Regional Application of Solar-Powered Membrane Capacitive Deionization (MCDI) in Saudi Arabia

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Abstract

In an attempt to address the growing water crisis in Saudi Arabia and align with its Vision 2030 goals, this report evaluates how the sustainable desalination method of Membrane Capacitive Deionization (MCDI) could be applied within the country. While Reverse Osmosis (RO) remains the primary choice for coastal cities, inland Saudi Arabia relies heavily on brackish groundwater aquifers. Because of this, MCDI serves as a highly viable solution for remote, inland communities to gain access to clean water through a renewable, low-maintenance process. MCDI is an electrochemical method that utilizes charged electrodes to remove salt ions from brackish groundwater, operated efficiently when powered by photovoltaic (PV) cells.

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1 Introduction

1.1 Background and Water Scarcity in Saudi Arabia

The kingdom of Saudi Arabia is implementing policies and strategies to fight back against the water crisis it is currently facing. Saudi Arabia's water crisis puts an immense amount of pressure on its economy, as there is a current heavy dependency on desalination, with desalination currently supplying around 60% of urban water demand. Furthermore, its harsh, arid climate heavily contributes to the lack of renewable water and the low recharge rates of its non-renewable groundwater reserves. Agriculture also presents itself as a major challenge, as 90% of the water supplied to this sector comes from non-renewable water resources. The kingdom already has a narrow amount of nonrenewable groundwater resources, and in 2015, water requirements were estimated at 24.8 bcm and reported to be growing by 7% yearly, making the need for immediate action towards the water crisis crucial.[1]

1.2 Seawater RO VS Inland Groundwater

When examining how different regions of the country obtain its water supply, desalinated water, which is increasingly yielded through reverse osmosis (RO), is a major source of urban water supply, especially in coastal regions of the kingdom. While coastal areas near the Red Sea and the Arabian Gulf, such as Jeddah and eastern KSA can easily rely on coastal desalination, many locations throughout inland Saudi Arabia cannot. The Central Region, for example, heavily relies on groundwater. Riyadh relies on a mixture of treated groundwater and transported desalinated seawater from the coast. In most regions of the kingdom, MEWA has announced plans to reduce groundwater reliance. However, regions such as Hail, Najran, Al Jowf, and Northern Borders are expected to continue relying on groundwater. Inland Central Saudi Arabia has relied on groundwater from non-renewable aquifers, the majority of which contain high-TDS water or brackish water. While Saudi Arabia has seen tremendous progress in their water availability through reverse osmosis plants, it creates a transmission issue for inland communities. Specifically, the transportation of desalinated water from coastal plants to inland communities demands long-distance pumping and widespread transmission infrastructure. With this said, it becomes of importance for methods of treating local brackish groundwater to be explored, in hopes of decreasing the coastal water transmission issue. Inland regions of the kingdom face a significant water-supply challenge, as coastal desalination reliance makes it difficult for potable water to be delivered without technical infrastructure and energy. Furthermore, the local brackish groundwater that is currently available requires desalination before it can be used. [2,3,4]

1.3 Problem Statement

Such challenges highlight the need for sustainable, low-energy technologies that can be used to treat local brackish water. This study investigates membrane capacitive deionization (MCDI), an electrochemical desalination technology for brackish water. This investigation explores the feasibility and obstacles of implementing MCDI in Saudi Arabia, specifically whether it can be implemented as a containerized desalination system for treating brackish groundwater in smaller inland communities. In addition, this study evaluates the potential for photovoltaic solar power to reduce MCDI's energy requirements.

2 Related Work

2.1 Basics of Membrane Capacitive Deionization

Membrane capacitive deionization (MCDI) is an electrochemical desalination technology that removes dissolved ions from water using porous electrodes and ion-exchange membranes. When an electrical potential is applied during the charging stage, dissolved ions move toward the oppositely charged electrodes, where they are stored within the porous electrode material. The ion-exchange membranes help control the movement of ions and improve the overall desalination process. During discharge, the stored ions are released from the electrodes, allowing them to be regenerated and reused in the next cycle [5,7].

2.2 Reverse Osmosis Energy Limitations for Low-Salinity Water

Reverse osmosis (RO) is a pressure-driven desalination process that uses a semi-permeable membrane to separate water from dissolved salts. Although RO is a well-established and widely used desalination technology, it requires the feed water to be pressurized, which contributes to its energy consumption. This becomes particularly important for decentralized treatment of brackish groundwater, where the relatively low salt concentration may make electrochemical methods such as MCDI a suitable alternative. A recent comparison of MCDI and brackish-water reverse osmosis (BWRO) reported lower energy consumption for MCDI under the tested brackish-water conditions [6].

2.3 Pairing MCDI with Photovoltaic Solar Power

Unlike RO, because MCDI operates using electricity rather than high-pressure pumping, it can be directly powered using renewable energy sources. One of which being photovoltaic (PV) solar power. Using PV-generated electricity could reduce the need for grid electricity and make MCDI more suitable for decentralized applications in areas with limited access to the grid. Furthermore, previous research has demonstrated the use of photovoltaic systems to power MCDI for brackish-water desalination, including the use of energy storage and different operating strategies [5]. More recent work has also demonstrated PV-powered MCDI at a larger scale, further supporting its capabilities for renewable-energy-based desalination in decentralized applications [7].

3 Methodology & Evaluation Framework

3.1 Selection of Representative Saudi Groundwater Regions

To begin determining whether PV-powered MCDI is compatible with Saudi Arabia, representative regions were selected based on several factors. These included the availability of groundwater TDS data, groundwater salinity within a potentially suitable range for MCDI treatment, and the potential relevance for decentralized MCDI to be deployed. One candidate that was selected is the Biyadh Aquifer in central Saudi Arabia, due to its reported groundwater TDS values aligning with that of a brackish-water range. Furthermore, the Umm er Radhuma Aquifer was also considered due to the availability of groundwater TDS data. It is important to note that these regions were selected as representative examples in order to assess the potential applicability of MCDI within Saudi Arabia. Although the primary focus is on inland groundwater resources, this technology can be applicable to isolated coastal communities where conventional RO systems could present challenges related to infrastructure.[9,10,11]

3.2 Specific Energy Consumption

To further analyze if MCDI could be applicable to Saudi Arabia, it is important to compare its energy consumption with that of an established desalination technology, specifically reverse osmosis (RO). As the proposed MCDI application focuses on brackish groundwater, brackish-water reverse osmosis (BWRO) was specifically selected for comparison. The specific energy consumption (kWh/m^3) was used as the main comparison metric, as it directly relates to the feasibility of powering a decentralized desalination system using photovoltaic energy. [6]

3.3 Off-Grid Solar PV Sizing & Regional Solar Irradiance Parameters

In order to evaluate the feasibility of powering MCDI using an off-grid photovoltaic (PV) system, regional solar irradiance was considered as an additional selection criterion. The primary solar resource parameter used was the Global horizontal irradiance (GHI), expressed as kWh/m^2/day. This parameter represents the total solar radiation received on a horizontal surface and can be used to assess the solar energy available for PV generation. Saudi Arabia's Renewable Resource Atlas, developed by K.A.CARE, provided measured and modelled solar irradiance data across the Kingdom [8]. Then, the previously selected regions were analyzed based on their solar resources and their potential suitability for decentralized PV-powered MCDI deployment. Afterwards, PV capacity can be determined by comparing the MCDI energy demand to the available regional solar resource.

4 Results & Comparative Analysis

4.1 Groundwater Profiles & Salinity Data for Principal KSA Aquifers

Table 1 Mean TDS measurements across study locations.

Aquifer	Study location	Mean TDS
Biyadh	Wadi Sahba	1,729 mg/L
Biyadh	Wasia Well Field	2,370 mg/L
Umm Er Radhuma	Eastern aquifer system	2,500–5,000 mg/L

The total dissolved solids (TDS) measurements in Table 1 indicate that the Biyadh Aquifer, located in central Saudi Arabia, exhibits brackish-water TDS values at two different locations. Wadi Sahbah, located south of the Wasia Well Field, has a mean TDS of 1,729 mg/L, while the Wasia Well Field has a slightly higher mean TDS of 2,370 mg/L. The Umm Er Radhuma Aquifer, located in the Eastern Province, exhibits a wide TDS range of 2,500-5,000 mg/L. The selected locations all exhibit TDS concentrations within the brackish-water range, indicating their potential suitability for the proposed MCDI application.[9, 10, 11]

4.2 Energy Efficiency Comparison: Solar-MCDI vs. Reverse Osmosis

The study used to compare BWRO with the proposed MCDI technology was conducted by a UNSW research group [6]. At the 20 m^3/day pilot scale, both systems achieved a similar reduction in TDS. However, BWRO consumed approximately 2.37 kWh/m^3, while MCDI consumed only 0.55–0.66 kWh/m^3. When scaled to a larger projected capacity of 1,000 m^3/day, MCDI maintained a lower estimated total energy consumption of 0.40–0.53 kWh/m^3, compared with 0.83 kWh/m^3 for BWRO. These results indicate that, under the brackish-water conditions investigated, MCDI exhibited lower energy consumption than BWRO. This demonstrates the potential energy

advantage of MCDI when treating low-salinity brackish groundwater and supports its potential integration with photovoltaic power.[6]

4.3 High-Suitability Target Deployment Regions in Inland Saudi Arabia

Through the solar resource assessment, it can be seen that inland Saudi Arabia provides favorable conditions for photovoltaic-powered desalination. Previous assessments of solar resources across the Kingdom have reported strong solar irradiation across inland regions, with particularly favorable conditions identified in the southeastern to northwestern parts of Saudi Arabia [12]. Furthermore, regional PV performance assessments have identified locations such as Najran and Tabuk as strong candidates for solar PV deployment [13]. When combined with the groundwater TDS assessment, this suggests that inland regions possessing both suitable brackish groundwater and high solar availability represent promising locations for decentralized PV-powered MCDI systems. Therefore, the Biyadh Aquifer and Umm Er Radhuma Aquifer locations identified in Section 4.1 can be considered potential target regions for further investigation, provided that sufficient solar resources and local community requirements are confirmed at the deployment site.

5 Discussion

5.1 Feasibility of Containerized PV-MCDI Systems for Remote Communities

The results suggest that containerized, PV-powered MCDI systems could be a promising solution for decentralized desalination in remote communities across Saudi Arabia. The selected groundwater locations had TDS levels within the brackish-water range, while the energy analysis showed that MCDI consumed less energy than BWRO under the conditions investigated. Saudi Arabia's high solar irradiance also makes photovoltaic integration particularly suitable. Previous studies by Waite and colleagues have demonstrated the feasibility of combining MCDI with photovoltaic energy for brackish-water treatment [5, 7]. Overall, a containerized MCDI system could offer a flexible and modular solution for communities where connecting to centralized desalination infrastructure is challenging.

5.2 Operational Considerations

Despite its potential, several practical factors need to be considered before PV-powered MCDI systems can be deployed. MCDI performance is influenced by the salinity of the feed water, operating conditions, and the level of desalination required. Since solar energy varies throughout the day, the system must be able to adjust its operation according to the available PV power or be supported by energy storage. Long-term operation also requires attention to electrode performance, membrane fouling, water recovery, and maintenance. Previous pilot-scale studies by Waite and colleagues highlighted the importance of optimizing both MCDI operation and energy management when using photovoltaic power [6, 7]. Further testing with actual Saudi groundwater is therefore needed to assess the system's performance and reliability before considering full-scale deployment.

6 Alignment with Saudi Vision 2030 and UN SDGs

6.1 Support for UN Sustainable Development Goals

The proposed PV-powered MCDI system aligns with several United Nations Sustainable Development Goals (SDGs). First and foremost, it aligns with SDG 6: Clean Water and Sanitation by

providing a potential technology for treating brackish groundwater and therefore improving access to freshwater in communities with limited access to centralized water infrastructure. Furthermore, the use of a renewable energy source, in this case photovoltaic energy, supports SDG 7: Affordable and Clean Energy by reducing reliance on conventional electricity sources. In addition, the development of a decentralized and potentially lower-energy desalination system contributes to SDG 9: Industry, Innovation and Infrastructure through the application of emerging desalination and renewable-energy technologies [14].

6.2 Contribution to Saudi Arabia's Water Security & Local Infrastructure

Saudi Arabia's Vision 2030 also aligns strongly with the potential solution of photovoltaic-powered MCDI. Specifically, it could contribute to Saudi Arabia's water security by enabling the treatment of locally available brackish groundwater, particularly in remote communities where centralized desalination infrastructure may be difficult to implement. Decentralized MCDI units could potentially be deployed closer to inland groundwater sources, unlike conventional seawater desalination, which is mainly concentrated in coastal areas. Integrating photovoltaic energy could reduce the dependence on grid electricity while making MCDI systems more suitable for remote communities. This approach also aligns with Saudi Arabia's larger goals under Saudi Vision 2030, particularly in improving water sustainability, developing more resilient local infrastructure, and expanding the use of renewable energy [15].

7 Limitations & Future Work

7.1 Technical Limits of MCDI

Despite its potential, like any technology, MCDI still has some technical limitations to be considered. As stated previously, MCDI's performance heavily depends on the salinity of the feed water and the amount of salt that needs to be removed. Furthermore, higher desalination requirements generally lead to greater energy use. The performance of the electrodes and membranes may also decrease over time due to fouling, scaling, or material degradation. Compared with conventional RO, MCDI also has less experience at large-scale deployment. Therefore, further long-term testing with representative Saudi groundwater is needed to assess the system's durability, water recovery, and energy consumption under realistic operating conditions.[6, 7]

7.2 Manufacturing Considerations: High-Viscosity Coating Physics

In order for MCDI to move from laboratory-scale production to large-scale manufacturing, the scalability and consistency of electrode development must be considered. Electrode production usually involves applying a carbon-based slurry onto a current collector, making the coating process a key step in determining electrode quality. The relatively high viscosity of these slurries can influence important factors such as how the material flows, the uniformity of the coating, the drying process, and the achievable production rate. Several coating methods could be explored for large-scale electrode manufacturing, including doctor-blade, slot-die, and electrostatic spray deposition. Doctor-blade coating is relatively simple and suitable for laboratory-scale fabrication, while slot-die coating offers greater potential for continuous production [16,17]. Additionally, electrostatic spray deposition could provide greater control over material deposition, although its process parameters would need to be carefully optimized. Electrostatic spray deposition has also been used with layer-by-layer (LBL) spraying of polymers to yield nanofiltration membranes with salt rejection and high permeability [18]. Future work could therefore explore how slurry viscosity and coating parameters affect electrode thickness and uniformity. By understanding

these relationships, an applicable coating method could be identified and support the transition of MCDI electrode production from laboratory fabrication to mass manufacturing.

7.3 Future Work

When looking at the future of this technology, it should begin with experimental testing of MCDI using the selected Saudi groundwater sources, followed by long-term testing under realistic operating conditions. The PV-MCDI system could then be further optimized by investigating suitable PV and battery sizes and testing the system at pilot or containerized scale. From a manufacturing perspective, different coating methods should also be evaluated using the high-viscosity electrode slurry to identify the most suitable method for producing uniform electrodes at higher production rates. Overall, combining field testing, PV system optimization, and scalable electrode manufacturing could help advance the development of a containerized PV-MCDI system for remote communities in Saudi Arabia.

8 Conclusion

This study explored the potential of photovoltaic-powered membrane capacitive deionization (PV-MCDI) for the decentralized treatment of brackish groundwater in Saudi Arabia. Through this assessment, both the Biyadh and Umm Er Radhuma aquifers were identified as suitable examples, as their groundwater TDS values fell within the optimal salinity window for MCDI. An energy comparison with brackish-water reverse osmosis also displayed lower energy consumption for MCDI under the conditions investigated, highlighting its potential for use with photovoltaic power.

The combination of abundant solar irradiance, locally available brackish groundwater, and the flexibility of containerized MCDI systems, PV-MCDI is seen as a promising option for decentralized desalination in remote communities. However, further testing is still needed to determine how the technology performs with actual Saudi groundwater and under long-term operating conditions. Future work should also focus on optimizing PV and energy-storage requirements and developing efficient methods for electrode production. Particularly, improving the coating process for high-viscosity electrode slurries could help overcome manufacturing challenges while supporting the transition of MCDI from laboratory-scale development to larger-scale, containerized systems.

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