The role of nuclear desalination in the Kingdom of Saudi Arabia

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Abstract: In this study, the role of nuclear desalination in Saudi Arabia is investigated. A water demand forecast between the years 2000 and 2025 was established for the Eastern region of Saudi Arabia as part of the collected input data for the DEEP computer code. The DEEP computer code was run for several options of energy sources such as PWR (600 MWe), SPWR (160 MWth), PHWR (450 MWe), HR (200 MWth) and GT (125 MWe or 175 MWe). These energy sources were investigated for different desalination plants such as RO, MSF, MED and the hybrid MED-RO. The levelised power cost, average daily water production, net saleable power and levelised water cost are presented for all cases. Two scenarios were investigated, the first assumes no interest and discount rates and the second assumes interest and discount rates equal to 8%. The first scenario assumes that the water utility will continue under the control of the government and the second assumes that the water utility will be privatised.

Keywords: nuclear desalination; RO; MSF; MED; DEEP computer code; Saudi Arabia.

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1 Introduction

Saudi Arabia constitutes approximately 80% of the Arabian Peninsula with a total area of 2,250,974 km^2. Saudi Arabia is considered a desert land, with a dry climate where no running water exists. The topography of the country varies drastically from one place to another. As a result of that, temperature, humidity and precipitation range from one region to the other. Temperature varies from less than 0^{o}C in the high elevation areas during winter and reaches up to 48^{o}C during summer months. The average annual rainfall is about 95 mm all over the kingdom per year. Amongst all the regions, the southern region receives the highest rainfall.

The eastern and western regions are very humid, humidity reaches up to 75% during summer and drops to 65% during winter.

Water resources in the Kingdom can be broadly divided into four categories, surface water, underground water, desalinated water and treated wastewater. Adequate rainfall in the southern and western regions is the main sources of surface water in the Kingdom. In order to store surface water efficiently, dams were constructed in some regions of the Kingdom. Underground water can be divided into two categories, renewable and non-renewable. Most of the renewable underground water is used in homes and for agricultural uses.

Saudi Arabia has 25.9% of the desalination plants in the world. These plants produce 1,938,864 m^3 of distilled water per day and 3,965 MW of electricity. The desalinated water is mainly used for drinking and home use. To transport water from some desalination plants to remote areas, the Saline Water Conversion Company has established pipeline systems with a total length of approximately 2000 km.

Treated wastewater is considered to be in its early stages of development and supplies only 0.8% of current needs.

Water consumption in the Kingdom can be divided into home, industrial and agricultural uses. Underground water conservation is very important for a country like Saudi Arabia because of its limited water resources. The underground water reservoir carries approximately 337,000 million m^3 of water at a depth around 300 m. When the minor reservoir is added to the above quantity it becomes approximately 500,000 million m^3 of water.

Many hydrological, economic and geological studies have been carried out to satisfy the ever-increasing water demand in the Kingdom. Some of the solutions offered are: constructing water channels, building water dams, digging wells and other solutions depending on the hydrology and geology of the region.

Nuclear desalination can be defined as: the production of potable water from seawater in an integrated complex, in which both the nuclear reactor and the desalination system are located on a common site, the relevant facilities and services shared, and the energy used for the desalination process is produced by the nuclear rector.

Since the early 1960s, scientists have agreed that nuclear energy would be ideal for desalination of water because nuclear reactors can produce a tremendous amount of heat. The heat source can either be utilised directly to evaporate, or be converted to electric energy to drive the reverse osmosis (RO) desalination units. However, the coupling of nuclear reactors with desalination processes has taken many years of study because of contamination problems. The same reasons behind the use of nuclear power for electricity generation also apply to seawater desalination. These reasons are: economic competitiveness in areas that lack inexpensive hydropower or fossil fuel resources, energy supply diversification, conservation of fossil fuel recourses, promotion of technological development, and environmental protection by avoiding emissions of air pollutants and greenhouse gases.

The International Atomic Energy Agency (IAEA) studies [1] examined costs for different types of applications. These assessments have shown that nuclear desalination could be technically and economically feasible. About 500 reactor years of operational experience from nuclear cogeneration and heat only reactors are now available in twelve countries.

Nuclear energy has been utilised for seawater desalination in Japan and in Kazakhstan. In Japan, the desalination plants are mostly for on-site water supply, however, Kazakhstan supplies water to a nearby population center.

Although most industrialised countries are in favour of large nuclear power plants for domestic application, there is a growing interest in small and medium reactors (SMRs) in several member states.

The small and medium plants would better fit smaller electricity grids and would better match the rates of projected growth in electricity and water demand.

Countries that are suffering from water shortages usually have grids for which SMRs could be an appropriate choice for electricity and seawater desalination. Many different SMR types of plants have been designed. Vendors have offered these reactors as possible options for coupling with desalination processes.

The options identification program was initiated in 1996 to identify and define the practical options for demonstration of desalination using nuclear energy.

The IAEA has developed a program to identify options for nuclear desalination and to demonstrate any related technology. The main objective of the program was to build confidence (through design, construction, operation and maintenance) and to prove that nuclear desalination can be technically and economically feasible. Another main objective is to prove that nuclear desalination is safe and reliable. A wide range of possible reactor types and desalination technologies can be selected using the Option Identification Program. The MED and RO desalination processes were found to be most promising because of relatively low energy consumption and investment costs, as well as high reliability. The MSF process has been excluded because, with its lower energy consumption, lower sensitivity to corrosion and scaling, partial load operability and greater flexibility, the MED process has many advantages over the MSF process.

The screening resulted in three options, which used the well-proven cooled reactors and desalination technologies. These options are:

- RO desalination in combination with a nuclear power reactor being constructed or in an advanced design stage with construction expected in the near term. The preferred capacity of the rector would be in the medium-size range
- RO desalination, as above, in construction with a currently operating reactor. Some minor design modifications may be required
- MED desalination in combination with a small reactor.

Nowadays, one can see a reasonable range of experience in the field of nuclear desalination [2–21]. Two countries have good experience in operating nuclear reactors for seawater desalination; Kazakhstan and Japan.

In Kazakhstan, a liquid metal cooled fast reactor BN-350 has been operating since 1973. In Japan, six pressurised water reactors (PWR) have been operating since 1973, 1975, 1983, 1988, 1989 and 1992 respectively. They are coupled with MSF, RO and MED desalination processes.

Besides this experience, many countries have shown an interest in nuclear desalination through several designs and studies. These countries are: China, India, the Republic of Korea, Morocco and the Russian Federation. The continuing international interest in nuclear desalination suggests a high potential market for the introduction and commercial development of nuclear desalination.

Many papers have been published [22–39] to investigate and analyse the possibility of using nuclear energy in seawater desalination plants in Saudi Arabia.

In this study, the role of nuclear desalination in Saudi Arabia was investigated. A water and electricity demand forecast for the years 2000 and 2025 was made for the Eastern region of Saudi Arabia and all the necessary input data for the DEEP computer code were collected. The DEEP computer code was run for several options of energy sources such as:

- Pressurised Water Reactor, PWR (600 MWe)
- Small Pressurised Water Reactor, SPWR (160 MWth)
- Pressurised Heavy Water Reactor, PHWR (450 MWe)
- Heat Reactor, HR (200 MWth)
- Gas Turbine, GT (125 MWe or 175 MWe).

2 Water supply and demand

Population growth, rising living standards and economic development in general determine the volume of water demand; on the other hand, the availability, quality and cost of water influence both the potential for growth and the nature and scope of long-term economic development. Water demand for the period 1980-1995 for Saudi Arabia is shown in Table 1.

Table 1 Water demand 1980-1995

Year	*Type of customer*	*% of total*	*Demand (million m^3)*
1980	Domestic and industrial	21.6	510
	Agricultural	78.4	1850
1985	Domestic and industrial	14	1200
	Agricultural	86	7400
1990	Domestic and industrial	10.2	1650
	Agricultural	89.8	14580
1995	Domestic and industrial	9.9	1800
	Agricultural	90.1	16400

Water is considered to be the most basic and valuable resource and an important factor in measuring the economic efficiency of public and private sector projects. Water resources in the Kingdom can be divided into four categories as shown in Table 2.

Table 2 Proven water resources for the period 1980-1995

Year	*Detail*	*% of total*	*Consumption (million m^3)*
1980	Shallow and ground water	48.3	1140
	Desalination	2.1	50
	Waste water reuse	*	*
	Ground water (non-renewable)	49.6	1170
1985	Shallow and ground water	21.5	1850
	Desalination	3.8	330
	Waste water reuse	1.2	100
	Ground water (non-renewable)	73.5	6320
1990	Shallow and ground water	13	2100
	Desalination	3.3	540
	Waste water reuse	0.7	110
	Ground water (non-renewable)	83	13480
1995	Shallow and ground water	13.7	2500
	Desalination	3.9	714
	Waste water reuse	0.8	150
	Ground water (non-renewable)	81.5	14836

According to the 1994/1995 estimates, surface and shallow ground water constitutes only 13.7% of the Kingdom's total needs, while non-renewable ground water supplies around 81.5%. Desalinated seawater has reached an advanced stage of development in the Kingdom, which now has the largest desalination plants in the world. This source, however, supplies only 3.9% of current water needs. Finally, reclaimed wastewater is still in its early stages of development and supplies only 0.8% of current needs.

The Kingdom's desalination plants continued to operate at optimal production capacity, producing about 1.9 million m^3 per day of desalinated seawater, Table 3.

Table 3 Production at desalination plants in the Eastern region during the period 1985-1994 (1000 m^3/day)

Year	*Al khobar*	*Al Jubail*	*Total (Eastern region)*
1985	65710	159893	225603
1986	75194	209754	284948
1987	85066	252820	337886
1988	78539	279792	358331
1989	83646	290446	374092
1990	88225	301503	389728
1991	77467	321749	399216
1992	73346	331273	404619
1993	73431	342217	415648
1994	73768	353110	426878

Many medium-sized water projects have been completed, such as those at Afif and Ad Dawadmi, Sudair Al Kabir, Nafi and Dhurma/Al Mazahimiyah. According to the succeeding development plans of the kingdom, water continued to be provided to all consuming sectors from available resources.

On the demand side, water used for agriculture ranges from about nine times the water consumed for domestic and industrial use (1994/1995) to about five times (1999/2000). On the resources side, ground (non-renewable) water consumption changed from about four and a half times the consumption of all other resources combined (1984/1985) to about three times (1999/2000). Therefore, the economic viability of the whole situation is questionable. This may be further explained by a thorough evaluation of other consequences.

The steady increase in the consumption of non-renewable ground water has further worsened the national water balance and has reduced the quality of the remaining reserves in some areas. Agriculture continues to consume almost 90% of water from all sources, and the expansion in grain production has been heavily dependent on non-renewable ground water in most areas.

There has been a serious depletion in the natural water springs used by the Al Hasa Irrigation and Drainage Authority. Thus, it is of the utmost importance to emphasise the need to increase the efficiency and utilisation of non-conventional water resources, e.g.:

- desalinated water
- treated waste water
- agricultural drainage water.

Presently, 14.6 x 106 m^3 of water is being used per year from the deep aquifers. The amount in 1980 was 1.86 x 106 m^3. The estimated non-renewable ground water reservoir is about 2 x 1012 m^3 at a depth of 300 m. This underground water is concentrated in the northern, north eastern and central parts of the KSA. The surface water resources are concentrated in the west and southwest parts, near the Assir mountains (2 x 109 m^3/year).

Although desalination technology has achieved large technological progress in the last 20 years, total world production of desalinated water is very small compared to natural fresh water resources. The uneven distribution of fresh water is becoming a vital issue for future planning. The present per capita use of water in the Middle East is around 1,744 m^3/year, in comparison with other countries where the average reaches 12,900 m^3/year (International standard). A daily consumption of 252 l/capita per day was reported for domestic uses in the KSA.

To meet the growing demand for water, the present desalination plants produce a quantity of 727,000 m^3 of desalinated water in additions to 22 TWH of electric power, Table 4.

Table 4 Water exported from and power generated for export by SWCC plants for the period 1990-1994

Year	*Exported water m^3*	*Generated power (MWH)*
1990	683,148,329	21,110,409
1991	692,302,294	21,613,770
1992	715,092,733	21,669,214
1993	703,314,096	22,718,415
1994	726,895,310	21,976,530

The projection for water demand in the KSA, as predicted by the Ministry of Agriculture and Water (MAW), for two sectors is shown in Table 5.

Table 5 Expected water demand for the period 2000-2025

Year	*Population (million)*	*% Increase in demand*	*Projected demand (million m^3/day)*
2000	20	13	5
2005	23	30	5.75
2015	29	64	7.25
2025	37	109	9.25

2.1 Production of potable water

Although the main source of water in the KSA is not the desalination plants, because the major water use is for agriculture, desalination plants provide 50% of the drinking water in the Kingdom. The other 50% is supplied by wells (surface or deep wells).

The total consumption rate for drinking water is 987,522,436 m^3. This annual rate of consumption is 5.32% more than the previous year. This rate of increase in demand for one year, as reported by the Ministry of Planning, is a high rate if it is sustained at this level for several years.

If true, this rate of increase – although highly questionable – implies that consumption will double every 13 years, or it will total four times its present value in 25 years (the period covered by the study).

Based on statistics published by the local utilities, the corresponding annual increase in SWCC production was only 1.3%, in which case, if growth in production of desalinated water remains constant, total production capacity will be doubled in 54 years. The gap between demand for potable water and supply of desalinated water is widening, and the water wells are actually the backbone for water security planning.

The basic role of SWCC is to supply an appreciable amount of potable water in the kingdom by desalting seawater. Through the years, and as the population of the KSA has grown steadily, there has been an increasing demand for potable water. In addition to population growth, a steady change of demographic and social patterns in the kingdom, urbanisation and development led to a growing demand for potable water. SWCC managed to keep their input to almost 50% of all potable water used in the kingdom. Allied to the process of desalination, electric power is generated as a by-product.

From Table 5, over the period 1990-1995, for each cubic meter of desalinated water it can be claimed that, on average, 0.32 MWH of electric energy is exported.

Based on a five-year interval, an optimistic forecast is given in Table 6 of the growth in exported desalinated water and the corresponding values of exported electric power. Referring to Tables 1 and 2, the desalination of seawater in the kingdom has steadily grown through the years and, similarly, the percentage of water used for domestic and industrial purposes is decreasing from about 21.6% in 1980 to only 9.9% in 1996.

The above may lead to different scenarios when considering the possibilities for nuclear desalination. First, there is an appreciable difference between estimates furnished by planning studies in the kingdom, which are mainly based on macro-economic, long-range assessment (optimistic) and last years, short-range values as per SWCC reports (conservative).

Further, any nuclear desalination study cannot be isolated from the general trend and policies for fuel prices, alternative desalination technologies, consumer behaviour, population growth etc. Therefore, there are broadly two different scenarios when considering the feasibility of nuclear desalination. The first is based on the optimistic estimate of growth of demand for potable water for the eastern region, Table 6.

Table 6 Forecast water exports (2000-2025) for the Eastern region based on the Ministry of Planning data

Year	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*
Exported water (m^3 x 1000)	483,480	515,730	550,100	586,850	626,010	667,780	712,310
Exported water (m^3/day)	1,324,600	1,413,000	1,507,100	1,607,800	1,715,100	1,829,500	1,951,500

Over the same period, and based on the values furnished by the successive SWCC annual reports, a more conservative estimation of the growth of exported desalinated water for the eastern region is given in Table 7.

Table 7 Forecast water exports (2000-2025) for Eastern region based on the SWCC data

Year	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*
Exported water (m^3 x 1000)	483,480	516,100	549,380	587,970	613,970	646,590	679,060
Exported water (m^3/day)	1,324,600	1,414,000	1,505,200	1,610,900	1,682,100	1,771,500	1,860,400

3 Results and analysis

This study assumes that, by the year 2025, nuclear desalination will furnish exported water of 1,951,500 m^3/day (optimistic estimate, Table 6) for the Eastern region of Saudi Arabia.

To investigate the role of using nuclear energy in nuclear desalination plants in Saudi Arabia, the DEEP [40] spreadsheet computer code is used. This computer code can compare the costs of various energy sources and desalination options. In this section, the results of the DEEP computer code for several options of energy sources are presented:

- Pressurised Water Reactor, PWR (600 MWe)
- Small Pressurised Water Reactor, SPWR (160 MWth)
- Pressurised Heavy Water Reactor, PHWR (450 MWe)
- Heat Reactor, HR (200 MWth)
- Gas Turbine, GT (125MWe or 175 MWe).

The above energy sources are compared for the desalination technologies MSF, MED, RO and the hybrid MED-RO.

Saudi Arabia is somewhat different from most other countries. The utility organisations, such as water, are constructed and run by the government. However, most of the utility organisations are moving in the direction of privatisation. The water utility organisation seems destined to continue under the control of the government. For this reason, two computer runs for each case have been carried out, one with interest and discount rates equal to zero and the other with interest and discount rates equal to 8%. The runs with zero interest and discount rates have been done assuming that the water utility organisation will continue under the control of the government and the runs with 8% rates have been done assuming that the water utility organisation will be privatised.

Table 8 shows the case name, energy source, desalination method, interest/discount rates, levelised electricity cost, average daily production, net saleable electricity and levelised water cost.

It can be deduced from Table 8 that, for the zero interest case, the HR with MED, GT with MED and GT with MED-RO give very comparable minimum levelised water costs. However, for the 8% interest/discount rate, the GT with MED gives the minimum levelised water cost followed by the PWR with RO, GT with RO and then PHWR with RO.

It can be concluded that, when interest and discount rates are assumed to be zero, nuclear energy seems to be the best option. Independent of the energy sources and regions considered, MSF costs for all the considered desalination plants seem to be higher in cost than that of RO MED.

Table 8 The Eastern region cases using DEEP, with their corresponding results

Case name	*Energy Source*	*Desalination Method*	*Interest and discount rates*	*Levelised electricity cost \$/kW-h*	*Desalination plant size m^3/d*	*Net saleable electricity MW(e)*	*Levelised water cost \$/m^3*
ECF	PHWR	MSF	YES	0.054	1,915,000	1,224	1.34
ECM	PHWR	MED	YES	0.054	1,915,000	852	.80
ECR	PHWR	RO	YES	0.054	1,915,000	14	.75
EGF	GT	MSF	YES	0.067	1,915,000	0	.97
EGM	GT	MED	YES	0.067	1,915,000	0	.60
EGR	GT	RO	YES	0.057	1,560,000	83	.74
EGRO	GT	MED-RO	YES	0.067	1,532,000	1,116	.65
EHF	HR	MSF	YES	N/A	1,915,000	0	.94
EHM	HR	MED	NO	N/A	1,915,000	0	.60
ECMN	PHWR	MED	NO	0.028	1,915,000	863	.45
ECRN	PHWR	RO	NO	0.028	1,915,000	27	.41
EGMN	GT	MED	NO	0.068	1,915,000	0	.38
EGRN	GT	RO	NO	0.068	1,560,000	83	.59
EGRON	GT	MED-RO	NO	0.068	1,915,000	1,116	.39
EHFN	HR	MSF	NO	N/A	1,560,000	0	.49
EHMN	HR	MED	NO	N/A	1,915,000	0	.37
EPFN	PWR	MSF	NO	0.029	1,560,000	1,007	.67
EPMN	PWR	MED	NO	0.029	1,915,000	735	.46
EPF	PWR	MSF	YES	0.1573	1,719,528	1431	1.29
EPM	PWR	MED	YES	.1704	1,719,528	735	.78
EPR	PWR	RO	YES	.1558	1,747,046	774	.73
EPRO	PWR	MED-RO	YES	.1549	1,402,103	732	.80
ESF	SPWR	MSF	YES	.7019	1,719,528	0	1.82
ESM	SPWR	MED	YES	.7698	1,314,889	0	.98
ESR	SPWR	RO	YES	3.1949	1,747,046	16	.96
ESRO	SPWR	MED-RO	YES	1.1641	1,462,357	96	1.08

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