Desalination 399 (2016) 53–60

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Life cycle assessment of environmental impacts and energy demand for capacitive deionization technology

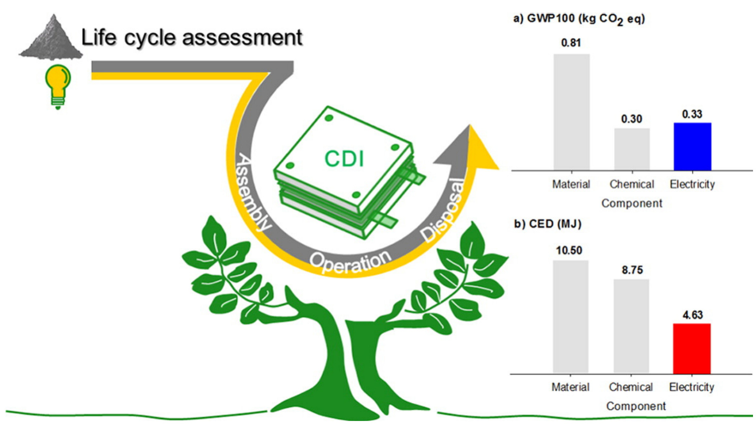
Ting-Hua Yu, Huan-Yu Shiu, Mengshan Lee, Pei-Te Chiueh *, Chia-Hung Hou *

Graduate Institute of Environmental Engineering, National Taiwan University, No.1, Sec. 4. Roosevelt Rd., Taipei 10617, Taiwan

HIGHLIGHTS

- Capacitive deionization is an environmentally friendly desalination technology.
- Cumulative energy demand was the highest at operation phase.
- Energy-related environmental impacts were lowest for electricity consumption.
- Material and chemical uses contributed to most of the environmental impacts.
- Decrease in use of Ti and DMAC is essential.

GRAPHICAL ABSTRACT.



ARTICLE INFO

Article history:
Received 26 April 2016
Received in revised form 31 July 2016
Accepted 5 August 2016
Available online xxxx

Keywords:
Environmental performance
Capacitive deionization
Brackish water
Activated carbon electrode
Desalination
Low energy demand

ABSTRACT

Assessment of life cycle environmental impacts and cumulative energy demand on a laboratory-scale capacitive deionizing (CDI) of brackish water was conducted in this study. The CDI system presented advantages of low energy demand at operation phase and low energy-related environmental impacts. With a measured electricity consumption for CDI operation at 1.44 MJ (0.4 kWh), the total cumulative energy demand for CDI system was estimated at approximately 23.9 MJ for production of 1 m^3 of desalinated water. Results from the impact assessment indicated a global warming potential (GMP100) at 1.43 kg CO_2 eq, which was mainly attributed to the major reduction in electricity consumption as compared to conventional desalination technologies. Moreover, material utilization and chemical use were shown to be most responsible for overall environmental impacts in the CDI system, particularly for the use of N,N-dimethylacetamide (solvent) and titanium (material for current collector). Use of such chemicals might produce derivatives that contributed to major impacts in ozone depletion and acidification potentials. This suggests that additional efforts in future studies of CDI system may be made to substitute or reduce the two to enhance overall environmental performance of the system.

1. Introduction

Clean and stable water supply is one of the greatest current and future global challenges. Exploration of new water resources and development of emerging water treatment technologies are expected to be the

* Corresponding authors.
E-mail addresses: ptchueh@ntu.edu.tw (P.-T. Chiueh), chiahunghou@ntu.edu.tw (C.-H. Hou).

http://dx.doi.org/10.1016/j.desal.2016.08.007

solutions to overcome the challenges. Desalination serves as a sustainable alternative to mitigate the reliance of surface water and groundwater owing to its higher product quality, large quantity of supplement and less affected by climate change. For instance, reverse osmosis (RO) is regarded as a leading desalination technology, and it is operated over 7500 desalination plants worldwide [1]. But its high electricity consumption and high associated environmental impacts are a matter of debate [2].

In a comparative study of conventional desalination processes of RO, multi-stage flash distillation (MSF) and multi-effects distillation (MED) using life cycle assessment (LCA) approach, their results indicated that RO was preferable over MSF and MED from environmental impact perspectives [3]. However, the electricity consumption in RO systems contributed to >80% of the overall environmental loads, especially during its operation phase [4]. Therefore, recent trends in desalination studies focused on substitution of seawater with brackish water or use of clean-fuel as energy supply to reduce the overall impacts of RO systems. A number of studies have shown that the use of brackish water as inlets could significantly lower its electricity consumption [5–7] and almost 50% of the associated environmental impacts [7]; and its airborne emissions could be reduced by increasing use of clean-fuel [8–9].

Among all of the conventional energy-intensive desalination technologies, capacitive deionization (CDI) is regarded as a promising desalination technology due to its unique properties of low electricity consumption (<1 kWh/m^3 or <3.6 MJ/m^3) and environmental friendliness [10–12]. CDI utilizes electrosorption process with highly porous carbon-based electrodes to remove charged dissolved substances from aqueous solutions through an external electric field. Notably, CDI does not require a high pressure pump in operation phase, and its energy can be recovered during desorption process. Besides, CDI was demonstrated to have higher desalination efficiency than RO for treating brackish water, mainly due to its higher charge efficiency at lower salt concentrations [13]. By far, no study has shown a comprehensive environmental assessment of CDI by the means of LCA or environmental impact assessment (EIA) [14].

To author's knowledge, this study is the first work investigating the overall environmental impacts of a laboratory scale CDI. The main objective of this study is to evaluate the resource demands as well as their associated environmental impacts of a CDI system using LCA approach. This study also aims at identifying the key component which contributes significant impacts in the system. Empirical measurements from a laboratory scale CDI system developed by our research group are used for the inventory analysis in LCA. Comparison of the impact results with conventional desalination technique of RO is also conducted. These results are expected to provide comprehensive information for future development and promotion of CDI for desalination.

2. Capacitive deionization (CDI)

CDI is a novel low-energy desalination technology. It also presents advantages of low fouling potential, high removal capacity, high water recovery, and free of secondary wastes and chemical additives [14–16]. Recently, CDI has been widely employed on various environmental applications, such as separation of dissolved inorganic salts (desalination), water softening, removal of heavy metals, and removal of charged contaminants [17–23].

A full cycle of CDI operation consists of charge (electrosorption) and discharge (desorption) processes, as shown in Fig. 1. During charging process, by applying an electrical potential difference onto a pair of highly porous electrodes, ions are forced to move towards oppositely charged carbon electrodes. Then, the ions can be temporarily immobilized in electrical double-layers (EDLs) at the solution/electrode interface, thereby it decreases the salinity level in the solution. On the other hand, during discharging process, which is commonly referred to as electrode regeneration, the system works under short circuited (zero voltage) or reversed electrical potential; therefore, the immobilized ions can release back into the solution. And the electrodes can continuously reuse for purifying water. Most of the published CDI studies were based on constant voltage (CV) during adsorption/charge period [19–26]. Recent investigations pointed that constant current (CC) has been demonstrated with lower electricity consumption as compared to CV. Application of CC also showed high stability for maintaining low salt concentration in effluents and the water quality could be easily adjusted by changing different control parameters [27–29]. Fig. 2 shows the results of a laboratory-scale CDI experiment performed by our research group, including the measurements of solution conductivity in effluent and cell current in the single-pass method. Herein, the electrodes were fabricated by mixing activated carbon (Filtrasorb 400, Chemviron Carbon Inc.) and polyvinylidene fluoride (PVDF, MW = 534,000, Sigma-Aldrich) at a weight ratio of 9 to 1. N,N-dimethylacetamide (DMAc, 99%, Alfa Aesar) was used as a solvent. The CDI cell contained 4 pairs of activated carbon electrodes. Each assembled electrode had an effective surface area of 20 cm × 30 cm with a thickness of approximately 400 μm. It was observed that the conductivity in effluent was maintained over a long period for approximately 36 min (Fig. 2a).

3. Methodology

Life cycle assessment (LCA) is an objective method to analyze and determine potential environmental burdens associated with a product, process or activity as defined by the Society of Environmental Toxicology and Chemistry [30]. SimaPro 8 software with EcoInvent version 3 databases was used to conduct the LCA; and, evaluation methods of CML 2 Baseline 2000 (CML) and Cumulative Energy Demand (CED) were applied in this study.

The LCA of CDI was performed using laboratory-scale experimental results conducted by our research group. For the comparative study between CDI and RO systems, information from a recent reported solar-powered RO system but excluded the solar photo-voltaic unit [31] was applied. The electricity consumption of RO (8.1 MJ or 2.25 kWh for desalination of 1 m^3 of brackish water) was adopted from AWWA [32]. These information were transformed into corresponding environmental impacts by LCA conducted in this study. Although the information used for the proposed RO system was not exactly the same as the information for studied CDI system, their difference is considered acceptable, as both of them were operated in laboratory scales. Economic evaluation of the systems was excluded from this study, as most of the information applied was based on a laboratory-scale set-up.

3.1. Function unit, system boundary and assumptions

Clear function unit and system boundary both play important roles in LCA. In this study, the function unit is defined as 1 m^3 of desalinated water and all calculations refer to this unit. Fig. 3 displays a typical CDI procedure and the considered system boundary. The system boundary mainly covers inputs and outputs for CDI manufacturing, operation and disposal. It was worth mentioning that the CDI module was hand-assembled, therefore, only equipment materials involved in the module, including storage tanks but excluding peristaltic water pumps, were considered in the system. The pumps were used to transport and control feed water into the CDI system at constant flow rates (20 mL/min) and had negligible low energy consumption. Besides, as the pump was regarded as a fixed and common equipment in most of the water treatment processes, its energy demand as well as associated environmental impacts during manufacturing stage were also excluded from the assessment [33].

Several assumptions regarding the LCA of CDI were summarized as follows: (1) the water distribution system was excluded from this