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Assessment of Potential Nuclear in selected sites in Saudi Arabia

Samar Dernayka*, **Fatimah Al Wuhayb, Gaydaa Al Zohbi**

Department of Mathematics and Natural Sciences, Prince Mohammad Bin Fahd University, Al Khobar, Kingdom of Saudi Arabia

***Corresponding Author:** Samar Dernayka, Department of civil engineering, Prince Mohammad Bin Fahd University, Al Khobar, Kingdom of Saudi Arabia, E-mail: sdernayka@pmu.edu.sa

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Abstract

The kingdom of Saudi Arabia plans to build nuclear reactor as a part of its vision 2030 that aims to diversify its energy mix. For this purpose, five cities have been selected in order to setup nuclear power plant. The country had intended 17 GW of nuclear capacity by 2040 to cover 15% of the power. The current study aims at assessing the suitability of the selected sites to build nuclear reactors based on the seismic, meteorology, population, hydrology and proximity to sensitive facilities criteria. In addition, an economic analysis for the installation of nuclear reactor in the Kingdom has been carried out in order to evaluate the feasibility of the project. Results revealed that Jubail city showed suitability to all criteria and it can be the best site to install nuclear reactor. Also, the Umm Huwayd and khor Duweihin sites could be appropriate places since they demonstrate their aptness to all criteria except the meteorological criteria related to high temperature and high dust and sandstorm. The economic analysis was carried out by evaluating the LCOE of different reactor designs in KSA and the results showed an average of $41/MWh.

Keywords: Nuclear power plant; Saudi Arabia; Uranium; Thorium; vision 2030; LCOE

Introduction

Saudi Arabia recorded the fastest growing electricity consumer in the Middle-East that is produced mainly from fossil fuel. The current electricity generation capacity is 55 GW with 65% from oil and 27% from natural gas [1]. Besides, the country's electricity needs are expected to increase and reach around 120 GW per year by 2030. This fact entails the Saudi economy to deviate towards the nuclear application, to diversify its electricity generation and to reduce its reliance on fossil fuel. In the framework of the Saudi's vision 2030, the Kingdom has a plan to create a domestic nuclear industry in anticipation of high growth in its domestic energy consumption.

Environmentally, nuclear plants contribute significantly to reduce the carbon dioxide emissions by 1.3 to 2.6 gigatons/year. More specifically, the uranium, fueled nuclear power, is a clean and efficient way of boiling water.

The attention attributed to the mining sector, under the Saudi's vision 2030, is un doubtfully a key pillar that contributes to the development of the national nuclear program. The Saudi uranium storage, that constitutes five per cent of the world's uranium reserves, implies a self- sufficient nuclear program that would secure the fuel for nuclear reactors. The intension is to explore and mine uranium in Al Hail province that comprises the main uranium deposits resources [2].

The Saudi Arabia's nuclear plans have been changed frequently so far and involved numerous outside parties [3]. Historically, the Kingdom has shown interest in establishing a civilian nuclear program in the 1970s, when the first nuclear plant was built in 1977 in Riyadh [4]. Three decades later, and due to multiple social and political factors, an agreement between Saudi and different Gulf Cooperation Council (GCC) countries has been settled to determine the usage method of nuclear energy.

In December 2006; the council manifested its intention in studying a peaceful use of nuclear energy. In August 2009, the Saudi government has officially announced a national nuclear power program. Investigations, conducted in 2011, led to the identification of 17 potential sites, including nine in the vicinity of the Red Sea coast, six on the Arabian Gulf and two locations further inland. The goal was to build 16 reactors over the following 20 years generating 20% of Saudi Arabia's electricity, with smaller reactors used for desalination.

In April 2013, the King Abdullah City for Atomic and Renewable Energy (KACARE) proposed a plan to install 17 GW nuclear power plants by 2030 and the construction was to begin in 2016; yet this plan has not seen any light. In September 2013, three sites were short-listed: Jubail on the Arabian Gulf, Tabuk, and Jizan on the Red Sea as per the World Nuclear Association. In April 2015, the country revealed a target of 6-7 GW of nuclear power by 2032 and 17 GW by 2040-41.

In mild- 2017, the government approved the Saudi National Atomic Energy Project (SNAEP) to implement a civilian nuclear energy program with three modules: a fleet of large nuclear reactors, a set of SMRs (Small Modular Reactors), and fuel cycle activities. Later, KACARE pledged to conduct a technical feasibility study to assess the location of building two large and two small nuclear reactors, and to explore the uranium in order to extract and process it to be used as fuel in the nuclear power plants [5].

In early 2018, MEED (Middle East business intelligence) has reported that two sites were shortlisted: Umm Huwayd and Khor Duweihin located on the Arabian Gulf Coast of Saudi Arabia near Qatar and the United Arab Emirates borders. The two sites were selected in accordance with sitting guidance issued by the international regulatory agencies, including the International Atomic Energy Agency (IAEA) and the US Nuclear Regulatory Commission (NRC). They were initially recommended due to their proximity to the industrial grid and the UAE's Al Barakah NPP (Figure 1).

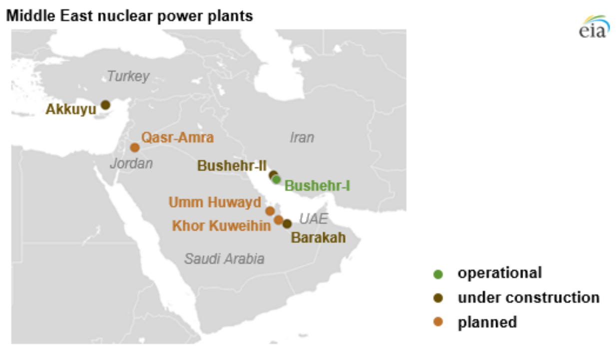

Figure1: Nuclear power plants in the Middle East (World Nuclear News 2018).

There are certainly huge challenges when deploying nuclear energy generation; since nuclear power plants offer high risks that have adverse impacts on the individuals, society as well as environment. The acceptability of a site is indeed the primary stone in the setup of NPP; so that the nuclear facility can be designed, constructed and operated with no accidents nearby.

The current paper highlights the most significant criteria for selecting the suitable site for setting up a nuclear power plant such as seismic assessment, hydrologic restrictions, meteorological characteristics, population density, and the potential effects on nearby industries as well as the environmental impacts at the operational stages. Besides, an assessment of the highlighted criteria in the three potential sites that were initially selected (Jubail, Tabuk and Jizan) and the recently short-listed sites (Umm Huwayd and Khor Duweihin) is carried out. Moreover, an economic analysis is conducted to evaluate the cost effectiveness of nuclear reactor in KSA.

Geography of the Studied Sites

The location of the selected nuclear sites is shown in Figure 2. The city of Al Jubail is located in the Eastern Province of Saudi Arabia and it covers 1016 square kilometers.

The province of Tabuk is located at the northwestern of Saudi Arabia, close to the Jordanian-Saudi Border. It has an area of 146,072 km^2 and contributes to 7% of the total area of the Kingdom. Jizan is located in the southwest corner of Saudi Arabia. This is the second smallest region in Saudi Arabia forming the direct northern border with Yemen. It is spread at 300 Km along the southern red sea coast and covers an area of 11,671 km^2.

Figure 2: Map of Saudi Arabia showing the location of the selected sites.

Umm Huwayd and Khor Duweihin: these two sites are located on the coast in the Eastern province of Saudi Arabia with the region font code of Africa/ Middle East. Umm Huwayd (also known as Jal Umm Huwayd) is located at an elevation of 43 meters above sea level. It is facing the Bahrain and Qatar Borders. Khor Duweihin is a bay that over shelf the Persian Gulf and separates the UAE and Qatar Borders. It is 10 Km away from Al Khuwayfiriayh plain to the north. The two sites are 100 Km distant approximately; they are aligned with Al Jubail to the west; and the Abu Dhabi Grid to the east.

Methodology

Site selection parameters

The following parameters are used in the current study to assess the suitability of the selected sites to setup a nuclear reactor:

Geology and seismology

The design and analysis of nuclear power plant require a seismic hazard assessment and a design of ground motion development for the site [6]. A nuclear power plant shall stand on stable soil such as bedrock and stable rock. Besides, *the nuclear power plant shall even be designed to remain functional in the event of probable displacement, and have* the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent and mitigate the consequences of accidents which could result in potential offsite exposures. Hazards issued from active ground motion at the NPP location are multiple such as [7] (i) Ground fracturing and building damages, (ii) Leakage of radioactive materials, (iii) Tsunamis which cause the flooding of watery areas adjacent to the power plant and (iv) Fire resulting from troubles in electricity network and reactors. Thus, the design basis of a nuclear power plant shall be in accordance with the potential of earthquake parameters (magnitude, focal depth and possible distance from the site) [8]. Moreover, the duration of an earthquake event is another factor in affecting the nuclear power plant. The duration term can be associated with various parameters as per [9] such as ground motion amplitude, frequency content, energy, and duration of shaking. In general, the duration tends to decrease with intensity increasing level and increases with the rise of the epicentral distance for a specified intensity level 3. For some sites, relatively low amplitude motions from distant, large earthquakes may pose a liquefaction hazard [10] due to the long duration of shaking. Site conditions can also enhance the duration of ground motion in particular trapped waves in deep basins surrounding the nuclear facility.

Upon the seismic design of NPP structures, it is essential to consider earthquake ground motions with both short and long duration [11] have recommended a minimum strong motion duration of 6 seconds (coupled with a built-up duration of 4 seconds) for nuclear power plant. On the other hand, the results in [9] revealed that for a base-isolated nuclear power plant, the lateral displacement of reactor containment building under both small (11 to 33 seconds) and long duration (62 to 96 seconds) ground motion suites were mostly identical; while the mean deformation at the base level for long duration motions was bigger than that for the small duration ones (for PGA greater than 0.4g).

Meteorology (Atmospheric extremes and dispersion)

Many Energy and nuclear associations (*i.e.,* AERB, USNRC) confirm that the surrounding atmosphere plays an important role in the dispersion of radioactive effluents in the air from both postulated accidents and routine releases of gaseous emission. Most specifically, it is necessary to evaluate the probability of dust and sandstorm phenomena, which is mainly affected by the wind speed, atmospheric stability and surface characteristics.

Sandstorms are usually characterized by local high wind. Heavy sand particles ranging from 0.08 to 1 mm appear at low altitude and dust particles are shown as high cloud; this phenomenon usually lasts for a limited duration (less than a day). Sand particles are confined to the lowest 3.5 m. While during dust phenomenon, the dust is driven from distant regions holding fine particles for longer duration. The dust particles may be elevated as high as 3 km.

Therefore, the occurrence of dust / sandstorm results in environmental as well as structural effects. The accumulation of dust / sand particles in the power plant structure might lead to clogging up effect, excessive stresses corrosive effects (leaks) and reduction of waves communication efficiency [12]. The dust may interact with radioactive particles which will create radioactive dust [13] and these can be transported thousands of kilometers away. Moreover, radioactive dust has a pneumo-toxic effect; it will harm the respiratory system of the working staff and decrease the lungs activity as concluded by [14]. On the other hand, the ambient temperature may have a great impact on the functionality of nuclear plant as well. In fact, the increase in ambient temperature contributes to reduction of the output power. According to [8], a 1°C increase in outdoor temperature leads to decrease the electrical output by 0.37 - 0.72%. Also, the nuclear power plant loses its full operating, which will decrease the amount of generated electricity.

Therefore, an evaluation of the following parameters shall be conducted for the selected site:

- Dust storm and sandstorm: Total dust or sand loading (mg·h/m3), duration (h) and average loading (mg/m3).
- Freezing precipitation and frost related phenomena: Nominal ice thickness and concurrent wind speed.
- Temperature

Population consideration

Nuclear power plants should be located away from densely populated centers. Low population or population distribution within a small area would likely result in a low mean probability of individual risk, if that population center was not in the path of prevailing winds for the region [15]. The population limitation facilitates the emergency planning; therefore, investigations about density populations are required at the preparation phase.

The *Nuclear Regulatory Commission* (NRC) guidelines limit the population density to 500 people per square mile, at the siting stage, averaged over any radial distance out to 30 miles, and 1000 people per square mile within the 40-year lifetime of a nuclear plant.

Hydrology

The nuclear power cycle uses water in three major ways: extracting and processing uranium fuel, producing electricity, and controlling wastes and risks. The quantity of water for the various uses may range from 10 gpm (0.63 1/s) for domestic supplies to greater than 100,000 gpm (6309 1/s) for service water and emergency cooling water supplies.

As per some references [16]; the federal regulation imposes the installation of an emergency supply of water with the nuclear power plant to cool the plant for at least 30 days in case of a serious accident, such as overheated reactor. Nuclear power plants shall be usually built on coastal sides or rivers to ensure abundant water resources for nuclear reactor that will act as coolant and moderator. It is important to examine the water aquifer in the underlying soil of the potential nuclear site. Any available cooled water or existing leakage will have a negative impact on the engineering characteristics of the nuclear installation.

On the other hand, the power plant presents adverse impacts on the underground water and aquifer nearby; which is mainly due to the withdrawal of condenser cooler water and the discharge of water cycle [17]. The thermal discharge effects associated with the withdrawal of huge amount of water and releasing it back to the water source; results in alteration of the temperature of the local body of water and may harm the aquatic life.

The pre-construction activities like excavation, fill and use of explosion can also cause pollution of the underground water. The surface water may be contaminated during the construction of harbor and the cooling water supplement and discharge units; as per [17]. The overall hydrology of the site might be greatly affected [18] temporarily or permanently due to the dewatering recharge and runoff, deep excavations and surface water diversion and impoundments.

Finally, other negative impacts might emerge especially during the last stages of construction including the permanent dewatering, the alteration of the surface water damage and the deviation of the groundwater flow field [18].

Industrial, military and transportation facilities

It is essential to check if there is any industrial and/or military facility in the vicinity of the nuclear site [19]. According to AELB regulations, areas within 16 Km of major airports and/or within 8 Km of hazardous facilities such as military bases, oil pipelines, chemical facilities, mining and quarrying operations should be avoided. If identified, the radiological effect that would emanate at any accident shall not exceed the dose specified in the Atomic Energy Licensing.

Economic features of nuclear power plant

Many factors affect the assessment of the unit cost of electricity generated by nuclear power plant. These factors are in direct relation with the country, the accessibility of cooling water, the resultant risks and the availability of appropriate power grid connections. The Levelized Cost of Energy (LCOE) of nuclear power plant is a comparative measure of the average net present cost of generated energy for a power plant during its life time. It is estimated based on the investment cost, fuel cost, waste treatment cost, operation and maintenance costs and the risk accident cost.

The LCOE is found by dividing the Net Present Value (NPV) of the total cost of building and operating the power generating asset with the total electricity generation over its lifetime. The total costs associated with the project cover in general:

- The initial cost of investment expenditures.
- Maintenance and operations expenditures.
- Fuel expenditures
- The total output of the power-generating asset presents:
- The sum of all electricity generated.

- Moreover, it is essential to consider the following factors in the equation:
- The discount rate of the project.
- The lifetime of the system.

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime}$$

$$LCOE = \left\{ \left(\frac{\text{overnight capital cost} \times \text{capital recovery factor} + \text{fixed O and M cost}}{8760 \times \text{capacity factor}} \right) + (\text{fuel cost} \times \text{heat rate}) + \text{variable O and M cost} + \text{waste treatment cost} + \text{risk accident cost} \right\}$$

Investment Cost

The investment cost represents the cost of financing and construction of nuclear plant; and it accounts a large percentage of the total cost of nuclear power plant. The investment costs indicate the capital costs that cover the Engineer-Procure-Construct (EPC) and contingency and owners' cost. The highest percentage of the capital cost is referred to EPC with 80% of the capital cost; while the contingencies and owners cost present 20% of the capital cost [20]. The investment costs are considered overnight cost which extract interest through the construction period. The investment costs depend on various parameters such as the reactor design.

There are many kinds of nuclear power reactors used to produce electricity. The two main reactors are the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). Recently, new designs of PWR and BWR have been developed. The main characteristics and the overnight capital cost of the new nuclear reactor design are displayed in Table 1. It can be noticed that the European Pressurized Reactor has the highest capacity factor and thermal efficiency; and the lowest overnight capital cost.

Name	Operating Life	Capacity Factor	Electrical Power(MWe)	Thermal efficiency (%)	Overnight capital cost (US $/kWe)
ABWR	40	0.87	1356	33	1300
AP600	40	0.8	600	33	1400
EPR	40	0.91	1600	36	1241
ACR	40	0.85	1400	33	1000

Table 1: Main characteristics of the new nuclear reactor designs.

Fuel cost

Several materials can be used to fuel nuclear reactor such as uranium, thorium and plutonium. Uranium is usually the most used, however, Thorium Oxide () has more advantages than uranium. Compared to uranium, thorium is more efficient, four times more abundant in nature, less waste generation; and the generated waste is less radioactive and shorter lived.

The uranium ore is extracted by mining; and then it is transported to mill for the release of uranium with a chemical process.

The main source of thorium is the phosphate monazite. Monazite is used as a raw material in order to produce the , and some other chemicals are used also in the whole process such as sulfuric acid, ammonium hydroxide, nitric acid, tri-butyl phosphate, kerosene and oxalic acid.

The estimation cost to procure 1 kg of Uranium Dioxide (UO2) used as fuel in nuclear reactors, is displayed in Table 2. The total cost to obtain 1kg of UO2 is $930. The energy generated from 1kg of enriched UO2 is 3400 GJ. The fuel cost by using enriched UO2 is 0.27$/GJ [21].

U3O8	US$200
Conversion	US$38
Enrichment	US$452
Fabrication	US$240
Total	US$930

Table 2: Approximated cost to procure 1kg of UO2.

Cost of disposal of radioactive waste

The cost of disposal of radioactive waste differs based on the radioactivity level. References in the UK have reported that the low-level waste is being disposed of at approximately a cost of £2,000/m^3; while high level waste's disposal is ranged between £67,000/m^3 and £201,000/m^3 [22].

The rate of low level to high level waste is represented by the ratio 80%/20%. It is worth to mention that one reactor releases annually around 12 m^3 of high-level waste.

Operation and maintenance

Operation and maintenance costs are the costs needed to operate and maintain the nuclear power plant. These costs vary in accordance with many parameters such as the size and the age of the nuclear plant. The fixed operation and maintenance cost is 1.28$/kW year; the variable operation and maintenance cost is 1.28$/MWh [23].

Risk accident cost

The risk accident in nuclear plant is caused by external events such as natural disasters and/or human poor knowledge of instructions and scanty security information. The unit accident risk cost is 0.0014$/kWh [24].

Results and Discussion

Technical assessment of the selected sites

The conformity of the five sites to the various criteria for a nuclear power plant site selection process is discussed below.

Seismic activity

The seismic activity of the selected sites for the installation of nuclear power plant is displayed in Table 3. Historical data show that the major areas of earthquake activities have fallen in the northwest of the kingdom (Tabuk area), the Gulf of Abaqa, North of the Red Sea and in the southwest (Jizan area) as per Table 3.

Province	Year of Activity	N0. Of Earthquakes	Magnitude and Depth (km)	Distance to the seismic event (km)
Al JUBAIL	-	-	-	-
TABUK	2004	2	3.9 (4-5 Km) 5.1 (4-5 Km)	70 km southeast of the city of Tabuk
JIZAN	1996	1	3.9 (10 Km)	87.08 Km
	2014	1	4.4 (18 Km)	100 Km
Umm Huwayd	-	-	-	-
Khor Duweihin	-	-	-	-

Table 3: Seismic activity for the five candidate sites from 1973 to 2019.

Tabuk: It is located in the northwestern part of the Arabian Plate. Tabuk went through several geological phases and tectonic activities, which creates ambiguity in its mapping faults [25]. This area includes rock structures of tertiary Era. Deposits of silt and gravels are brought by the quaternary formations. Moreover, the collision between the Arabian and the Turkish plates led to some volcanic eruptions mostly known by the white mountains. Accordingly, the tectonic activity of the area of Tabuk is dominated by the northwest-southeast striking faults (parallel to the Red Sea), the Gulf of Suez rift, the Najd faults system, the Aqaba fault line, and northeast-southwest and east-west trending pattern. Thus, it can be said that Tabuk is a moderately active seismic zone. The main affected zones are classified as follow [26] 1) Tabuk Zone; 2) Northern Red Sea Zone and 3) Gulf of Aqaba Zone (Figure 3). Previous seismic data revealed that the city of Tabuk was significantly affected by Aqaqa earthquake that occurred in Jordan in 1995 with a magnitude of 6 causing major damages. In 2004, zone 2 witnessed of two felt earthquakes that were located at 70 km southeast of the city of Tabuk. According to the National Earthquake Information Center, the first occurred on June 9 with a magnitude of 3.9 and resulted in minor damage in the epicentral area, while the second "moderate size" event (Mw=5.1) occurred on June 22. The latter was followed by a few felt aftershocks without any reported damage [27]. The Seismic Assessment developed in concluded that the maximum predicted magnitude for Tabuk zone is 7. The maximum obtained Peak Ground Acceleration was 218 cm/sec^2 [7] at the bedrock while, the response spectrum values for pseudo spectra acceleration vary in the range of 300 to 700 cm/ s^2 for damping of 3% up to 10%.

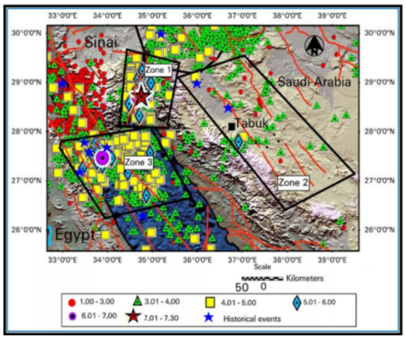

Figure 3: Seism-tectonic source zones affecting Tabuk area (Al Besher 2013).

Jizan: This is another prominent seismic source that is located in the south west of Saudi Arabia overlooking both the Red Sea and the Gulf of Aden Spreading center. Earthquakes affecting Jizan may be either internal or external. Over many years, the biggest earthquakes occurring near Jizan were located in Yemen (*i.e*., Dhahmar in Yemen in (1982) with a magnitude of 6.3) and in the Northern Red Sea Region (*i.e.,* Massawa, Eritrea in 1977 with a magnitude of 6.6 and depth of 33m). Usually, earthquakes with magnitude greater than 6 may have a significant impact on the infrastructure [28]. The recent Earthquake occurred in the coastal city of Jizan in 2014 spreading in 100 -200 km crucial deformation zone with an estimated depth of 18 Km (Figure 4). The analysis of focal mechanism solution shocks conducted in Abdelfattah [29] revealed that a dextral strike–slip faulting over the ENE fault trend was behind this shock. That clearly implied a reactivation of a high-angle fault, buried in the Precambrian basement, which is conjugate to the Red Sea spreading axis and NNW-SSE Najd fault system.

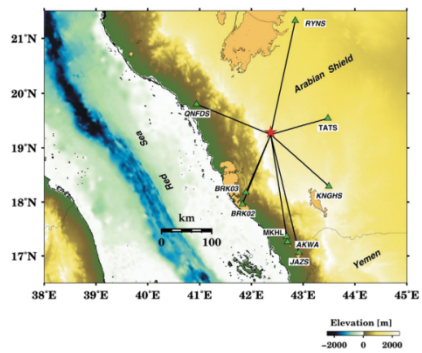

Figure 4: Map showing the parameters of the mainshock of Jizan Earthquake in 2014 [29].

Al Jubail: Although this area is not seismically active to date, it can be said that it will be certainly affected by any potential quake occurring in the Eastern Province. The tectonics of the Eastern Province is controlled by a collision between the Arabian Plate and the Eurasian Plate along Zagros and Bitlis Thrust belt. Seven seismogenic source zones have been identified as per [30]: Zagros fold and thrust

Belt, Zagros Fore deep zone, Zagros Mesopotamian Foredeep, Dibba Fault Line zone, Makran subduction zone, Southwestern Kuwait (Minagish Umm Qudair) zone and Al-Ghawar uplifting zone. From Zagros fold, the earthquake locations in this folded belt designate a zone about 200 Km wide that runs parallel to its central axis. These earthquakes could produce a significant ground shaking in the Eastern Province of Saudi Arabia with a maximum magnitude up to 7.4. The potential effect in Al Jubail area will depend on the distance to the epicenter.

Simulations for the Peak Ground Acceleration with respect to the fault distances from 1 to 300 km show high PGA values ranging from 190 cm/sec^2 for a moment magnitude of 5 to 450 cm/sec^2 for Mw=6.5 [30]. These values are associated to the shortest distance between the projection of the rupture and the site of interest; and they can be produced from southern Kuwait seismogenic source.

Umm Huwayd and Khor Duweihin: Apart from the seismic effects that would emanate from the same events affecting Al Jubail, the two areas of Umm Huwayd and Khor Duweihin might be exposed to tolerable shaking events originating from multiple surrounding areas. The tectonic setting of the Eastern bloc in Saudi Arabia reveals clearly that the two areas of Umm Huwayd and khor Duweihin are found in the vicinity of Al Ghawar Anticlines and Qatar Arch (Figure 5).

The Ghawar antic lines, extended over 174 miles length and 12 miles width has a general trend oriented almost NNE-SSW Mukhopadhyay [31]. They are bounded by the orthogonal NE-SW trending (Wadi Batin) and NW-SE trending (Abu Jifan) strike-slip faults. Al-Ghawar and Qatar arch area was subjected to some earthquakes with magnitudes greater than 5.0. Most of these seismic events are located south to southeast of the Ghawar anticlinal structure which is aligned with Khor Duweihin; while others occurred to the west of Qatar peninsula. The occurrence of these earthquakes is attributed to the extraction of oil and/or recent tectonic activities of the area. A recent study conducted in has shown a low recorded seismicity magnitude ranging from 0.17 to 4.24 with maximum magnitude as 4.24 and magnitude completeness [32] as 2.7 within a focal depth of 22 km. Most of seismic events occurred within a depth of 5 km due to the hydrocarbon-fluid extraction from the Ghawar oil-gas fields. It was concluded that current seismicity in the region, in particular, for the GA and its surroundings extends deep into the crust, ~ 22- Km depth, and thus suggests for continuing tectonic stress across the platform.

The two areas of Umm huwayd and khor Duweihin lie within the seismic Zone 1 of the delineation of UAE seismic zones (Figure 6). This zone refers to a low seismicity level where the PGA in 50 yeas time period (corresponds to 475 years return period) does not exceed 100 *i.e.*, 0.1 of the gravitational acceleration (0.1g).

On the other hand; the historical data has recorded only one earthquake located in northern UAE in MasafI with magnitude approximately 5.

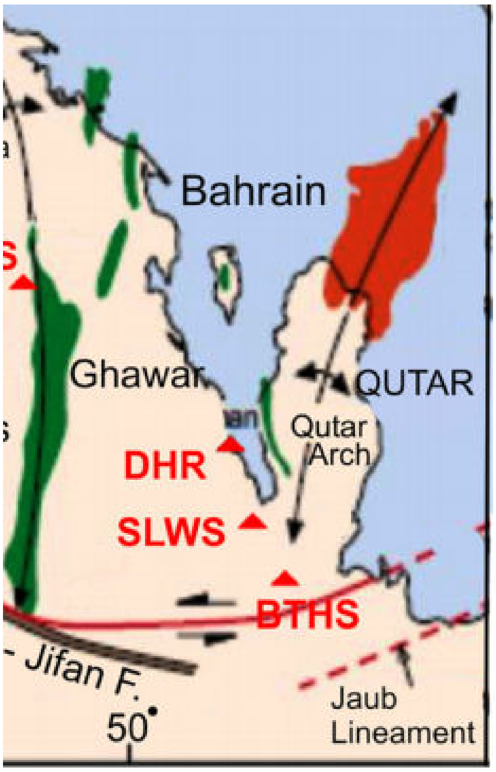

Figure 5: Tectonic setting of the eastern block of Saudi Arabia [31] (The red triangles are seismicity recording stations).

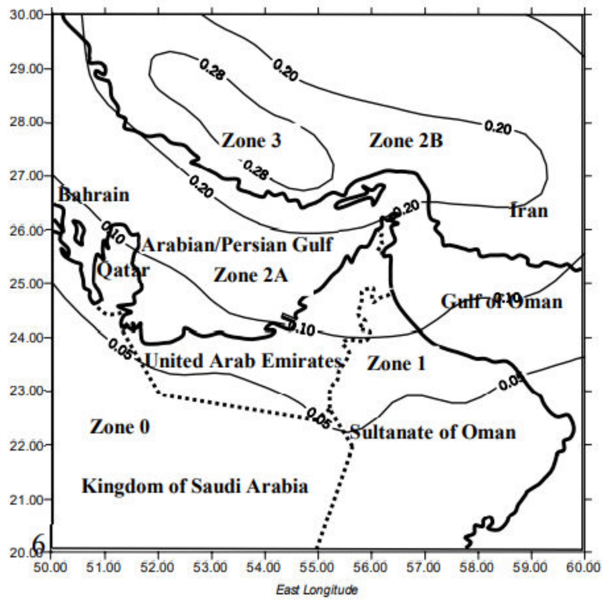

Figure 6: Seismic zoning map of UAE and its vicinity.

Meteorological Variables

Dust

Waves of Dust are often sweeping parts of Saudi Arabia due to the desert climate and soil characteristics. Figure 7 displays the annual change in dust storm frequency over the kingdom between 2000 and 2016. It can be seen that the areas of Jizan and Tabuk have medium rate of dust compared to the Eastern part (1 -1.7). Usually, sand and dust storms are accompanied with a rise in temperature and a high wind speed that carries the dust particles in the air. The frequency of dust storm is usually the highest in April and May when it is time for seasonal variation, and it coincides with an overall highest frequency of precipitation [33]; since dust storms are mostly followed by rainfall. Therefore, it can be said that the occurrence of dust storms can be predicted based on the rate of precipitation.

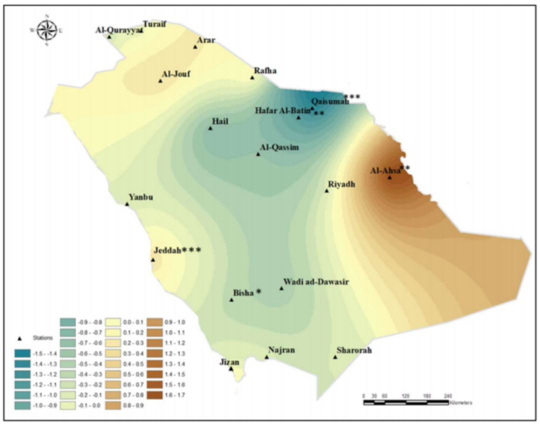

Figure 7: Annual change in dust storm frequency over Saudi Arabia [33] Years of study (2000-2016) .

Figure 8 reveals the frequency of precipitation in the studied sites except Khor Duweihin in 2019. The calculated rate of precipitation, based on Meteo-blue weather website data [34], indicates how often precipitation event has occurred within a month. It can be seen that Jubail had experienced the highest peak of raining (4 times) in the period of February – May, which explains the dust storm occurring at the same time. In Tabuk, precipitation has occurred similarly 2 times during the months of March, June, October & November, implying a uniform triangular graph. The two rainfall seasons in the summer and spring are depicted in the graph of Jizan where the peak of precipitation is attained in September- October. An overlap is observed between Jizan and Tabuk in the period of September to November which may imply similar probability of dust storms. For Tabuk, precipitation occasionally occurs in the period from December to February as a result of the Mediterranean cyclones. Whereas, no or very limited rainfall occur in summer [35]. The frequency of precipitation recorded in Umm Huwayd exceeded the values seen in Al Jubail during the first 5 months and the last 2 months of the year. This justifies the great number of dust storms occurring between February and April. The peak has reached 12 dust storms in April.

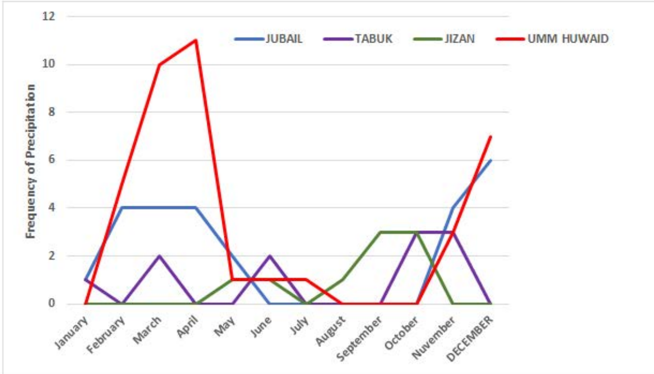

Figure 8: Frequency of precipitation in the candidate cities in 2019.

Wind speed

As per Albugami [23], the two meteorological variables of precipitation and wind speed are positively correlated with the occurrence of dust storms. Figure 9 displays the annual wind speed average for the five candidate cities; as well as the extreme wind values for Umm Huwayd and Khor Duweihin areas. Due to the lack of data for Khor Duweihin, the weather variables collected for this area refer to Al Kuwayfirīyah that is 10 km away from Khor Duweihin bay. The wind data collected over the last 10 years (based on the hourly wind speed recorded by timeanddate.com weather platform) show that the two areas of Umm Huwayd and Khor Duweihin have experienced the highest annual average wind speed with similar fluctuations that exceed 20 km/h; which implies strongest wind gusts and highest rate of dispersion in the air. This is an evidence of the occurrence of sandstorms rather than dust storms in these two areas, since wind speeds are higher during a sand storm. The collected data permitted to identify the extreme annual values (in dash line) that have reached a peak of 60 km/h in 2018 and 2019. The peak wind speed data associated with the time duration are usually determined to be critical for a design of any facility. High wind fluctuations have significant effect on the potential nuclear power plant; especially in arid and semi- arid regions due to the occurrence of dust storms and sandstorms. The latter events occur when wind forces exceed the threshold value at which loose sand and dust are removed from a dry surface and become airborne. These particles contribute to the blocking process of filters and mechanical elements of the plant. Also, they are merged with the radioactive particles and expand in the air in the surrounding area. On the other hand, Tabuk and Jizan have the lowest average annual speed in comparison with the other areas (less than 15 Km/h); and the rate of variation does not exceed 4 Km/ h. In Jizan, the probability of dispersion of dust particles is low since the soil is mostly made of sabkha. Also, there are few outcrops of the salt deposits at the southern coastal plain [36]. The soil in Tabuk is a mix of sandstone, clay shale (in the northern) and (Silt, clay, and blown sand with gravel and rock fragments) which is in favor of occasional dust / sandstorms.

The study conducted in revealed significant positive correlation of 0.69 between the frequency of dust event and wind speed in Saudi Arabia. While, the lower frequency of dust storm especially in the period November – January is characterized by lower wind speeds.

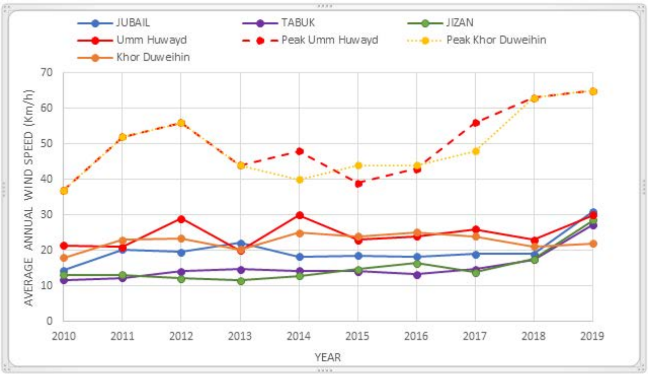

Figure 9: Wind Speed data in different cities for the period [2010 – 2019].

It is clear that Jubail had a constant average wind speed during all these years; with an increase in year 2019. This implies a less frequent dust or sand storms in this area. Another factor contributing to the spread of dust in Jubail is the non-sabkha terrain that is mostly aeolian silty sand deposits and dune-sand [36]. In addition, storms often travel from Iraq and Iran with areas rich in silt and clay soil.

In the light of the above, it can be said that among the selected three sites, Umm Huwayd and Khor Duweihin constitute a potential risk for the setup of a nuclear power plant in terms of occurrence of dust and sandstorm. Therefore, quantification of the density of dust in the air would be crucial at the design stage. The natural hazard arising from sand dispersion can surely never be prevented, but it has to be dealt with carefully in order to avoid the formation of radioactive dust. Special filters might be probably implemented within the construction of the reactors to prevent accumulation effects and blocking issues.

Sandstorm

In order to examine further the sandstorms trends in the considered sites in the last 3 years; the frequency of sandstorms has been compiled on the basis of hourly weather observations when visibility is 10 kilometers or less (Figure 10). The results were plotted only for the months of January, February, March, June and July; since the most sandstorms occur during these months. It can be noticed that sandstorm events are mostly frequent in the 2 areas of Umm Huwayd and Khor Duweihin at the same rate with a peak of 12 days in June 2018; 8 days in March 2019 and 9 days equally in January and June 2020. The data show clearly that sandstorms event occur randomly during these months from one year to another without having one specific month with a constant rate of sand occurrence. Jubail (2 days in January 2020) and Tabuk (1 day in March 2020) have occasional sand storm event; while the area of Jizan is not subject to any sand storm.

This plot probably reflects the highest annual wind speed data seen in Figure 10; as well as the extreme values shown for Umm Huwayd and Khor Duweihin. The observation of recorded wind data proves that wind speed can exceed 50 km/h reaching or exceeding 80 km/h; during windstorms especially during the month of February and March. The sandstorm may last up to 5 consecutive hours or more. While during dust storm, the wind speed is around 19 km/h on average. Also, this is followed by a dense fog.

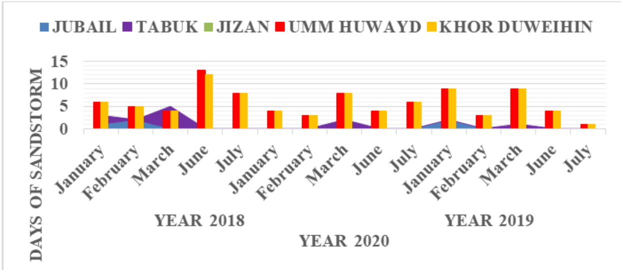

Figure 10: Frequency of sandstorm.

Temperature

Figure 11 reveals the trend of another meteorological variable: the temperature. In general, the seasonal maximum temperature occurs in a period (July to September) characterized by a relatively small number of dust storms. The studied cities are ranked in a decreasing order from the highest to the lowest maximum temperature over the past ten years. The Eastern cities are characterized with quite high temperatures due to their arid nature. The two areas of Umm Huwayd and khor experience the highest temperature reaching 50 degrees; followed by the city of Jubail that shows a temperature lesser by 5 degrees. Tabuk has a medium temperature (less than 40); while Jizan comes in the last with an average maximum temperature of 35.

The high temperature presents potential negative impacts on the functionality and the efficiency of a nuclear power plant. In fact, feeling the heat is harmful for the operation of condensers and cooling equipment's. Nuclear stations use an enormous amount of cooling water, and return it back into rivers, lakes or the sea, after being used; much warmer than when it was extracted. Troubles occur if then water intake is too warm to cool the plant; then this will slow and deteriorate the condensers and might force nuclear activities to shut off. Therefore, it can be said that the two areas of Umm Huwayd and Khor Duweihin offer harsh temperature conditions for the nuclear activity, which will be difficult to deal with; and might lead to intermittent functionality. This has previously occurred in summer 2018 that has witnessed of the complete shut down and reduced power in five European countries: Finland, France, Germany, Sweden and Switzerland because of hot temperature exceeding 35°C (The Guardian).

The trend shown in Figure 11 shows negligible or no increase in the ambient temperature from one year to another, which will be suitable for the functionality and the efficiency of a nuclear power point, if it persists for the next 10 years, specifically in Jizan.

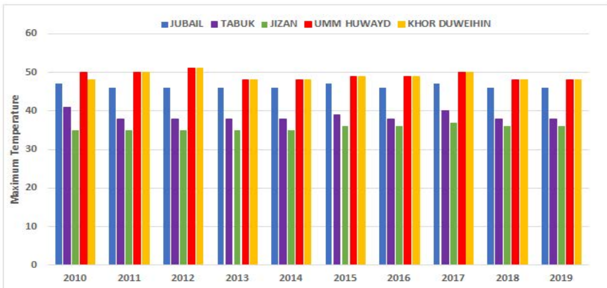

Figure 11: Maximum Temperature in different cities for the period [2010 – 2019].

Population density and safety zones

The population data of the five discussed sites, based on the Saudi Demographic statistics, are given in Table 4. Jizan has the highest population density in the kingdom (130 persons/ km2). This city has witnessed a rapid expansion in the period of 2000 to 2017 which is reflected in the rate of growth (5.31%); the urban development or the built-up area is about 45 square kilometers. Jubail and Tabuk are classified as medium areas in terms of population since the number of inhabitants is ranging from 300,000 to one million. The available population data shows that the three sites of Jubail, Tabuk and Jizan comply currently to the maximum allowed population density required by the USNRC regulations 10CFR part 100.21(1998) that is 194 persons per square kilometer. Preferably, the population density shall remain under this limit at the time of initial site approval and within 5 years thereafter [34]. Probably, this cannot be guaranteed for the city of Jizan due to its high population; which will make this city an unfavorable site for nuclear projects.

Province	Population (2017)	Population density (persons per km2)	Growth Annual Rate
Jubail	500,000	7.3	6.63% (2010 – 2014)
Tabuk	946,300	6.2	1.37 % (2030)
Jizan	1,636,600	130	5.31% (2000 – 2017)
Umm Huwayd	--	--	--
Khor Duweihin	--	--	---

Table 4: Population Data (Urban areas).

There is no clear estimation of the data population of Umm Huwayd area. Also; khor Duweihin is initially a bay so it is unpopulated. It is worth to mention that according to [1], the rural population growth is estimated to be only 18% in 2030 due to the declining role of rural economy; in comparison to 82% of urban population growth

Hydrology

The five studied locations are found in the vicinity of two major surface water resources in Saudi Arabia: The East Coast and The Red Sea Coast; which constitutes an advantage in favor of the hydrological criterion in principle (Figure 12). The two areas of Jubail and Umm Huwayd found on the East Coast water, have their water intake from the seawater and to a much lesser extent from the non-renewable groundwater resources and treated wastewater. The khor Duweihin bay itself as depicted in geographic maps; is situated within the Arabian Gulf; while the land is considered as a part of the Arabian platform that comprises only non- renewable water resources with a remote supply of the desalinated Seawater.

The three areas of Al Jubail, Umm Huwayd and Khor Duweihin include the Neogene Aquifer which represents one principal acquirer of the upper mega aquifer system in the Kingdom of Saudi Arabia.

For Jubail area; The water table is only 0.5 m from the surface in the sabkha areas, complicating the geotechnical problems.

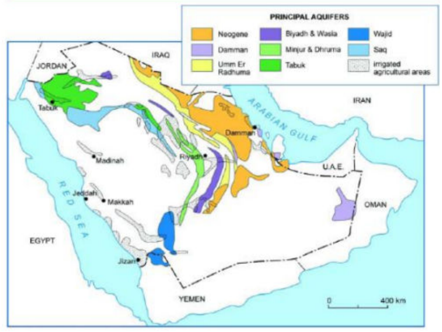

Figure 12: Principal aquifers in Saudi Arabia.

The ground water in Tabuk area is mostly used for agriculture during the last 2 decades [35]. Therefore; the setup of any nuclear project would require the use of the sea water only, with a limited consumption of the groundwater resources. The groundwater in Jizan area derives from the Quaternary deposits that have led to the formation of the water-bearing aquifer within the Jizan Plain.

When examining the hydrological conditions of the considered sites, it is worth to mention the potential impacts of nuclear activities on the surrounding water resources. In fact, the operation of nuclear power plant will affect the water quality due to the release of radioactive substances in the returning cooling water. In addition to the radionuclides that are naturally available in underground water, the discharges from power reactors and reprocessing plants will produce anthropogenic radionuclides which will cause contamination of the underground water. This might be more susceptible in the shallow aquifer areas (Jubail) and at the seawater level (Umm Huwayd and Khor Duweihin). Therefore, it is worth to estimate the time of migration of radioactive pollutants to the underground water in these areas.

Moreover, the elevated concentration of potassium related to fertilizer usage as detected in the underground water of Tabuk and Jizan, is a major parameter that controls the concentration levels of specific radionuclides in the saturated part of the aquifer system and would consequently trigger the combination of radioactive isotopes or their decay. This is another factor that would easily contribute to the pollution of the underground water especially in the existence of high aquifer transmissivity of ($1572m_2$/day) for Tabuk.

Other adverse impacts might surround from the operation of a nuclear power plant as well like the change in ground water flow direction, gradients and flow velocity as a result of site modification [18], the aquifer over-exploitation or depletion especially in Tabuk and Jizan due to the huge amount of water withdrawal for agriculture or the deterioration of fresh water resources and occurrence of dry rivers (in Jubail).

Proximity to sensitive facilities

The three areas of Jubail, Jizan and Tabuk are considered as engine of economic growth in the Saudi Kingdom due to the variety of industrial facilities.

Al Jubail province is designated to be the largest industrial area in the Eastern Province on the Persian Gulf Coast (Figure 13). It houses numerous oils and gas industries, refineries, plants and desalination plants; which makes it unfavorable place for nuclear activity. The expansion of sensitive facilities all along the cost threaten the functioning of nuclear power plant which requires a suitable space and an independent transportation system.

The area of Jizan might not be favorable as well for a nuclear activity. Its proximity from International Borders of other countries (north of Yemen) would pose instability and unsafety issues. In addition, its strategic location at the Red Sea makes it one of the main components of trade routes to Europe with the growth of commercial activities along the Cost.

On the other hand, Tabuk also hosts quite fewer sensitive facilities since it is mostly characterized by the development of its agriculture. Spacious lands are reserved for farms, plants and touristic projects. Thus, any nuclear activity nearby the agricultural areas will pose serious damages to the plants and the vegetation due to radioactive releases.

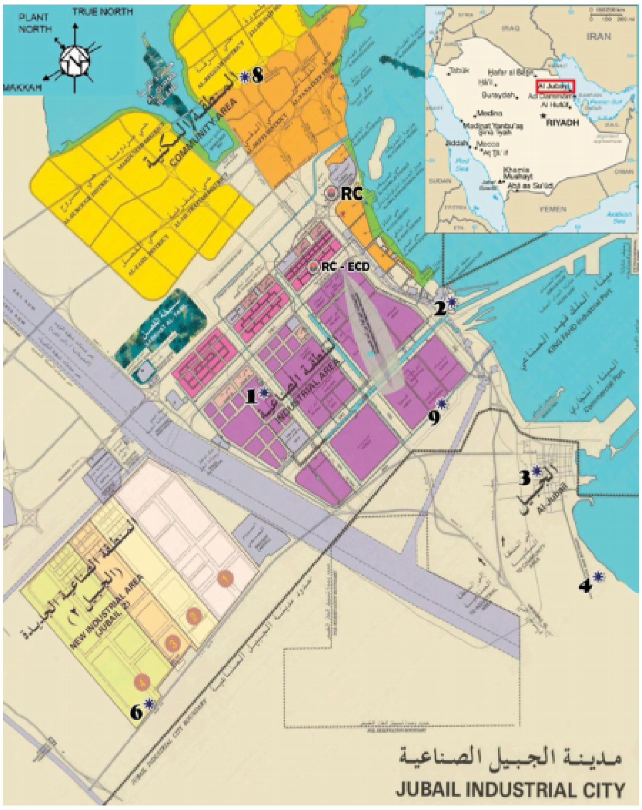

Figure 13: Al Jubail province.

Economic analysis

The estimation of the levelized cost of energy produced by nuclear power plant in KSA for the four different designs of nuclear reactor is displayed in Figure 14. It should be mentioned that the interest rate in KSA is 3.56% and the capacity factor used in the current study is 90%.

It can be seen that the LCOE varies between 40.4 $/MWh for Advanced CANDU Reactor and 42.3 $/MWh for Advanced Pressurized Reactor 600.

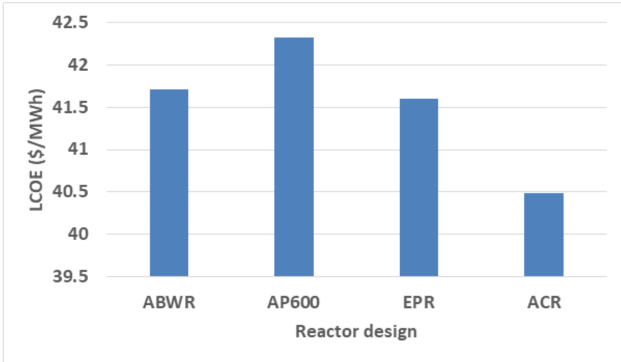

Figure 14: LCOE for different designs of nuclear reactor –KSA.

The LCOE for electricity generated from gas and solar energy is presented in Table 5. It can be noticed that the LCOE of nuclear exceeds slightly that of the gas; but it is much less than solar.

	Gas	Solar (CSP)	Solar (PV)
LCOE ($/MWh)	34	86	82

Table 5: LCOE for electricity generated from gas and solar energy.

Conclusion

The Kingdom of Saudi Arabia intends to build two large nuclear power reactors in order to cover 17 GW of nuclear capacity by 2040 and therefore ensure the demand of 15% of the power in the country. In September 2013, three sites were short listed as potential candidate sites in the first phase: Jubail, Tabuk and Jizan. Recently, in 2018, two sites are shortlisted: Umm Huwayd and Khor Duweihin on the Gulf coast.

The current paper aims at examining the suitability of the selected sites for installation of nuclear power plant based on the seismic, meteorology, population, hydrology and proximity to sensitive facilities criteria. The current study aids to determine theoretically the acceptable sites. Table 6 shows the tradeoff of criteria between the different candidate sites. The cross designates the compliance of each site with the corresponding criterion

Site criteria	Seismic	Meteorology	Population	Hydrology	Proximity to sensitive facilities
Tabuk	.	x	X	X	X
Jizan		x		X	
Al Jubail	x	x	X	X	
Umm Huwayd	x		X	X	X
Khor Duweihin	X		X	X	X

Table 6: Suitability criteria for the candidate site for nuclear power plant.

It can be said that Al Jubail would have been the optimum site for establishing a nuclear reactor without the existence of numerous industries. The data collection has shown suitability to all criteria covering the geology and seismic, hydrology, meteorological conditions and population.

The area of Tabuk is complying with all the criteria except for the seismic. The geology of the region as well as its history with seismic events are not favorable for nuclear activity, although twenty percent of nuclear reactors are installed in high seismic countries according to the Word Nuclear association (2018).

Jizan is not the preferred place for nuclear as well, although it presents excellent meteorological conditions. Many elements would have a bad influence on the decision makers such as the low magnitude seismic events and its proximity from International Borders of other countries. Besides, the continuous growth of rate of population would result in troubles in terms of safety. The two areas of Umm Huwayd and khor Duweihin appear to be the most susceptible locations for the construction of nuclear power plant. By examining their suitability criteria, it can be said that the only obstacle is the meteorological criteria. The two unpopulated arid areas offer the optimum site for the setup of nuclear reactor from the safety viewpoint. The engineers will have the freedom to design and establish a multi – defense plan and evacuation system. At the same time, the investors shall be aware that there shall be implementation of new technology in order to ensure the continuous workability of reactors.

However, it is worth mentioning that they both show severe meteorological conditions characterized by high temperature and high probability of dust and sand storms, especially during the summer season. This is quite challenging in terms of maintaining the cooling and used water in good condition; and in controlling the release of the radioactive dust as well. In all cases, the setup of prime nuclear power plants in the zones of Umm Huwayd and Khor Duweihin will undoubtfully contribute to the implementation of an economic path that emerges from the United Arab Emirates and crosses the kingdom of Saudi Arabia. The National Spatial strategy 2030 aims for the development of economic and infrastructural five major corridors that govern the forthcoming kingdom's economic model. The eastern development corridor on the Arabian Gulf coast is one of the major planned corridors that will link the borders of the United Arab Emirates with Dammam and Kuwait.

Based on LCOE analysis above, generating electricity using nuclear reactors has LCOE (about $40/MWh) slightly higher than gas ($34/MWh) but less than solar energy. This would be certainly an additional benefit for Saudi Arabia when developing nuclear reactors, such as ABWR, AP600, EPR, and ACR, for electricity production.

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