Using High Temperature Gas-Cooled Reactor for Seawater Desalination: Challenges and Opportunities

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Abstract. Freshwater availability is a global concern. Thus seawater desalination became a variable solution to that issue. However, most desalination plants are powered by fossil-based energy. That fact drove many countries to find an alternative solution in which nuclear desalination became a consideration for many countries like Japan and Saudi Arabia. Different approaches were considered regarding nuclear-desalination, one of which using a High-Temperature Gas-Cooled Reactor (HTR) as an energy source. This paper discusses the challenges and opportunities of using HTR as an energy source for commercial-scale desalination. The findings show the most critical challenges and opportunities related to the technological, economic, social, environmental, regulatory, and infrastructural aspects of HTR-Desalination.

1. Introduction and background

1.1. Global view
Energy and Water are linked. Energy is required to pump, desalinate, treat, and distribute water, while water is usually part of the power production chain as an energy transfer and cooling medium. However, freshwater accessibility and availability is a global concern with areas facing water scarcity. According to a United Nations report that about 30% of the world population lives in areas facing high water stress, and about 57% of the world population experience severe water scarcity at least one month a year [1]. Increased stress levels with global economic development will increase the global demand for freshwater. As a result, seawater desalination became an essential consideration to meet global demand. However, most large-scale desalination plants are fossil fuel-based, producing about 95 million m³/day of freshwater with massive brine discharge [2], which will further stress economies and the environment. Whilst developing infrastructures and transformation towards sustainable freshwater production is a crucial consideration for sustainable development. Based on that, different countries like Saudi Arabia, Japan, and China expressed interest in considering nuclear desalination using different reactor technologies.

1.2. Desalination processes
There are two primary ways for desalination seawater, either through thermal energy-consuming processes or power-consuming process. Multi-effect desalination (MED), multi-stage flash (MSF), and the underdeveloped adsorption desalination (AD) technologies are all processes that consume
primarily thermal energy. In contrast, reverse osmosis (RO) and electrodialysis (ED) are power-consuming processes. [3][4]

1.3. Nuclear desalination
Since the 1970s, studies and demonstration projects considered nuclear energy for seawater desalination. The increased demand for freshwater resources, the competitiveness of nuclear energy, and the useful utilization of waste heat from the nuclear power plant drove the interests of nuclear desalination. However, economic and technical factors hindered commercial-scale development of nuclear desalination [5]. Different nuclear power technologies were considered for nuclear desalination or co-generation such as sodium-cooled fast reactors, heavy water reactors, pressurized water reactors (PWR), and high-temperature gas-cooled reactors (HTR). Recently, Increased interests from countries facing water scarcity on commercializing the use of small and modular reactors for desalination due to their flexibility and applicability. For example, Saudi Arabia within the framework of the Saudi National Atomic Energy Project (SNEAP), worked on different feasibility studies with China National Nuclear Corporation (CNNC) for using HTR and with the Korea Atomic Energy Research Institute (KAERI) for using the System-integrated Modular Advanced Reactor (SMART), for large scale seawater desalination, respectively.

1.4. High-temperature gas-cooled reactor
High-Temperature Gas-Cooled Reactor (HTR) is a promising generation IV reactor technology that can significantly contribute to the future of sustainable and safe nuclear energy. HTR uses Helium as a coolant, and the technology features inherent safety, high efficiency, and modular design. Moreover, HTR design allows its use in remote areas, flexible for various industrial applications, and can function as a clean technology that contributes to the reduction of greenhouse gas emissions [6]. During the past few years, China invested in its HTR-PM Demonstration project and constructed the first demonstration plant in Shidao-Bay with an output electric power of 200 MWe. HTR-PM Demonstration project is considered as a significant milestone in the development of Generation IV reactors.

The purpose of this paper is to analyze potential challenges and opportunities of using HTR for commercial scale seawater desalination on the basis that different countries expressed the interests in developing HTR for industrial and desalination uses. Data about the HTR were retrieved based on the recent updates of the Shidao-Bay project, while the data about the desalination were obtained from Saudi Arabia's experience and other global estimates.

2. Case analysis of HTR desalination

2.1. Technology
Nuclear Desalination can be either a single purposed or a co-generation plant. In a single purposed nuclear desalination plant, the energy produced in the reactor is fully dedicated for seawater desalination. On the other hand, in a co-generation nuclear desalination plant, the reactor simultaneously produces energy for seawater desalination and electricity to the grid. The best way of coupling both plants and the decision of either a single-purposed or co-generation plant depends on different economic, technical, and business modeling factors.

The maturity of the generation IV reactor technology is a major concern that might hinder its development nowadays [7]. However, it is argued that the maturity of HTR technology is a significant concern to countries with no or little HTR technology and the experience of China from the HTR-10 and the HTR-PM demonstration project will help reducing concerns related to design, engineering tests, manufacturing, civil work, commissioning, licensing, and project management for future HTR development [8]. Another challenge is related to the availability of Tristructural-isotropic (TRISO) fuel and the HTR overall fuel cycle. The three considered options for nuclear waster disposal are (a) waster reprocessing, (b) disposal in a monitored geologic repository, or (c) long-term on-site storage. However, reprocessing HTR TRISO is challenging due to its extremely tough structure [9].
The integration of the HTR and Desalination plant poses further challenges in terms of the interfaces and influences between the nuclear plant and the desalination plant, which raises concerns about the safe operations of both plants. Therefore, the plants may require design and engineering development as a result of issues such as the power interfaces between the reactor and desalination plants, and the integration of the MED with the HTR. Furthermore, thermal desalination processes require relatively low temperatures compared to the HTR reactor. The question is why to use a reactor that can potentially provide more value when it supplies high temperatures if we considered the reactor as a heat supplying source. The typical current thermal desalination temperature range is between 30-100 °C. However, there are high-temperature desalination processes under development. Such as the emerging desalination technologies that pressurize and heat seawater up to 300°C and release the water into flash chambers for brine and slat crystal separation. Another promising technology is the Forward Osmosis Desalination, with operating temperatures of up to 140°C [9]. Despite this argument, a detailed economic and technical feasibility study can determine if HTR-Desalination would be a feasible energy supplying source regardless of the temperature intervals. [10]

Besides the aforementioned challenges, HTR, as a power source, has foreseeable advantages. In terms of safety, the HTR adopts the internet safety concept like the self-acting decay heat removal system and the fuel design that even in extreme accidents, a meltdown is avoided and can retain radioactive substance. Moreover, the reactor is considered modular, which allows its implementation in remote areas and makes it flexible to various industrial applications and co-generation. The possibility of dry air cooling makes HTR as a viable option for arid regions. [11]

RO systems can be used for desalination brackish water to produce drinking water quality or for agricultural purposes at relatively low cost [5]. Furthermore, given the advantages mentioned above, besides desalinating seawater, HTR can be a useful, sustainable energy source for desalinating brackish water in remote and arid areas. The online-refuelling system of HTR-PM design is advantageous since the need for continues reactor shutdown is minimized compared to current PWR. Moreover, HTR as an energy source is highly efficient due to the high heat yield, homogeneous heat production in the fuel, and good heat conductivity in the graphite core.

2.2. Economy

Beyond this paper, a techno-economic pre-feasibility study for Saudi Arabia about large-scale seawater desalination with HTR cogeneration with different scansion of HTR-Desalination using only RO as a desalination technology, and a hybrid HTR-Desalination coupling both RO and MED. The nuclear power plant in both scenarios produces a portion of electricity to the grid. The estimation of costs and operational factors of the HTR is based on an analysis framework that suggests that the best estimation methodology for Gen IV reactors in their early stage is a top-down method that considers data from similar reactors and scaling depending on different project specifications [12]. While using a tool developed by the International Atomic Energy Agency (IAEA) called the Desalination Economic Evaluation Program (DEEP) which is based on a simplified economic evaluation methodology that allow users to input different techno-economic data for the nuclear power plant and the desalination and calculates costs accordingly. However, further development of DEEP is recommended for effective calculations for HTR that uses helium as a coolant and operating at high temperatures. Table 1 concludes the main economic and technical results considered in the pre-feasibility study.
Table 1. Economic Parameters of HTR-Desalination coupled with RO

| Parameter                              | Unit       | Value  |
|----------------------------------------|------------|--------|
| Power Plant Type                       | -          | HTR-PM 200 |
| Reactor electric power                 | MWe        | 210    |
| Reactor efficiency                     | -          | 40%    |
| Plant lifetime                         | Years      | 40     |
| Constriction duration                  | Months     | 60     |
| Overnight EPC (global estimate)        | USD/kW     | 4000   |
| Estimated total capital cost           | USD/kW     | 5400   |
| Estimated average annual cost          | Million USD| 85     |
| Final Power Cost                       | USD/kWh    | 0.05   |
| Desalination Plant                     | -          | RO     |
| Electric power used                    | MWe        | 143    |
| Water production                       | Million m³/ year | 394 |
| Total Capital cost                     | USD/m³/day | 1540   |
| Total annual cost (Inc. energy cost)   | Million USD| 240    |
| Final Water Cost                       | USD/m³     | 0.61   |

As per the results obtained, water and power costs of HTR-Desalination is relatively economically competitive with a sensitive analysis that shows the significant effects of the discount rate, interest rate, and overnight EPC. While the change in seawater temperature and total dissolved salts (TDS) has a minimal impact on both the power and produced water costs.

There is no doubt that the economic competitiveness of nuclear desalination, in general, is promising, and that was the primary driver of continuous development in this area. Cost estimates of desalinated water using nuclear energy ranges from 0.40 $/m³ to 1.80 $/m³ based on the desalination technology and reactor type and the cost estimation of HTR desalination using MED process was about 0.51 $/m³ [5] comparing to the water cost using conventional energy of at least 1.2 $/m³. Our study for HTR-Desalination shows that prices can be as low as 0.60 $/m³ based on the estimations concluded in Table 1. However, we believe that several operational considerations can strongly influence economic factors, such as the disturbance of operation by shutting down the reactor or the desalination due to regular maintenance. In that matter, it is assumed that the reactor is operational 90% of the year which is approximately similar to the availability of the desalination plant. With that in mind, the operation of the power plant and the desalination plant can be synchronized to allow optimized operation.

2.3. Society

Besides resolving issues associated with the techno-economic and regulatory factors, public acceptance can play a significant role in the development of nuclear desalination. Nuclear energy development has always been associated with public acceptance due to obvious reasons related to the general safety, public health, possible relocation of communities, and environment [13]. The main issue in nuclear desalination is the co-location of the nuclear reactor, and the desalination plant and serious issues could arise in the case of radioactive release from the nuclear plant passing through the chain to the freshwater produced. Currently, very few studies were performed to assess the public acceptance of nuclear desalination. Communicating facts regarding freshwater availability and needs can be a strong argument for the public to accept the option of nuclear desalination. Technology, safety improvement, and the strong regulations in the nuclear energy sector show that there is an increasing trend of positive attitude towards nuclear energy globally [13]. However, the major
development in the renewable energy sector and the effort to use renewable energy for desalination could reduce the popularity of nuclear desalination and public acceptance. Therefore, effective communication on nuclear desalination is essential to maintain public acceptance. Another important consideration regarding the HTR is the promising utilization of the Thorium fuel cycle that has clear advantages with regards to reducing Plutonium and minor-actinides for long-term radio-toxicity [11]. This is an essential consideration for public acceptance. Nevertheless, the Thorium fuel cycle for HTR is still for the long-term development of HTR. Beyond public acceptance, nuclear desalination can contribute positively overall its value-chain by providing power, freshwater for the residential, industrial and agricultural sectors, creating jobs, and reduce greenhouse gas emissions.

Figure 1. Greenhouse gases released from different energy source [14].

2.4. Environment
Environmental severe impacts can be caused as a result of large-scale nuclear-desalination if not appropriately managed. The construction works, land-use, and visual and auditory distortion could cause disturbance to the local and surrounding environments [15]. Large-scale seawater desalination poses real concerns for marine life due to seawater intake, discharge, and risk of radioactive release. The discharge of desalination pant contains a high level of brine, different pH levels due to pre-heating and chemical treating of seawater [5] [13]. Effective brine management is therefore essential, and studies are undergoing better utilization of brine through commercial salt production, which could turn an environmental challenge into an economic opportunity [2].

It is evident that nuclear energy is considered as clean energy and with the least global warming impact alongside wind and hydropower. For desalination, assuming the RO process consumes 3 kWh/m³, then the release of greenhouse gas emissions by using nuclear power, according to Figure 1, will range between 10-70 gCO2-eq compared to 1200-2400 gCO2-eq for natural gas and 1400-3600 gCO2-eq for oil. Nuclear Desalination projects shall set measures of sustainable development and effective environmental management to mitigate the risk that can negatively impact the environment.

2.5. Further regulatory considerations
It is noted that the necessary regulatory and infrastructural requirement for the HTR is like any other nuclear plants. In general, if the desalination plant is electrically coupled with the reactor in the case of RO desalination, there are no safety issues to be considered in the co-location. On the other hand, if the desalination plant is thermally coupled in the case of MED desalination, additional safety concerns can be raised. However, significant risks can be eliminated by setting an appropriate regulatory framework and measures for the design.

It should be noted that the safety standards for nuclear reactors producing power may not be in the entirety appropriate for reactors dedicated to desalination, district heating, and other industrial application [16]. We believe that the regulatory frameworks for the nuclear plant and desalination plant are mature enough, independently. However, the concern is related to the common and shared facilities and interfaces, and therefore there should be considerations for specific regulations and
licensing for the integrated system. In general, regulations shall follow the basic safety standards that shall ensure the safety and protection of the public and environment of potential risks. In addition to impacts resulting from transient interactions between both plants and environmental stresses due to shared resources and water discharges.

3. Infrastructural and developmental considerations

Infrastructural development, readiness, and preparedness of countries intending to develop nuclear desalination is a vital issue. The three milestones approach with 19 infrastructural issues of IAEA is necessary for countries intending to develop a nuclear power program. We believe that similar consideration is required for adopting and developing a new generation reactor like HTR coupled with a desalination plant. The three milestones are:

- Ready to make a knowledgeable commitment to a nuclear power program;
- Ready to invite bids/negotiate a contract for the first nuclear power plant;
- Ready to commission and operate the first nuclear power plant.

While the 19 infrastructural issues are: National position; Nuclear safety; Management; Funding and financing; Legal framework; Safeguards; Regulatory framework; Radiation protection; Electrical grid; Human resource development; Stakeholder involvement; Site and supporting facilities; Environmental protection; Emergency planning; Nuclear security; Nuclear fuel cycle; Radioactive waste management; Industrial involvement; and Procurement [17]. Ensuring these 19 issues will require efforts from the government, regulatory body, operator, and other stakeholders. Of course, different countries have different readiness levels; however, this gives us an indication of the complexity and the level of commitment of different sectors when it comes to developing nuclear energy-related projects. Moreover, Intellectual Property (IP), technology transfer, and local content aspects are critical considerations for some countries. For example, Saudi Arabia, as part of the Saudi Vision 2030, has specific requirements of local content and technology transfer for any project to be developed, and that was the case with the SMART technology, and similar consideration as part of the Saudi National Atomic Energy Project (SNEAP) that involves developing HTR for desalination and industrial purposes.

Lastly, most of the economic and technical aspects of the HTR-Desalination plant will depend on the business model intended for the project. The business model will determine whether the HTR will solely be a source of energy for water desalination or co-generation. As well as determining the freshwater off-taker will determine the water quality if it is for drinking or agriculture. Furthermore, the share of electricity versus the water produced, reactor power level, location, and infrastructural availability and development are all parameters that will directly influence the technical and economic aspects of HTR-Desalination.

4. Summary and conclusion

Table 2 below gives a bird's-eye view on the main challenges and opportunities of HTR desalination that were discussed in this paper:

Nuclear-desalination has not been developed on a commercial scale. Many studies showed that there are economic and environmental advantages of nuclear desalination. However, there are issues of plant integration, regulatory frameworks, and public acceptance. These are critical issues associated with nuclear desalination. Regarding HTR-Desalination, more advantages can be observed as the reactor is modular, flexible for industrial applications, the possibility of dry cooling, and, most importantly, the inherent safety feature bring more value to the HTR technology. However, technology maturity, required human capital, fuel availability, and IP and technology transfer aspects are challenges that shall be addressed.
Table 2. Summary of HTR-Desalination challenges and opportunities factors

| Challenge | Opportunity |
|-----------|-------------|
| Technology |             |
| High energy temperatures relative to desalination needs | High energy efficiency |
| TRISO fuel availability | TRISO fuel retaining radio-substances |
| Aligning power and desalination plant operation | HTR-Desalination co-generating power and fresh water |
| Maturity of technology | Modular reactor design, can be developed in remote areas and dry cooled |
| Economy |             |
| Lack of extensive analysis due to lack of global data availability | Different countries interested in Nuclear-desalination and prefeasibility studies shows economic advantages |
| Society |             |
| Public acceptance | Global trend shows increased interests in favour of nuclear energy |
| Possible re-location | Increased demand on freshwater |
| Environment |             |
| Construction, land-use, and visual and auditory distortion | Clean energy with least greenhouse gas emissions |
| Brine discharge effects on marine life | Economic advantage by utilizing brine for commercial salt production |
| Regulation |             |
| Lack of comprehensive regulatory framework | Learning from global experience and global efforts towards establishing set of regulations to serve nuclear-desalination purpose |

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