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Natural gas and grid electricity for seawater desalination: An economic and environmental life-cycle comparison

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HIGHLIGHTS

- Grid electricity and onsite power generation using LNG were compared based on LCC.
- Environmental benefits of onsite power generation using LNG/NG were assessed.
- Key factors impacting the life cycle cost comparison were identified.

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ABSTRACT

In recent years, natural gas (NG)- and liquefied natural gas (LNG)-based power generation options have been considered as a potential alternative to grid electricity at desalination plants to reliably meet the increasing energy demand and reduce the associated environmental impacts. This study comparatively evaluated on a life cycle basis the economic and environmental cost-benefits of LNG/NG for self-generation of power with those of the grid electricity supply. The analysis conducted showed that for desalination plant sizes of 75–570 ML/day, the LNG-based onsite power generation option is 20–30% more economical than the alternative connection to the grid. However, the life cycle cost (LCC) of the LNG-based onsite power generation system is from 43% to up to 86% higher than the NG-based counterpart for desalination plant sizes that increase progressively from 10 to 570 ML/day. A sensitivity analysis conducted on two conceptual mid-range capacity seawater desalination plants showed that variations in the electric tariff rate, fuel cost, plant efficiency, and economic parameters affect the LCC of various power supply options. The study also showed that when the grid electricity with a cleaner mix (i.e., low emission factor) is available, this option results in lower GHG emissions than the LNG/NG power source alternatives.

1. Introduction

Municipalities and water suppliers are increasingly considering seawater desalination to supplement inadequate freshwater sources worldwide [1,2]. Despite the technical improvement in desalination technologies, seawater desalination still remain a high energy intensive process compared to more conventional treatment systems [3]. Typically, the total energy requirement for seawater desalination using reverse osmosis (RO), including pre- and post-treatment, is on the order of 3 to 6 kWh/m^3 [3,4]. In addition, the grid electricity, traditionally selected as preferred power supply option at desalination plants, often relies on the use of conventional fossil fuel resources, known to be responsible for emission of air pollutants and significant GHG emissions [5]. CO_2 emissions of 1.78 kg/m^3 and NO_x emissions of 4.05 g/m^3 of desalted water have been reported for an RO system used to desalinate seawater with traditional fossil fuel-based energy sources [4,6]. In California, the proposed 2 Mm^3/day seawater desalination capacity is estimated to increase energy use by about 2800 GWh per year with related GHG emissions of about 1.0 $MMTCO_{2e}$ annually, assuming that all of the desalination plants are powered by the electricity grid [7].

To reliably meet the increasing energy demand and reduce cost and the associated environmental impact, desalination utilities often look for a diversified portfolio of energy alternatives to grid electricity based on conventional fossil fuels. In recent years, the development and use of nonconventional fossil fuel resources, such as shale natural gas (NG) and liquefied natural gas (LNG) have been considered as potential alternatives to meet this demand [5].

To date, the application of NG power plants for operating seawater desalination has been primarily located in regions, such as the Middle

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East, where natural gas is readily available at a low price [8]. The liquefaction process, where the NG volume is reduced by 600 times, makes LNG more economical to store and transport than NG and provides opportunities to store NG to meet peak demand electricity periods [9]. However, the LNG option to power desalination is not widespread in other parts of the world and only available in regions, such as Singapore, where the pipeline infrastructure for the natural gas option is limited or nonexistent [10,11]. The cost of NG, and consequently that of LNG, has declined over the last couple of years, primarily because of increased domestic production, making NG a feasible economic choice compared to other fuels. The U.S. Energy Information Administration (EIA) forecasted that NG will continue increasing as a share of overall U.S. energy production in the coming decades because of the continued expectation that the cost of NG will remain low [12]. In addition, the spot market of LNG has emerged in recent years because of an increase in the number of LNG tankers, the overcapacity in liquefaction worldwide, and increased contractual flexibility [9]. In evaluating the environmental impact of these alternatives to fossil fuels, the U.S. EPA reported that burning NG for electricity generation results in lower quantities of nitrogen oxides, carbon dioxide, and methane emissions, with the latter two being greenhouse gases [13]. In Israel, where a number of power generation plants supply power to desalination plants, NG-driven power generation produces only 20% of the CO_2 emissions generated by coal power plants and is also 7–8% cheaper than the energy provided by the national coal-based power system, thus providing opportunities to further reduce the cost of producing the desalinated water [14]. The liquefied option of NG is cleaner upon removal of all higher hydrocarbons, inert components (N_2 and CO_2) and most impurities. LNG also has a higher Wobbe Index—the measure of the amount of energy delivered to a burner via an injector—than pipeline NG, making it a more sustainable alternative to fossil fuels to power desalination plants [15]. The 2011 U.S. GHG Inventory estimates that the contribution of methane from LNG operations represents 1.3% of methane emissions from all the segments that make up the NG systems [13]. In addition to being a lower carbon intensity fuel, NG combustion technology has become substantially more efficient over the years. In 2011, the CEC reported that the efficiency gain in California's gas-fired power plant fleet since 2001 was >24% [16].

The benefits and challenges of the application of LNG is inherently dependent on its geography-driven abundance, technological and economic scale-up issues associated with engines/turbines, maturity of the technology, storage and transmission capabilities, environmental impacts and overall, on the familiarity of utility managers and policy makers with key implementation matrices. As availability of NG and LNG is continuously growing in the United States and other parts of the world, LNG/NG-powered desalination may be a feasible alternative to energy from an electrical grid. However, to date, the majority of the recent peer-reviewed literature on energy portfolios to power desalination utilities and related energy independence concepts focused on renewable energy sources [4]. Despite the growing interest in the US for co-located configurations, no systematic study has been conducted to identify the economics and environmental benefits of LNG/NG power plants solely designed to operate a desalination plant. Economic information on different power supply options at existing or proposed desalination applications are rarely found in the public domain and mostly the domain of private entities. In addition, most of the cost information available is based on the first-year present cost value; life cycle cost analyses are often lacking. This study aimed at filling these gaps by providing a more perspicuous understanding of the application of LNG/NG for self-generation of power at desalination plants as an alternative to grid electricity. This paper will assist designers, practitioners and decision-makers that face the challenge of selecting the appropriate energy mix to power desalination plants and provide reference values, with a sensitivity analysis on impacting parameters, on life cycle cost and GHG emissions. The main objectives of this study were to:

- Perform an economic analysis of the application of LNG/NG for power generation at desalination facilities;
- Compare the grid electricity and LNG/NG-based power generation based on life cycle cost (LCC) analysis;
- Identify the factors impacting the life cycle costs through sensitivity analysis on a set of parameters (electric tariff rate, fuel cost, plant efficiency, and economic parameters); and
- Perform life cycle environmental benefits/impacts of incorporating LNG/NG at desalination facilities was also developed.

2. Materials and methods

The cost and environmental analysis developed for this study incorporates three power supply options: on-site power generation using NG as a primary fuel, on-site power generation using the LNG alternative, and the sole power grid option. Fig. 1 summarizes the different alternatives considered.

2.1. Design specification of NG/LNG power generation plants

On-site LNG and NG power generation plants of 5 to 100 MW size were considered for developing conceptual designs for 10 to 570 ML/day desalination plants. The correlation factor used in this study to determine the total unit energy requirement of a seawater reverse osmosis desalination plant (4.07 kWh/kL) was obtained from a seawater desalination plant demonstration study conducted in California [17]. From this reference study, the process requiring most of the energy per unit of water produced is the operation of high-pressure pumps (49%), followed by the product water energy use (31%), operation of other RO pumps (13%), desalination plant intake (5%) and the remaining by facility's energy needs, solid handling and membrane cleaning systems. Typically, pilot or demonstration studies are recommended to estimate the energy consumption values for SWRO influenced by feed water recovery, intrinsic membrane resistance (permeability), operational flux, feed water salinity and temperature fluctuations, product water quality requirements, and system configuration (e.g., use of energy recovery devices). This study does not provide guidance on how to determine the energy use at the desalination plant; rather it focuses on the life cycle cost analysis of different power source alternatives.

Table 1 summarizes the details on the configuration and main process components of the LNG/NG power generation plants selected for this study. Power plants operating in simple cycle or combined cycle modes were considered depending on the plant power output. Typical process components of a NG simple cycle power generation plant include the prime mover and generator; whereas in a combined cycle configuration an additional steam cycle is integrated including a heat recovery system, steam turbine, and a generator. From an economic standpoint, the use of engine generators is the preferred option for smaller size plants (5–10 MW); however gas turbines and combined cycle processes are preferred for power generation plants of sizes >20 MW. Frame size gas turbines were considered for power plant sizes >75 MW, whereas for lower sizes the aeroderivative counterparts were preferred.

When LNG is selected as the fuel option, regardless of the power plant configuration, a regasification process is needed to regasify the LNG into NG for use by the gas engines or turbines. For this study, the intermediate fluid vaporizers (IFVs), which uses an intermediate heat transfer fluid, was considered to revaporize LNG before delivery to the prime mover. An air emission control systems, a selective catalytic reduction unit that removes nitrogen oxides prior to the air heater and uses ammonia and a catalyst to reduce nitrous oxides, was considered for both simple and combined cycle options.