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TECHNO-ECONOMIC ANALYSIS OF CAPACITIVE DEIONIZATION TECHNOLOGY: AN OVERVIEW AND CASE STUDIES IN VIETNAM

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Abstract

This paper offers a comprehensive techno-economic analysis of capacitive deionization (CDI) technology, examining its significance in water treatment. The analysis begins with a detailed elucidation of CDI principles, emphasizing its operational framework, and delineating both advantages and limitations. A global overview surveys the adoption of CDI across industries worldwide, comparing it with alternative water purification technologies to establish benchmarks in terms of cost, efficiency, and scalability. Central to this analysis is a robust techno-economic assessment framework for CDI, incorporating a multifaceted approach that considers capital investment, operational expenses, and maintenance costs. The paper expounds on methodologies for evaluating cost-effectiveness, providing insights into the economic feasibility of CDI implementation. Furthermore, the study delves into specific case studies within the context of Vietnam, a region facing distinct water quality challenges. Through meticulous examination, the case studies highlight the applicability of CDI in addressing Vietnam's water issues while conducting a detailed techno-economic analysis of its implementation. Challenges hindering widespread adoption are outlined alongside opportunities for enhancing cost-effectiveness and scalability. Regulatory and policy considerations crucial for promoting CDI technology within Vietnam's context are also addressed. The paper culminates in a forward-looking assessment, prognosticating the future trajectory of CDI technology in water treatment. Recommendations are provided to optimize CDI's techno-economic feasibility globally, emphasizing avenues for further research and development. In summary, this paper substantiates the pivotal role of CDI in addressing water treatment challenges, underscoring its potential impact on water sustainability in Vietnam and across the globe within a comprehensive techno-economic framework.

Keywords: capacitive deionization, water/wastewater treatment, techno-economic analysis, case studies, water challenges, energy consumption.

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1. Introduction

Capacitive deionization (CDI) presents a groundbreaking advancement in the domain of water treatment, operating on the fundamental principle of electrochemistry to address the pressing need for effective desalination and water purification solutions [1]. This innovative technology relies on the manipulation of electrical double-layers formed at the surface of porous electrodes submerged in an aqueous solution. When a voltage is applied across these electrodes, an electrical potential is

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generated, attracting ions from the water into the electrode material's porous structure. This mechanism facilitates the selective removal of ions, contaminants, and dissolved solids, effectively deionizing the water. Unlike traditional methods such as reverse osmosis or ion exchange, CDI does not rely on membranes or chemicals. Instead, it harnesses electrostatic forces to adsorb ions onto the electrode surfaces, storing them temporarily until the electrodes are regenerated [2, 3]. This unique approach enables CDI to offer a sustainable and environmentally friendly method for reducing salinity and improving water quality. The potential scalability, coupled with its low energy consumption and chemical-free operation, positions CDI as a transformative technology capable of revolutionizing water treatment strategies worldwide [4].

Understanding the techno-economic viability of capacitive deionization (CDI) emerges as a pivotal facet in the evaluation and implementation of this innovative water treatment technology [5]. As the global demand for clean and potable water intensifies, exploring sustainable, economically viable solutions becomes imperative. CDI, with its capacity to remove contaminants and ions from water sources, presents a promising avenue. However, the successful adoption and widespread implementation of CDI hinge significantly on a comprehensive techno-economic analysis. This analysis goes beyond mere financial considerations, encompassing a holistic understanding of the economic viability, operational efficiency, and long-term sustainability of CDI. Evaluating the techno-economic aspects of CDI not only ensures the efficient allocation of resources but also determines its feasibility across diverse applications and geographical contexts [6, 7]. In essence, comprehending the techno-economic dimensions of CDI is instrumental in charting a path toward accessible, scalable, and economically viable water treatment solutions that are indispensable in addressing the burgeoning global water crisis.

Since 2013, the exploration of CDI technology's techno-economic dynamics has witnessed a substantial uptick, evidenced by a growing corpus of research dedicated to understanding its feasibility, efficiency, and commercial viability, especially within the sphere of water treatment [5, 8]. This burgeoning literature has traversed diverse sectors, illuminating CDI's multifaceted applicability—from its role in industrial water purification to its potential in augmenting domestic water supplies [5, 9]. However, amidst these global advancements, Vietnam stands out due to a noticeable research gap in the exploration of CDI's techno-economic facets. Despite facing distinct water quality challenges, Vietnam's exploration of CDI's techno-economic facets remains relatively limited, creating a significant knowledge void. This deficiency hampers the country's ability to grasp the full spectrum of CDI's potential benefits and implications for addressing its pressing water treatment needs. As such, there exists an imperative to bridge this research gap in Vietnam, not merely to cater to the nation's specific requirements but also to enrich the broader discourse on CDI's global applicability and its role in fostering sustainable water treatment strategies across diverse international contexts.

The primary objective of this paper is to conduct a thorough techno-economic analysis of CDI technology, offering a comprehensive view that encompasses both a global perspective and specific case studies within Vietnam. In alignment with this revised focus, the paper unfolds in a structured manner, systematically navigating through various facets pivotal to understanding CDI's techno-economic dimensions. The ensuing sections comprise an in-depth exploration of CDI's operational principles, a global overview delineating its adoption and comparison with alternative water purification technologies, and a robust framework for assessing its techno-economic viability. The focal point then shifts towards scrutinizing specific case studies within Vietnam, spotlighting the region's water quality challenges and the potential application of CDI from a techno-economic standpoint. Furthermore, the paper identifies prevalent gaps in research, particularly concerning the techno-economic evaluation of CDI in Vietnam, emphasizing the necessity to fill these voids. Ultimately, the paper strives to provide a holistic perspective on CDI's techno-economic analysis, aiming to contribute to the discourse on sustainable and economically viable water treatment solutions.

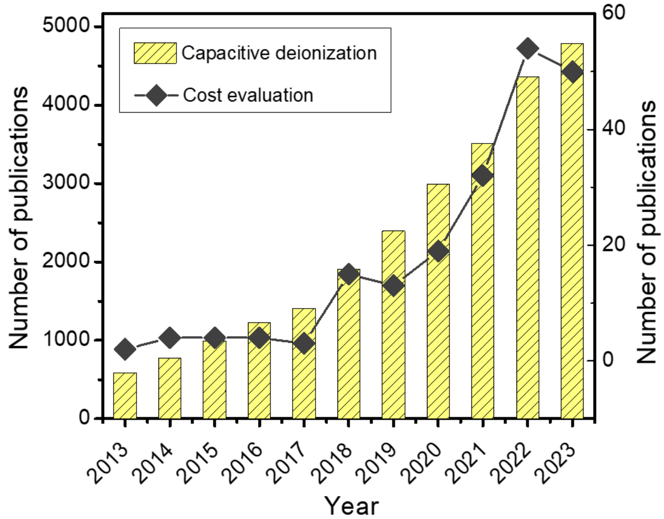

Figure 1. Statistics of the number of scientific publications from 2013 to 2023

2. Understanding capacitive deionization technology

2.1. Working principle of a CDI stack

Capacitive deionization operates on electrochemical principles that leverage the adsorption and desorption of ions to purify water [10]. The process begins with two electrodes immersed in an electrolyte solution. These electrodes, often composed of porous materials like activated carbon or carbon nanotubes, possess a high surface area, which is crucial for ion adsorption. When an electric potential is applied across these electrodes, a process known as adsorption occurs. Ions present in the water move towards the oppositely charged electrodes due to the electric field created. Anions migrate towards the positively charged electrode (anode), while cations move towards the negatively charged electrode (cathode) [11]. As they approach these electrodes, ions are attracted and held within the porous structure of the electrode material through electrostatic forces. This adsorption phase effectively removes ions and impurities from the water, leading to its purification. Subsequently, during the desorption phase, the applied electric potential is removed or reversed. This causes the stored ions to be released back into the electrolyte solution, making the electrodes ready for the next adsorption cycle. The released ions are then disposed of or collected as necessary, completing the cycle of ion removal and regeneration [12].

2.2. Structural component of a CDI stack

The capacitive deionization (CDI) stack serves as the core unit in the implementation of CDI technology, playing a pivotal role in the electrochemical removal of ions from aqueous solutions [13]. The stack is meticulously designed to optimize the deionization process, typically comprising alternating layers of porous electrodes, current collectors, separator (spacer) or membrane and housing (Fig. 2). (1) Electrodes: The electrodes are the core components of the CDI stack and are responsible for ion adsorption and desorption. Usually made of porous materials like activated carbon or carbon aerogels, these electrodes have a high surface area to maximize ion capture. They are arranged in pairs:

one electrode acts as the anode (positively charged) and the other as the cathode (negatively charged). The porous nature of the electrodes enhances their capacity to adsorb ions during the deionization process. (2) Current collectors: These are conductive elements that facilitate the flow of electricity through the electrodes. They ensure uniform distribution of the electric potential across the electrode surfaces. Typically made of materials like graphite or conductive metals, current collectors are in direct contact with the electrodes and help maintain electrical connectivity within the stack. (3) Separator or membrane: In some CDI configurations, a separator or membrane is placed between the electrodes to prevent their physical contact while allowing the passage of ions. This separator assists in maintaining the separation of anions and cations during the deionization process, preventing their unintended recombination and ensuring effective ion capture by the respective electrodes. (4) Flow channels: CDI stacks often incorporate flow channels or compartments through which the water to be treated flows. These channels enable the movement of water through the electrode pairs, ensuring contact with the charged surfaces of the electrodes for effective ion adsorption. Proper channel design and flow control are essential for optimizing the contact time between water and electrodes, enhancing the efficiency of the deionization process. (5) Housing or casing: The entire CDI stack is typically enclosed within a housing or casing made of non-conductive materials. This casing provides structural support, protects the components from external elements, and maintains the integrity of the stack's internal components. It also ensures that the CDI system remains safe and operational [14].

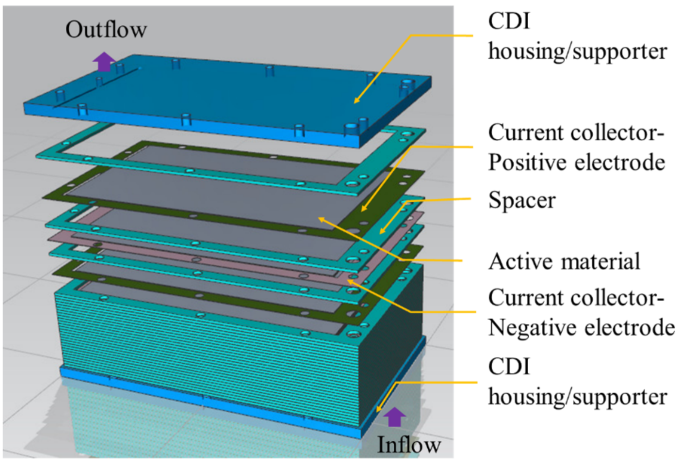

Figure 2. Structural components of a CDI stack

2.3. Advantages and limitations of CDI in water treatment

CDI emerges as a sustainable and promising desalination technology, characterized by its unique operational features and environmental benefits [15]. Unlike conventional methods, CDI offers distinct advantages, notably its low energy consumption, minimal chemical usage, and eco-friendly operation. This technology harnesses electrochemical principles to efficiently remove ions and contaminants from water sources [16, 17]. Its highly controllable process efficiency allows for adaptable ion removal rates, making it suitable for various applications. When juxtaposed with other desalination technologies such as Reverse Osmosis (RO) and Electrodialysis (ED), CDI exhibits competitive advantages (Table 1). RO, while efficient in removing contaminants, often demands significant energy inputs and regular maintenance, coupled with brine discharge, posing environmental concerns [18, 19]. ED, on the other hand, faces challenges related to moderate scalability and pre-treatment needs to prevent scaling on membranes. The distinctive attributes of CDI, including its low energy requirements, minimal environmental impact, and controllable efficiency, position it as an attractive alternative for desalination applications. Its capacity for effective ion removal, particularly for most ion-type pollutants, and moderate to high water recovery rates further solidify its appeal in addressing water treatment challenges [20].

Table 1. Comparison of desalination technologies through different characteristics

Characteristics	CDI	RO	ED
Energy consumption	Low	Moderate to High	Moderate
Process efficiency	Controllable, depends on system	High	Moderate
Environmental impact	Minimal chemical usage, eco-friendly	Chemical use, brine discharge	Moderate chemical usage
Maintenance	Low maintenance, minimal consumables	Regular maintenance, membrane replacement	Moderate maintenance
Operating cost	Relatively low	Moderate to high	Moderate
Scalability	Moderate to High	High scalability	Moderate scalability
Removal of specific contaminants	Highly effective for most ion-type pollutants, variable		
effectiveness for specific contaminants	Effective for most contaminants	Moderate effectiveness	
Water recovery range	Moderate to High (50-90%)	Low to Moderate (20-50%)	Moderate (60-90%)
Pre-treatment needs	Pre-treatment for particulates, organics	Pre-treatment for particulates, organics	Pre-treatment for scaling

3. Global overview of CDI implementation and cost assessment framework

3.1. Major industries and applications utilizing CDI

In the realm of CDI, several major industries and applications have harnessed this innovative technology to address diverse challenges related to water treatment and purification [20]. One prominent sector is municipal water treatment, where CDI systems have proven effective in removing contaminants from drinking water sources [8]. Additionally, industrial processes, such as those in the pharmaceutical and electronics industries, benefit from CDI's ability to efficiently eliminate ions and impurities from water used in manufacturing processes, ensuring the high quality of end products [21]. The energy sector also finds applications for CDI, particularly in power plants and the oil and gas industry, where the technology aids in minimizing the impact of brackish water on equipment and processes. Moreover, CDI has gained traction in the agricultural domain, contributing to sustainable water management practices by mitigating the effects of salinity in irrigation water [15]. As CDI continues to evolve, its versatility and efficacy across various industries underscore its significance in advancing water treatment technologies and promoting environmental sustainability [16].

3.2. Techno-economic comparison of CDI with other water purification technologies

The comprehensive techno-economic analysis presented in Table 2 offers a detailed examination of various water and wastewater treatment methods, with a particular focus on critical parameters such as water recovery and energy consumption. Within this spectrum, CDI and MCDI technologies emerge as exceptionally promising alternatives, demonstrating either comparable or superior performance when compared to other conventional methods. A notable case study conducted by Dinh et al. in Vietnam showcases the efficacy of CDI in treating brackish groundwater, achieving an impressive energy consumption rate of 0.09 kWh m^{-3} [11]. Furthermore, the MCDI system developed by Voltea in the Netherlands underscores its technological prowess by exhibiting outstanding results in treating cooling tower feed water, boasting an exceptional water recovery rate of 90% coupled with a remarkably low energy consumption range of 0.1–0.2 kWh m^{-3} [22].

In contrast, traditional RO systems, exemplified by a case study in Malaysia, exhibit significantly higher energy consumption levels at 1.1 kWh m^{-3} compared to the reported CDI/MCDI systems [13]. This discrepancy emphasizes the superior energy efficiency of CDI and MCDI technologies. Additionally, the ED technology, as elucidated by Metcalf and Eddy, presents energy consumption ranging from 1.5–2.6 kWh m^{-3} in wastewater treatment, further underlining the favorable techno-economic attributes of CDI and MCDI [23]. This in-depth comparative analysis underscores the undeniable potential of CDI and MCDI technologies as not only more energy-efficient but also as economically viable and sustainable solutions for a wide range of water and wastewater treatment applications. Their promising performance in diverse settings, as evidenced by the case studies, positions these technologies as frontrunners in the pursuit of efficient and environmentally conscious water treatment solutions.

Table 2. Major techno-economic information of different treatment methods in water/wastewater treatment

Treatment techniques	Flow rate (m^3/day)	Influent	Water recovery (%)	Energy consumption (kWh m^{-3})	Ref.
CDI, Vietnam	0.5	Brackish groundwater 584.4 ppm NaCl, total dissolved solids (TDS) 2800 mg L^{-1}	45-50	0.088	[11]
CDI, Spain	0.1-0.2	Desalination	-	0.02	[24]
CDI, EST, China	3600	Desalination, offering versatile applications across various industries		0.55-1.00	[4]
MCDI, Taiwan	0.014	Softening secondary effluent from a domestic wastewater treatment plant	-	0.12	[25]
MCDI, Voltea, Netherland	158	Treating feed water of cooling towers facilities	90	0.10-0.20	[22]
RO, Malaysia	4.6	Brackish water, TDS 2000 mg L^{-1}	78.5	1.1	[13]
RO, Tunisia	50	Groundwater treatment, TDS 4000–4500 mg L^{-1}	-	1.7–1.9	[26]
RO, Germany	-	Brackish water ~20	2.5 [27]		
ED, India	18	Groundwater treatment, 1300–1500	-	2.67	[28]
ED, Metcalf, Eddy	-	Wastewater treatment, TDS 1000-2500 mg L^{-1}	-	1.5-2.6	[23]

3.3. Components influencing CDI costs

a. Technical parameters

The removal efficiency of salinity or pollutant ($E\%$) quantified by the fraction of ions removed through the desalination facilities as shown in Eq. (1) [18]:

$$E(\%) = \frac{C_0 - C_i}{C_0} \times 100\% \tag{1}$$

where C_0 and C_i are the salinity ($\mathrm{g\,L^{-1}}$) of feed and effluent streams, respectively. In this part, we briefly illustrate the definition of several key performance indicators, including the treatment capacity, water recovery, specific energy consumption, and operation and maintenance (O&M) costs.

Treatment capacity (Q_i) and water recovery (R) are essential to evaluating the cost effectiveness of a desalination plant. The R value of a desalination plant also directly determines the volume of the rejection brine, which requires subsequent treatment and management. The R value can be determined by Eq. (2) [18]:

$$R(\%) = \frac{\text{Clean water production}}{\text{Treatment capacity}} \times 100\% = \frac{Q_0}{Q_i} \times 100\% \tag{2}$$

where Q_i and Q_0 are the flow rate of feed water and permeate (clean water), respectively. The R value is dependent on the ion removal mechanisms of a desalination facility, as well as the types of the applied materials (e.g., electrodes and membranes). Other factors, such as losses from flushing, can also influence the R value.

Specific energy consumption (SEC, $\mathrm{kWh\,m^{-3}}$) is the electrical energy used to product a unit of clean product water. It is considered as the most important parameter characterizing the performance of the desalination plant. The SEC of a desalination process can be approximately determined via Eq. (3) [18]:

$$SEC = \frac{\text{Total electric consumption}}{\text{Clean water production}} = \frac{\int_0^{t_{TOT}} I \times V dt}{Q_i \times t_c \times R} \tag{3}$$

where V is the applied voltage (e.g., the range of voltage in the desorption process for CDI), I is the current, t_{TOT} is the total operation time, including adsorption and desorption time, and t_c is the treatment time (e.g., adsorption time in the charging phase for CDI).

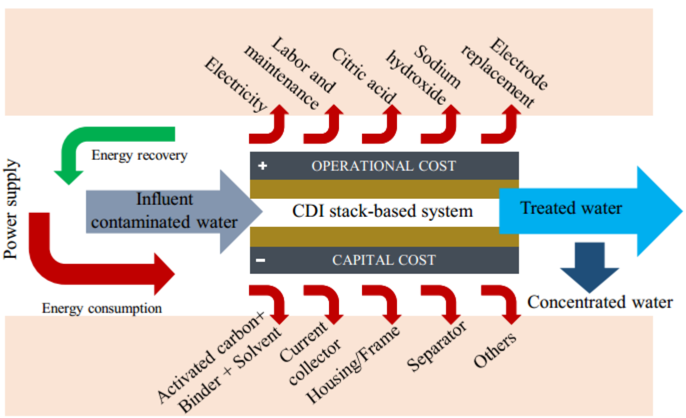

Figure 3. Schematic diagram of capital costs and operational costs of the CDI system

b. Capital cost

The capital cost of a CDI system is a critical consideration in its economic evaluation. For small capacity systems, various components contribute to the capital expenditure. This includes the costs of activated carbon, binder, solvent, current collector, housing/frame, separator, balance of plant (BOP), construction and commissioning, and pre-treatment (Fig. 3). The specifics of these costs, detailed in Table 3, provide a comprehensive breakdown for a more granular analysis. In the case of larger capacity systems, additional expenses such as contingency and indirect costs become significant factors influencing the overall capital investment. These extra fees, also outlined in Table 3, play a crucial role in understanding the financial commitments associated with scaling up CDI technology. Prospective adopters can use this information to make informed decisions based on the specific capacity and scale of their intended CDI implementation.

Table 3. Techno-economic analysis parameters of CDI implementation in Vietnam

Component	Parameters and unit price from previous reports	Our CDI pilot in Vietnam			
		Unit price	Parameters are calculated in m^3 for a machine per year		
			Tap water	Saline groundwater	Saline groundwater
			EC = 350 μS/cm	EC = 2610 μS cm^{-1}	EC = 5540 μS cm^{-1}
Technical parameters					
System capacity (m^3 d^{-1})	5000	-	0.5	0.3	0.1
Estimating electrode life (y)	2.5	-	5	2	1
Estimating system life (y)	20	-	10	7	5
Pumping efficiency	80%	-	-	-	-
Feed pumping head (m)	5	-	-	-	-
Water recovery (%)	80	-	50-60	50-60	50-60
Charge efficiency (%)	45	-	-	53	53
Operating voltage (V)	1-2	-	1.2	1.2	1.2
Energy recovery (%)	30-45	-	-	-	-
Power (kW)	-	-	0.057	0.082	0.132
Capital cost (C) ($/system)			141.47	253.15	443.73
Activated carbon ($ kg^{-1})	5-12	4.5	1.98	3.96	7.92
Binder ($ kg^{-1})	7-21	20	0.88	1.76	3.52
Solvent ($ kg^{-1})	1.65-4.95	6.5	5.2	10.4	20.8
Current collector ($ kg^{-1})	77	71	58.67	117.33	234.67
Frames	1-3 ($ m^{-2})		5	10	20
Separator	1.5-4.5 ($ m^{-2})	-	4.79	9.58	14.38
Balance of plant cost (BOP) ($ $kWpeak^{-1}$)	0.15-0.45	0.2	0.011	0.016	0.026
Construction and commissioning	0.48-0.72 ($ $kWpeak^{-1}$)	-	50	75	100
Pre-treatment (UF)	20 ($ $m^3 feed^{-1}$ day^{-1})	-	0.83	0.83	0.83
Post-treatment (UV)	-		1.25	1.25	1.25
Contingency	10%	5%	6.43	11.51	20.17
Indirect	27%	10%	6.43	11.51	20.17
Operational cost per year (O)			16.43	23.63	54.61
Electricity ($ kWh^{-1})	0.08	0.096	15.95	22.95	36.94
Labor for maintenance ($ y^{-1})	3%	3%	0.48	0.69	17.68
Maintenance cost per year (M)			5.37	10.53	20.37
Citric acid ($ kg^{-1})	0.75	-	0.1	0.2	0.4
Sodium hydroxide ($ kg^{-1})	0.5	-	0.05	0.1	0.2
Electrode replacement ($ y^{-1})	-	-	4.03	8.06	16.12
Other equipment replacement ($ y^{-1})	-	10%	1.2	2.2	3.6

c. Operational cost

Operational costs of a CDI system encompass ongoing expenses incurred during its regular functioning. The two primary contributors to operational costs are electricity and labor/maintenance (Fig. 3). The cost of electricity per kilowatt-hour (kWh) and annual expenditures on labor and maintenance are key parameters for assessing the economic feasibility of CDI systems. By examining these operational costs in detail, stakeholders can gauge the efficiency of the system and predict the financial implications over its operational lifetime. This information aids in budgeting and planning for the sustainable operation of CDI facilities [6].

d. Maintenance cost

Maintenance costs are integral to ensuring the longevity and effectiveness of CDI systems. Detailed in Table 3, these costs include citric acid for removing residual inorganic salts adhering to the CDI electrodes, sodium hydroxide for eliminating accumulated organic matter, as well as expenses related to electrode and other equipment replacements (Fig. 3). Understanding these maintenance requirements is essential for planning and budgeting for ongoing system upkeep. Regular maintenance not only ensures consistent performance but also contributes to the overall cost-effectiveness of CDI technology in the long run. In conclusion, a thorough analysis of the capital, operational, and maintenance costs provides a holistic view of the economic considerations associated with Capacitive Deionization systems. This detailed breakdown, as outlined in Table 3, equips researchers, engineers, and decision-makers with valuable insights for effective planning and decision-making in the adoption and operation of CDI technology [6].

4. Case studies of CDI in Vietnam: Challenges and opportunities

4.1. Specific applications of CDI implementation in addressing water issues

The research endeavors conducted by our group in Vietnam have resulted in the development and operation of three CDI-based systems, as illustrated in Fig. 4. These systems are intricately designed with three primary components: ultrafiltration (UF) for the preliminary treatment of suspended particles, colloids, bacteria, viruses, and larger organic compounds, featuring a pore size of approximately 0.1 µm; a CDI stack incorporating two modules in parallel for efficient electrosorption of ions; and a UV light component for disinfection purposes. In this study, water quality was characterized using electrical conductivity (EC) or TDS, as commonly presented in previous studies [11, 13, 23]. The first system, denoted as #1, features a single module comprising 20 pairs of electrodes and is specifically engineered for treating tap water with the EC value of approximately 330 µS cm^{-1}. In contrast, the second system, labeled #2, incorporates two CDI modules to address the needs of lower salinity groundwater, with an EC value of 2610 µS cm^{-1}, as mentioned in our previous study [11]. The third system, designated as #3, is equipped with four CDI modules to effectively treat higher salinity groundwater, with an EC value of 5540 µS cm^{-1}. Impressively, under an applied voltage of 1.2 V, CDI systems #1, #2, and #3 autonomously operate at distinct flow rates of approximately 0.5, 0.3, and 0.1 m^3 day^{-1}, respectively. The effluent from CDI system #1 achieved an EC value of approximately 40 µS cm^{-1}, while the effluent from CDI systems #2 and #3 were below approximately 300 µS cm^{-1}. The capacity of these systems can be easily expanded by adding appropriate module units. This comprehensive configuration showcases the versatility and adaptability of CDI technology in addressing various water treatment challenges, while the applied voltage and flow rates underscore the flexibility of these systems in catering to different water sources and quality requirements.

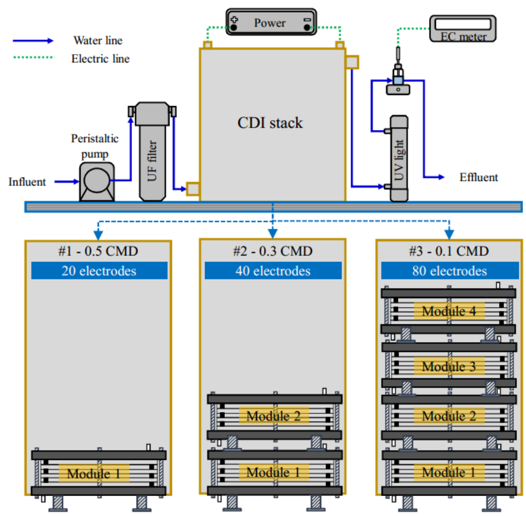

Figure 4. Applications of CDI in addressing water issues in Vietnam

4.2. Techno-economic analysis of CDI implementation in Vietnam

In Table 3, the technical parameters of CDI systems #1, #2, and #3 are detailed, each with capacities of 0.1, 0.3, and 0.5 m^3 day^{-1}, respectively. Notably, the estimated electrode life of System #3, operating in water with high salinity (EC = 5540 μS cm^{-1}), is projected to be limited to one year. In contrast, System #1 exhibits a potential lifespan exceeding five years, contingent upon actual operating conditions. The water recovery rate of the CDI systems in this study, ranging from 50-60%, differs from previous reports, potentially attributed to variations in operating conditions. Additionally, the electrical capacities of Systems 1, 2, and 3 are measured at 0.057, 0.082, and 0.132 kW, respectively.

Moving to the economic analysis, Table 3 outlines the capital costs (C) for construction and installation. Direct costs encompass various components such as activated porous carbon, binder, solvent, current collector (titanium), frames, separator, balance of plant cost (BOP), construction, pre-treatment (UF), and post-treatment (UV). The total construction and installation costs for Systems #1, #2, and #3 are $141.47, $253.15, and $443.73, respectively. Notably, the current collector, constituting 36.7% (System #1), emerges as the most significant component cost, followed by expenses related to the protection and control electrical system and BOP (26.1%) (Fig. 5(a)). On the operational front, annual operating costs (O) encompass electricity and labor for maintenance. Systems #1, #2, and #3 incur yearly operating costs of $16.43, $23.63, and $54.61, respectively. The cost breakdown reveals that, for System #1, electricity constitutes 76.9% of operating costs, while labor for maintenance accounts for the remaining 23.1% (Fig. 5(b)). Maintenance costs per year (M) are evaluated, encom-

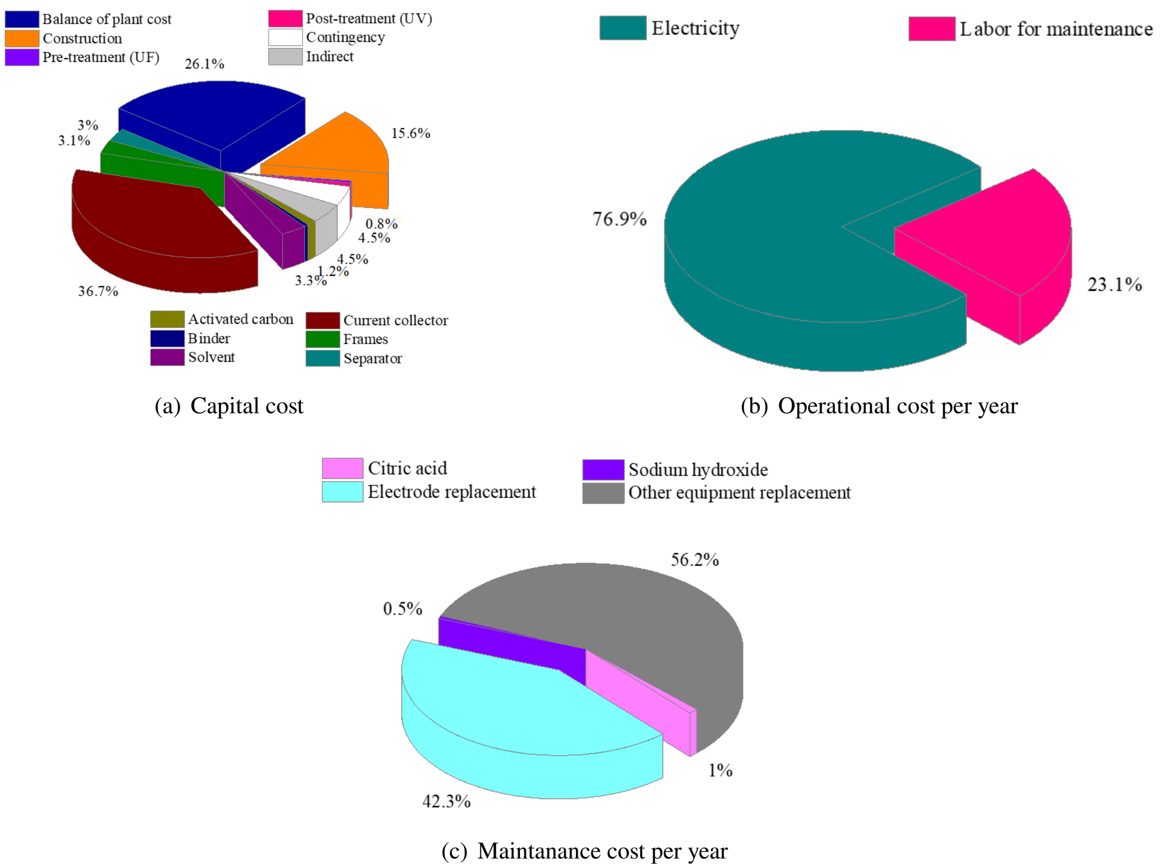

Figure 5. Percentage distribution of capital, operational, and maintenance cost components annually

passing citric acid for inorganic salt removal and sodium hydroxide for organic substance elimination from electrode surfaces. Remarkably, these chemicals contribute only 1.0 to 0.5% of maintenance costs, respectively. Furthermore, electrode replacement and other equipment replacement costs constitute 42.3% and 56.1% of maintenance costs, respectively (Fig. 5(c)). When enhancing the capacity of systems by adding modules, one can estimate the capital and operational costs of the system by referencing the component costs outlined in Table 3.

4.3. Challenges hindering widespread CDI adoption in Vietnam

Table 4 encapsulates a nuanced exploration of the impediments constraining the widespread adoption of CDI technology in the specific context of Vietnam. The challenges are systematically categorized across various thematic areas, providing a comprehensive understanding of the multifaceted issues involved in CDI integration. Within the thematic realm of Awareness & Understanding, the table underscores the critical issue of limited awareness surrounding the benefits and applications of CDI. It emphasizes the necessity for educational campaigns, industry collaboration, and knowledge transfer programs to address this informational gap. In the Regulatory Framework category, the absence of a tailored regulatory framework for CDI is highlighted, calling for the development and implementation of comprehensive regulatory measures and collaborative efforts with regulatory bodies.

Table 4. Challenges hindering widespread CDI adoption in Vietnam

Challenges	Subcategories and Specific Issues	Solutions
(1) Awareness & understanding	Limited awareness of CDI benefits and applications	- Educational campaigns; - Industry collaboration; - Knowledge transfer programs
(2) Regulatory framework	Lack of regulatory framework tailored to CDI technology	- Develop and implement comprehensive regulatory framework for CDI; - Foster partnerships with regulatory bodies;
(3) Financial constraints	High capital costs associated with CDI implementation	- Explore financial incentives and funding options; - Foster partnerships for cost-sharing initiatives; - Research and develop affordable CDI solutions;
(4) Material sourcing challenges	Difficulty in sourcing raw materials for CDI production	- Diversify material sources; - Strengthen supply chain management
(5) Competition and alternative tech	Cost competitiveness of traditional water treatment methods and prevalence of alternative technologies	- Strategically position CDI in the market - Research and develop cost-effective CDI solutions; - Promote the unique advantages of CDI
(6) Technical expertise gap	Skilled manpower and technical expertise in CDI operation and maintenance	- Develop training programs; - Collaborate with educational institutions; - Establish partnerships for knowledge exchange

Financial Constraints emerge as a substantial barrier, with high capital costs associated with CDI implementation acting as a deterrent, prompting the exploration of financial incentives, funding options, and partnerships for cost-sharing initiatives. Material Sourcing Challenges are elucidated, shedding light on the difficulty in acquiring essential raw materials, necessitating strategies such as diversification of material sources and the strengthening of supply chain management. The Competition and Alternative Technologies section delves into the cost competitiveness of traditional water treatment methods and the prevalence of alternatives, advocating for strategic positioning of CDI in the market and the development of cost-effective solutions. Finally, the Technical Expertise Gap is addressed, emphasizing the need for training programs and collaboration with educational institutions to bridge the skillset and knowledge gap. This detailed categorization not only identifies the challenges but also proposes targeted solutions, offering a strategic roadmap for stakeholders. The table serves as a valuable resource for comprehending the intricate landscape of obstacles impeding CDI adoption in Vietnam and provides insights into potential avenues for surmounting these challenges, ultimately paving the way for the successful integration of CDI into the water treatment infrastructure of the country.

5. Future outlook and recommendations

The future outlook and recommendations for CDI within the context of technological and economic analysis are highly promising, signalling significant strides and widespread acceptance. Projections indicate a continual refinement of CDI systems, emphasizing improvements in energy efficiency, scalability, and adaptability across diverse water treatment scenarios. As the technological landscape advances, the integration of intelligent monitoring and control systems is expected to optimize CDI performance. This entails real-time adjustments for enhanced ion removal rates and operational efficiency, aligning with the broader techno-economic perspective. In tandem with technological innovations, the incorporation of novel electrode materials and configurations is poised to revolutionize CDI. This transformation not only augments its capacity for targeted contaminant removal but also contributes to further reducing operational costs. Moving beyond a singular focus on cost analysis, the techno-economic approach encompasses considerations of both technological advancements and economic viability, ensuring a holistic evaluation of CDI's potential.

To maximize the techno-economic effectiveness of CDI globally, collaborative efforts are imperative across various fronts. Foremost is the imperative for standardization and optimization of manufacturing processes. This strategic initiative aims to drive down production costs while maintaining or enhancing system quality. Concurrently, collaborative research initiatives centered on material science, electrode design, and regeneration techniques hold the promise of reducing energy consumption and extending system longevity. Promoting knowledge-sharing platforms and incentivizing interdisciplinary collaborations among academia, industry, and policymakers will facilitate the dissemination of best practices, fostering innovation that aligns with both technological and economic imperatives.

Future research endeavors within the techno-economic paradigm of CDI should strategically address critical gaps and explore novel frontiers. Investigations into advanced electrode materials, including but not limited to nanomaterials or tailored carbon structures, stand out as a promising avenue. These materials can revolutionize CDI's ion adsorption capacity and selectivity, significantly enhancing water treatment efficacy. Furthermore, comprehensive studies focusing on system optimization—encompassing flow dynamics, electrode architectures, and ion transport mechanisms—are essential for unlocking the full techno-economic potential of CDI. Embracing sustainability-focused research, such as the development of environmentally benign regeneration methods and recycling strategies for CDI components, will undoubtedly steer the technology towards greater eco-friendliness and long-term viability within the techno-economic framework.

6. Conclusions

In conclusion, the exploration of CDI within the realm of water treatment unveils a technology brimming with promise and potential. Through a meticulous technoeconomic analysis of CDI on a global scale and comparative examination with various desalination technologies, this study elucidates CDI's distinct advantages, notably its low energy consumption, minimal environmental impact, and controllable efficiency. While acknowledging its strengths, it's evident that CDI isn't without its challenges. Its slower ion removal rate and nuanced effectiveness for specific contaminants highlight areas for refinement and further research. Looking ahead, the future of CDI in water treatment shines bright. Envisioned are advancements that transcend existing limitations, harnessing innovative electrode designs, material breakthroughs, and smart monitoring systems to catapult CDI into an era of heightened efficiency and adaptability. Recommendations centered on optimizing technoeconomic factors underscore the importance of collaborative efforts, standardization, and sustainability-focused research to ensure CDI's affordability and environmental conscientiousness on a global scale. As this paper draws to a close, it's clear that CDI stands at the precipice of transformative evolution within the water treatment landscape. Its journey, fuelled by innovation and collaborative endeavors, holds the promise of delivering sustainable, technoeconomically viable, and environmentally benign solutions to the pressing challenges of water purification worldwide. Embracing these prospects and investing in the continued advancement of CDI will undoubtedly pave the way for a more sustainable and water-secure future for generations to come.

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