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Economic Prospective of Small/Medium Nuclear reactors for Hybrid Seawater Desalination Systems

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Abstract

Technical and economic analysis of the most recent reported world experience of small/medium nuclear reactors (SMRs)are essential to decision making regarding dual purpose power/water generation in developing countries. In this work, firstly, analysis of reported economic aspects concerning SMRs has been highlighted. A desalination system of 150,000 m3 water production capacity to cope with the need of small community (about 375,000 persons) has been then proposed. Techno-economic study has been performed among small/medium reactors (SMR) to identify the appropriate power source for the integrated power desalination complex. IRIS nuclear reactor shows the lowest power cost of $0.029/KWh in the choice matrix of different SMRs with thermal output less than 1000 MWth. The selected reactor "IRIS" gives the ability to combine the desalination plant with a thermal desalination plant (MSF) type in a hybrid configuration scheme involving MSF/RO with varying ratios. Sensitivity analysis of hybrid desalination process shows that, at MSF/RO ratio 11% the unit water cost is $0.77/m3, the lowest water cost has been approached for RO system (0.73 $/m3) in an inverse relationship with permeate TDS. Empirical cost correlations have been developed for the corresponding permeates concentration.

Keywords: small/medium scale nuclear reactor, SMR, economic, desalination

1. Introduction

The International Atomic Energy Agency (IAEA) defines ‘‘small’’ reactor as a reactor built in modular arrangements with an electrical output less than 300 MWe, while ‘‘medium’’ reactor as one having electrical output between 300 and 700MWe. The two sizes of reactors are combined into the common term of ‘‘small and medium-sized reactor’’ (SMR) representing reactors with electrical output less than 700MWe [1]. Typical small reactors are in operation in several countries e,g, Korea, USA and China, while other types of small reactors are under development such as High-Temperature Reactor (HTR) of output from 5 to 10 MWe ,which is considered to be much safer, and is able to run for 5-10 years before requiring refueling or servicing [2-5]

"SMR" reactors are suitable for remote locations where specific energy output is required. This type of reactors has been proposed as an energy source for seawater desalination plants [2]. Due to significant enhancements in the reactor design that contribute to the upgraded safety requirements, installing small reactors systems is expected to have economic, safety and infrastructural benefits. Generally, modern small reactors for power generation are expected to have economy of mass production, reduced footprint costs, and a high level of passive safety in the event of malfunction [6].

Nuclear desalination is being discussed at the IAEA, in response to the request from countries affected by water shortage and desertification. Recently, several SMRs have been proposed by the member states of IAEA as an urgent and clean alternative for both energy source and potable water production [2]. Due to the experience gained in nuclear desalination, current developments and plans for nuclear-powered desalination based on different nuclear reactor types in many countries e.g.China, Egypt, Moroco, Algeria and USA [7].

There are two major types of desalination technologies broadly adopted classified as either thermal processes or membrane desalination processes. The main thermal processes are multi-stage flash distillation (MSF), multi-effect distillation (MED) and vapour compression variants – thermal and mechanical (TVC, MVC). The main membrane process is reverse osmosis (RO) [6].

Most of the desalination plants today are produced in "industrial-sized facilities". These include large thermal distillation plants in the Middle East with production capacities up to 1.6 Mm3 /day. Seawater reverse osmosis (SWRO) is the dominant process worldwide, where plants distribution according to capacity is 59% which accounts for small (1000 m^3 /day) representing only 5% of the worldwide production, while 2% repreaenting (42 large facilities)

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(≤50,000 m^3 /day) account for almost (45%) of the worldwide production [2].

The average investment cost required for engineering, procuring, and constructing a MSF distillation plant is about US$ 1235/m^3 and the capital costs for "MED" and "SWRO" plants are with an average of US$ 916/m^3 and US$ 641/m^3 respectively. The average production costs of desalinated seawater are in the range of US$ 0.45–0.60 m^3 , which varies according to capacity range and energy prices as desalination is an energy extensive process water production costs have risen – depending on the location, supply/demand, and technology adoped to US$ 1–1.5/m^3[2,4].

This article addresses updated technical and economic analysis regarding SMR-hybrid sea water desalination complex as a key to future dual purpose power/water generation in developing countries.

2. Approach and Methodology

The adopted approach comprises review, categorization and compilation of SMRs according to reported technical and economic features. Economic aspects have been then thoroughly analyzed Simulation of a proposed nuclear desalination system of capacity 150,000 m^3 water production has been developed using both WTCostII© [8], which is a software for Modeling the Capital and Operating Costs of Thermal Desalination Processes in addition to Desalination Economic Evaluation Program (DEEP code) [9], whichare widely used for analysis of desalination systems. Figure 1, represents the flowchart of the adopted methodology.

2.1 Technical and Economic Aspects of SMR

SMRs distribution around the world has been investigated by being classified as operated, under construction, proposed or planned. The total number exceeds one hundred with total capacity around 700,000 MWe [10]. According to a previous review [7], there are seven land-based proven designs available for commercial use of SMRs.

2.2 Integrated Desalination Plant Features

A proposed desalination scheme is investigated with a capacity of 150,000 m^3/d .An economic assessment was undertaken using DEEP for the proposed SWRO desalination plant coupled with different reactor types. Selected schemes were investigated for energy consumption and related financial indicators. The choice matrix comprised nuclear/combined cycle, nuclear/ gas cycle and nuclear/steam cycle.

Cost comparison among possible alternatives aimed at identification of the least water production cost. Selected case based on minimum water production cost was then investigated coupled with different hybrid RO/MSF schemes using DEEP. Coupling RO and MSF with "nuclear steam supply system (NSSS)" will achieve some economical and technical advantages. Sensitivity analysis has been undertaken for different water production costs with different viable hybrid schemes.

3. Results

3.1. Technical and Economic Aspects of SMR

SMRs data have been reviewed compiled and analyzed according to technical and economic features. Table (1), presents a comparison between lowest costs of SMRs reactors while Table (2), illustrates the updated cost data of small and modular reactors (SMR) for 2015 using ENR [11].

Table 1. Comparison of the lowest costs of different reactor types

Reactor Design	Reactor Type	Mwe	$/kWe*	Ref.
IRIS	PWR	335	1200	12
CAREM-300	PWR	300	1200-1300	12
VK-300	BWR	250	1100	12
AHWR	HWR	300	1300	13
GT-MHR	GCR	287	1200	12
SVBR	FBR	102	1200	14

*updated cost 2015 using ENR

As desalination is an energy intensive process, the cost of desalination is sensitive to the cost of energy. Coupling schemes have been calculated using DEEP code. Different schemes have been investigated for energy consumption and related financial indicators using the DEEP code. The choice matrix comprised nuclear/combined cycle, nuclear/ gas cycle and nuclear/steam cycle. The apparent energy costs per kWh were $ 0.07, 0.065, and 0.058 respectively. The corresponding water production unit costs were$ 0.857, 0.844, and 0.824 per m^3 respectively. The results were based on constant thermal output capacity of 1800 MWh, and different electrical output varying from 300-700 MWe with thermal utilization of 32% for power plant types gas cycle and steam cycle and 45% for combined cycle. The water to power ratio is 22% for gas cycle and steam cycle and 30% for combined cycle. It has been concluded that nuclear/steam cycle manifests the lowest unit energy and unit water costs.

A choice matrix have been investigated for lower thermal output reactors less than 1000 MWth; the water production cost is presented in Tables(3) and (4), where Table (3) presents the cost indicators of Nuclear-(Combined cycle/steam cycle)/RO desalination using default DEEP parameters, while Table (4) shows the economic indicators of Nuclear-(Combined cycle/steam cycle)/RO desalination using levelized updated cost values into DEEP. According to the results of the choice matrix presented, "International Reactor Innovative and Secure"IRIS reactor type shows the lowest power cost of $ 0.029/KWh for the levelized cost updated DEEP. The thermal output of the selected reactor "IRIS", which is almost 1000MWth, gives the ability to adopt thermal desalination plant using the thermal output from the reactor.

Another choice matrix has been investigated for lower thermal output reactors less than 1000 MWth for steam cycle hybrid desalination plant. Different hybrid capacities have been investigated. According to DEEP output results for nuclear-steam cycle hybrid desalination plant, "Gas Turbine Modular Helium Reactor (GT-MHR)" which is a nuclear fission power reactor design under development by a group of Russian enterprises gives the lowest water and power cost for steam cycle-hybrid nuclear powered desalination plant. Figure (2), shows a screen shot of an integrated case using DEEP.

This situation reflects that the nuclear power source for a given remote community will cover electrical/non-electrical applications. Moreover, electricity will be imported from the nuclear power plant with the cost concluded in Table (4).

This cost indicator may be increased due to other factors e.g. overheads, cost of finance, rate of return… etc.

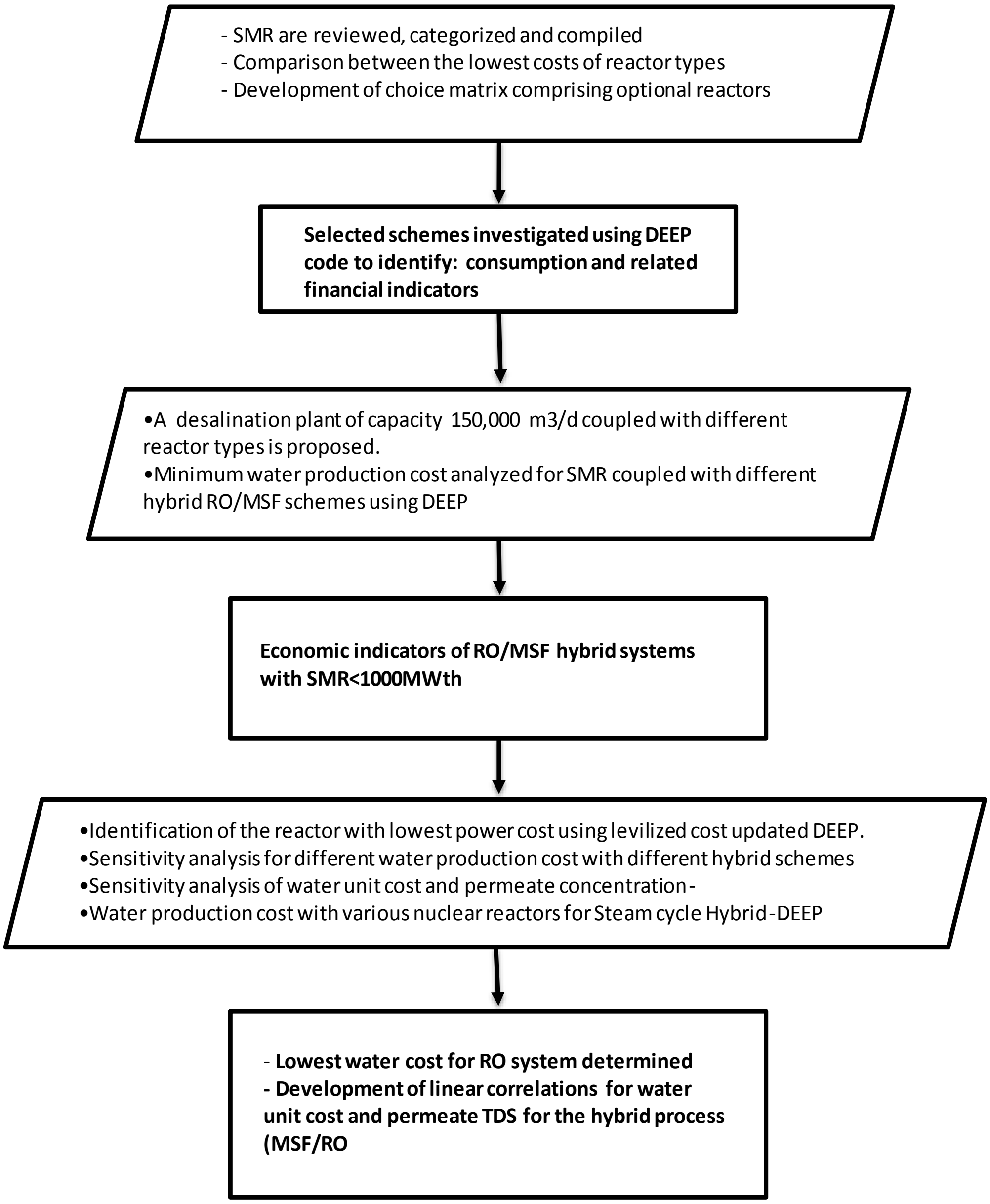

Fig. 1. Approach and Methodology flowchar

Table 2. UpdatedCost data for small modular SMR nuclear reactors

Reactor Design	Reactor Type	O&M + Fuel costs USD/MWh 2015	Updated desalinated water cost $ /m^3 (2015)	Ref.
ABV	PWR	39.79	<1.90	14
KLT-40S	PWR	11.8	1.06	15
SMART	PWR		0.83	12
CAREM-300	PWR	16.7		12
PHWR-220	HWR		1.24	16
HTR-PM	HTGR	24.8		12
PBMR	HTGR	12		12
GT-MHR	HTGR	14.4		12

Table 3. Cost Indicators of Nuclear-Combined cycle/steam cycle RO desalination using default DEEP parameters.

Reactor type	Power output: Reference thermal output MWth	Power output: Reference electricity output MWe	Total capital cost* M$	Total capital cost** M$	Total annual cost* M$	Total annual cost** M$
I	1000	332	2871	1727	91	245
II	900	299	2584	1554	82	220
III	750	249	2153	1295	68	183
IV	920	305	2641	1589	84	225
V	600	199	1723	1036	55	147
VI	280	93	804	484	26	68

*combined cycle
**steam cycle

Table4. Cost Indicators of Nuclear combinedcycle and steam cycle /RO desalination using levelized updated cost values into DEEP.

Reactor type	Power output: Reference thermal output MWth	Power output: Reference electricity output MWe	Total capital cost* M$	Total annual cost* M$	Total capital cost** M$	Total annual cost** M$	Power $/kWh*	Power $/kWh**
IRIS	1000	310	529	103	686	88	0.029	0.036
Carem300	900	495	782	115	530	75	0.036	0.034
VK-300	750	412	597	93	404	60	0.035	0.033
AHWR-220	920	506	886	122	586	79	0.038	0.035
GTMHR	600	330	521	77	353	50	0.036	0.034
SVBR	280	154	243	36	161	23	0.036	0.036

*combined cycle
**steam cycle

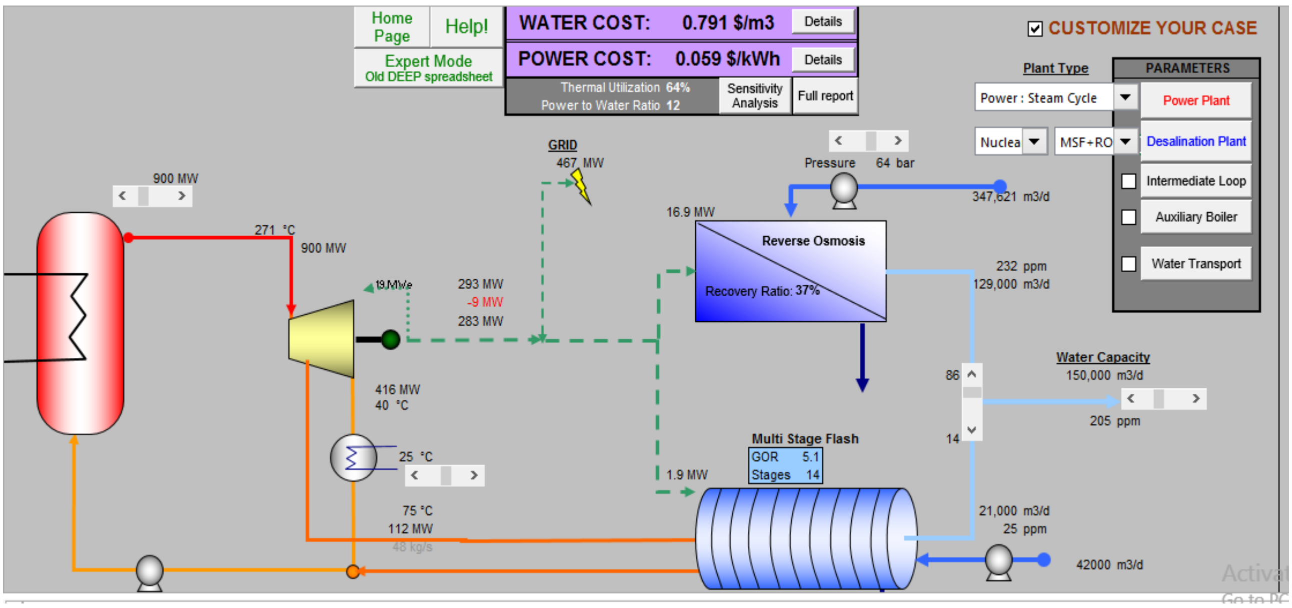

Fig. 2. Simulated case using DEEP

3.2. Integrated Desalination Plant Features

Hybrid desalination plants with different output ratios has been investigated using DEEP with power cost assumed to be $ 0.03/KWh. The results of the simulation are presented inTable (5) andFigures(3) and (4).

Table 5. Water production cost with different hybrid schemes of the optimized case

Water Cost $/m^3	RO Capacity m^3/day	MSF capacity m^3/d	permeate TDS ppm
0.747	150,000	0	254
1.074	45,000	105,000	90
1.021	60.000	90,000	110
0.969	75.000	75,000	130
0.924	90,000	60,000	150
0.872	105,000	45,000	170
0.821	120,000	30,000	189
0.772	135,000	15,000	207
1.241	0	150,000	25
1.184	15,000	135,000	47
1.15	22,500	127,500	58
1.129	30,000	120,000	69

3.3. Sensitivity Analysis

Sensitivity analysis on using hybrid nuclear desalination system (MSF/RO) has been carried out.The sensitivity of water unit cost in $/m^3 and the concentration of permeate in ppm as a function of (% system integration)for sea water desalination system (150,000 m^3/d) powered by nuclear reactor is illustrated in Figures (3) and (4).It has been indicated that the lowest water cost has been approached for pure RO system (0.73 $/m^3) in an inverse relationship with permeate TDS (the corresponding permeate concentration is 225 ppm). At MSF/RO ratio 11% at which an acceptable product water TDS of 200 mg/l is achieved, the produced unit water cost is $0.77/m^3.Empirical correlations developed from the simulation results of using IRIS nuclear reactor with hybrid MSF/RO,indicatesthat both relations are linearas follows(withcorrelation coefficients exceeding 0.99):

C= -0.0058(%RO) + 1.2877…………..…………………………….(1)

TDS= 1.99(%RO) + 28.56 …………………………………………...(2)

where :

C is the unit water cost in $/m^3
%RO is the MSF/RO ratio
TDS is the permeate concentration in ppm

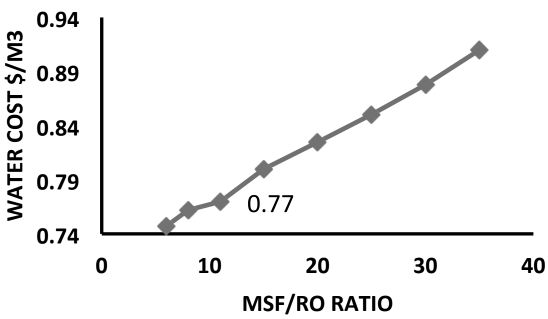

Fig. 3. Sensitivity analysis for different RO/MSF ratios

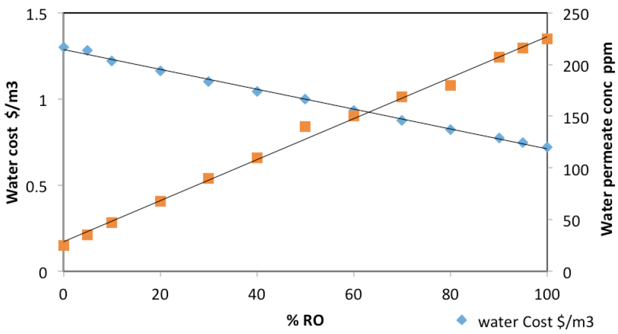

Fig. 4. Sensitivity analysis of water unit cost and permeate concentration

Detailed data on nuclear desalination for high capacities for the adopted technologies are sparse. However, to enable validation of our results we refer to the work of Yan, X.L., et al., 2016 and S.U.-D. Khan, et al., 2016 as follows:

- The water cost with the GTHTR300 cogeneration is US$0.57/m3 for a desalination capacity 54,552 m3/day with a unit power cost of $0.035/kWh [17]
- Identified outputs based on studies from IAEA for nuclear desalination plants in the range of 80–100,000 m3/day to 200–500,000 m3/day, showed that unit water cost range is US$ 0.5 to 0.94/m^3 for RO, US$ 0.6 to 0.96/m^3 for MED, and US$ 1.18 to 1.48/m3 for MSF processes [18].
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These values are in agreement with the findings of this work

4. Conclusions

Due to technological advances in nuclear reactor design and safety, SMRs are strongly recommended in offering energy with high reliability, passive safety and economic competitiveness. SMRs construction time is about 1/3 of large reactors, with lower financial risk and unit capital M$/MWe. A desalination system of 150,000 m^3 water production capacity to cope with the need of small communities has been proposed and analyzed. The desalination system requires about 19.1 MWe, SMR reactor type being proposed as a power source. Techno- economic study has been performed to compare between different SMR types to select preferred technical and economic features. For the proposed desalination scheme powered by IRIS nuclear reactor,the lowest power cost has been estimated to be $0.029/KWh using updated levelized cost. The thermal output of the selected reactor “IRIS”, which is almost 1000 MWth, gives the ability to combine the desalination plant with thermal desalination plant type to use the thermal output from the reactor. Sensitivity analysis of hybrid desalination process shows that according to different MSF/RO ratio the unit water costs varies linearly. At MSF/RO ratio 11% ,the unit water cost is \$0.77/m^3at corresponding permeate TDS 200 ppm. The lowest water cost has been approached for RO system (0.73 \$/m^3) in an inverse relationship with permeate TDS (the corresponding permeate concentration is 225 ppm).Linearcorrelations for water unit cost and permeate TDS have been developed for the hybrid process (MSF/RO) withcorrelation coefficients exceeding 0.99.

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Appendix

BWR	Boiling Water Reactor
GT-MHR	Gas Turbine Modular Helium Reactor
HTGR	High Temperature Gas Reactor
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
MSF	Multistage Flash Distillation
MWe	Mega Watt electric
MWth	Mega Watt thermal
PBMR	Pebble Bed Modular Reactor
PWR	Pressurized Water Reactor
RO	Reverse Osmosis
SMR	Small Medium/Modular Reactor
SWRO	Sea Water Reverse Osmosis
IRIS	International Reactor Innovative and Secure
CAREM-300	Central Argentina de ElementosModulares
AHWR	Advanced heavy-water reactor
SVBR	“Svintsovo-VismutovyiBystryiReaktor” - lead-bismuth fast reactor