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Environmental and economic assessment of beach well intake versus open intake for seawater reverse osmosis desalination

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HIGHLIGHTS

- Life cycle assessment of the SWRO desalination plant with beach well intake
- Life cycle assessment of the SWRO desalination plant with an open intake
- Plant with beach well intake results in up to 31% less environmental impact.
- Plant with beach well intake results in 13% lower total costs.

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ABSTRACT

This paper presents a comparative life cycle assessment (LCA) and levelised cost (LC) analysis of two scenarios: an *open intake scenario* in which a seawater reverse osmosis (SWRO) desalination plant employs an open intake and membrane pre-treatment prior to RO, and a *beach well scenario* in which feedwater is extracted from the subsurface using beach well intake and cartridge filtration prior to RO. In both scenarios, desalination plants with 35,000 m^3/day capacities were modelled. Results indicate that the beach well intake plant life cycle environmental burdens and LC were as much as 31% and 13% lower respectively, compared with the open intake plant. A detailed contribution analysis revealed that the better environmental performance of the beach well intake plant was significantly influenced by its comparatively low electricity use in the simplified pre-treatment process. The better economic performance of the plant with beach well intake was mostly due to savings in chemical use. The results are based on site specific assumptions. However, the LCA and LC framework developed herein could be used to determine the optimum SWRO seawater intake and pre-treatment configuration at plant sites with different characteristics to those modelled herein, provided sufficient data is available.

1. Introduction

Reliable water supply systems are crucial elements of urban infrastructure, and planning their expansion is challenging. The threat of climate change and global population growth has cast doubt upon the sustainability of traditional water supply sources. This has led to a shift away from reliance on traditional climate dependant supplies such as groundwater and surface catchment dams towards a combination of novel technologies, integrated water sources, water reuse and seawater desalination to provide water security for future urban areas. Seawater desalination provides high quality water. Approximately three billion people — about half of the world's population — live within 200 km of a coastline [1] and 97% of all the water on the planet is saline, so seawater is an accessible resource. Currently, reverse osmosis (RO) is the leading technology for desalination [2]. However, there are concerns over its high cost and environmental impacts when compared to traditional water sources.

Life cycle assessment (LCA) has been utilised to explore strategies for reducing the environmental impacts of RO processes, such as moving towards renewable energy inputs [3–8], cleaner fossil fuels [9,10] and plants' size and location optimization [11]. Muñoz and Fernández-Alba [12] quantified the environmental performance improvement that could be obtained by extracting low salinity groundwater instead of seawater for an RO process. Hancock et al. [13] investigated the improvement in environmental performance of coupled seawater desalination and water reclamation by application of new hybrid technologies. The environmental impacts of seawater reverse osmosis (SWRO) with alternative pre-treatment facilities of ultra filtration (UF) and granular media filter have been also reported [14–16]. However, to the authors' best knowledge, the comparative environmental

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performance of extracting high quality seawater using subsurface intakes for SWRO has not been previously quantified.

Intake facilities extract and provide feedwater for desalination plants. There are two main categories of intake, namely surface intakes and subsurface intakes. Surface intakes collect seawater directly from the ocean and deliver seawater to desalination plants while subsurface intakes tap into the saline coastal aquifer under the ocean floor, onshore or off-shore [17]. The quality of seawater extracted from the subsurface is very site specific. There are sites in which seawater extracted via subsurface filtrates naturally through the seabed, and compared to an open intake extraction, the use of the technology at these sites usually results much lower solids, silt, oil and grease, natural organic contamination, and aquatic microorganisms [18] in the feedwater which leads to simplification of pre-treatment prior to RO and less chemical consumption for membrane cleaning [17,19–21]. For example, in Malta and the Caribbean there are numerous subsurface intake technology-based SWRO plants which only use bag filters or cartridge filters ahead of their SWRO membrane systems. This minimal level of pre-treatment is feasible when subsurface intakes are located in a well flushed ocean bottom or shore, away from surface fresh water influence, with seawater collected from a coastal aquifer of uniformly porous structure such as limestone [17]. Without the appropriate site specific conditions, subsurface intake technology could be a costly choice. Factors such as low productivity of the seashore, low subsurface water quality, high concentration of iron or/and manganese or CO_2 in feedwater, high variation of source water quality and temperature, and polluted subsurface intake water under influence of contaminated groundwater all present challenges for SWRO projects with subsurface intakes [19,22]. Thus, to avoid ineffective employment of the technology, site-specific feasibility assessment is essential prior to plant construction [19].

The most common type of subsurface intake for SWRO desalination plants is beach well intake [18,19]. However, there are a number of factors restricting beach well technology as the intake choice for large plants. First, the modular configuration of beach well intake facilities does not deliver the economies of scale enjoyed by open intake facilities [19], making beach well intakes a cost competitive choice only for smaller plants [18]. Second, open intake technology is a better option than beach well technology for large plants due to the limited source water capacity of beach wells [2]. For large plants there is a need for a large number of constructed wells which could disturb a significant area of seashore land and natural habitat, because wells are typically located on seashore within 100 m of the ocean [18]. Despite these technical and economic constraints, previous literature [19] has reported that at numerous sites the environmental performance of beach well intake plants was superior to open intake fed plants due to lower chemical and electricity use in the pre-treatment phase, although these advantages were not quantified.

This paper quantifies the environmental and economic performances of a SWRO plant using beach well intakes under favourable hydro-geological conditions and compares the results to those obtained for an open intake plant. Comparative LCA and levelised cost (LC) estimates are made for two SWRO process configurations, these being one *open intake scenario* and one *beach well scenario*. For the *open intake scenario* we focus on a 35,000 m^3/day design capacity SWRO desalination plant with an open intake and membrane pre-treatment prior to RO. For the *beach well scenario*, we again focus on a plant with design capacity of 35,000 m^3/day, but in which feedwater was extracted from the subsurface using beach well intake and filtered by only a cartridge filter prior to RO. Although the results are based on site-specific assumptions, the analytical framework detailed below could be readily adapted to assess the comparative environmental and economic performances of SWRO intake/pre-treatment configurations at other sites, such as those with less favourable hydro-geological conditions.

2. Methodology

2.1. Life cycle assessment

The LCA method applied the ISO14040 [23] standard, with the LCA conducted in four stages: goal and scope, life cycle inventory (LCI), life cycle impact assessment, and interpretation. Uncertainty analysis was conducted to assess the influence of variations in process data and model choices on the results. The software SimaPro [24] with connected databases as described in the following sections was used for all LCA modelling and uncertainty analysis.

2.1.1. Goal and scope

The goal of this LCA was to quantify and compare the life cycle impacts of the *open intake scenario* and the *beach well scenario*. The input and output flows of the SWRO plants were determined by conceptual design and site data. The scope of this study was primarily cradle to gate. The LCA covered the construction and operational phase of both SWRO configurations. The main flows in the operational phase were chemical use, consisting of clean in place (CIP) and chemical enhanced backwash (CEB) processes, materials consumed for membrane replacement, and electricity consumption associated with seawater extraction, disc filter (DF), cartridge filter (CF) ultra-filtration (UF) and RO. Disposal of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged brine to sea was also covered. The same functional unit (1 m^3 of desalinated water) was chosen for both scenarios to make them comparable. A time boundary of 30 years was selected for both scenarios. The scenarios' system boundaries and input flows are illustrated in Fig. 1.

2.1.2. Life cycle inventory

LCI analysis is a key step in LCA, involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle [23]. Suh and Huppes [25] identify three main categories of LCI method: process-LCI; economic input–output (EIO)-LCI, and hybrid-LCI. Process-LCI tracks the material and energy flows into the system at the process engineering level and is highly detailed, but suffers from onerous data requirements that make the modelling of complete systems impossible. EIO-LCI quantifies environmental impacts across economic sectors and is able to model a complete economic system using publicly available data, but lacks engineering detail. In general terms, a hybrid-LCI links together a process-LCI and an EIO-LCI in a manner that removes the weaknesses of each approach while retaining their strengths [25].

In this study, SWRO plant construction phase impacts were accounted with EIO-LCI and operational phase impacts were accounted with process-LCI.

2.1.2.1. Desalination plant construction phase: EIO-LCI. An EIO-LCI model augments a country's economic input–output matrix [26] with a matrix of ecological output of each economy sector to obtain a supply chain of product environmental data. In EIO-LCI, the final inventory vector can be calculated by the following mathematical model [27]:

$$Q = N \cdot X^{-1} \tag{1}$$

$$A = Z \cdot X^{-1} \tag{2}$$

$$E = Q \cdot (I - A)^{-1} f, \tag{3}$$

where $N = [n_{kj}]$ is a matrix of ecological commodity output, n_{kj} indicates the amount of ecological commodity output k associated with the output of economy sector j in physical units, $X = \text{diag}[x_i]$ is a matrix of "Total Output", x_i indicates the total industry output summation of output consumed by intermediate industries, final users and exports, X is a