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Feasibility study of a small-sized nuclear heat-only plant dedicated to desalination in the UAE

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HIGHLIGHTS

- Proposed a small-sized nuclear heat-only plant dedicated to desalination with maximized safety features for the UAE
- Well-matched with the current energy and water status of the UAE
- Minimized the reactor operating pressure and maximized safety
- More cost-competitive than the target nuclear thermal desalination system
- Will ultimately contribute to safely and cost-effectively remedy serious water shortages

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ABSTRACT

The development of a small-sized nuclear heat-only plant with maximized safety features dedicated to seawater thermal desalination was proposed to address both a serious water crisis and nuclear safety issues, which continue to be perennial problems. In this study, the feasibility of a dedicated nuclear heat-only desalination system for a target country was evaluated in comparison with a target nuclear thermal desalination system. First, the target country was selected, and its current energy and desalination status was investigated. The suitable nuclear desalination options for the target country were then selected. Finally, using corresponding analysis tools, performance and economic analyses were conducted for a dedicated nuclear heat-only desalination system and the target nuclear thermal desalination system. The results of the analyses indicate that operating the small-sized nuclear heat-only plant at low pressures coupled with a seawater thermal desalination plant will considerably improve both the safety and economy without a significant loss in desalination performance. In conclusion, the proposed dedicated nuclear heat-only desalination system is expected to have high potential for solving both problems.

Abbreviations: ADWEA, Abu Dhabi Water and Electricity Authority; ADWEC, Abu Dhabi Water and Electricity Company; ANS, American Nuclear Society; BWR, Boiling Water Reactors; CCGT, Combined Cycle Gas Turbine; CSIS, Center for Strategic and International Studies; CSP, Concentrating Solar Power; DEEP, Desalination Economic Evaluation Program; DEWA, Dubai Electricity and Water Authority; DL, Desalination Loop; DOE NE, U.S. Department of Energy, Office of Nuclear Energy; EIA, U.S. Energy Information Administration; ENEC, Emirates Nuclear Energy Corporation; ENG, Emirates National Grid; EPC, Engineering, Procurement, and Construction; EPIC, Energy Policy Institute at Chicago, University of Chicago; FANR, Federal Authority for Nuclear Regulation; FEWA, Federal Electricity and Water Authority; GCC, Gulf Cooperation Council; GCCIA, Gulf Cooperation Council Interconnection Authority; GOR, Gained Output Ratio; GT, Gas Turbine; HPT, High-Pressure Turbine; HRSG, Heat Recovery Steam Generator; HTGR, High Temperature Gas-cooled Reactor; IAEA, International Atomic Energy Agency; IDA, International Desalination Association; IEA, International Energy Agency; IHX, Intermediate Heat eXchanger; IL, Intermediate heat transfer Loop; INET, Institute of Nuclear Energy Technology, Tsinghua University; KEPCO, Korea Electric Power Corporation; LEC, Levelized Energy Cost; LMFBR, Liquid Metal cooled Fast Breeder Reactor; LNPP, Large-sized Nuclear Power Plant; LOCA, Loss-Of-Coolant Accident; LPT, Low-Pressure Turbine; LWC, Levelized Water Cost; MED, Multi-Effect Distillation; MEDRC, Middle East Desalination Research Center; MSF, Multi-Stage Flash distillation; MSR, Molten Salt Reactor; NBS, UAE National Bureau of Statistics; OECD NEA, Organization for Economic Cooperation and Development, Nuclear Energy Agency; OPEC, Organization of the Petroleum Exporting Countries; PCS, Power Conversion System; PHWR, Pressurized Heavy Water cooled Reactor; PL, Primary coolant Loop; PWR, Pressurized light Water cooled Reactor; RO, Reverse Osmosis; SARO, Stand-Alone Reverse Osmosis; SCAD, Statistics Center Abu Dhabi; SCGT, Simple Cycle Gas Turbine; SEWA, Sharjah Electricity and Water Authority; SG, Steam Generator; SNHP, Small-sized Nuclear Heat-only Plant; SNPP, Small-sized Nuclear Power Plant; ST, Steam Turbine; TBT, Top Brine Temperature; TDS, Total Dissolved Solids; TFC, Total Final Consumption; TPES, Total Primary Energy Supply; TVC, Thermal Vapor Compression; WCR, Water Cooled Reactor; WNA, World Nuclear Association.

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1. Introduction

Fresh water is essential for the health of all life and the environment. For human beings, the fresh water supply is closely related to economic development. Unfortunately, much of the world's population is suffering from a serious shortage of fresh water, and this number will increase if the water supply cannot keep pace with population growth and economic expansion. Water can be found everywhere on the earth's surface, but only a small portion of the surface water supply is available as fresh water; most of the water supply exists in the form of ice and groundwater.

Desalination is a process that converts abundant seawater or brackish water into fresh water by removing salt and other minerals to the desired level using a certain amount of energy. The selection of the optimal energy and desalination technologies is crucially important to the success of desalination projects. Optimal energy and desalination technologies are selected based on various factors such as relative economics, performance, safety, environmental impact and suitability.

Many countries, including the UAE, already have large-scale seawater desalination plants. Most of these plants are powered by fossil fuels, which pose economic problems due to soaring and unstable fossil fuel prices and cause environmental concerns, such as greenhouse gas emissions. In contrast, nuclear desalination, which uses the energy released by nuclear fission, has less environmental impact and is generally cost-competitive with fossil-fuel desalination in many countries that lack fossil fuel resources. This technology is also favorable to diversify the energy supply and conserve finite fossil fuel resources [1].

Various types of nuclear reactors are in operation or under development. Among these, water cooled reactors (WCRs) account for the majority of nuclear reactors currently being operated in the world. Other reactor types have accumulated relatively less operational and regulatory experience and require more time to become widely commercialized [2]. Other reactor types produce heat at higher temperatures: 500 °C for liquid metal cooled fast breeder reactors (LMFBRs), 860 °C for molten salt reactors (MSRs), and 950 °C for high temperature gas cooled reactors (HTGRs) [3]. However, such high temperatures are not necessary in desalination applications, especially when using thermal desalination processes, such as Multi-Stage Flash distillation (MSF) and Multi-Effect Distillation (MED). The MSF and MED processes generally only require heat between 70 and 130 °C, which is low enough to be provided by WCRs [4].

Nuclear desalination has already been demonstrated over 200 reactor-years of experience in countries including Japan, the USA, India, Kazakhstan, and recently, Pakistan and China. Furthermore, this technology has been extensively studied worldwide over the past few decades [4]. With one exception, namely the LMFBR-type BN-350 reactor in Aktau, all reactors used for nuclear desalination are WCRs, such as pressurized light water cooled reactors (PWRs) and pressurized heavy water cooled reactors (PHWRs), but not boiling water reactors (BWRs). The pressurized types are preferable to BWRs for thermal desalination applications because these reactors, by default, provide an additional barrier fluid between the reactor coolant and seawater [5].

Despite the many advantages of nuclear desalination, countries that want to apply this technology must consider various aspects of nuclear energy applications. One of the most important issues for nuclear energy application is safety. The Fukushima accident that occurred in March 2011 has drawn increased attention to nuclear safety, especially in terms of the development and widespread application of inherent and passive safety features [6]. To respond to such needs, this study proposed to develop a small-sized nuclear heat-only plant with maximized safety features dedicated to seawater thermal desalination. To evaluate the feasibility of this dedicated nuclear desalination system, a target country was first selected, and its current energy and desalination status was investigated.

2. Current energy and desalination status of target country: UAE

2.1. Target country: UAE

The six member countries of the Gulf Cooperation Council (GCC), Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE, have expended great efforts to overcome the water crisis through the use of seawater desalination over the past decades. The GCC countries have accumulated extensive desalination experience and invested considerably in establishing a desalination infrastructure since the 1950s. For instance, the UAE has spent over 3 billion dollars per year on desalination [7]. The desalination capacity of the GCC countries currently accounts for more than half of the global desalination capacity [7]. Saudi Arabia retains 17% of the global desalinated water capacity, while the UAE and the USA place second, just behind Saudi Arabia, with 14% of the global share [8]. Apart from these efforts, the GCC countries have also embarked on various programs to identify alternative energy sources to address the energy crisis. The GCC countries have focused on a nuclear energy program since 2006. Countries that suffer from water shortages generally do not possess nuclear technology [2]. Thus, the establishment of nuclear desalination infrastructures represents a huge burden for such countries. However, the UAE is known to currently have the most advanced nuclear energy program of the six GCC countries and the 45 countries that are actively considering embarking on nuclear energy programs [9,10]. The UAE plans to build four APR-1400 nuclear power plants at the Braka site by 2020, and the first commercial operation is planned for 2017 [11]. The UAE was selected as the target country in this study based on its strengths in both the desalination and nuclear energy fields.

The UAE is a Middle Eastern federation of seven emirates, Abu Dhabi, Dubai, Sharjah, Ajman, Ras Al Khaimah, Umm Al Quwain, and Fujairah. Among these seven emirates, the Emirate of Abu Dhabi is the largest and most populated, accounting for approximately 83.7% of the total area [12] and 23.8% of the total population of the UAE [13,14] (42.7% based on the population of Emirati nationals) [13]. Abu Dhabi city within the Emirate of Abu Dhabi is the capital city of the UAE and the center of the UAE's politics, industries, culture and economy. The Emirate of Abu Dhabi is at the core of the energy and resource flows in the UAE; therefore, this study mainly focuses on the Emirate of Abu Dhabi.

2.2. Resources and energy in the UAE

The key factor in the current successful economy of the UAE is its oil wealth, which accounts for approximately 80% of total government revenues and efficient investment strategies [15]. The UAE is a member country of the Organization of the Petroleum Exporting Countries (OPEC), which in 2010 held the sixth largest proven crude oil reserve, at 97.8 billion barrels, and the seventh largest natural gas reserve, at 6091 billion cubic meters, in the world [16]. In 2010, the UAE produced 2.3 million barrels per day of crude oil (the world's ninth largest), most of which was exported, at 2.1 million barrels per day (the world's fifth largest) [16]. On the other hand, the UAE is a net importer of natural gas, even though it is the eighteenth largest producer of natural gas in the world (based on marketed production). In 2010, the UAE produced 51.28 billion cubic meters of natural gas, while importing 25.7 billion cubic meters of natural gas, which was nearly five times the quantity of the 5.18 billion cubic meters of natural gas exports [16]. The reason why the UAE consumed this large quantity of natural gas is that natural gas is the most important domestic source of energy in the UAE.

Table 1 shows that in 2009, the UAE's natural gas shares of the total primary energy supply (TPES) and total final consumption (TFC) reached 82.5% and 59.3%, respectively [17]. In the same year, 98.2% of the electricity in the UAE was generated using natural gas on a GWh basis [18]. Although natural gas remains the major energy source for the foreseeable future, the government of the UAE is well aware of the need to reduce its reliance on its valuable and finite natural gas