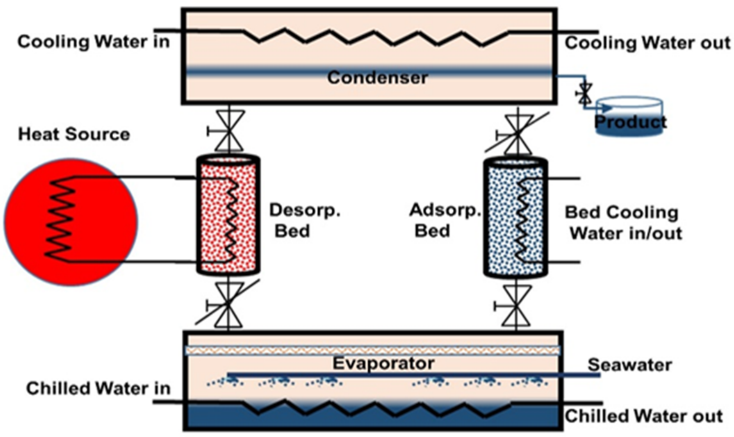

Figure 6. Main components of standard configuration of ADD.

The ADD thermodynamic cycle, as shown in Figure 7, starts with isosteric heating at point 1 when hot fluid flows in the heat exchanger of an isolated saturated bed at evaporator pressure and temperature until the pressure exceeds the condenser pressure at point 2. The bed connects to the condenser at point 2 and starts isobaric heating to desorb all the vapor from the bed until the maximum temperature is reached at point 3. At point 3, the bed is isolated and isosteric cooling starts until the bed pressure reaches the evaporator pressure at point 4. The bed connects to the evaporator at point 4 and starts isobaric cooling to adsorb the vapor from the evaporator until the evaporator temperature is reached at point 1. It is worth noting here that there are two types of heat in the ADD system: first, latent heat gained in the evaporator and released in the condenser, and second, bed regeneration heat ($Q_{12} + Q_{23}$), required from an outside heating source to desorb the vapor from the bed. It is stored in the adsorbent particles and bed heat exchanger and has to be removed from the bed during the adsorption process by circulating cooling water from points 3–4 and 4–1.

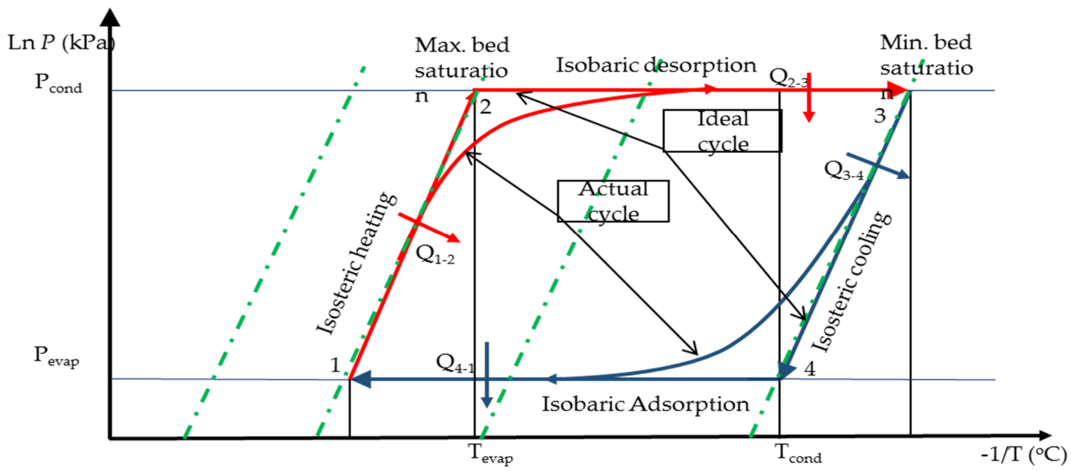

Figure 7. P–T-ω diagram of ideal and actual ADD cycle (1 → 2 isosteric heating, 2 → 3 desorption, 3 → 4 isosteric cooling, 4 → 1 adsorption).

Applications of the adsorption process in seawater and brackish water desalination started after a long time of using it in cooling systems. It has been considered as an efficient replacement for mechanical and thermal compression vapor components in cooling systems by low-grade heat adsorption systems to generate a cooling effect [84,85]. One of the main drivers behind using adsorption phenomena in desalination is the ability to harness water vapor from seawater or brackish water at ambient temperature without applying significant external energy in heating the feed water or creating a vacuum. At the same time, low-temperature (55–85 °C) closed loop heating fluid was used to release the vapor and condense it. The difference between ADD and adsorption cooling systems is that the adsorbate (water vapor) in ADD is collected as a distillate in the potable water tank, while in cooling systems, it recirculates again to the evaporator in a closed circuit.

The published literature on ADD covers different aspects, including the effects of different designs and/or control and operational parameters, such as condenser and evaporator temperature, number of beds, and operation strategies, on ADD performance such as specific daily water production (SDWP), coefficient of performance (COP) of the cooling system, performance ratio (PR) of the desalination system, and overall conversion ratio (OCR). Additionally, different energy sources coupled with the ADD system have been studied, the effects of different types of adsorbents on the performance of ADD have been compared, the effects of combining ADD with MED or other desalination technologies have been studied, and models and simulations have been conducted utilizing different isotherm models and validating the results with experimental data. The primary goal of the majority of these studies was to reduce the unit water cost and environmental impact, and to raise SDWP and the performance ratio.

To attain this goal, researchers investigated and modified the system components and the processes by which the components interact. One or more of the following three parameters are usually evaluated to assess the performance of the ADD cycle: PR, which measures the amount of heat adsorbed by the condenser from the water vapor per the amount of heat input during the desorption process, indicating the thermal effectiveness of the system; SDWP; and OCR, which indicates the total amount of heat exchanged in the evaporator and condenser per external heat input in the desorption process.

Before 1997 there were no publications on ADD as a stand-alone system. The focus was mainly on improving cooling systems using adsorption–desorption cycles. From then on, different configurations were developed and published in the literature for ADD systems. Historically, many ADD configurations related to reduced input energy were developed and studied for cooling systems in order to improve the COP [69,84,86–88]. The same configurations were modified and applied to desalination systems [5,61,70,89,90]. ADD system configurations are classified into five groups, as shown in Figure 8.

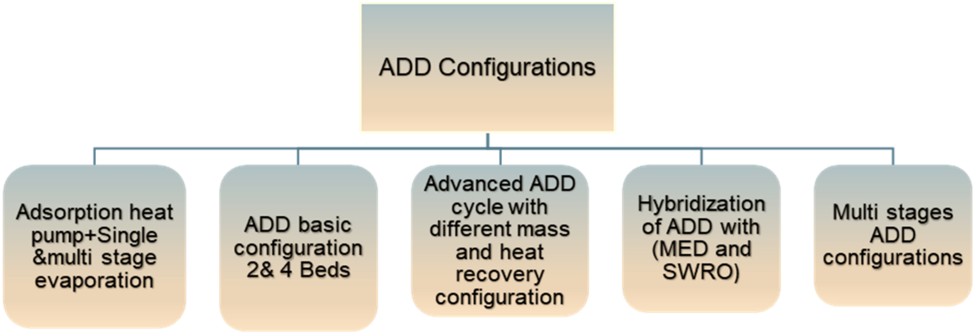

Figure 8. Classification of ADD configurations.

Single and multi-stage evaporation desalination were the basic configurations for the desalination process, comprising a condenser, an evaporator, and a heat source. The performance ratio was less than one because the amount of vapor flow to the condenser was low. To improve the process and increase the vapor flow to the condenser, mechanical and thermal compression MVC and TVC were introduced to the system, as shown in Figure 9. However, both required additional mechanical or thermal energy to compress the vapor and increase its amount.

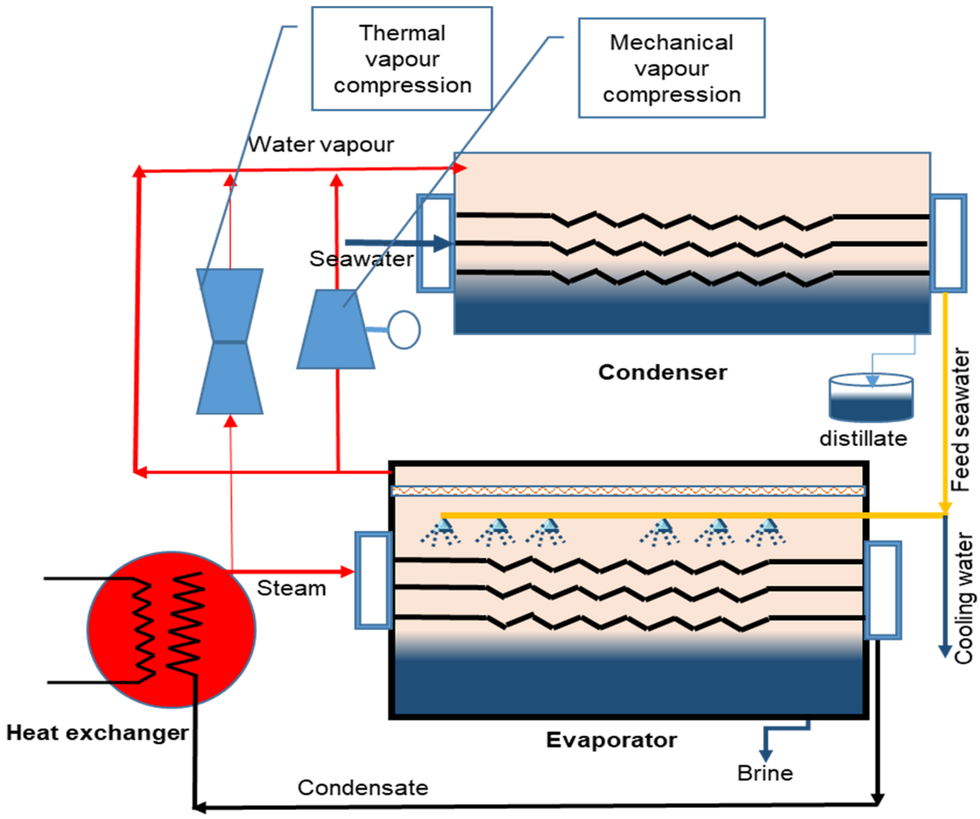

Figure 9. Single stage evaporation with thermal/mechanical vapor compression.

4.1. *Adsorption Heat Pump with Single and Multi-Stage Evaporator*

The adsorption bed was utilized as a heat pump to replace the thermal ejector and the mechanical compressor to increase the performance ratio of single-stage evaporation desalination. Introducing the adsorption bed was intended to reduce the amount of heat input to the system. Based on the above analysis, [91] introduced the adsorption bed as a heat pump, as shown in Figure 10. They compared four types of single-effect evaporator desalination hybrid systems based on the performance ratio and specific power consumption, among other parameters.

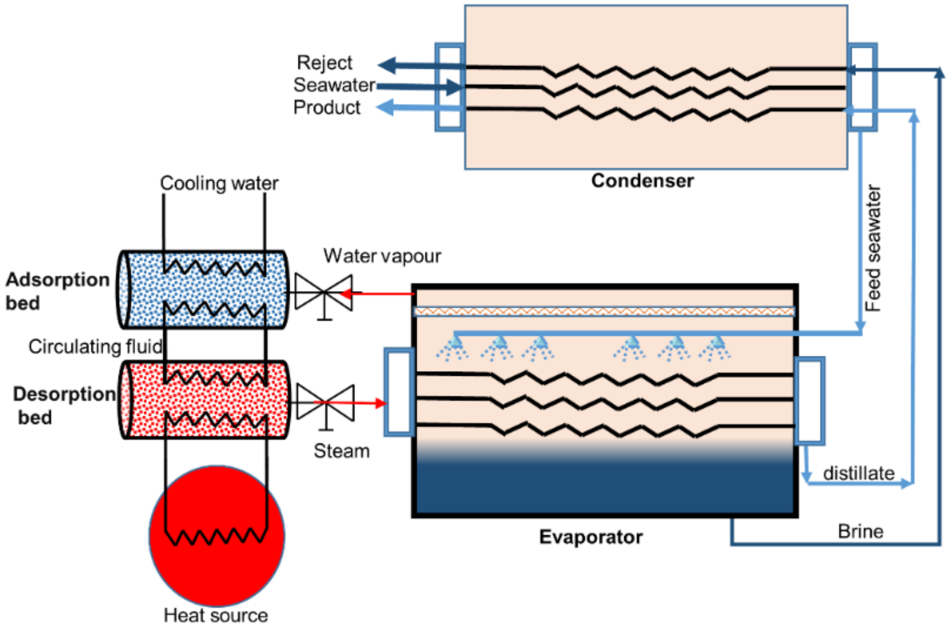

Figure 10. Single-stage evaporation with adsorption/desorption beds as heat pump.

One of these configurations was adsorption vapor compression (ADVC). In this configuration, the desorbed vapor flows inside the tube of the evaporator; the vapor condenses as a distillate and the latent heat transfers to evaporate the sprayed seawater outside the tube bundle. The energy of the distillate and the brine exchanges with the feed seawater to increase system efficiency. The system performance ratio from this study was found to be between four and five at low steam temperature.

The performance of a single-effect desalination evaporation unit coupled with a water–zeolite adsorption heat pump was analyzed in [92]. The configuration was analyzed in terms of three performance parameters, namely performance ratio, heat transfer area per product water, and cooling water flow rate per product water flow rate. Additionally, they conducted a parametric analysis of 12 design parameters for desalination and adsorber, such as intake and feed salinity and temperature, production rate, desorber temperature, and water content. These parameters were investigated as a function of brine boiling temperature. The study compared the parameters of adsorption vapor compression with different types of vapor compression, namely mechanical, thermal, and absorption. They concluded that adsorption vapor compression had the highest performance ratio and the same heat transfer area and cooling flow rate per product flow rate compared to the other processes. After the successful implementation of adsorption–desorption beds as a heat pump, they investigated the possibility of using different refrigerants as working pairs for ADD systems.

The use of heat pumps in desalination by using either agent R12 or water as a source of heat in the evaporator heat exchanger was discussed in [93]. They concluded that using agent R12 in heat pumps is not feasible due to the low heating capacity of R12 but using water and vapor is feasible. To improve the performance ratio, a configuration of a hybrid system was theoretically studied in [89], comprising one evaporator placed between two adsorption–desorption beds packed with zeolite as a heat pump, with the two beds connected in one loop to recover adsorption heat. The evaporator was connected to the first cell of a three-multi-effect desalination (MED). The system was connected to a parabolic trough solar collector as a heat source. They investigated the effect of the temperature difference between the two beds on heat recovery and the performance ratio. They concluded that maximum heat recovery occurred when the temperature difference between the two beds was minimal. This configuration increased the performance ratio of the system three to four times in proportion to the number of effects.

4.2. ADD Configuration with Multiple Beds

Many researchers have studied the basic ADD configuration including two beds, as shown in Figure 11, and four beds. A four-bed ADD was constructed and specific water yield from the ADD plant for different primary coolant and feed conditions was experimentally investigated in [94]. They obtained an optimal specific daily water production (SWP) of 4.7 kg/kg silica gel. The SWP yield from the plant could be further increased by using a larger chilled water temperature supply for the evaporator and a lower cooling water temperature for the designated adsorption beds. The most critical point of this study is that the ADD plant functioned even when the heat source temperature was lowered to 65 °C. Additionally, an adsorption desalination plant guarantees no possibility of bio-contamination in the potable water, and this is attributed to the evaporation and desorption processes of the adsorption cycle. The ADD performance of laboratory-scale two-bed and four-bed mode cycles, utilizing solar hot water or waste heat, was investigated in [26]. The adsorption cycle produced SDWP of 3 m^3 of potable water per ton of silica gel per day. In dual-mode operation of the ADD cycle, the cycle produced 7.2 m^3 of potable water per ton of silica gel per day. The OCR of the adsorption cycle was 1.5 if the heat source temperature was 65 °C.

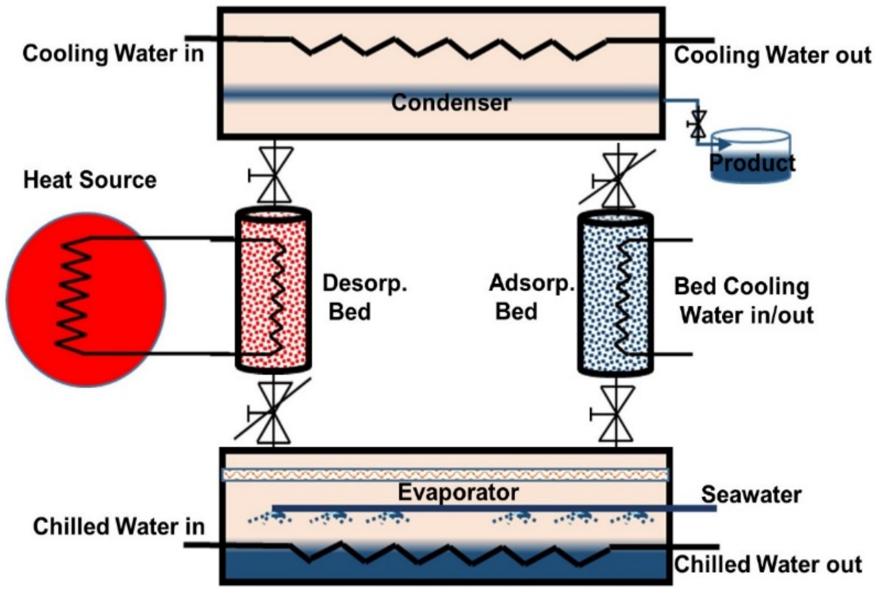

Figure 11. ADD standard configuration.

The adsorption cycle obtains high efficiency due to the generation of two useful effects, cooling and desalting. A single-stage system with four-bed silica gel ADD configuration was investigated in [95] to study the condenser temperature and the optimum cycle time for maximum water production. The system simulation showed that the optimum time for maximum SDWP was 600–900 s, but production decreased drastically with increasing condenser temperature due to increased operating pressure ratio. Therefore, they recommended using a two-stage ADD system.

A similar configuration was investigated mathematically in [96], highlighting the influence of evaporator and condenser temperatures on adsorption cycle performance for water production and cooling effects using silica gel as adsorbent. The researchers found that as the condenser temperature decreased, the system produced more water and achieved higher specific cooling capacity. Furthermore, the system achieved improvements in water production and cooling when the evaporator temperature increased, producing 10 m^3 water/ton silica gel/day.

4.3. Advanced ADD Cycle with Different Mass and Heat Recovery Configurations

The advanced ADD cycle, as shown in Figure 12, includes five configurations: (i) mass recovery between adsorber/desorber beds, (ii) heat recovery between adsorber/desorber beds, (iii) mass and heat recovery between adsorber/desorber beds, (iv) heat recovery between condenser and evaporator, (v) heat recovery through a thermal wave among adsorber/desorber beds and heating and cooling sources in a single loop [97], and (vi) convective heat recovery [98].

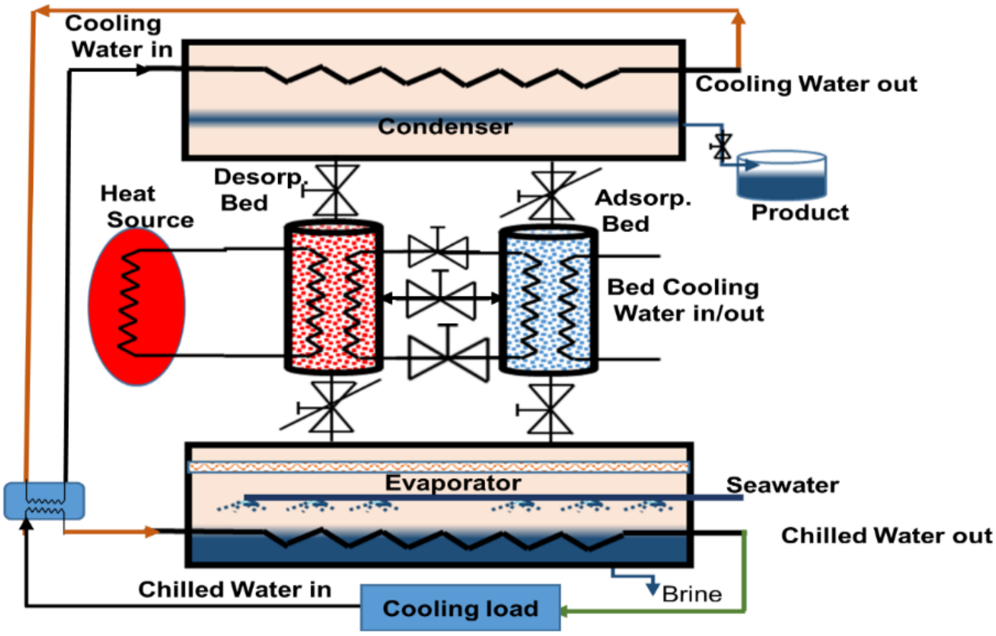

Figure 12. Advanced ADD with mass and heat recovery configuration.

Several studies [99–102] experimentally investigated ADD with heat and mass recovery. Performance tests were conducted with and without heat and mass recovery procedures. The experiments showed a significant boost in specific daily water production and performance ratio of ADD by 15.7% and 42.5%, respectively. Many studies focused on the operational parameters of ADD with heat and mass recovery and two and four beds.

The performance of the ADD system in two-bed and four-bed operational modes was investigated in [103]. The study presented the outcomes in terms of the main performance parameters (SDWP, cycle time, PR) for several input operational parameters, such as heat source temperature, mass flow rate, and cycle time. They found that the maximum water production per ton of silica gel per day was 10 m^3 while the corresponding performance ratio was 0.61.

All three configurations of the advanced ADD cycle were investigated in [100], in which a mathematical model was developed and verified with experimental data to assess the performance. The study showed that the advanced ADD cycle was able to produce SDWP of 9.24 m^3/ton of silica gel per day at 70 °C hot water inlet temperature. The corresponding PR was comparatively high at 0.77. They found that the cycle could be operational at 50 °C hot water temperature with SDWP of 4.3. Similarly, a series of theoretical and experimental studies of the advanced cycle in in Saudi Arabia were conducted in [5]. They built a 485 m^2 solar ADD pilot plant and highlighted that the payable electrical energy for the ADD to produce both water and cooling effect was just 1.38 kWh/m^3 compared to 3.5 kWh/m^3 for the most efficient SWRO system. An advanced ADD cycle with an integrated condenser–evaporator loop was numerically modeled in [104] using silica gel as adsorbent. Owing to that design, increased pressure of the adsorption process was achieved by heat recovery from the condensation process. As a result, it was noted that the operating pressure range of the advanced AD cycle was elevated, and the net adsorbent uptake reached up to 15% compared to the conventional ADD. It was concluded that SWP improved from 8.1 m^3 to 26 m^3 at 50 °C and 85 °C, respectively.

The same authors [79] modelled and experimentally validated the performance of an advanced silica gel-based ADD and focused on the effect of the heat source temperature change on SDWP and PR. The researchers found that at a range of 50 °C to 70 °C, DSWP ranged from 4.3 m^3 up to 15 m^3 per ton of silica gel, which is twice the amount produced from a standard configuration under the same operating conditions. The results indicated that the advanced ADD cycle continued producing water even with a low heat source temperature (50 °C). Recently, a mathematical model was developed in [70] to predict ADD performance with heat and mass recovery, conducting an energy–economic analysis. SDWP was estimated to be 11.92 with 5.9% second law efficiency. Additionally, a proposed ADD was theoretically and experimentally studied in [105] with mass and heat recovery using ground heat source comprising a single-stage evaporator coupled with adsorber and desorber beds. The SDWP and PR of the system were found to be 4.69 and 0.766, respectively. The heat recovery did not contribute to increasing the SDWP but did reduce the energy consumption of the system and enhanced the efficiency to 74.7%.

4.4. Hybridization of ADD with MED and SWRO

Different hybrid configurations with MED and SWRO were studied by researchers to utilize the advantages of both systems and overcome their limitations. The advantages of hybridizing ADD and MED to overcome the limitation of scalability of ADD and the requirement of MED to reject heat at the final condenser at a temperature higher than ambient were described in [106,107]. Coupling of MED with ADD, as shown in Figure 13, allows rejecting MED temperature at only 5 °C. The work simulated an eight-stage MED cycle coupled with ADD (silica gel), and the results showed a 60% increase in production compared to MED alone, while PR improved by 40%. They claimed that production increased threefold with the same heat input. Additionally, researchers in [107] presented experimental results of a hybrid system of a three-stage MED and ADD (MED–ADD) plant. The study focused on heat source temperature ranging from 15 °C to 70 °C. The results showed the advantages of the MED–ADD system compared to MED alone. Production increased 2.5- to 3-fold, while the lower brine temperature decreased to 5 °C from 40 °C in MED.

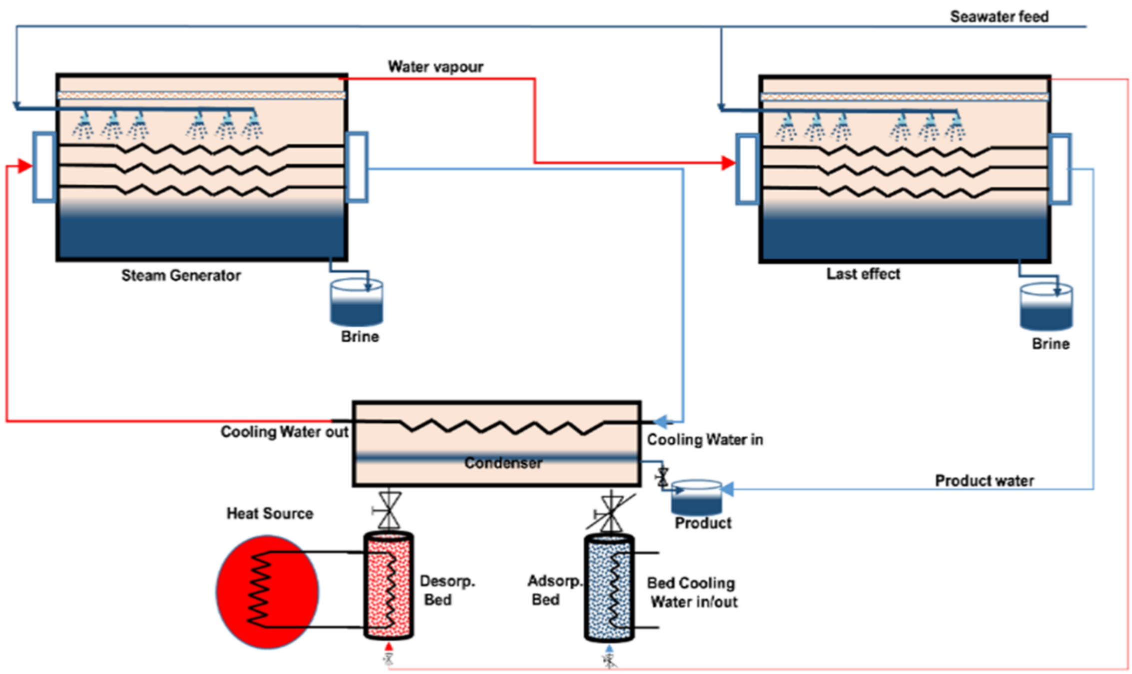

Figure 13. Hybrid MED–ADD (MEAD).

The previous study of [108] was validated, and the author built a prototype for the proposed system. The experimental results of a thermally driven MEDAD hybrid desalination system showed a significant increase in water production as a result of the synergetic operation of MED and ADD systems. Additionally, a different study [109] experimentally demonstrated ADD coupled with MED and theoretical ADD and eight-stage MED. This MEAD configuration utilized internal latent heat recovery from the condenser unit of ADD to the top-brine stage of MED. The results showed that a PR of 4.8 could be reached for the eight-stage MEAD, while PR approached 1 and 0.52 for the three-stage and conventional ADD, respectively. The performance of a multi-effect silica gel ADD configuration coupled with MED (MEAD) applying low heat source temperature and passive heating for the feed water was reported in [90]. Several operational parameters for ADD and MED were investigated, such as cycle time, heat source temperature, and number of intermediate effects. The results showed that with low heat source temperature, PR was higher than in the other ADD configurations.

A hybrid silica gel ADD and MVC (MVC–ADD) system was theoretically studied and modeled in [110]. Some performance operational data were investigated and compared with the conventional ADD system. It was found that 14 m^3/day per ton of silica gel could be achieved.

The effects of hybrid reverse osmosis (RO) brine recycling and ADD adsorption desalination (RO–ADD) on overall system desalinated water recovery were investigated in [111] as shown in Figure 14. It was found that system recovery increased by about 25% compared to a single-stage RO system. Another type of hybrid system was studied in [112], presenting a mathematical model for a MED+RO and ADD system called MEDADRO, a hybrid thermal–membrane desalination configuration. A thermo-economic analysis was conducted, and it was found that the permeate water flow rate increased by 65.5%, and the price of producing water was reduced by 38.4% with respect to the basic configuration. The optimum layout led to a 59.7% increase in water production and a 32.3% decrease in water production cost. In the same direction, authors in [113] numerically investigated a hybrid of brackish water reverse osmosis (BWRO) and ADD. It was designed to produce water for irrigation and domestic use as well as for cooling. SDWP and specific energy of the combined system were 6.3 and 0.8 kWh/m^3, respectively, at RO recovery of 45%.

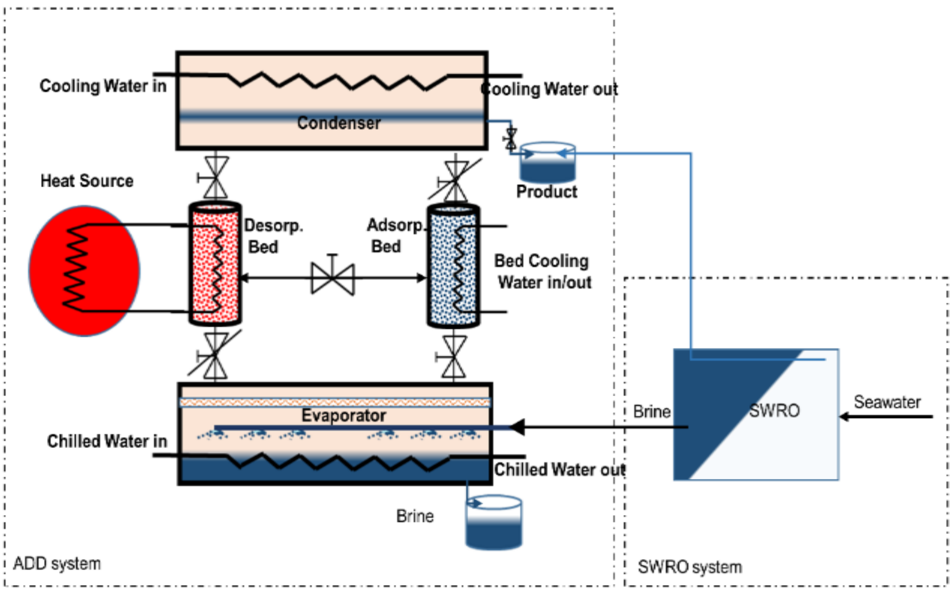

Figure 14. Hybrid of ADD and SWRO.

4.5. Multi-Stage ADD Configurations

One of the drawbacks of a single-stage ADD system is the inability to operate when there is a small temperature difference between the heat source and the feed [114]. Using multi-stage ADD to have additional compression of the vapor in the second and subsequent stages could overcome this problem, as shown in Figure 15.

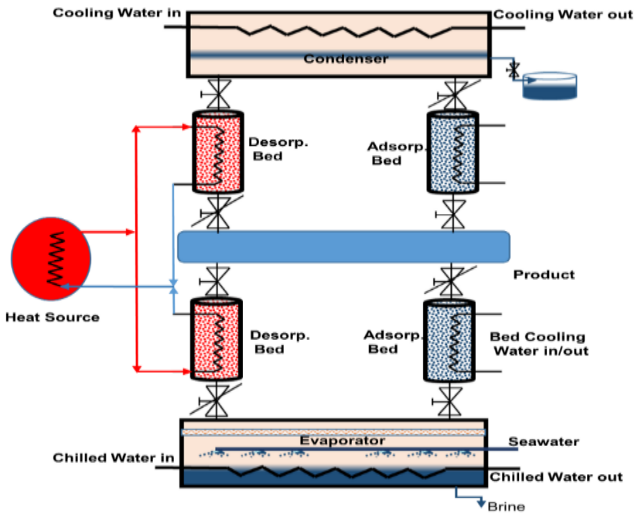

Figure 15. Two-stage ADD system.

Three stages with two beds each, with a heat source temperature of only 50 °C and cooling requirement of 30 °C, was studied in [115]. This arrangement could be applied in tropical climates when the feed temperature increases and approaches the heat source temperature. Different configurations of multi-stage multi-beds were investigated in [116,117]. The work proposed inserting plenum 1 as a vapor collector and pressure fluctuation damper between the two stages, and plenum 2 before the condenser. They observed that the SDWP obtained was lower than in the advanced ADD cycles. The reduction in production was attributed to different reasons, such as the larger radius of silica gel particles used in the study, which leads to slower adsorption kinetics based on the linear driving force (LDF) model. The air-cooled heat exchangers in the system and the operation in a tropical climate resulted in higher condenser and evaporator temperatures. Different ADD configurations are summarized in Table 6 based on the method of study, type of adsorbent, temperature of the heat source, and specific daily water production per ton of adsorbent (Ton_{ads}).

It can be seen that both theoretical and experimental studies were conducted on most of the investigated configurations. The theoretical modelling gave more flexibility to investigate more operation and design parameters, and also to justify the investment in the experiments. ADD investigated mainly two types of adsorbents, zeolite and silica gel. Additionally, AQSOA-Z02 was simulated with four beds and 85 °C heat source temperature, and it could produce 6.2 $m^3/Ton_{ads}/day$. Zeolite and silica gel are silica-based, with physical and chemical characteristics suitable for water production. While zeolite has more uptake capacity, it needs more regeneration temperature, which was used in [91,92] in their theoretical study to obtain higher PR. On the other side, most studies used different types of silica gel with maximum regeneration temperature of 85 °C and minimum of 55 °C to 47 °C in the cascading configuration. The table shows that the maximum production proven experimentally was 13.46 $m^3/Ton_{ads}/day$. with a two-bed advanced condenser and evaporator heat recovery configuration using silica gel type A++ with an 85 °C heat source, while theoretically, twice the SDWP obtained from the two-bed configuration and the same adsorbent but with integrated condenser and evaporator.

Table 6. Summary of reviewed design and performance parameters of ADD configurations.

Ref.	System Configuration	Method	Adsorbent	Source Temp. (°C)	SDWP (m^3/Tads/d) PR
[91,92]	2-bed/single-stage evaporator	Theoretical	Zeolite	Steam	N/A PR > 1
[89]	2-bed/3 multi-effect evaporator	Theoretical	Zeolite	Solar	N/A PR (3–4)
[85]	4-bed	Experimental	Silica gel	85	4.7
[26]	2- and 4-bed	Experimental	Silica gel, type RD	65–85	4-bed/8.79–10 2-bed/3–5
[108]	4-bed mode	Simulation	Silica gel, type RD	85	8
[26]	2- and 4-bed	Experimental and Simulation	Silica gel, type RD	85	3–5
[100]	2-bed (heat recovery)	Experiment	Silica gel, type RD	70	9.2
[79]	2-bed, evap.-cond. heat recovery	Experiment	Silica gel, type A++	85	13.46
[95]	4-bed mode	Experiment	Silica gel, type RD	85	2.4
[114]	2-stage	Experiment	Silica gel, type RD	85	1
[96]	2-bed mode	Simulation	Silica gel, type RD	85	10
[110]	4-bed mode	Simulation	AQSOA-Z02	85	6.2
[111]	1-bed, 2- evaporator	Simulation	Silica gel A+++	55–85	6.5
[104]	2-bed, integrated evap./cond.	Simulation	Silica gel, type A++	85	26
[112]	CE–ADD	Simulation/ experimental	Silica gel	47	
[113]	4-bed master/slave internal heat recovery	Simulation/ experimental	Silica gel A+++	70	10

5. Potential of Implementing ADD in Saudi

The business as usual (BAU) scenario would be to use SWRO in future desalination plants, which is expected to increase energy utilization from 29 m^3 BOE in 2018 to 86.1 m^3 BOE in 2030, as shown in Figure 2. This scenario assumes power plant efficiency of 60% and specific energy consumption of SWRO of about 4 kWh/m^3. Decentralization of water supply production in SA is proposed to be one of the sustainable solutions. Its implementation would reduce production and transmission water cost, reduce carbon emissions, and improve the utilization of local resources such as abundant solar irradiation. Figure 1 shows the availability of ground and transmission line networks lying mostly on the top of aquifers, which may be considered a topographical advantage of using a decentralization strategy for small and medium inland cities with a population of less than 5000 and from 5000 to 20,000. At the same time, the targeted population ranges coincide, as shown in the same figure, with the existing transmission network, solar radiation zones, and aquifer locations. In addition to the decentralization strategy, desalination technology with low cost and low environmental impact require a sustainable water supply. The studied ADD configurations revealed that the following two might be capable of meeting the new demand of the target cities: the advanced ADD cycle with mass and heat recovery, and the hybrid configuration. The first one could operate at heat source temperatures ranging from 50 °C to 70 °C and produce about 4.3 m^3 to 15 m^3 of water per ton of silica. A series of theoretical and experimental studies of the advanced ADD cycle in Saudi Arabia were reported in [5]. They built a 485 m^2 solar ADD pilot plant; the results showed that the specific energy consumption for the ADD to produce water and cooling was just 1.38 kWh/m^3 compared to 4 kWh/m^3 for the most efficient SWRO system. In addition, the researchers studied it numerically, and the promising results revealed that it could produce up to 25.1 m^3 at 85 °C. The second configuration is selected to retrofit the existing MSF, MED, and RO units when the cost of retrofitting is less than or equal to the life cycle cost of constructing new ADD plants. Using the ADD system to supply Abha city and the nearby towns instead of the planned SWRO in 2025, as shown in Table 2, could eliminate the pipeline pumping cost and reduce the energy cost and carbon emissions of the production by more than 70%. The potential impact of using the proposed ADD configuration with specific energy consumption of 1.38 kWh/m^3 on the existing systems in SA is shown in Table 7. The reduced energy consumption and carbon emissions by the Shoqaiq plant reach 91% and 92.4% in the Jubail plant. The massive reductions in both parameters justify the importance of utilizing ADD as an emerging desalination technology associated with decentralization strategy. On the other hand, scalability is an issue for the selected ADD configuration due to the dependence of water production on the amount of silica gel used. For instance, to produce 750 m^3/day of water and meet the demands of 5000 individuals at 150 L/capita/day would require packing 50 tons of silica gel in the series of reactors; 200 tons of silica gel are required to produce water for 20,000 persons. Technically, no such scale has been built and operated up to now.

Table 7. Potential impact of using ADD and decentralization on energy consumption and CO_2 emissions on existing systems in SA by the Saline Water Conversion Corporation (SWCC).

City	Plant	Length (km) Height (m)	Water Flow (M^3/day)	Existing Plan Transmission Pipeline + Current Plants		Proposed Plan Decentralized-ADD without Pipeline	
				Water-Transmission Energy Cost (MUSD/year)	Emissions (tons CO_2/year)	Water-Production Energy Cost (MUSD/year)	Emissions (tons CO_2/year)
Makkah	Shoaibah	90 240	550,000	82.9	653,943	12.8	101,671
Madinah	Yanbu	162 631	450,000	99.5	784,530	10.5	83,186
Abha	Shoqaiq	105 2084	100,000	25.1	198,165	2.3	18,485
Riyadh	Jubail	400 612	950,000	290.6	2,291,034	22.2	175,615

Approximately half of these quantities are required for ADD with productivity of 30 m^3/day/ton of silica gel. Therefore, hybrid systems of ADD and MED or SWRO are excellent candidates to overcome this problem. The hybrid ADD–MED cycle has specific power of 1.94 kWh/m^3 [5], which is higher than the ADD energy consumption and lower than the SWRO energy consumption, while in the proposed scenario, the heat source used is the renewable energy, without the transmission capital and operational cost, in addition to the remarkable reduction in the carbon emission. By producing 10% of the demand by ADD, about USD 0.225 billion of oil market price could be saved from production only, in addition to transmission and carbon credit saving, estimated to be around 40% and 70%, respectively [114].

6. Conclusions and Future Works

This work presents a comprehensive review of the ADD studies focusing on different configurations of desalination systems. The main aim of the current study was to evaluate the state of the art of ADD system configuration and explore the decentralized/distributed production strategy, which can provide a sustainable solution for the water shortage crisis in SA and similar arid areas in the world, specifically for urban communities with small and medium size populations. Four major centralized desalination plants that supply water in four major cities and many small towns and villages via pipelines were studied based on energy consumption, cost, and CO_2 emissions. In this review, ADD systems were categorized based on their configuration features: (i) heat pump with single and multi-stage evaporator, (ii) standard ADD configuration, (iii) advanced ADD with mass and heat recovery, (iv) hybridization of ADD with other commercialized desalination technologies, i.e., RO, MED, and MSF, and (v) multi-stage ADD. The study revealed that two ADD configurations with the highest SDWP could be used. First is the advanced ADD cycle with internal heat and mass recovery between condenser and evaporator and an integrated evaporator–condenser device; its SDWP is 15 m^3 and 26 m^3, respectively. The second is hybrid systems of ADD and MED, and MSF and RO, which can be retrofitted into the existing systems. SDWP of both systems is a function of the tonnage of silica gel, which currently limits the scaling-up of ADD systems. The study highlights that replacing the four existing desalination plants with decentralized small and medium size thermally enhanced ADD could reduce the specific energy consumption from 4 kWh/m^3 (SWRO) to less than 1.38 kWh/m^3. The combination of reduced energy consumption from desalination plants and the elimination of supply pipelines could potentially result in a significant reduction in energy consumption and carbon emissions. Although ADD is a promising technology, it requires further investigation, and future works should focus on improving the adsorbent characteristics, the configurations, and the operational strategies to obtain more vapor uptake while reducing regeneration temperature and operational cycle time. A more thorough study on the impact of decentralization of desalination plants and the use of low-energy-intensive technologies at the macroeconomic level maybe needed to justify the required investment for developing these emerging technologies.

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