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Discussion Paper

Carbon Dioxide Utilization in Saudi Arabia's Desalination Sector

An Opportunity for Achieving Negative Emissions

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Abstract

The global pursuit of sustainable solutions to mitigate climate change has intensified, necessitating innovative approaches that transform traditional carbon-intensive industries into potential carbon sinks. Carbon capture, utilization and storage (CCUS) is a key tool for achieving net-zero targets by 2060 in Saudi Arabia. The country has set targets to achieve 9 megatons per year (Mt/y) of CCUS by 2027 and 44 Mt/y by 2035. Recent work has characterized the Kingdom's geological carbon dioxide (CO_2) potential as around 445 gigatons (Gt), but to date, there has been no detailed analysis of the CO_2 utilization potential in the Kingdom. Current research at KAPSARC aims to review existing and emerging CO_2 utilization routes relevant to Saudi Arabia. This paper focuses on evaluating the untapped potential for CO_2 utilization in the Kingdom's desalination sector and explores the potential of this sector to become a carbon sink, thus contributing to carbon dioxide removal (CDR). Results show that, by 2030, the desalination sector in Saudi Arabia could store up to 458 million tons of CO_2 annually in the brine discharged from desalination plants, transforming brine into a useful product and reducing environmental impacts while also potentially creating negative emissions. The study recommends that policies are introduced to encourage a circular carbon economy (CCE) approach within industry. Policies and regulations supporting the installation of brine recovery equipment as well as CO_2 capture and utilization (CCU) are considered a priority for the desalination sector. Encouraging CCU from atmospheric and biogenic origins is attractive as it provides the potential for carbon removals and offsetting in the desalination sector as Saudi Arabia transitions to a net-zero carbon economy.

Keywords: Desalination, CCU, CDR, Brine, Carbon Utilization, Carbon Storage, Carbon Sink.

1. Introduction

1.1 Carbon Capture and Utilization (CCU) in Saudi Arabia

Anthropogenic climate change, driven primarily by the ever-increasing levels of greenhouse gases (GHGs) in the atmosphere, is one of the most critical challenges facing humanity in the 21st century (IPCC 2023). While mitigating CO_2 emissions remains a global imperative, the simultaneous exploration of innovative and sustainable approaches to deal with existing CO_2 in the atmosphere has emerged as a prominent pathway toward a more environmentally sustainable future (IPCC 2018). Carbon capture, utilization and storage (CCUS) is recognized as indispensable, especially in hard-to-abate sectors, and represents an opportunity to reduce emissions across diverse industries while transforming carbon emissions into valuable commodities.

Carbon capture and utilization (CCU) represents a revolutionary approach as it can transform CO_2 from a liability into a valuable resource (Zhao et al. 2023). A market for carbon dioxide as a commercial product has existed for many decades, with its main applications being in the production of food and beverages, urea manufacturing, enhanced oil recovery (EOR), in greenhouses, fire extinguishers, medicinal equipment, and other smaller markets. The global market for industrial CO_2 ranges from 180 to 230 Mt/y (the largest markets globally being urea [57%], EOR [34%], and food and drink [6%]) (IEA 2019). The main source of industrial CO_2 for these applications has been CO_2 from ammonia production, ethanol fermentation, natural gas sweetening plants, or, in some cases, natural CO_2 reservoirs (Bashmakov et al. 2022). The use of CO_2 in existing applications is driven by economic, not environmental, factors. However, in recent years, new markets for CO_2 have emerged that use CO_2 captured from industry and power plants as a way of combatting climate change.

Geological storage is usually considered the preferred option for CCS due to its high permanence and durability. However, in the last decade, CO_2 utilization in industrial applications has increasingly become highly important as a way of reducing or avoiding carbon. Even so, much of the literature on industrial CO_2 utilization has concluded that such processes are either expensive or lead to significant life cycle emissions. For example, Cuéllar-Franca, and Azapagic (2015) critically assessed the life cycle environmental impacts of carbon capture, utilization, and storage (CCUS) technologies. They concluded that few CO_2 utilization technologies perform better than conventional processes in terms of their overall GHG emissions. The authors emphasized that the energy intensity of CO_2 capture and conversion processes, especially when using fossil-based energy, can lead to higher indirect emissions. Additionally, the economic viability of CO_2 utilization technologies is a key challenge, as many options require large investments with limited financial returns, unless they are supported by carbon pricing or subsidies.

Pérez-Fortes, Bocin-Dumitriu, and Tzimas (2014) provided a comprehensive assessment of various CO_2 utilization pathways, including methanol production, synthetic fuels, and polymers. They highlighted that while some CO_2 utilization technologies show promise in terms of CO_2 reduction, many remain economically unviable without significant subsidies. Additionally, the life cycle analysis indicates that certain CO_2 utilization processes can lead to higher net CO_2 emissions, depending on the energy source. A study by The Joint Water-Agriculture Ministerial Council (2022) provided a life-cycle assessment (LCA) framework for evaluating CO_2 capture and utilization processes. The assessment pointed out that while CO_2 utilization can offset emissions by reducing reliance on fossil fuels, many technologies are energy intensive and can result in net-positive CO_2 emissions if powered by non-renewable energy.

However, in order to deal with such challenges, CCU needs to be considered at the sectoral level, where CO_2 is captured and utilized on site or within a sector. Such an approach helps evaluate sectoral potential on a case-by-case basis. It also provides opportunities for optimum system integration to reduce energy consumption and, subsequently, costs, alongside minimizing life cycle impacts and creating additional revenue streams for sites, thus improving the business case for its adoption. This paper focuses on the role and potential of CCU in Saudi Arabia's desalination sector and highlights the opportunity for this sector to serve as a carbon sink.

1.2 CO_2 Utilization in the Saudi Desalination Sector

This paper proposes using CO_2 in brine to create alternative concrete and store carbon. This could make the desalination sector a carbon sink and potentially contribute to negative emissions, thus contributing to Saudi Arabia's Nationally Determined Contributions (NDC).

In recent years, there has been a growing interest in exploring the potential for brine produced from seawater desalination to be a carbon dioxide sink. Research has investigated the chemical interactions between CO_2 and the dissolved salts in brine, leading to the formation of carbonates and bicarbonates. This mineralization process has been identified as a promising means of long-term CO_2 storage. Mustafa et al. (2020) presented a comprehensive review of the techniques and experiments available in the literature and industry for storing CO_2 in brine. The review presented various techniques, each focused on the extraction of different metals from brine. For example, reacting brine with cement kiln dust can extract 59% to 95% of the magnesium (Mg) in the brine and, at the same time, store CO_2.

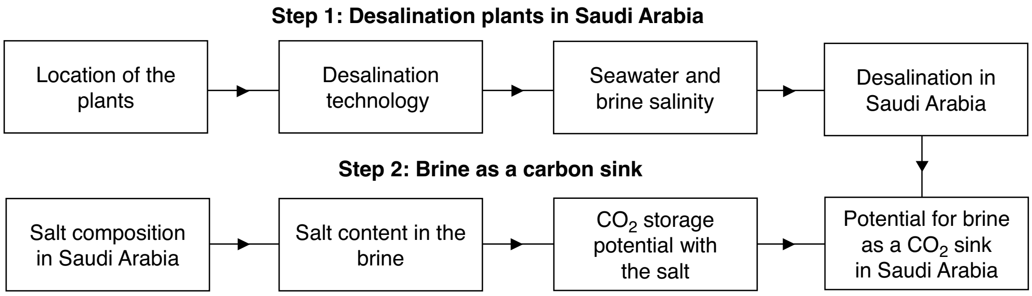
The benefits of brine carbonation are that it addresses environmental concerns surrounding brine disposal and utilizes a readily available natural resource. Brine mineralization serves as a viable CCU method, providing a tangible and scalable solution for capturing and permanently storing CO_2. This can contribute significantly to global efforts to mitigate climate change by reducing atmospheric CO_2 concentrations. Brine-based carbon sequestration can be integrated with resource recovery strategies, such as extracting valuable minerals and metals during the mineralization process. This approach aligns with the principles of a circular economy, where waste streams are transformed into valuable resources. In regions facing water scarcity, such as Saudi Arabia, where desalination is a critical water supply strategy, the integration of brine-based carbon sequestration and storage, and minerals extraction can enhance the sustainability of the region's economy.

This paper aims to estimate the total potential for CO_2 utilization and removal (in Mt/y) of brine from desalination plants in Saudi Arabia as a carbon dioxide sink. Section 2 describes the methodology, and Section 3 presents the results of the analysis. Section 4 discusses the opportunity available for desalination plants across the Kingdom to contribute to CO_2 utilization, introducing a new business model that would help desalination plants decarbonize their operations while also potentially remaining profitable. Section 5 concludes the paper and provides recommendations for future work.

2. Methodology

Figure 1 presents the methodological framework applied in the paper. It is divided into two steps. Step 1 reviews the current status of desalination in Saudi Arabia and investigates its technologies, including their seawater and brine salinity. Step 2 describes how brine can be used as a carbon sink. It investigates the seawater composition in Saudi Arabia, estimates the salt content in the brine for different desalination technologies, and estimates the CO_2 storage potential in Saudi Arabian brine.

Figure 1. Methodological framework applied in the paper.



Source: Authors.

2.1 Step 1: The Desalination Sector in Saudi Arabia

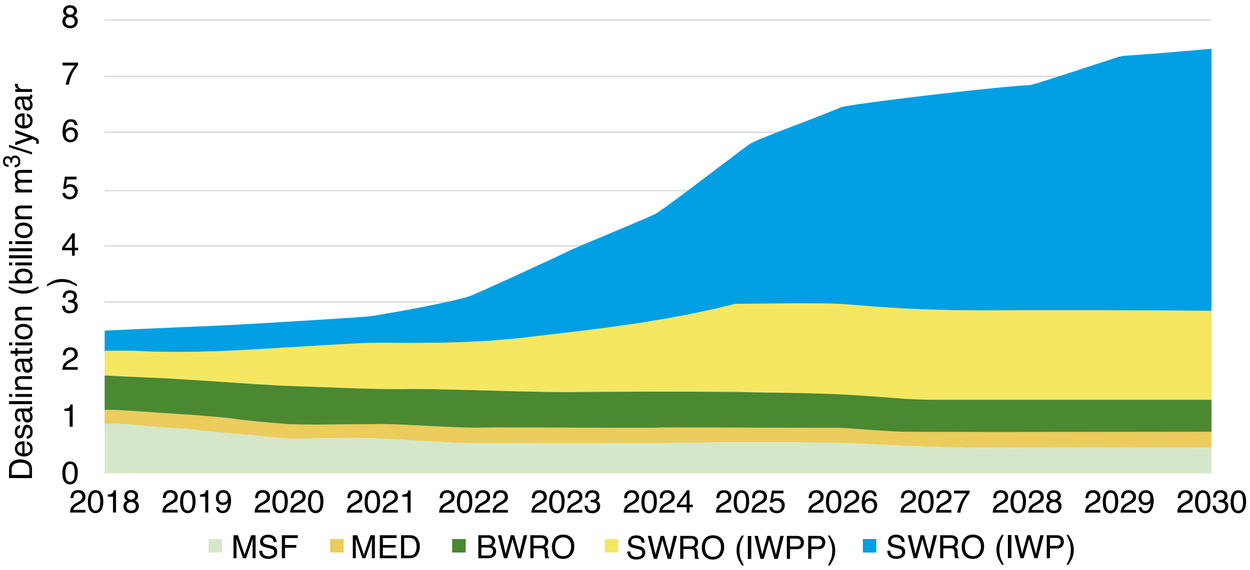
The demand for desalination is poised for significant growth, particularly in countries such as Saudi Arabia, as the world confronts an escalating water scarcity crisis (The Joint Water-Agriculture Ministerial Council 2022). The challenge of securing a sustainable and dependable supply of fresh water has never been more pressing for the Kingdom. Thermal desalination plants, long regarded as a cornerstone of freshwater production in arid and water-scarce regions, are now undergoing a significant transformation. This is mainly driven by the compelling economic and environmental advantages offered by reverse osmosis, including lower initial investment costs and reduced energy consumption (Jones et al. 2019). As a result, an increasing number of regions, including arid coastal areas traditionally reliant on thermal desalination, are now switching to reverse osmosis systems.

Saudi Arabia is the global epicenter of seawater desalination, and current procurement trends suggest sustained momentum (SWPC 2023). The recent green light for the Rabigh 4 Independent Water Project (IWP),[1] boasting a formidable 0.6 million cubic meters per day (Mm³/d) capacity and achieving financial closure in September 2023, exemplifies this ongoing surge. In a strategic move, the National Center for Privatization revealed plans for an additional seven desalination plants capable of collectively producing 3.4 Mm³/d and set to be tendered over the next 13 years. Managed by the Saudi Water Partnership Company (SWPC), these projects contribute to the nation's commitment to expanding its water infrastructure. Running parallel to privately financed initiatives, the Saudi Water Authority (SWA) is replacing aging thermal plants with more energy-efficient membrane facilities. The groundbreaking Jubail 2 replacement plant, contracted in 2022 and set to operate at 1 Mm³/d, is poised to become the world's largest membrane-only facility.

Given the substantial thermal capacity still in operation, the ongoing replacement of such plants is anticipated to be a pivotal force propelling the market forward. Saudi Arabia's industrial landscape is forecast to witness the initiation of one or two major projects annually, aligning with the trend observed since 2014 (Subramani and Jacangelo 2014). For instance, in January 2023, Saudi Aramco awarded a contract to develop an 80,000 cubic meters per day (m³/d) reverse osmosis plant to cater to its Jafurah gas development initiative. Saudi Aramco's shift towards private financing for water infrastructure is noteworthy, awarding concession agreements for three major water projects to the private sector.

In its pursuit of comprehensive resource utilization, Saudi Arabia is making significant investments in brine mining, seeking to extract value from the waste streams generated by its extensive desalination fleet. For example, the Kingdom already uses desalinated brine in its chloralkali plants to produce caustic soda for its downstream industrial plants. The country is exploring zero-liquid-discharge strategies, presenting burgeoning opportunities for innovative technologies in these domains. This strategic approach aligns with Saudi Arabia's commitment to sustainability and the efficient management of its water resources. Figure 2 presents the desalination capacity in Saudi Arabia from 2018 to 2027.

Figure 2. Desalinated water production in Saudi Arabia From 2018 to 2030.



Sources: DesalData (2023); Hunt (2024).

Note: MSF – multistage flash; MED – multi-effect distillation; BWRO – brackish water reverse osmosis; km3 – cubic kilometers.

The shift from thermal desalination plants to reverse osmosis can be explained by the data provided in Table 1 and Table 2. Even though multi-effect distillation (MED) consumes less electricity than seawater reverse osmosis (SWRO) plants, it requires 42 kilowatt-hours per cubic meter (kWh/m^3) of thermal energy. If this thermal energy is transformed into electricity at an average efficiency of 12% for MED and 18% for multistage flash (MSF) plants, it would generate 5.2 kWh/m^3 and 12.3 kWh/m^3 (IAEA 2013), respectively, which is higher than the electricity consumption of SWRO plants. Table 1 compares the costs of desalination plants with a capacity of 250,000 m^3/d (DesalData 2023). Other reasons for the use of membranes are that: (i) the efficiency of SWRO plants is expected to keep increasing, (ii) the costs of SWRO plants are expected to reduce further (SWA 2024), and (iii) SWRO plants have substantially lower CO_2 emissions than thermal desalination plants (DesalData 2023).

Table 1. Comparison of electricity consumption between SWRO, MED, and MSF.

	Electrical energy		Thermal energy		Total energy consumption	
	Value (kWh/m^3)	Comparison to SWRO (ratio)	Value (kWh/m^3)	Electricity from thermal energy (kWh/m^3)	Value (kWh/m^3)	Comparison to SWRO (ratio)
SWRO	3.5	1	0	0	3.5	1
MED	1.5	0.4	42	5.2	6.7	1.9
MSF	4	1.1	69	12.3	16.3	4.6

Source: Xie et al. (2018).

Table 2. Cost comparison between SWRO, MED, and MSF.

Technologies	Capacity in Saudi Arabia in 2023 (1,000 m^3/year)	CapEx*		OpEx*		Water price	
		Value (million US$)	Comparison to SWRO (ratio)	Value (million US$)	Comparison to SWRO (ratio)	Value (US$/m^3)	Comparison to SWRO (ratio)
SWRO	2,438,518	265	1	39.6	1	0.79	1
MED	235,926	391	1.5	43.3	1.1	0.97	1.2
MSF	572,043	528	2	60.7	1.5	1.33	1.7

** These figures are based on a capacity of 250,000 m^3/d.*

Source: DesalData (2023).

The desalination sector is essential to the supply of water in Saudi Arabia. However, it results in substantial CO_2 and brine emissions. For instance, in 2022, the desalination sector emitted 75 million tons of carbon dioxide, mainly from combustion processes (Ye et al. 2023).

2.2 Step 2: Estimating Brine Potential in Saudi Arabia

In order to estimate the total potential for brine from desalination plants in Saudi Arabia to store CO_2, we utilized a stoichiometric approach where we assumed that CO_2 would react with all sodium, magnesium, potassium, and calcium ions. Several operational parameters, including temperature, alkalinity and pH, the concentration of calcium and magnesium ions, brine composition, pressure and mixing, and flow conditions influence the capacity of brine to store carbon. The stoichiometry estimates from equations 1-4 provide a theoretical estimate of how much carbon dioxide can be stored in brine produced by Saudi desalination plants.

The carbon is first converted to carbonates and bicarbonates. Partanna's patented process uses a binder composed of natural and recycled materials, including brine, which are readily found in Saudi Arabia (KAUST 2024). This binder hardens at room temperature, eliminating the need for the clinkering process or industrial heating. Additionally, during a chemical reaction, the binder forms compounds that actively capture and absorb CO_2 from the atmosphere. Equations 1 to 4 are applied; the cations with the highest concentration in brine (Na^+, Mg^+, K^+ and Ca^{2+}) react with carbon dioxide.

$$Na^+ + HCO_3^- = NaHCO_3 \quad (1)$$

$$Mg^{2+} + CO_3^{-2} = MgCO_3 \quad (2)$$

$$K^+ + HCO_3^- = KHCO_3 \quad (3)$$

$$Ca^{2+} + CO_3^{-2} = CaCO_3 \quad (4)$$

Table 3 presents the paths required to estimate the total potential of CO_2 storage in the ions in seawater. The ion concentration per liter of seawater assumes the average concentration in the Arabian Gulf around Jubail, Saudi Arabia (Sharkh et al. 2022), which is 44.46 grams per liter (g/L). Only the cations (Na^+, Mg^{2+}, K^+, Ca^{2+}) have the potential to store CO_2. The number of ion moles in 1 kilogram (kg) of salt is calculated by dividing the number of moles by the molar mass (mol/kg) of the ions. The number of captured CO_2 molecules per cation ions is assumed to be 1, which results in the maximum potential for CO_2 storage. This assumes that the sodium ions are used to produce sodium bicarbonate ($NaHCO_3$).[2] We assume that all the cations react with dissolved carbonate and bicarbonate in the brine to estimate the total potential for CO_2 storage in brine. However, the share of cations that react with carbonate and bicarbonate varies substantially, according to the technology applied in the carbonation process. These technologies are detailed in Mustafa et al. (2020). Table 3 shows that the amount of CO_2 that can be captured by brine is 0.669 $kgCO_2$/kg salt.

Table 3. Potential for CO_2 storage with relevant ions in seawater.

Ions	Ion concentration (g/L)	Ion weight on salt (g/kg of salt)	Ion molar mass (g/mol)	Ion molar on salt (moles/ kg of salt)	CO_2 stored per ion	Carbonated molecule	CO_2 captured* (kg/ kg of salt)
Cl^{-1}	25	56.2	35.45	15.9	0	–	–
N^{a+1}	13.5	30.4	22.99	13.2	1	$NaHCO_3$	0.581
SO_4^{-2}	3.4	7.6	96	0.8	0	–	–
Mg^{+2}	1.53	3.4	24.31	1.4	1	$MgCO_3$	0.062
K^{+1}	0.53	1.2	39.1	0.3	1	$KHCO_3$	0.013
Ca^{+2}	0.5	1.1	40.08	0.3	1	$CaCO_3$	0.012
Total	44.46	99.4**	–	–	–	–	**0.669**

Source: Sharkh et al. (2022).

* *The molar mass of CO_2 is 44 g/mol.*

** *This is not 100% because there are traces of other ions in the salt.*

3. Results

Table 4 presents the estimated salt available for CO_2 storage with different desalination technologies in Saudi Arabia in 2030. This assumes the installed capacity of desalination plants is larger than 50,000 m^3/d and up to 1 Mm^3/d (DesalData 2023). Desalination plants typically operate at a rate of 75%-90% of their annual capacity due to maintenance and downtime and demand variations, among other factors. For the current analysis, we estimate the potential of brine as a CO_2 sink, assuming the plant operates at 80% capacity throughout the year.

The salinity of seawater flowing into the desalination plants is taken from Sharkh et al. (2022). The salinity of the plant's processed water is assumed to be 80 g/L for SWRO and BWRO, and 150 g/L for MFS and MED. Reverse osmosis can store 60% more CO_2 in brine compared to thermal desalination. This is because thermal desalination produces less salt per m^3 of desalinated water. There will be an estimated 685 million tons per year of salt produced in brine using desalination in Saudi Arabia in 2030. Using the ratio for salt in brine of 0.669 kg of CO_2/kg of salt (Table 3), the estimated potential for CO_2 storage in Saudi Arabia in 2030 will be 458 million tons of CO_2 per year. This is sufficient capacity to store all annual emissions from the industrial and power generation sector in Saudi Arabia.

It should be noted that, unlike with geological storage, this brine capacity is renewable and resets every year if desalinated water and brine are being produced. The advantage here is that brine can be utilized immediately for CO_2 storage, while geological storage sites need to be selected, characterized and evaluated before CO_2 injection starts. In addition, geological sites need to be continuously monitored to ensure the safety of storage, thus adding significantly to the costs. The early deployment of CCUS for utilization projects (in this case for CO_2 storage in brine) provides an opportunity to launch and speed up the development of a CO_2 capture industry, while the CCS infrastructure develops with time.

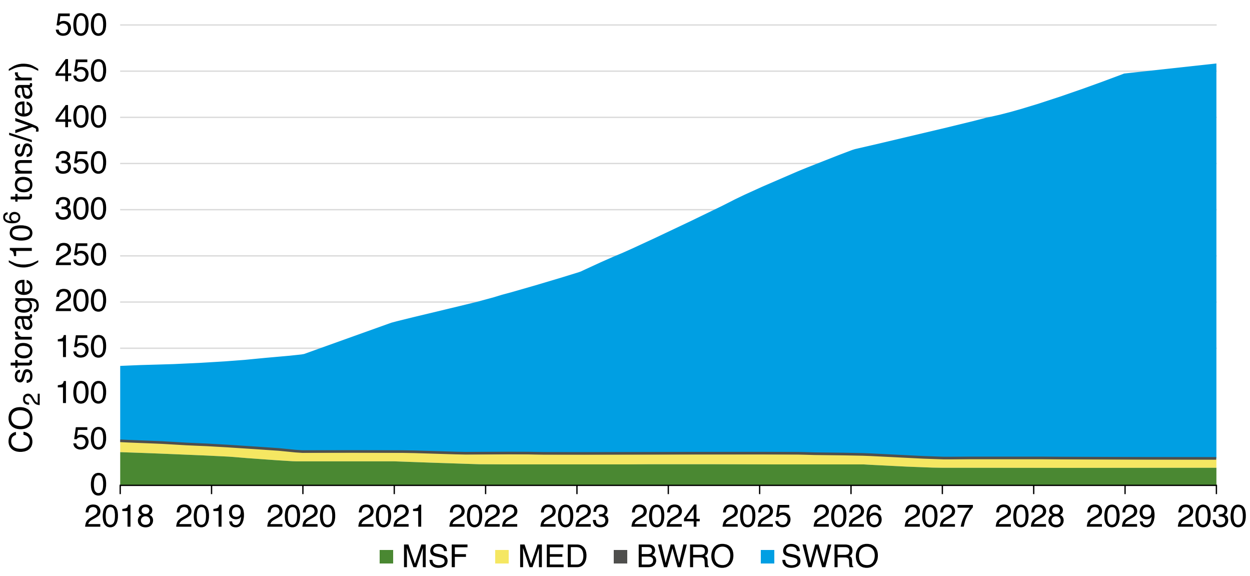
Following the same rationale and the data presented in Figure 2, the estimated potential for CO_2 storage in brine in Saudi Arabia from 2018 to 2030 is presented in Figure 3. The majority of CO_2 storage in brine will come from SWRO plants, as expected. Figure 4 shows that the largest potential for CO_2 storage in brine is in the Eastern and Mecca provinces, at 211 Mt CO_2/y and 137 Mt CO_2/y, respectively.

Table 4. Salt available for CO_2 storage with different desalination technologies.

Description	SWRO	BWRO	MFS	MED	Total
Salinity in (g/L)	45	5	45	–	–
Salinity out (g/L)	80	80	150	150	–
Desalination in 2030 (million m^3/year)	6.18	0.61	0.47	0.24	7.50
Inflow in 2030 (million m^3/year)	14.12	0.65	0.68	0.34	15.79
Brine in 2030 (million m^3/year)	7.94	0.04	0.20	8.19	16.37
Salt in brine (million tons/year)	635.45	3.25	30.38	15.42	684.49
CO_2 storage potential (10^6 tons/year)	425.11	2.17	20.33	10.32	457.93

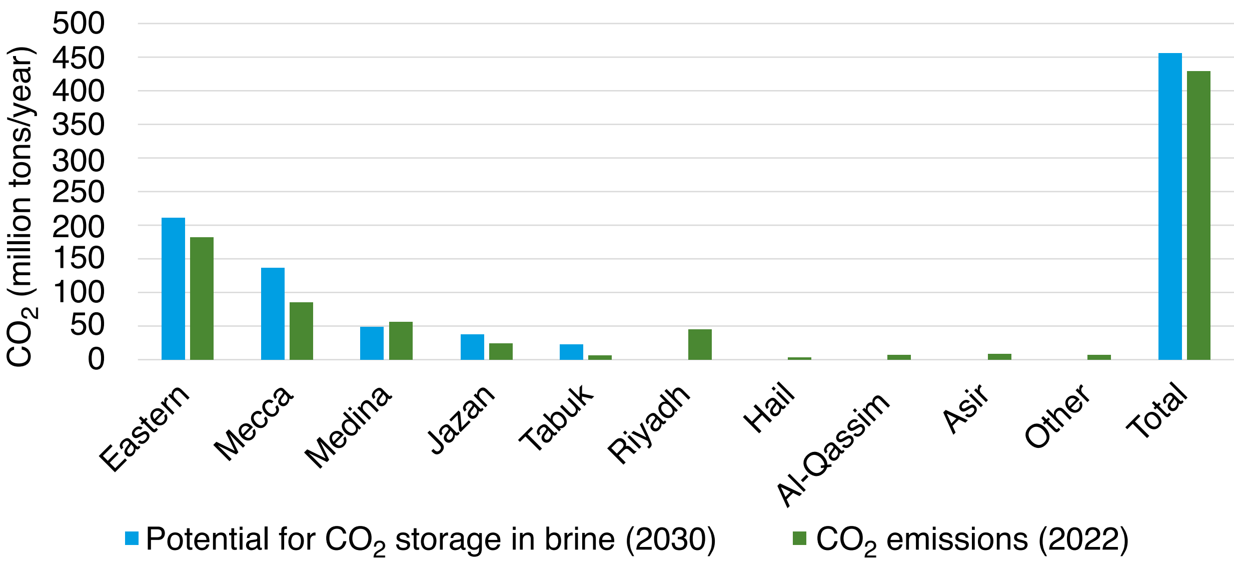
Source: Author's calculations.

Figure 3. Potential for CO_2 storage in brine in Saudi Arabia from 2018 to 2030.



Source: Authors based on DesalData.

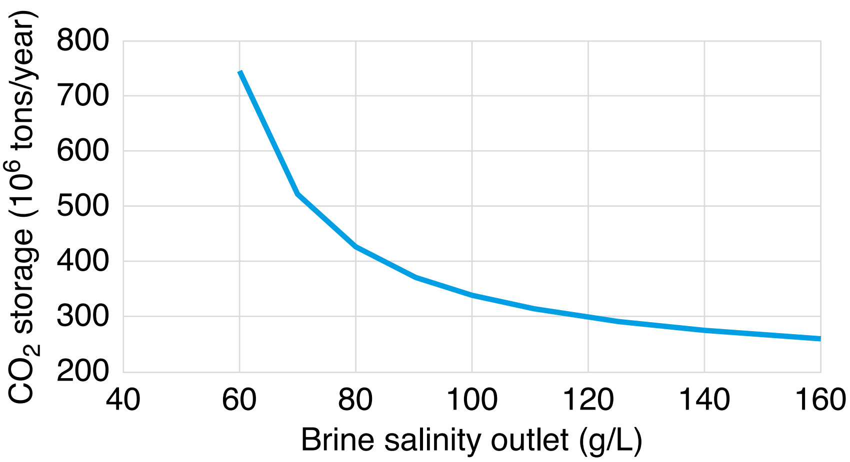
Figure 4. Regional CO_2 storage in brine in Saudi Arabia in 2020.



Source: Authors.

The change in brine salinity has a substantial impact on the potential for CO_2 storage in brine. For instance, with a SWRO brine salinity of 80 g/L, the potential for SWRO brine CO_2 storage is 425 million tons of CO_2 per year. If the brine salinity reduces to 70 g/L, the potential for SWRO brine CO_2 storage increases to 521 million tons of CO_2 per year. Figure 5 shows the change in CO_2 storage potential against the change in brine salinity outlet concentration in SWRO plants in Saudi Arabia in 2030. Depending on the future need for CO_2 storage in brine, Saudi Arabia could reduce the salinity of future SWRO plants to increase the potential for CO_2 storage in brine. Note, however, that depending on the mineral carbonization process applied, the smallest salt concentration in brine increases the cost of mineral carbonization. Future work will examine the optimum SWRO brine concentration for maximizing the potential for CO_2 storage while minimizing the costs of mineral carbonization.

Figure 5. Change in CO_2 storage potential against the change in brine salinity outlet concentration in SWRO plants in Saudi Arabia in 2030.



Source: Author calculations.

4. Discussion

Section 3 presented the major findings, highlighting the potential for CO_2 utilization in Saudi Arabia's desalination sector. This aim aligns with Saudi Arabia's sustainability targets, particularly the ambition to achieve net-zero emissions by 2060. The findings emphasize that the desalination sector, traditionally considered carbon-intensive, has the potential to act as a significant carbon sink when combined with carbon utilization technologies. This transformation could have far reaching implications for both the desalination industry and Saudi Arabia's broader environmental goals. The discussion below highlights a new opportunity for desalination plants in Saudi Arabia. It also discusses the benefits, barriers, policy, and regulatory requirements, and future research and development (R&D) needed for the desalination sector to lead the way in decarbonization through implementing a sector-wide CCE approach.

4.1 The Next Generation of Desalination Plants

Table 5 provides a summary of how desalination plants in Saudi Arabia have changed over time. The first generation (Figure 6a) of desalination plants consisted of MSF operating with oil. They had lower capital expenditure (CapEx) but higher operating costs (OpEx) and CO_2 emissions than MED. Some of these plants still exist in the Kingdom. In the 1980s, a second generation of desalination plants (MED) emerged where oil was replaced with gas (Figure 6a). Both first- and second-generation plants were Independent Water and Power Project (IWPP) plants, producing energy and power simultaneously. The switch from thermal desalination (MSF and MED) to reverse osmosis (SWRO) occurred in the 1990s with third-generation desalination plants (Figure 6b), which still operated as IWPP plants. SWRO IWPP desalination plants were connected to combined cycle gas turbine (CCGT) power plants, operating in full condensing mode (i.e., with waste heat dumping), and producing both power and water.

With the need to decarbonize the power and desalination sectors came the need to increase the flexibility of power generation and desalination plants, and fourth-generation plants emerged as SWRO IWP plants (Figure 6c). These plants consist of an SWRO plant built in the vicinity of a gas power plant, with both plants operating independently. In other words, the SWRO plant can operate using power from the grid if the power plant is switched off. Also, when the desalination plant is switched off, the power plant, operating in condensing mode, can feed electricity into the grid. Even though new SWRO desalination plants are still being built next to existing power plants, they are built separately from them. This increases the costs of desalination and power plants as both utilities require individual substations. See, for example, the Rabigh 3 IWP Phase 3.

The fifth-generation large-scale desalination plant, the SWRO IWP (see Figure 6d), is built completely disconnected from a thermoelectric power plant, relying entirely on grid electricity. This setup allows the IWP plant to potentially operate with 100% renewable energy. In contrast, the SWRO IWPP is designed to function as a base load facility, producing power and desalinating seawater continuously throughout the year. However, base load operations typically rely on fossil fuel-based grid power to ensure a consistent supply, which conflicts with Saudi Arabia's objective of achieving 50% of its power capacity from renewable energy sources by 2030 and becoming GHG net zero by 2060 (Kingdom of Saudi Arabia 2021; Ritchie and Roser 2023). This reliance on constant non-renewable power limits the grid's ability to integrate renewable energy flexibly, thereby constraining the shift toward a more renewable-based grid. Additionally, the sustained use of fossil fuels for base load desalination and power generation increases greenhouse gas emissions, posing challenges for the Kingdom's net-zero targets.

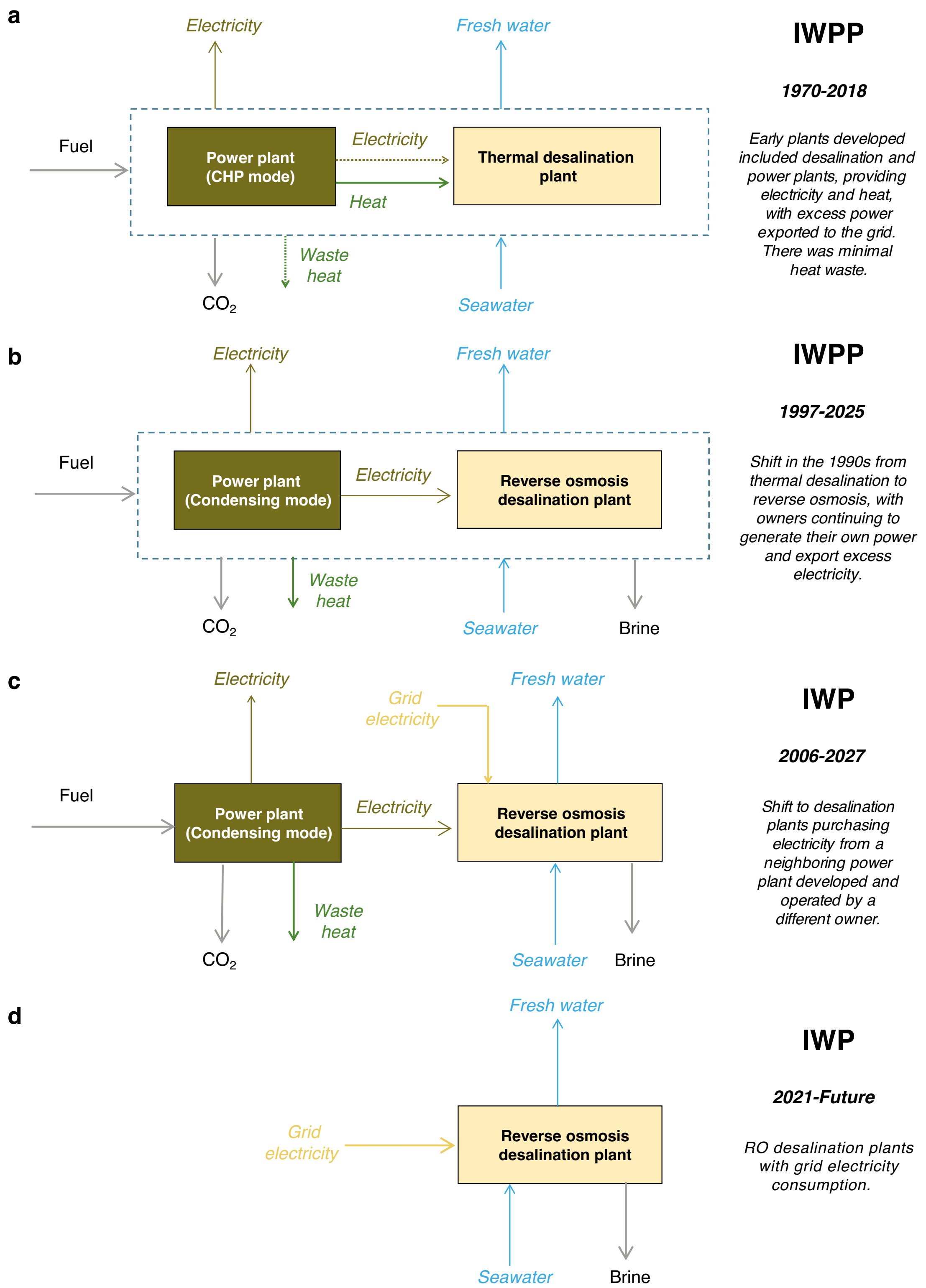
The SWRO IWP plant, on the other hand, offers greater flexibility. It can be powered during periods of excess renewable energy in the grid, allowing it to desalinate water using only surplus renewables. During times of low renewable generation, the grid's power plants can focus on electricity production rather than desalination. Ultimately, the SWRO IWP model supports an adaptable approach, operating desalination with renewable energy primarily during peak production periods and aligning better with Saudi Arabia's renewable energy and GHG reduction goals.

Table 5. Desalination plants transition in Saudi Arabia.

Type	Technology	Timeline	Fuel	Advantage	Disadvantage
Thermal	MSF IWPP	1970-2016 (1st generation)	Waste heat + thermal electricity	• Lower CapEx compared to MED.	• Higher OpEx compared to MED. • Base load operation.
	MED IWPP	1986-2018 (2nd generation)	Waste heat + thermal electricity	• Lower OpEx compared to MSF.	• Higher CapEx compared to MSF. • Base load operation.
SWRO	SWRO IWPP thermal	1997-2025 (3rd generation)	Thermal electricity	• Lower CapEx compared to IWP. • Allow CO_2 storage in brine.	• Thermal electricity is the only source of electricity. • Base load production of power and desalinated water.
	SWRO IWP thermal	2006-2027 (4th generation)	Thermal or renewable electricity	• Lower emissions if renewable electricity is used. • Flexibility for power generation and desalination.	• Higher CapEx compared to IWPP. • Higher emissions if thermal electricity is used. • Does not allow CO_2 storage in brine.
	SWRO IWP renewables	2021-future (5th generation)	Renewable electricity	• No CO_2 emissions. • Flexibility for desalination.	• Does not allow CO_2 storage in brine.
	SWRO IWCCUP	Future (6th generation)	Thermal or renewable electricity	• Low CO_2 emissions. • Negative CO_2 emissions. • Flexibility for power generation and desalination. • Circular carbon economy.	• Fugitive CO_2 emissions. • High CapEx for the CCS.

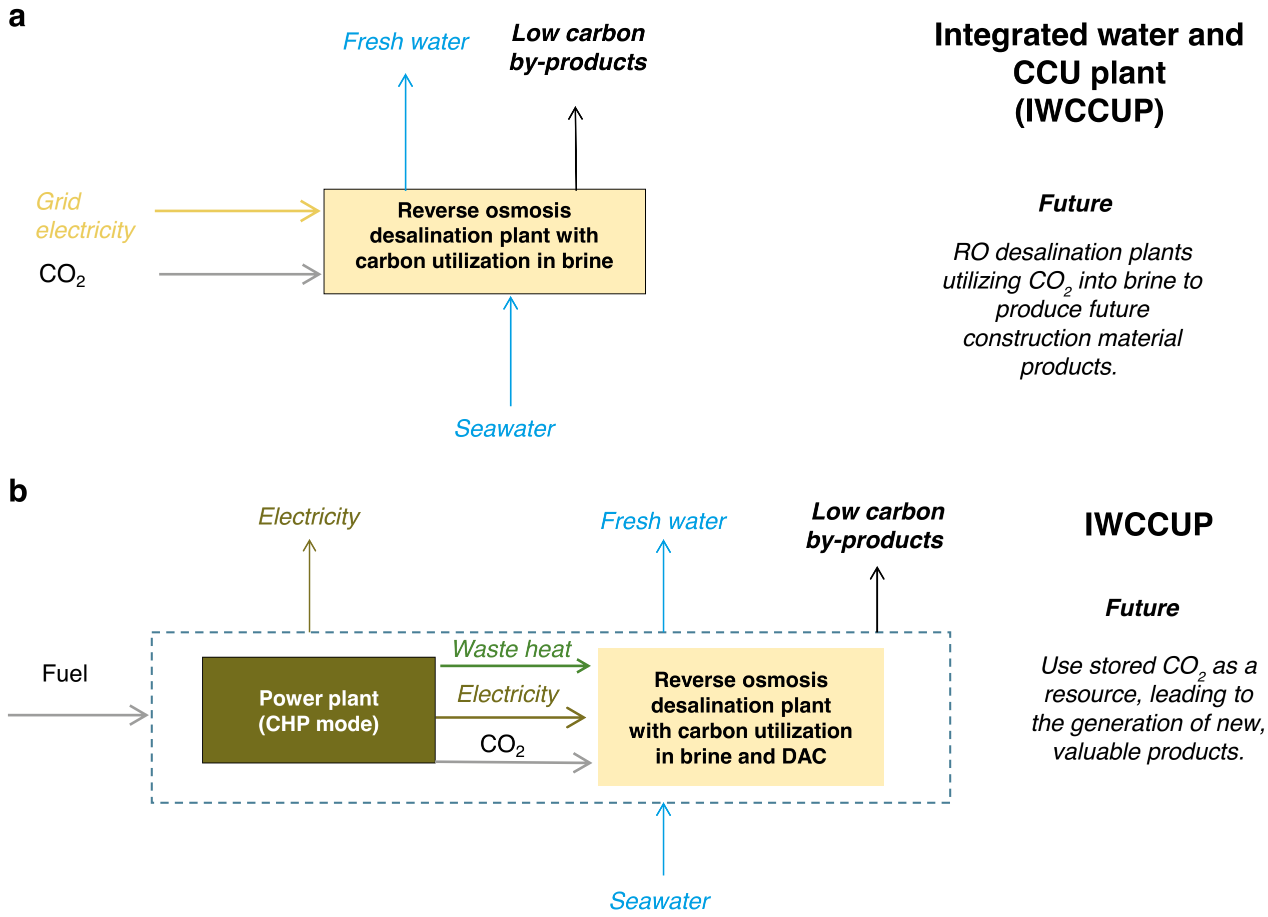
Source: Authors.

Figure 6. Diagram of (a) thermal IWPP, (b) SWRO IWPP thermal, (c) SWRO IWP close to the thermal power plant, and (d) SWRO IWP operating with grid electricity.



Source: Authors.

Figure 7. Diagram of the proposed SWRO IWCCUP (a) with grid electricity and CO_2 from an external source, and (b) with electricity from an onsite power plant and capture plant.



Source: Authors.

In this paper, we propose that the sixth generation desalination plants (Figure 7a and 7b) are SWRO independent water and carbon capture and utilization projects (IWCCUP), with the brine produced from the plants used to store CO_2 and produce useful products, thus adding value through the creation of new revenue streams. The CO_2 can be sourced from other industrial plants in the vicinity of the desalination plants within the same industrial cluster, or from direct air capture (DAC) plants constructed next to the desalination plants. IWCCUP plants can become carbon sinks and create negative emissions by utilizing CO_2 from various sources, such as from DAC plants or from other biogenic emission sources (e.g., CO_2 captured from energy-from-waste, EfW, plants equipped with CCS).

4.2 Benefits and Limitations of Using Brine for CO_2 Storage

This paper shows that the desalination sector has the potential to store all annual CO_2 emissions from stationary sources today. This substantial addition to CO_2 storage complements the huge potential for CO_2 to be injected and stored in geological formations. For instance, the estimated total effective storage capacities in deep saline aquifers, future depleted oil reservoirs, and non-associated gas reservoirs are 432 gigatons (Gt), 5 Gt, and 9 Gt, respectively (Ye et al. 2023).

Utilizing desalination brine for CO_2 storage provides the dual benefit of reducing CO_2 emissions while also addressing the environmental impact of brine disposal. Current practices for brine disposal in marine environments often pose ecological challenges. By diverting this waste stream into a CO_2 sink, desalination plants can transform brine into a valuable resource, thus aligning with circular carbon economy principles. However, challenges remain, including potential ecological impacts from the brine's altered chemistry post-carbonation, and economic factors related to mineral carbonization costs. Future research should prioritize assessing the ecological consequences of modified brine on marine ecosystems.

4.3 Integration With Existing CCS Infrastructure

The analysis shows the potential for desalination plants to complement geological CO_2 storage solutions by providing a more immediate and renewable storage option. Unlike geological sites, which require extensive characterization, desalination brine can be utilized for CO_2 storage immediately. This approach could enable the early development of a CO_2 capture industry in Saudi Arabia, helping to bridge the gap while the Kingdom expands its CO_2 transport and storage infrastructure. However, further work is needed to evaluate the long-term viability and cost-effectiveness of brine storage compared to conventional CCS methods.

4.4 Policy and Economic Considerations

To maximize the CO_2 storage potential in brine, strategic policy support will be essential. Currently, the high costs associated with carbon mineralization and the economic viability of brine-based CO_2 utilization require financial incentives, carbon pricing, or subsidies for these activities to be commercially viable. Policies that support the desalination sector in taking a leading role in the CDR industry, alongside targeted R&D investment, can help drive innovation in carbon utilization technologies. This policy framework could attract investment in next-generation desalination plants equipped for CO_2 storage, thus positioning the desalination sector to be a cornerstone of Saudi Arabia's climate strategy.

4.5 Future Research and Technological Development

Our analysis identified several areas for future research that would enhance the practicality and impact of brine-based CO_2 storage. Specifically, optimizing brine salinity and developing cost-effective mineral carbonization processes are critical for scaling this approach. Additionally, integrating desalination plants with DAC or bioenergy with carbon capture and storage (BECCS) solutions could help the sector offset its emissions while it becomes carbon negative. Research into the future availability of waste heat from industrial sectors, which could power DAC units near desalination facilities, would be valuable for a more sustainable CO_2 capture system. Future work should also consider using a techno-economic analysis to determine the costs and revenues associated with brine mineralization, considering factors such as the demand for and price of low-carbon products and carbon credits.

Future research should also evaluate the techno-economics of CO_2 storage in brine. The main limitation currently to developing a detailed techno-economic analysis of CO_2 storage in brine is the cost of the different carbon mineralization processes involved. Currently, only a few carbon mineralization processes have cost estimates available in the literature (Park et al. 2023). The implementation of brine-based CO_2 sequestration also faces other challenges, including the potential ecological impacts of altering brine chemistry and releasing it into the ocean.

Future work could also explore CO_2 emission sources and sink matching (with desalination plants being the sink in this case) to optimize costs. This could include exploring whether CO_2 can be sourced from stationary sources (e.g., petrochemical, cement or refinery sites), and whether waste heat from nearby facilities can be utilized to combine DAC facilities (as the CO_2 source) with desalination plants (as the CO_2 sink).

4.6 Challenges and Recommendations

Brine recovery equipment already exists on the market, including brine concentrators and crystallizers. These systems can be adapted for CO_2 sequestration, with CO_2 injected into the brine via specialized reaction chambers, leading to the precipitation of carbonates, a process known as “mineral carbonation.” However, implementing brine-based CO_2 storage will still encounter technical challenges, including how to integrate it effectively into desalination plants and sources of CO_2, the high cost of mineralization, and ecological and other environmental impacts.

5. Conclusion

The research outlined in this paper highlights a transformative approach for Saudi Arabia's desalination sector, emphasizing its potential to act as a substantial carbon sink. As the world confronts increasing water scarcity and climate change challenges, innovative strategies that repurpose traditionally carbon-intensive industries into contributors to carbon dioxide removal are crucial. This study meticulously examines Saudi Arabia's desalination sector's capacity to store CO_2, proposing a framework that could align with the Kingdom's national and international sustainability goals.

By 2030, Saudi Arabia's desalination sector will potentially be able to store 458 million tons of CO_2 annually in brine, making a significant contribution to the global carbon dioxide removal efforts. The transition from thermal desalination plants to more energy-efficient SWRO technology has contributed to an increase in the potential of the Saudi desalination sector to store CO_2, given the lower brine salinity content of reverse osmosis (RO). Saudi Arabia's strategic investments in RO technology, coupled with a move toward renewable energy sources for desalination, underscore the country's commitment to reducing its carbon footprint while addressing its freshwater needs. The integration of CCU technologies with desalination processes presents a promising avenue for maximizing CO_2 sequestration. In addition, utilizing brine, a byproduct of desalination, for CO_2 storage through mineralization processes can yield valuable carbonates and bicarbonates, turning waste into a resource. This approach not only addresses environmental concerns associated with brine disposal but also aligns with CCE principles by extracting valuable minerals and metals during the carbon sequestration process. The proposed framework and policy recommendations provide a roadmap for transforming Saudi Arabia's desalination sector into a cornerstone of the country's climate strategy, providing a holistic approach to sustainable development and climate change mitigation.

Depending on the source of the CO_2, the storage of CO_2 in brine can lead to both CO_2 utilization and the removal of CO_2 from the atmosphere. Combining CO_2 utilization in brine with direct air capture or with other engineered CDR technologies (for example, energy-from-waste incineration plants equipped with CCS) can help meet future negative emission and CDR requirements.

Endnotes

[1] 1 An IWP is a type of project where a private entity is responsible for the development, financing, construction, and operation of a standalone water desalination plant without the production of electricity. The sole purpose of an IWP is to produce power without generating electricity. An IWPP, on the other hand, is a project where a private company develops, finances, constructs, and operates a facility that simultaneously produces both desalinated water and electricity. The combined production of power and water optimizes the use of resources and infrastructure, reducing costs and increasing efficiency.

[2] Note that this is not the case for all carbonation routes. For instance, Na^{+1} could react with CO_3^{-2} and produce sodium carbonate (Na_2CO_3).

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Notes

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About the Project

This paper, led by KAPSARC in collaboration with King Abdullah University of Science and Technology (KAUST), is part of a comprehensive project (60020) that aims to assess the potential and feasibility of CO_2 capture and utilization (CCU) in selected industrial sectors. This paper evaluates the opportunities for CO_2 storage in existing brine desalination plants in the Kingdom. Future work involves spatial modeling and evaluating the techno-economics of various CO_2 sources using brine as a CO_2 sink. The project will also assess opportunities for CCU and potential carbon removal in the cement and concrete, and petrochemical sectors.

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