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Review

Potential areas for nuclear power plants siting in Saudi Arabia: GIS-based multi-criteria decision making analysis

Mohammed M. Damoom[a,b,*], Suhairul Hashim[a,d], Mohammed S. Aljohani[b], Muneer Aziz Saleh[c], Ned Xoubi[b]

[a] Physics Department, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[b] Nuclear Engineering Department, King Abdulaziz University, Jeddah, 21589, Saudi Arabia
[c] Nuclear Engineering Programme, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, UTM Skudai, Johor, Malaysia
[d] Centre for Sustainable Nanomaterials (CSNano), Ibnu Sina Institute for Scientific and Industrial Research (ISI-SIR), Universiti Teknologi Malaysia, UTM, 81310, Skudai, Johor, Malaysia

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ABSTRACT

This paper reports the identification modus operandi (in Phase-I) of prospective sites to situate nuclear power plants (NPPs) in Saudi Arabia. Currently, the nation has taken a strategic imitative to introduce nuclear power to resolve future energy crises. Potential areas for installing these NPPs were determined via geographical information system (GIS)-based multi-criteria decision making approach. Nine significant criteria were applied to screen out unsuitable areas for such NPPs construction. Results revealed that scarcity of water in Saudi Arabia was the major reason to discard 96% of the possible sites. Furthermore, the overlaying process of all these criteria could dispose of nearly 98% of the contiguous Saudi lands. The remaining 2% land area was discerned to be suitable for positioning NPPs, which amounts to an area coverage of 21473 km^2 and 13395 km^2 on the western and eastern coast, respectively. The dominant siting issues on the western coast were related to the geological features (slope, fault, and flood), while the population concern could overweigh the others on the eastern coast. Meanwhile, the survey revealed that the sea-level rise sensitivity must be considered on the eastern coast for the safe operation of NPPs. Further analyses disclosed that sea-level rise of about 2 m could reduce the possible land areas by 20% and 13% in the eastern and western coast correspondingly. The net feasible areas were inversely proportional to the aggregation of suitable lands into specific NPP footprint. It was established that the proposed assemblage strategy could reduce the net effective area on the western coast for siting the NPPs such as SMR350 (small reactor), AP1000 (moderate reactor) and EPR1600 (large reactor) by almost 22%, 37%, and 47%, respectively. Present findings may constitute a basis for future development in selecting particular sites for NPP installation in Saudi Arabia.

1. Introduction

Saudi Arabia is the world leading producer of oil and the nation consumes nearly 34% of oil for domestic energy production (International Energy Agency, 2017). Approximately 28% of the domestic fuel consumption (622 million tons) is allocated for electricity generation. Saudi Arabia is one of the highest electric power consuming nation (9444 kWh/capita) (The World Bank, 2018) having a population of 31.5 million (International Energy Agency, 2017). Furthermore, residential use of electricity amounts to 49.4% with an annual growth rate of 2%. In fact, the annual growth of electricity consumption was 7.7% between 2014 and 2015 (International Energy Agency, 2017). Certainly, this continual increase in the electricity demand may cause serious future problems including the oil export and carbon dioxide emissions. The carbon dioxide emissions by Saudi Arabia in the year of 2015 was 531 million tonnes (Mt) (International Energy Agency, 2017). Thus, alternative energy resources must be explored to mitigate the issues related to power crises, revenue generation, and environmental pollution, where nuclear energy production may a suitable option.

To confront these upcoming challenges and conserve the oil reserves, Saudi Arabia is considering alternative energy sources such as renewable and nuclear energy (K.A-CARE, 2017). In 2010, King Abdullah City was established for Atomic and Renewable Energy (KA-CARE) generation to implement a sustainable mix of nuclear and

* Corresponding author. Nuclear Engineering Department, King Abdulaziz University, Jeddah, 21589, Saudi Arabia.
E-mail address: moftah98@gmail.com (M.M. Damoom).

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renewable energy which could mitigate the net carbon dioxide emission. Saudi Arabia aspires to generate 50% of its electricity from non-fossil fuels, recommending the installation of 15 nuclear reactors with a capacity of 17.6 GW by 2032 (K.A-CARE, 2017).

Worldwide, since the 1950s the nuclear power has been utilized as a source for electricity generation. According to International Atomic Energy Agency (IAEA), in 2017, 448 nuclear power plants (NPP) were operational worldwide including 40 reactors shutdown in Japan. Presently, the USA is leading the world with 99 reactors in operation having capacity of 99.185 GWe. Meanwhile, 59 reactors are under construction worldwide where six of them belong to developing nations. For instance, the United Arab Emirates (UAE) is constructing four nuclear reactors with a capacity of 5.4 GWe (International Atomic Energy Agency, 2016), which is the first nuclear program in the Arabian Gulf region. Recently, Saudi Arabia has announced its nuclear power program initiative to be completed by 2040 (World Nuclear Association, 2017).

In a publication entitled fundamental safety principles (SF-1), IAEA established ten principles for nuclear safety. Principle eight states that "all practical efforts must be made to prevent and mitigate nuclear or radiation accidents." This document argued that such standard can be achieved by implementing the 'defense in depth principle.' Defense in depth has been implemented primarily through the arrangement of many consecutive and independent levels of protection that would have to fail before harmful effects could be caused to people or the environment. This code has been applied through an adequate combination of many measures, wherein the selection of a proper NPP site is regarded as one of the primary measures (International Atomic Energy Agency, 2006). Besides, the Electric Power Research Institute (EPRI) suggested a four-step mechanism for perfect selection of NPP site. These steps involve the identification of the candidate areas (suitable areas for siting NPP), potential sites, candidate sites and accepted sites. Accordingly, three phases were suggested (International Atomic Energy Agency, 2015) for NPP installation such as regional analysis, screening (potential sites) and evaluation (comparison and ranking sites).

Because of the aerial nature of regional analysis (called Phase I), the maps serve as the main data source. Undoubtedly, the best tool to deal with and analyze these maps is the geographical information system (GIS) (Electric Power Research Institute, 2002). Additionally, IAEA encourages utilizing GIS to manage the huge amount of spatial data required for NPP siting (International Atomic Energy Agency, 2012). GIS allows the users to visualize, inquire, analyze and interpret the vast amount of geological data for better understanding and problem solving. Furthermore, GIS software aims to gather, analyze, and display geological data in a simplistic manner. It is needless to mention that over the years several GIS software sets have been developed and one of the most celebrated packages is ArcGIS. Driven by this idea, the present study utilized ArcGIS version 10.6 to perform all processes needed for effective NPP sites identification in Saudi Arabia (ESRI, 2018).

To the best of authors' knowledge, very few studies have been conducted on the NPPs installation in the context of Saudi Arabia (Abdul-Fattah and Abulfaraj, 1982; Al-Othmany et al., 2015; Aljohani et al., 2005; Hussein et al., 1987). First three of them dealt with NPPs, and the last one involved the selection of an adequate location for high-level radioactive waste storage (HLW). However, all these investigations focused mainly on the selection of specific sites without addressing the safety issues of the available areas for NPPs construction. In 1981, Abul-Fattah and Abulfaraj (Abdul-Fattah and Abulfaraj, 1982) compared the feasibility of siting NPP in Dhahran and Jeddah. It was acknowledged that Dhahran (eastern coastal area of Saudi Arabia) could rank as the first choice for the potential NPP site, indicating the eastern coast preference over the western one. Hussein et al. (1987) proposed four sites in the western coast of Saudi Arabia suitable for NPP construction. Initially, the eastern coast of Saudi Arabia was excluded from the feasible NPP sites due to the following reasons: (i) the existence of oil fields and refineries representing the main source of income of Saudi Arabia, (ii) the proximity to the Arabian (Persian) Gulf countries where the released radioactivity from the plant could affect these nations, and (iii) the political issues among some countries in this region (Hussein et al., 1987).

The first paper was published in 1982 before the Chernobyl disaster in 1986 and the second one was published in 1987 nearly one year after the disaster. Since then, very good countermeasures have been introduced to enhance the NPP safety and public protection. Furthermore, some countries in the region have already built (Iran) or in the process of constructing (Emirate) NPPs. Accordingly, it was argued that both coasts must be considered for the siting of NPP without any discrimination. Moreover, the works of Abdul-Fattah's and Hussein's are outdated now. In fact, during the last three decades, the population density and distribution in Saudi Arabia and neighboring regions have largely varied wherein these factors must be considered vital for safety criteria of NPPs installation. Aljohani et al. (2005) focused only on the seismic hazards in the context of Rabigh city on the Red Sea coast of Saudi Arabia and argued that it is a safe site for constructing a nuclear desalination plant (Aljohani et al., 2005). Likewise, Al-Othmany et al. (2015) suggested two tentative and preliminary HLW disposal sites located in or nearby ArRub' Al-Khali desert (Al-Othmany et al., 2015). Despite some studies, the in-depth knowledge of NPP siting criteria in the context of Saudi Arabia remains debatable.

For the first time, we took an attempt to identify the potential areas feasible for NPPs siting in Saudi Arabia. Phase I of the NPPs installation process (regional analysis) was evaluated using GIS-based multi-criteria decision making strategies. Detail analyses revealed that the selection of such areas in Saudi Arabia could play a significant role for future development in the safe and environmental friendly NPP siting processes related to Phase II and III.

2. Material and methods

2.1. Study area

The nation Saudi Arabia (Fig. 1) is located in the Middle East (having area of $2.51 \times 10^6\,km^2$), spreading between the Red Sea (western coast) and the Arabian Gulf (eastern coast). Yet, the contiguous area of the country is $1.92 \times 10^6\,km^2$. The main feature of the country is the plateau that rises rapidly from the Red Sea and then slopes down to the Arabian Gulf with emerging high lands along the

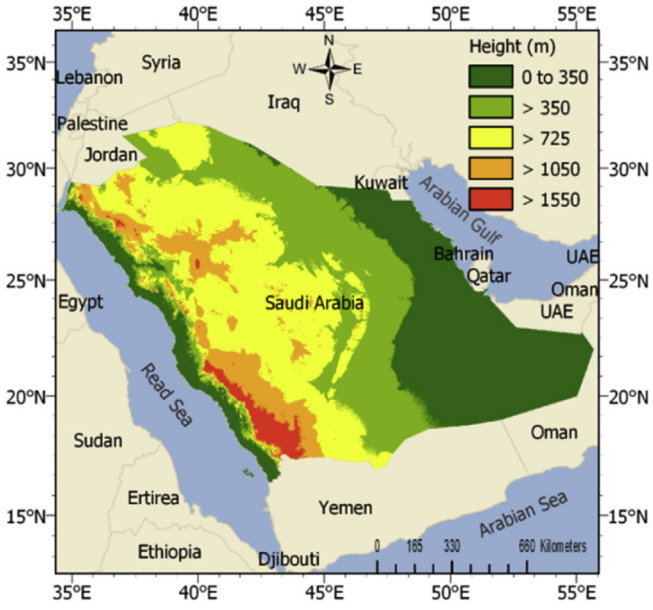

Fig. 1. Map of Saudi Arabia.