POTENTIAL NUCLEAR POWER PLANT SITES SELECTION USING MULTI-CRITERIA DECISION ANALYSIS

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DEDICATION

This thesis is dedicated to my father, mother, wife and children for their unlimited love and support which always overwhelms me. It is also dedicated to all my teachers and instructors, from when I was in the first grade to the last letter I wrote in this thesis.

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ABSTRACT

Strategic decision-making is very difficult, particularly when multicriteria are involved. Multi-Criteria Decision Analysis (MCDA) method is an important approach that is applied to many complex decisions-makings. MCDA has been combined with Geographical Information System (GIS) to tackle spatial decision-making problems. One of the hardest spatial decision-making problems is the Nuclear Power Plant sites selection (NPP siting). This study has developed hybrid GIS and MCDA models to conduct NPP siting. Saudi Arabia was chosen to be the case study for this research. The identification of NPP siting area was divided into two phases. Phase I was a survey of all potential suitable areas for siting NPPs in the country. Phase II was a suggestion and ranking of the preferable suitable NPPs sites. The spatial analysis software ArcGIS 10.6 was utilized throughout this study. Thirteen significant criteria were applied to screen out unsuitable areas for siting NPPs. The results of phase I revealed that a 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 covered an area of 21473 km^2 and 13395 km^2 on the western and eastern coast, respectively. Meanwhile, the survey revealed that sea-level rise sensitivity must be considered on the eastern coast for the safe operation of NPPs. Further analyses disclosed that a sea-level rise of 2 meters could reduce the possible land areas by 20% and 13% in the eastern and western coastal areas correspondingly. The net feasible areas were inversely proportional to the aggregation of suitable lands into specific NPP footprint. It was concluded that the proposed assembly strategy could reduce the net effective area on the western coast for siting NPPs such as SMR350 (small reactor), AP1000 (moderate reactor) and EPR1600 (large reactor) by almost 22%, 37%, and 47%, respectively. The results of phase II (identification and ranking process) revealed that there are many locations available for siting NPPs in Saudi Arabia. Since the first-option areas, whose suitability scored 9/10, would be more than enough for proposing reasonable number of NPP sites on both coastal areas, the other options of ranked areas 2, 3, 4 and 5 (whose suitability were 8, 7, 6 and 5 respectively) were ignored for this time. There were 20 proposed NPP sites; 11 of which were on the western, and the other 9 on the eastern coast. Both coasts were sensitive for change of the criteria’s weights, particularly the eastern coast that expressed significant response.

ABSTRAK

Strategi untuk membuat keputusan didapati sangat sukar, terutamanya apabila melibatkan berbilang kriteria. Kaedah Analisis Keputusan Kriteria Berbilang (MCDA) adalah pendekatan penting yang digunakan untuk membuat banyak keputusan yang rumit. MCDA telah digabungkan dengan Sistem Maklumat Geografi (GIS) untuk menangani masalah membuat keputusan berkaitan ruang. Salah satu masalah membuat keputusan berkaitan ruang paling sukar ialah pemilihan tapak Loji Tenaga Nuklear (penempatan LTN). Kajian ini telah membangunkan model GIS dan model MCDA hibrid untuk menempatkan LTN. Arab Saudi telah dipilih sebagai kajian kes untuk penyelidikan ini. Pengenalpastian kawasan penempatan LTN terbahagi kepada dua fasa. Fasa I adalah satu tinjauan ke atas semua kawasan yang sesuai untuk penempatan LTN di negara tersebut. Fasa II adalah cadangan dan kedudukan tapak LTN yang sesuai. Perisian analisis ruang ArcGIS 10.6 telah digunakan sepanjang kajian ini. Tiga belas kriteria penting telah digunapakai untuk menyaring kawasan yang tidak sesuai untuk menempatkan LTN. Dapatan fasa I mendedahkan bahawa kekurangan air di Arab Saudi adalah alasan utama untuk membuang 96% daripada kemungkinan tapak LTN. Tambahan pula, proses pertindanan kesemua kriteria ini membolehkan hampir 98% daripada tanah berdekatan di Arab Saudi turut dibuang. Baki 2% kawasan tanah yang tinggal dilihat bersesuaian untuk menempatkan LTN, yang merangkumi kawasan seluas 21473 km^2 dan 13395 km^2 di pantai barat dan pantai timur. Sementara itu, tinjauan mendedahkan bahawa kenaikan aras laut mesti dipertimbangkan di kawasan pantai timur bagi operasi NPP yang selamat. Analisis lanjutan mendedahkan bahawa kenaikan aras laut sebanyak 2 meter masing-masing dapat mengurangkan kawasan tanah sebanyak 20% dan 13% di pantai timur dan pantai barat. Kawasan-kawasan yang tersaur bersih ini adalah berkadar songsang dengan pengagregatan tanah yang sesuai dengan jejak kaki LTN yang khusus. Adalah disimpulkan bahawa strategi pemasangan yang dicadangkan dapat mengurangkan kawasan bersih berkesan di kawasan pantai barat untuk menempatkan LTN seperti SMR350 (reaktor kecil), AP1000 (reaktor sederhana) dan EPR1600 (reaktor besar) masing-masing hampir 22%, 37% dan 47%. Dapatan fasa II (proses pengecaman dan proses ranking) menunjukkan terdapat banyak lokasi yang tersedia untuk menempatkan LTN di Arab Saudi. Sejak kawasan yang menjadi pilihan pertama, di mana kesesuaiannya memberikan skor 9/10, adalah lebih daripada mencukupi untuk mencadangkan bilangan LTN yang munasabah di kedua-dua kawasan pesisiran pantai, pilihan kawasan lain di kedudukan 2, 3, 4 dan 5 (di mana kesesuaiannya adalah 8, 7, 6 dan 5) telah diabaikan buat kali ini. Terdapat 20 cadangan tapak LTN; 11 daripadanya berada di pantai barat manakala 9 lagi di pantai timur. Kedua-dua kawasan pesisiran pantai menunjukkan kepekaan terhadap perubahan pemberat kriteria, terutamanya kawasan pantai timur yang menunjukkan sambutan tindak balas yang penting.

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LIST OF ABBREVIATIONS

AHP	-	Analytical Hierarchy Process
AP1000	-	Westinghouse pressurised reactor 1100 MW
BP	-	British Petroleum
CGIAR	-	Consultative Group for International Agricultural Research
CGIAR-CSI	-	CGIAR Consortium for Spatial Information (
DEM	-	Digital Elevation Model
DID	-	Defense in Depth
ECRA	-	Electricity & Cogeneration Regulatory Authority
EPR1600	-	European Pressurised Reactor 1600 MW
ESP	-	Early Siting Permit
ESRI	-	Environmental Systems Research Institute
FAHP	-	Fuzzy Analytical Hierarchy Process
GIS	-	Geological Information System
IAEA	-	International Atomic Energy Agency
IEA	-	International Energy Agency
KA-CARE	-	King Abdullah City for Atomic and Renewable Energy
MCDA	-	Multi-Criteria Decision Analysis
MW	-	Megawatt
MW(e)	-	Megawatt electrical
NPP	-	Nuclear Power Plant
NRC	-	Nuclear Regulatory Commission
NS	-	Net suitability
ROI	-	Region of Interest
SLR	-	Sea Level Rise
SMR350	-	Small Modular Reactor (350 MW)
TOPSIS	-	Technique for Order of Preference by Similarity to Ideal Solution
TWh	-	Terawatt hour
UTM	-	Universiti Teknologi Malaysia

LIST OF SYMBOLS

A	-	Area
E	-	Exclusionary
P	-	Population
R	-	Radius of population centre buffer
S	-	Suitability
w	-	Weight

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CHAPTER 1

INTRODUCTION

1.1 Background

Electricity is one of the vital driving forces of economic development of all nations. Both developed and developing countries face the constant challenge of generating electricity and meeting growing demand, which exerts tremendous pressure on the energy infrastructure (Kaundinya, Balachandra and Ravindranath, 2009).

As a fast-growing developing country, Saudi Arabia has been confronting a vast increase in demand for electricity. Figure 1.1 shows electricity consumption in Saudi Arabia surged from 70 Terawatt-hour (TWh) in 1990 to approaching 330 TWh in 2015. Power generation has grown almost five-fold within 27 years.

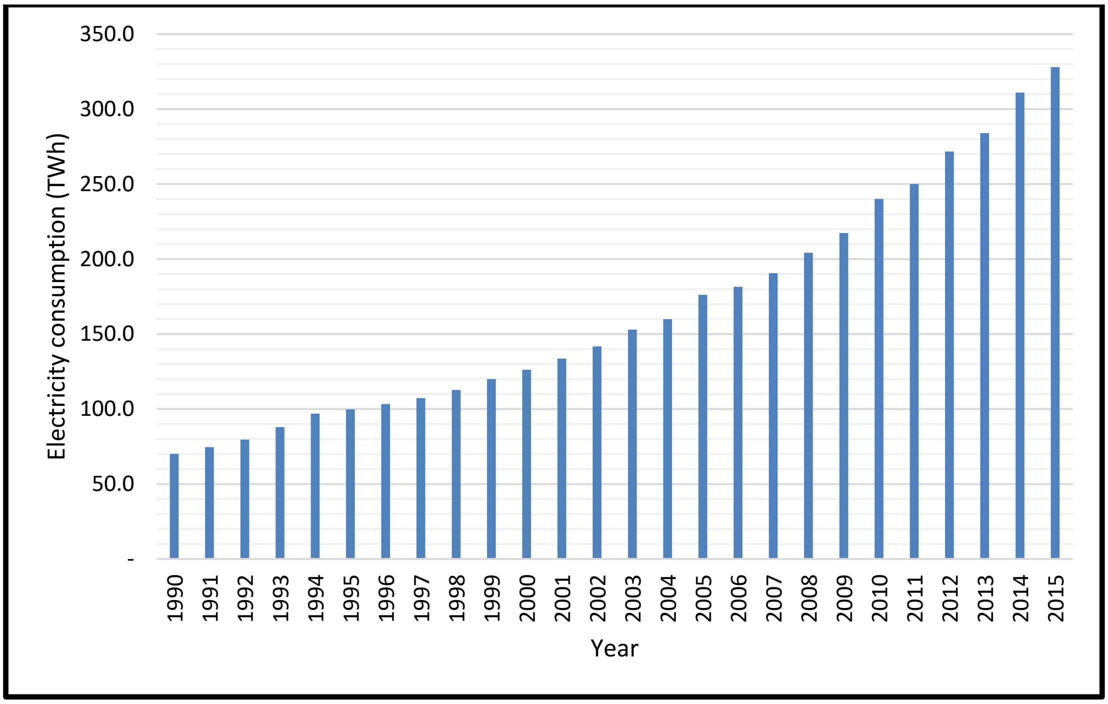

Figure 1.1 The electricity consumption in Saudi Arabia from 1990 to 2015 (British Petroleum, 2017).

1.1.1 Electricity Demand Trend and its Impacts

One of indicators of electricity consumption is the consumed power in a particular year in relation to the population in the same year. Figure 1.2 represents electricity consumption per capita for different countries. The Saudi Arabian curve continues to increase from 2010 to 2015 (International Energy Agency, 2018) hitting 10 MWh per capita in 2015. The peak load capacity leaped by 15 GW within only five years; it was 45 GW in 2010 and 62 GW in 2015 (ECRA, 2015, 2017). Accordingly, peak load capacity of Saudi Arabia is forecasted to reach 120 GW by 2032 (Ouda *et al.*, 2016). On the other hand, the other countries shown on Figure 1.2 managed to render their curves flattened or even have been decreasing since 2010, such as Japan.

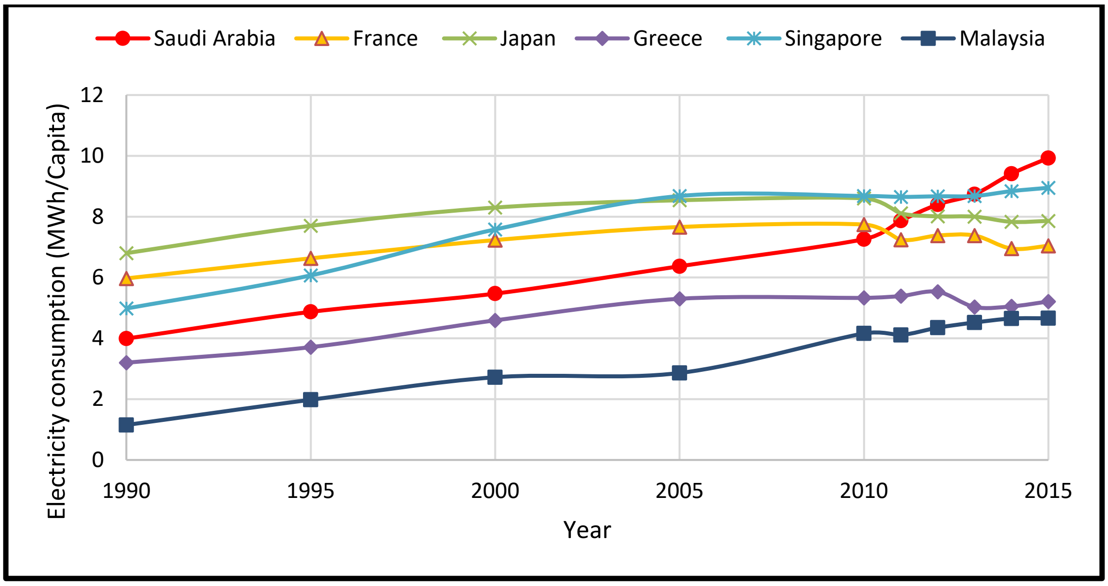

Figure 1.2 Electricity consumption per capita for some countries (International Energy Agency, 2018)

One of the most negative impacts of such increasing demand for electricity is its associated carbon dioxide (CO_2) emissions. Generating one gigawatt-hour (GWh) of electricity using oil and natural gas emits 733 and 499 tons of CO_2 respectively, while CO_2 emissions due to nuclear power are only 29 tons per GWh (World Nuclear Association, 2018). Saudi Arabia uses only fossil fuels (oil and gas) to generate its need of electricity. Figure 1.3 shows that 43% of electricity was generated by natural gas and the other 47% generated by oil and its derivatives in 2015. In this year, the country consumed 328 GWh (see Figure 1.1) and emitted 531 million tons of CO_2 as a result.

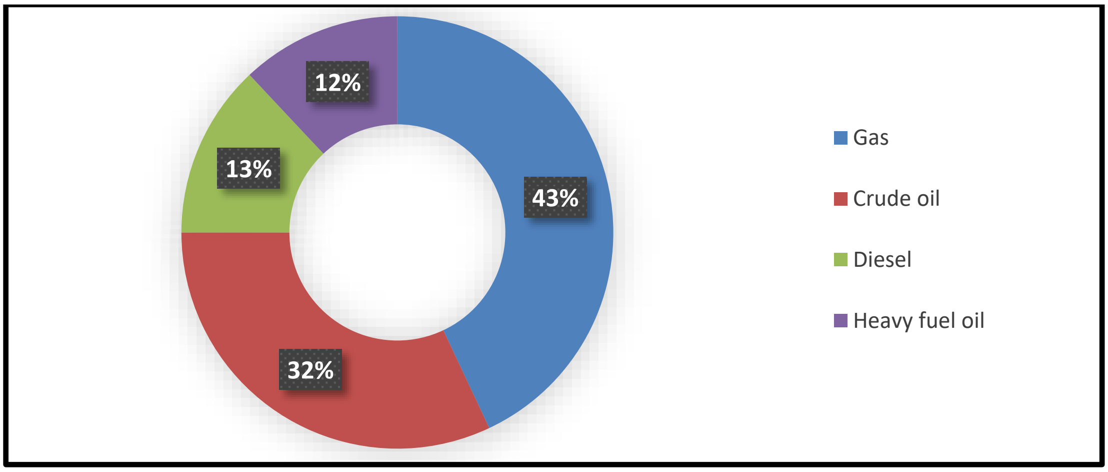

Figure 1.3 Annual fuel consumption for the generation of electricity in Saudi Arabia for 2015 (ECRA, 2015).

Figure 1.4 shows that countries like Japan, France, Singapore, Greece and Malaysia have managed to reduce their carbon dioxide contributions through utilizing renewable and nuclear energy. Since the Saudi Arabian energy mix does not incorporate these alternatives, Saudi Arabia's curve was still rising to approach 17 tone per capita in 2015.

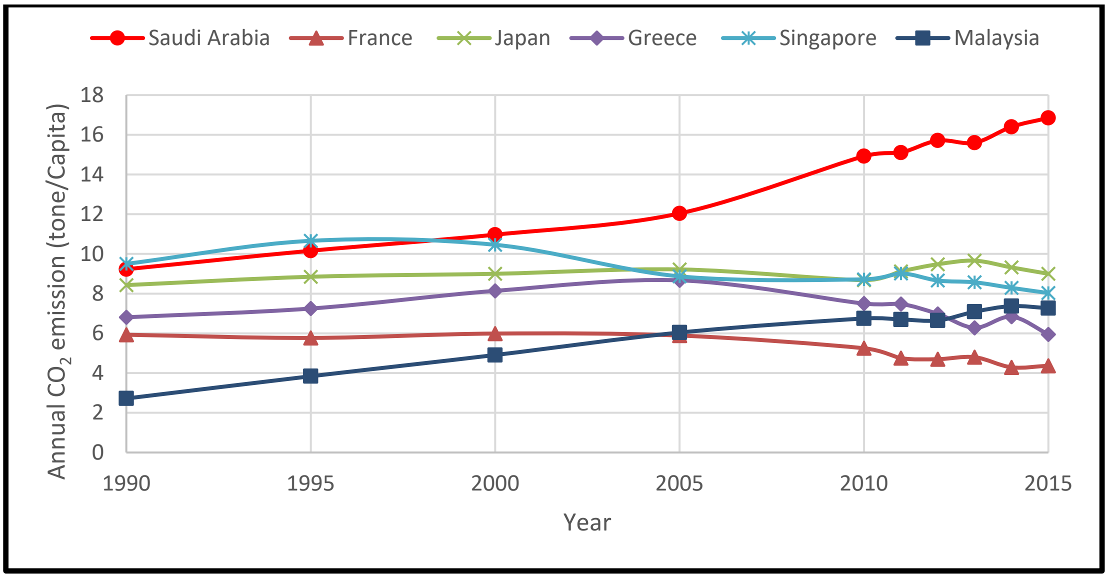

Figure 1.4 Annual carbon dioxide emissions for some countries (International Energy Agency, 2018).

According to the International Energy Agency (IEA), electricity and heat generation is the first reason behind carbon dioxide emissions. Figure 1.5 indicates that 41% of carbon dioxide emissions come from the generation of electricity and heat, while the industry sector releases only 19% of carbon dioxide emissions (International Energy Agency, 2017).

Looking at the current statistics regarding meeting new power demands, expansion may generate further CO_2 worsening conditions as air pollution would be affected in major cities worldwide and not just limited to India and China. Out of all factors influencing the increment of greenhouse gases emissions, 40% is produced from the power generation sector. However, during 2017, 25% of electricity was generated by renewables showing a significant growth over the past years. Therefore, the power sector still needs to play a major role in transiting to clean energy and decarbonizing the sector.

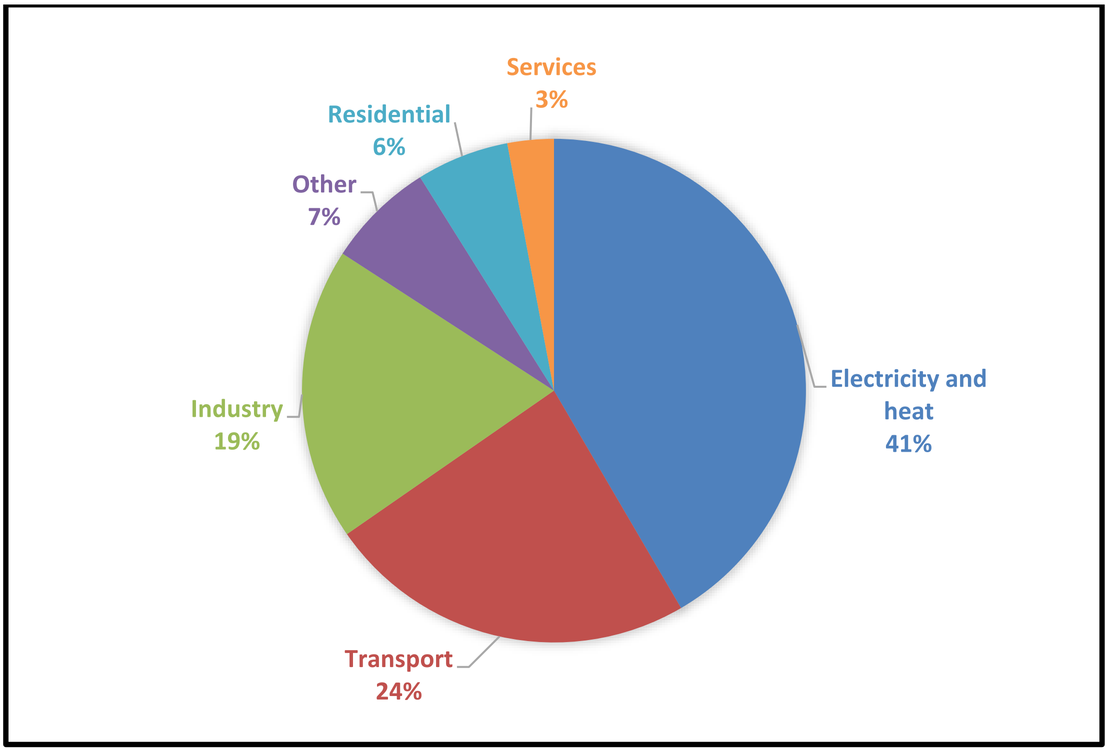

Figure 1.5 World carbon dioxide emission by economic sector (International Energy Agency, 2017).

We live in a new era, where societies and modern economies are heavily dependent on electricity, where it is almost impossible to find technology and advancement that does not require electricity. The supply of electricity from any type of energy generation, including coal, renewables, natural gas and nuclear, as well as many of the energy technologies is driven by the power sector, putting it in a powerful and critical position in the global energy system. Thereby, creating a hospitable environment for investors in the electricity sectors making a new milestone where it took the lead against gas and oil combined. During the period from 1990 to 2016, the demand for electricity doubled globally, outgrowing other energy sources. Studies predict that within the next 25 years energy demand would double as well as the growth of electricity energy sector (Environmental Protection Agency, 2018).

1.1.2 Nuclear Power Alternatives

To achieve sustainable development there are many factors that need to be considered and one requirement that stands out to be the most important one is having fully sustainable energy resources (Dincer, 2000). In addition, since fossil fuels are depleting and people are starting to become more aware of the environment and saving it from greenhouse gases emissions, alternative energy resources that are renewable have been receiving a large boost in priority during the current century (Hepbasli and Alsuhaibani, 2011).

All nations are doing their best to adopt and develop this kind of energy. Two large events advancing renewable energy were held during 2015: the G7 (the seven largest advanced economies in the world) and the G20 (twenty countries that account for 85% of the gross world product; Saudi Arabia is one of them), where high-profile agreements were made. These agreements help governments to move towards advance energy efficiency and accelerate access to renewable energy (Sawin, Seyboth and Sverrisson, 2016).

Since the 1950s nuclear energy has been used in many countries, especially by developed countries such as The United States, Japan, Korea and Russia, as part of their energy mix. The only form of energy generation that could replace fossil fuels energy sources was thought to be nuclear energy. Now about 30 countries, mostly industrialized ones, rely on nuclear energy, and others are taking steps to open their first NPPs. As of December 31, 2014, 438 nuclear power plants were operating around the world, with an installed capacity of 376.216 GW(e) (IAEA, 2015a).

Under normal operation conditions for NPPs, even with the best shielding materials and design methods, small amounts of radiation will be released into the environment around the NPP due to the random nature of the interaction between radiation and matter. However, the doses delivered to the general population from radioactive emissions resulting from nuclear power reactor operations are insignificant. Although research has shown that population doses due to NPP emissions are low, choosing a suitable site for NPP installations is vital for public and environmental safety. Moreover, choosing a suitable site can serve as mitigation to minimize accidental uncontrolled release of radiation (European Commission, 2002).

1.1.3 Defense in Depth Philosophy

The Defense in Depth (DID) is a safety philosophy that guides the design, construction, inspection, operation, and regulation of all nuclear facilities. The central tenet of DID is to protect the health and safety of the public and workers. Other objectives include protecting the environment and ensuring the operational readiness of the facility. Successful DID requires creating, maintaining, and updating multiple independent and redundant layers of protection to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon (IAEA, 1999).

DID is implemented through a number of measures, including robust physical barriers, redundant and diverse safety systems, strong physical security, and emergency response readiness. Figure 1.6 illustrates the different five levels of DID. The NPP siting considerations start from the first level (Prevention of abnormal operation and failures) to the fifth level (Off-site emergency response) (International Nuclear Safety Advisory Group, 1996). Thereby, NPP siting plays very serious role in safety.

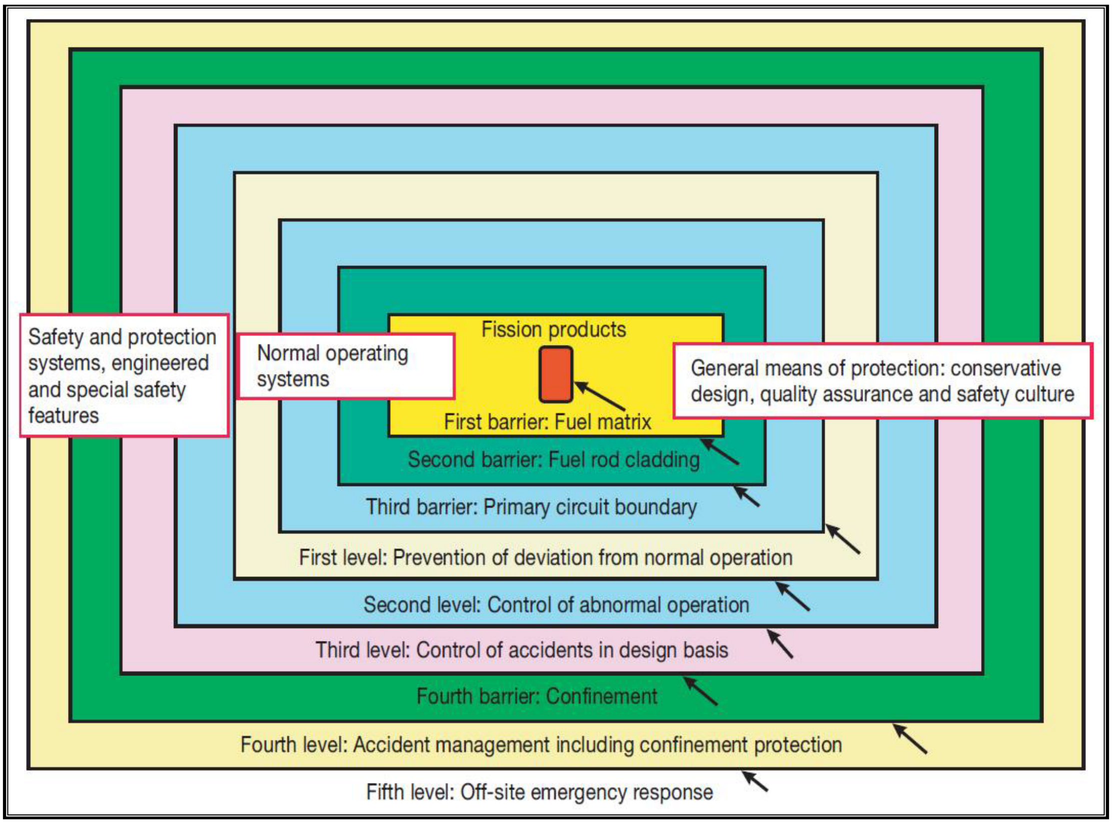

Figure 1.6 The five levels of Defense in Depth philosophy.

1.1.4 Nuclear Power Plant (NPP) Siting

There are important issues concerning the readiness of Saudi Arabia to launch a nuclear power programme. The first significant issue is selecting a suitable site to host the power plant(s). According to IAEA publication SSG-16, "Site approval is likely to be the first license for a nuclear power plant to be issued by the new entrant regulator" (IAEA, 2011b). Figure 1.7 shows that the siting process must be conducted earlier than other activities. Siting studies should be initiated as soon as possible after taking the decision to launch a nuclear programme. This because of some of the critical activities depend on the determination of the NPP site, such as the environmental impact assessment (Figure 1.7).

1.1.4.1 NPP Siting Phases

The siting process is projected to choose suitable sites for the prospective NPP(s). The location's characteristics must be well-suited to withstand all types of external event hazards induced by human beings or naturally. This can be achieved by applying existing engineering protective actions, from which the required level of safety can be realised.

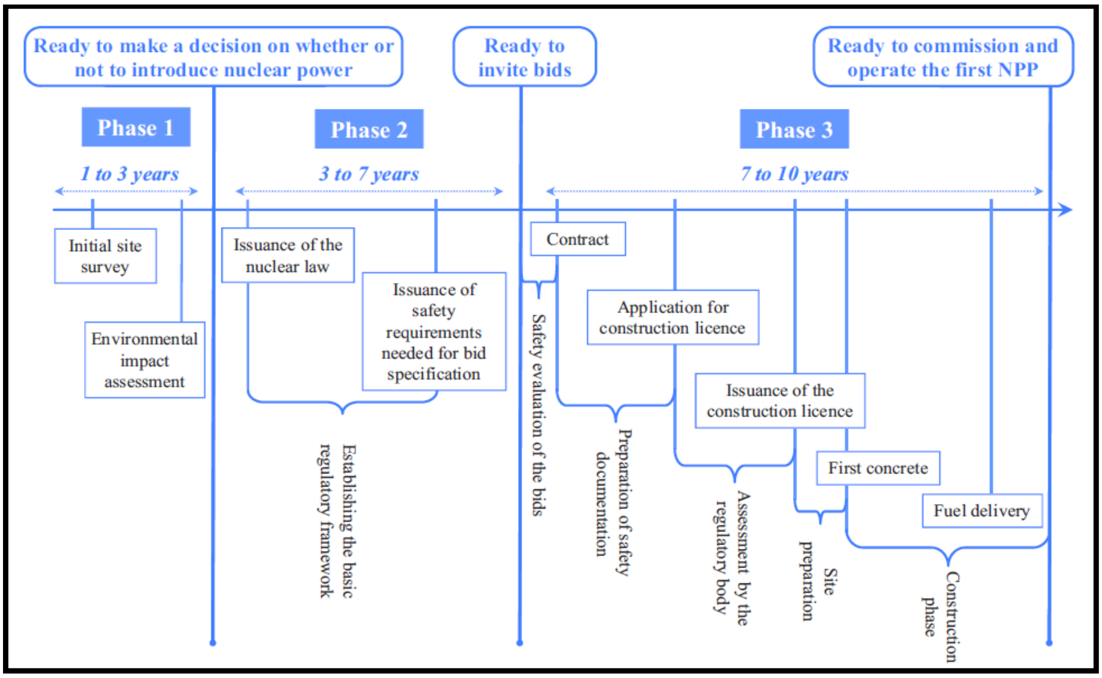

Figure 1.7 The first three phases of a nuclear power programme. Siting is prominently listed as the first step for launching a nuclear power programme (IAEA, 2011b).

Due to the safety issues of NPPs some places would be considered unsuitable locations. By applying several screening criteria successively and systematically this decision can be given according to the application of a series of actions that are linked to the main objective of picking a favourable location for the new NPP.

According to the IAEA (IAEA, 2015b), the siting process has to undergo three different steps:

a) **Regional analysis:** During this first step an analysis is run on different regions that are of interest, to choose and identify initial potential sites. Some sites may not be identified as potential sites. However, unless there is a reasonable justification a site can join the list that will go to the next step, which is screening. All potential sites in a region should be taken to the next step (screening) unless their exclusion can be appropriately justified.

b) **Screening:** The main objective of the second step is to filter the results we obtained so far by screening the candidate potential sites so that unfavourable sites are excluded based on both safety related criteria (population density and seismicity) and non-safety-related factors (proximity to grid and seaports).

c) **Evaluation, comparison and ranking:** There are two main goals from this step:

i. To ensure the construction and installation the NPP can proceed with no obstacles on site or in the surrounding area of operation that would delay or obstruct the workflow; and

ii. To rank each one of the candidate sites to evaluate them over each other for the advantages and disadvantages of constructing and installing the NPP at each site.

1.1.4.2 Geographical Information System (GIS)

The Environmental Systems Research Institute (ESRI), based in the United States, developed software that allows the gathering, storage, analysis and presentation of spatial data. This group of software is called Geographic Information Systems (GIS). One application of GIS is ArcGIS. ArcGIS gives the user the ability to analyse spatial information, create interactive queries, edit data in maps and present these operation results (Environmental Systems Research Institute, 2018a).

1.2 Problem Statement

Saudi Arabia has recently considered nuclear power to conserve traditional energy sources, decrease environmental pollution (Wang, Su and Nguyen, 2018). In July 2018, the IAEA Integrated Nuclear Infrastructure Review (INIR) team of experts concluded a twelve-day mission to Saudi Arabia to review its development of infrastructure for a nuclear power programme. The INIR mission reviewed the status of nuclear infrastructure development using the Phase 2 criteria of the IAEA's Milestones Approach; which provides detailed guidance across three phases (consider, prepare, construct) (IAEA, 2018). The IAEA considers the siting of a NPP as a very crucial process. It can significantly affect the cost, public acceptance and safety of the plant over its operating lifetime. NPP siting must be performed early in the nuclear power programme process (IAEA, 2012c, 2015b).

The Multi-criteria Decision Analysis methods are used widely to help in making decisions; particularly, when many conflicting criteria involved. NPP siting is including very conflicting criteria. Some of MCDA methods have been utilized to conduct NPP siting such as AHP, FAHP and TOPSIS (Abdul-Fattah and Abulfaraj, 1982; Wang, Su and Nguyen, 2018). Recently, the MCDA have been combined with the Geological Information System (GIS) making the siting process more reliable and accurate (Abudeif et al., 2015; Baskurt and Aydin, 2018a; Omitaomu et al., 2012).

This study has designed hybrid GIS and MCDA models to make the NPP siting reliable and capable to be conducted for a whole country instead of specific sites. This study applied these models for Saudi Arabia as a case study. This goal was achieved through two stages (phases). The first stage was a general survey of all potential suitable areas to site NPPs, (phase I). The second stage was an identification process of those suitable preferable (ranking) areas to be selected as the first option to host

NPP(s), (phase II). These two stages were conducted by utilizing a GIS-based Multi-Criteria Decision Analysis approach and ArcGIS software.

1.3 Objectives of the Research

The main aim of this study is to propose some potential suitable NPP sites in Saudi Arabia. This goal will be achieved through realizing the following objectives:

1- To quantify the negative impact of each exclusionary criterion on siting of NPPs in Saudi Arabia.

2- To identify potential suitable areas for NPP sites in Saudi Arabia.

3- To identify the potential NPP sites and rank them according to their attractiveness as NPP sites.

1.4 Scope of the Research

This study utilized the MCDA method to tackle the NPP sites selection. It developed hybrid GIS and MCDA models to help in NPP siting process. There were two phases (stages): the first was to survey the suitable areas for NPP siting; the second was to identify and rank the preferable suitable areas and sites. Three types of NPP were addressed: the European pressurized reactor 1600 MW (EPR1600); AP1000 reactor; and Small Modular Reactor (SMR350). The cooling tower reactor type was not considered in this study. Saudi Arabia was chosen as a case study. Depending on the exclusionary criteria, the surveillance was conducted to primary recognise the feasible land of the country for NPP siting (first stage). The next stage was to differentiate these areas based on suitability criteria. There were four models to conduct this level of the study: demographic; external hazards; economic suitability; and the fourth was built to overlay the previous three models based on their weights that calculated via AHP method. Since the all potential NPP siting lands found to be on coastal areas, this study conducted sea-level rise sensitivity analysis. There was no site visit in this study.

1.5 Significance of the Research

This study has proposed several hybrid GIS and MCDA models for successive NPP siting process steps. These models could help in making the NPP siting process more reliable and accurate; because the errors due to human factor would be only concentrated in inserting data. The suggested models were: 1) survey the suitable areas for NPP siting; 2) suitability based on demographic issue; 3) suitability based on external hazards issue; 4) suitability based on economic issue; 5) and the final, total suitability based on the previous models.

These models were applied for Saudi Arabia as a case study. It is the first study ever that covered the whole Saudi Arabia. moreover, its results can be reliable due to the hybrid of GIS and MCDA. The previous studies addressed the NPP siting in Saudi Arabia have two shortcomings. Firstly, they focused on specific sites to compare between them. Secondly, they did not combine the GIS with the MCDA methods; which was utilized (Abdul-Fattah and Abulfaraj, 1982; Hussein et al., 1987). The results of NPP siting of Saudi Arabi in this study could be used as a guideline for NPP licensing.

The unavailability of some specific data, missing attribute data, lack of metadata, and data traceability issues were the main obstacles of this study. For example, ownership data could not be provided because data is classified, so the impact of land ownership and expropriation could not be covered by this study. Likewise, because spatial data for military zones and cultural conservation areas are not available, the possible effects of these data on screening could not be evaluated. Also, sandstorm data was one of this unavailable important information.

1.6 Thesis Organization

This thesis contains six chapters. Chapter one is an introduction. It casts light on the background of this research problem, addressing the Saudi Arabia's electricity consumption trend and its negative effects. It also includes the problem statement; the objectives, the scope, and the significance of the study were addressed.

The second chapter deals with the literature review of the study. The chapter contains details of: the study area (Saudi Arabia), general information, electricity future demand, electricity new policy; NPP siting criteria types; NPP siting procedures; ArcGIS software and its applications.

Chapter 3 presents the methodology that was followed to conduct this research. This chapter addresses: data collection; procedures (step by step details); the software used in the study and its tools; analysis methods.

The results and their relative discussions are presented in Chapter 4. The results of phase I (survey of suitable NPP sites) and includes the discussion relating to these results. In this chapter the suitable safe areas that can accommodate NPP(s) are depicted. Moreover, many more analyses pertaining to phase I are illustrated therein. Chapter 5 demonstrates the results and discussion pertaining to phase II (ranking the NPP suitable sites) of this study. In this chapter the identification of preferable suitable NPP(s) sites across the nation and related discussions are showed. Finally, Chapter 5 addresses the conclusion of this research.

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