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Desalination supply chain decision analysis and optimization

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HIGHLIGHTS

- The desalination supply chain strategic and operational considerations were modeled.
- A systematic decision making process for large-scale investments was proposed.
- A formal optimization model considering quantitative and qualitative decision metrics.
- A real world case and GIS visualization exemplify the use of the proposed methodology.

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ABSTRACT

The desalination industry has been growing progressively in the last few decades. A large number of new plants are contracted every year. Strategic decisions related to plant locations and capacity, the selection of the desalination technology, and many other technical decisions related to the plant design and operation are very critical to these strategic investments. Viewing the desalination industry network as a supply chain provides a holistic view allowing decision makers to perform optimization of water desalination operations end to end. The methodology we propose provides the decision makers with (1) a set of investment alternatives comprising combinations of the different desalination locations, capacities, technologies, and energy sources, and (2) a decision graph showing the performance of each decision alternative in terms of quantitative and qualitative performance metrics chosen by the decision maker. The case study of Saudi Arabia, the world leader in desalination, shows how the methodology can present strategic planners with an optimal configuration of the desalination supply chain.

1. Introduction

Many countries around the world have realized desalination as a practical solution for critical water shortage problems. Desalination capacity has been growing steadily worldwide with a large number of new plants contracted every year. The global contracted capacity of desalination reached 80.47 million m^3/d with about 600 new plants added during 2012 [1]. With the increasing population worldwide (and the resulting increase in demand for fresh water), diminishing natural water resources, and the constant advances in desalination technologies, these numbers are expected to continue to grow in the future. Strategic planning for the expansion and operation of desalination systems is essential to maximize the economical and the social return on these large-scale investments. Each strategic plan should evaluate systematically a large number of desalination alternatives to avoid sub-optimality. Furthermore, strategic planning should account for the environmental consequences of the desalination facilities in order to avoid unsustainable solutions.

We propose a methodology to support strategic decision making for the water desalination supply chain. Our methodology provides decision makers with a set of investment alternatives for various desalination supply chain configurations. Viewing the desalination network as a supply chain provides a holistic view allowing decision makers to optimize on a global level. This also allows for the application of existing supply chain theories, models, and standards for performance measurement so as to increase overall efficiencies [2,3]. In the previous work [3] we proposed the idea of viewing the desalination network as a supply chain and coined the term "water desalination supply chain" in the literature. We also defined the strategic and operational decisions involved in the desalination supply chain and proposed a simple mathematical model to represent the network. In the current work, we extend the mathematical model to include detailed financial and environmental considerations and to model the network in more detail. We also propose a methodology to support systematic decision making for large-scale investment in desalination.

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With the increased importance of the role of desalination, several methodologies have been developed to guide the design and the operation of desalination systems [4–6]. The work on desalination process modeling and optimization focuses on the process within the plant and is limited to decisions related to operational level design and parameters. Optimization of water resource management has been employed to guide strategic decisions related to the supply and distribution of water to meet the overall demand [7–11]. Decision support systems and tools have been also implemented for the desalination optimal water management decisions [12–14]. However, these tools typically are limited to providing a set of design components from which the user must choose; this then limits the number of available configurations. By contrast, our proposed methodology provides decision makers with a systematic decision process to evaluate a wide range of desalination decision alternatives to support strategic planning for desalination.

The main contributions of the current work include (a) describing the various decisions involved in the strategic planning of desalination options; (b) proposing a methodology to address strategic planning for the desalination supply chain; (c) implementing a formal optimization model; and (d) conducting a case study with real world data, proposing a simple data framework for GIS visualization, and discussing the case results.

2. Desalination supply chain

In [3] we introduce the concept of a desalination supply chain and specify it as follows:

> "The supply chain for water desalination includes all relevant supplies and materials, processes, and resources for producing water and for storing and distributing this water to meet the demand. The management of the supply chain focuses on the question of how best to match supply to demand. The value of the supply chain perspective comes from being able to plan or optimize at a system level rather than at a component or unit level, and hence, to obtain system plans or designs that are closer to being "globally optimal." In essence, the supply chain perspective attempts to avoid sub-optimization."

We next describe the various decisions involved in desalination supply chain planning.

2.1. Desalination supply chain design considerations

In [3] we define the design decision for a supply chain for this context as:

> "At the design stage, supply chain management translates into determining the number, type and location of desalination plants, as well as the distribution system (e.g., pipelines) connecting these facilities and connecting to the demand points."

2.1.1. Plant location

The source of feed for a desalination facility and the use of the product water usually determine the location. When seawater is the source of the feed and the product water is to be used for domestic purposes (vs. agricultural or industrial) the facilities will typically be located along the coast closest to the city generating the domestic demand [15]. Other possible locations include inland plants that use other water resources such as brackish ground water and wastewater. Plant location and site characteristics greatly influence the design of the desalination unit and the capital and operational costs encountered. Plant location also plays an important role in determining the method for brine disposal and the overall environmental impact of the facility [15]. In some new installations, the locations of new desalination plants can be chosen to replace retired plants in the same location; this provides advantages in cost reductions if support facilities of the old plant are reused for the new plant. Footprint considerations in general are less important in areas with higher availability of land such as in the Middle East. However, new installations are now designed to optimize footprint requirements due to the value of the land especially in developing and residential areas [15].

2.1.2. Technology type

Different desalination technologies are appropriate for different water salinity levels, feed sources, product quality, and plant sizes. Desalination technologies have been rapidly changing, with substantial innovations made available in recent years which diminish these differences and allow for more options. Traditionally, thermal processes including Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression (VC) have been more efficient for higher salinity seawater; however recent developments have increased the efficiency of membrane technologies (i.e., Reverse Osmosis (RO), and Electrodialysis (ED)), and allowed higher salinity levels, various feed sources such as Seawater (SW) and Brackish Water (BW), and higher reliability and service factors. The integration of thermal desalination with energy production systems (e.g., conventional power plant, combined cycle, hybrid plant, residual heats), or renewable energy such as solar thermal, wind energy, photovoltaic energy, and hydro-power energy increases the competitiveness of thermal technologies and improves efficiencies whenever there is a need for a cogeneration of power and water. Hybrid systems of multiple technologies provide the advantages of reducing water intake, extending membrane life of RO systems, and blending products to reach desired quality.

2.1.3. Design capacity

The size of the plant and its design capacity are determined based on the demand as well as other key factors related to economical and budget constraints, technical considerations, and water requirements. Traditionally, MSF processes have been the choice for large plant sizes. Larger plant sizes offer the opportunities of economy of scale in thermal desalination, as investment costs decrease significantly with the increase in the plant capacities which might form an incentive to increase plant size. However, with very large thermal processes (e.g., larger than 1 million m^3/d) the seawater requirements (amount abstracted from the feed) and the brine discharge would require larger amounts of energy with the majority disposed back into the sea. The RO technology is typically modular which reduces the economy-of-scale factor; consequently, as demand grows, gradual expansion becomes a more viable option. In addition, the larger the plant size the larger the investment and the greater the risk for the government or for the off-taker (who is purchasing the produced water to deliver it to final customers) depending on the project and the contract type. The capacity of recent large scale projects varied between 272,500–880,000 m^3/d for MSF, 25,000–800,000 m^3/d for MED, 65,000–347,000 m^3/d for SWRO, and 28,400–66,670 m^3/d for BWRO [16].

2.1.4. Network structure and distribution capacity

Planning and construction of water transmission pipelines and connection to distribution networks are not examined in the desalination cost literature when evaluating desalination investment options. However, strategic expansions and development usually include investments in new pipeline structures to increase the distribution capacity. Plant locations should be evaluated by considering the current distribution systems and the possibilities to avoid additional costs of water transfer or not running the plant under its optimal condition because of the limited distribution capacity. This is particularly important when land cost at demand points is a significant factor, requiring greater water transmission costs [16].