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System Simulation for Coupling Nuclear Power Plants and Desalination in Different Scenarios

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Abstract— Nuclear power plants generate low carbon electricity, but also a lot of waste heat. That is what makes them particularly suitable for co-location with desalination plants. Analysis of coupling nuclear power with desalination plants is a mandatory prerequisite for such project establishment. This paper describes detailed analyses of power and water costs for several nuclear reactors operating in a cogeneration mode (e.g. PWR, the PHWR, the BWR, high temperature reactors, such as the gas cooled GT-MHR and the small modular reactor SMR). NPP's are coupled to three main desalination processes, multiple effect distillation (MED), (MSF), reverse osmosis (RO) and two scenarios for hybrid plants (MED+RO, MSF+RO). Comparisons are verified for desalination costs from the cheapest of conventional energy based systems, the 600 MW(e) gas turbine and combined cycle plant (CC-600) to the nuclear energy in various analysis settings for selected site specific conditions. System simulations are performed using IAEA- Desalination Thermodynamic Optimization Program (DE-TOP) and DEEP-4 software. Results have been tabulated or plotted for facilitate taking decisions.

Index Terms— Cost Evaluation, Desalination, Fourth Generation, Modeling RO, MSF, MED, NPPs Simulation.

1 INTRODUCTION

GENERATION IV nuclear energy roadmap recognized the important role that future nuclear energy systems must play in producing fresh water. In nuclear cogeneration plants, the primary product has usually been electricity production, but some of the generated energy can additionally drive a desalination unit for producing fresh water from sea as a byproduct. Coupling of Nuclear Power Plants (NPP) with commercially large desalination plants is mainly classified into two different groups, based on the kind of supplied energy [1]:
a. Electrical energy for Reverse Osmosis (RO) and Vapor Compression (VC) processes.
b. Heat energy for distillation processes; Multi-Stage Flash (MSF) and Multiple-Effect Distillation (MED).
Plans development for setting up of nuclear power-desalination plants at suitable sites, study the common difficulties in carrying out economic evaluations. Comparisons should be made between the economics of nuclear power and fossil power to guide the selection of a set of economic parameters for a "fair" comparison. As a matter of fact nuclear power plants have high capital cost, relatively long construction times, and relatively low fuel cycle costs whereas fossil fuelled power plants typically have low capital cost, shorter construction times and higher fuel cycle costs. The specific values of these competing factors may change the results towards one of these power options. Also complex calculations must be made to determine the power and water production costs resulting from each technical combination in order to fine-tune the economical optimization for cogeneration plants. Advanced modeling and simulation are adopted to provide great opportunities for responsible development of future nuclear energy systems. Benefits of modeling and simulation of nuclear reprocessing systems can be motivated by the expected potential in cost and design margines reduction and development of chemical and thermodynamic processes, also providing accurate prediction for interactions to reduce risk. As a concrete step towards pre-evaluation for Nuclear power plant project the IAEA recently released the Desalination Thermodynamic Optimization Program (DE-TOP). This software is excel based tool that models generic water cooled reactors coupled with seawater desalination plants to compares their performance for different configurations [2] which can be used with the IAEA DEEP software. System simulation presents the three interconnected systems: NPP conversion cycle for the steam power generation, coupling system (intermediate isolating loop IIL) and thermal seawater desalination plant. This paper aims to present comprehensively a detailed key factors which controlling the steady state behavior for different coupling options and have been considered for DE-TOP and DEEP4 for plants evaluation and economic analysis. The paper is organized as follows, section II is a models specification, section III is DEEP results tabulation and drawing, section IV is a major factors evaluation, section V is a results analysis, and section VI is the conclusion.

2 MODELS SPECIFICATIONS

For each geographical area its own characteristics which mainly control the water and power plant choice, such as cooling water specifications and human resources specifications [3]. In this analysis the results which have been obtained dedicated for a specific site in a North Africa south region, the range of sea temperature and salinity also personal cost are presented. Table 1 illustrates the differences between input data for three specific geographic areas.

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TABLE 1
Geographical Areas Specifications

Geographic area	Sea water conditions		Personal cost	
	Temp. c	TDS ppm	Management	Labor
South Europe	20	38000	160000	80000
North Africa	25	41000	60000	30000
Arabian Sea	30	45000	60000	30000

Site specific data, such as cooling water temperature, is also modeled as a necessary input to show the impact of ambient temperature to the performance of the dual purpose plant. In dual-purpose water and power plants, steam has to be extracted from the power plant to deliver heat for the desalination process [4].

Detailed thermodynamic model for coupled system is of the main importance when assessing nuclear desalination. In this analysis DE-TOP has been used for primary energy investigations for all water cooled nuclear power plants also for steam and condensed temperature adjustments. Nuclear power plant model and coupling arrangements are simulated for various types of reactors, main input parameters are introduced to the software such as thermal capacity, live steam conditions, reheat pressure ratio, feedwater preheating conditions, isentropic efficiencies, etc [5]. DE-TOP results are summarized in Table 2. Table 2 connection scenarios are used for DEEP system simulation.

TABLE 2
Typical Steam Production by Different Reactor Types

Nuclear Power Plant	Thermal Power (MWth)	Gross Mechanical output (MW)	Net Power Output (MWe)	Gross Efficiency %	Condenser Temp	Steam Parameters	
						Pressure (Mpa)	Temp. (°C)
PWR	1800	629	617	34.9	42.7	6.65	280
PWR	3002	1049	1029	34.9	42.7	6.7	285
BWR	1800	599	588	33.3	49	5.6	271
BWR	3002	1004	987	33.5	49	5.7	275
PHWR	3002	1085	1062	36.1	24.5	4.7	260
PHWR	1800	651	637	36.1	24.5	4.7	265
HTGR	600	300	284	48.3	126	17.3	300
HTGR	1000	500	489	48.3	128	17.4	310
SMR	330	98	92	42.1	40.3	3.0	274

3 DEEP Models & Results

Coupling configuration models have been built in two directions; one concerns the power source and the other concerns desalination process type. Each coupling description and its results will be explained in the followings:

3.1 Coupling With PWR

Pressurized water reactor (PWR) is the most common reactor type in operation today. Many different design configurations exits, but all have in common the use of light water as both coolant and moderator for the reactor core [6]. The reactor efficiency in this case is about 33%. Results are plotted for PWR-600 evaluation are presented in figure1.

This reactor has been tested when it is coupled in three desalination processes: MED, MSF, RO, hybrid (MED + RO and MSF + RO) in a 1: 1 ratio process.

TABLE 3
Results of DEEP calculations for PWR interest rate 5% with intermediate loop

Power option	Desalination plant size	Levelized electricity cost	Levelized water cost				
			MED	MSF	RO	Hyb MED+RO	Hyb MSF +RO
PWR 600	50,000	0.063	0.855	1.134	0.8	0.814	0.946
	100,000		0.842	1.12	0.788	0.801	0.933
	200,000		0.832	1.11	0.779	0.791	0.923
PWR 1000	50,000	0.063	0.852	1.129	0.798	0.811	0.942
	100,000		0.839	1.116	0.786	0.799	0.93
	200,000		0.829	1.105	0.777	0.789	0.92

3.2 Coupling With BWR

Boiling water reactor (BWR) is a type of light water nuclear reactor used for electrical power generation.

TABLE 4
Results of DEEP calculations for BWR interest rate 5% with intermediate loop

Power option	Desalination plant size	Levelized electricity cost	Levelized water cost				
			MED	MSF	RO	Hyb MED+ RO	Hyb MSF+ RO
BWR 600	50,000	0.064	0.829	1.014	0.782	0.792	0.879
	100,000		0.816	1.000	0.77	0.779	0.867
	200,000		0.806	0.99	0.761	0.77	0.857
BWR1 000	50,000	0.064	0.828	1.012	0.781	0.791	0.878
	100,000		0.815	0.999	0.769	0.779	0.866
	200,000		0.805	0.988	0.76	0.769	0.856

It is the second most common type of electricity-generating nuclear reactor after the PWR. The BWR reactor typically allows bulk boiling of the water in the reactor. Current BWR reactors have electrical outputs of 570 to 1300 MWe. The reactor is about 34.5% efficient. Cost calculations are plotted in table 4 for BWR in 50,000 to 200,000 m3/d water production levels.

3.3 Coupling With PHWR

Pressurized heavy water reactor (PHWR) is characterized by a horizontally oriented core, with the fuel channels housed in individual small diameter pressure tubes through which heavy water (D2O) circulates as the primary coolant [7].

TABLE 5
Results of DEEP calculations for PHWR (5% interest rate and intermediate loop)

Power option	Desalination plant size	Levelized elect. cost	Levelized water cost				
			MED	MSF	RO	Hyb 50% RO+MED	Hyb50 % RO+MSF
PHWR 600	50,000	0.058	0.97	1.399	0.782	0.859	1.062
	100,000	0.058	0.957	1.386	0.77	0.846	1.049
	200,000	0.058	0.947	1.376	0.761	0.836	1.04
PHWR 1000	50,000	0.057	0.963	1.379	0.763	0.847	1.046
	100,000	0.057	0.95	1.366	0.751	0.835	1.034
	200,000	0.057	0.939	1.355	0.741	0.825	1.024

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Pressure tubes are housed in a large diameter horizontal tank (calandria) containing low temperature, low pressure heavy water as the moderator. The reactor is about 36% efficient. DEEP results for PHWR plants in 600MWe are illustrated in table 5.

3.4 Coupling With GT-MHR

Gas turbine-modular high temperature reactor (GT-MHR) is an advanced reactor design, which integrates demonstrated high temperature gas cooled reactor (HTGR) and industrial gas-turbine technologies, to meet all Generation IV goals with significant margins [8]. It is a helium cooled direct-cycle nuclear power plant. The designers claim to have relatively high electricity production efficiency (~50%) and enhanced safety, economic, non-proliferation and environmental characteristics.

TABLE 6

Results of DEEP calculations for GT-MHR (5% interest rate and intermediate loop)

Power option	Net electricity MWe	Desalination plant size	Levelized electricity cost	Levelized water cost		
				MED	RO	Hybrid MED/RO
GTMHR 300	284	50,000	0.068	0.472	0.812	0.64
		100,000		0.459	0.803	0.627
		200,000		-	0.791	0.618
GTMHR 500	489	50,000	0.068	0.472	0.812	0.64
		100,000		0.459	0.803	0.627
		200,000		-	0.791	0.618

Table 6 is the results for 300 MW(e) power level. For such coupling configurations MSF water plant requires higher power or less water capacity.

3.5 Coupling With SMR

Small Modular Reactors (SMRs) have been indicated as the most suitable size for the majority of nuclear desalination applications. Large-scale deployment of solid-uranium-fueled nuclear reactor desalination on a commercial basis will depend primarily on economic factors. SMRs is very flexible and appears to be particularly suitable for cogeneration of electricity and water in relatively weak or non-interconnected electricity grids. Table (7) gives an overview for DEEP results. MSF process needs higher energy in such coupling configurations.

TABLE 7

Results of DEEP calculations for SMR (5% interest rate and intermediate loop)

Power option	Desalination plant size	Levelized electricity cost	Levelized water cost			
			MED	MSF	RO	Hyb
SMR 130	50,000	0.063	0.487	-	0.8	0.639
	100,000		-	-	0.788	0.626
SMR 330	50,000	0.064	0.478	2.746	0.799	0.635
	100,000		0.465	-	0.787	0.622
	200,000		-	-	0.778	0.612

3.6 Coupling With Conventional Power Plant

Heat or electricity to be used for desalination purposes may be produced by burning conventional fuels. Several power plant options are applicable and some of them are presently used to produce the majority of desalted water in the world. In this study, two conventional power production plants have been taken into consideration. Plants included two cooling options gas cycle and combined cycle electric production plants. Result of DEEP calculations for these plants are in table (8).

TABLE 8

Results of DEEP calculations for Fossil power plant

Power option	Desalination plant size	Levelized electricity cost	Levelized water cost				
			MED	MSF	RO	Hyb. MED+ RO	Hyb. MSF+ RO
CC600 Comb. cycle	50,000		1.339	2.443	1.049	1.198	1.569
	100,000	0.148	1.325	-	1.037	1.185	1.556
	200,000		1.314	-	1.028	1.175	-
CC600-Gas Cycle	50,000	0.219	0.915	1.162	1.257	1.094	1.136
	100,000		0.901	-	1.245	1.081	1.123
	200,000		0.890	-	1.236	1.071	-

4 Major Factors Evaluation

Coupling configuration between desalination and nuclear power plants not only entails technical and safety considerations but also it has a strong influence on the overall economics of a nuclear desalination system. Accordingly, for each power/desalination plant combination the detailed input parameters included different connection scenarios for evaluating the competing influence of factors such as reactor type and size, desalination type and plant capacity, interest /discount rate, transport cost, carbon tax and gas price are examined for this analysis.

4.1 Power Plant Type and Size

DEEP cost evaluation cases have been concluded to be presented in figures (1) to (5). Figures 1, 2 compare between NPP plants which are engaged in co-generation scenarios in term of produced water cost. In figures 3, 4 two power plants sizes 600, 1000 MWe are added to the comparison. Figure (5) illustrates electricity cost comparison for different energy sources.

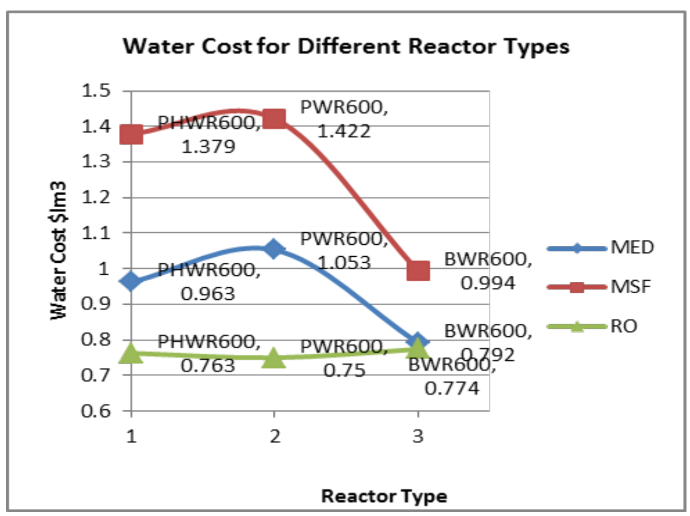

Fig. 1. Water cost for three water cooled NPP and 600 MWe

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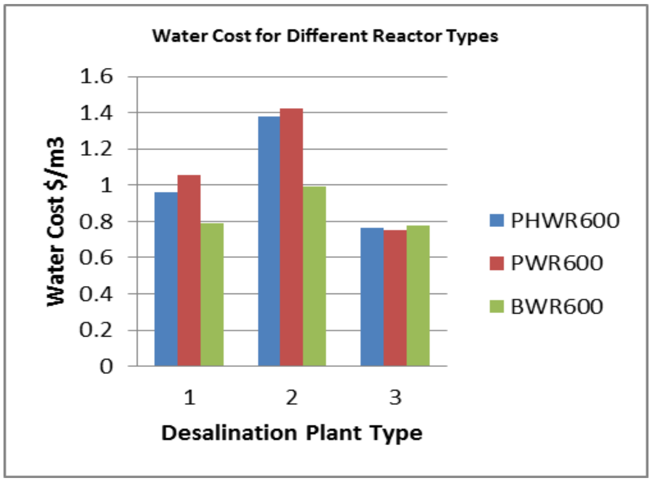

Fig. 2. Water cost for 1-MED, 2-MSF, 3-RO for 600MWe NPPs

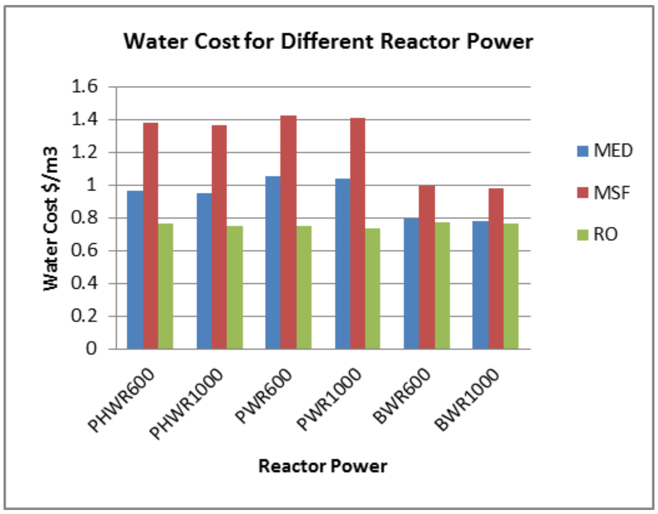

Fig. 3. Water cost comparison for three water cooled NPP and 600, 1000 MWe

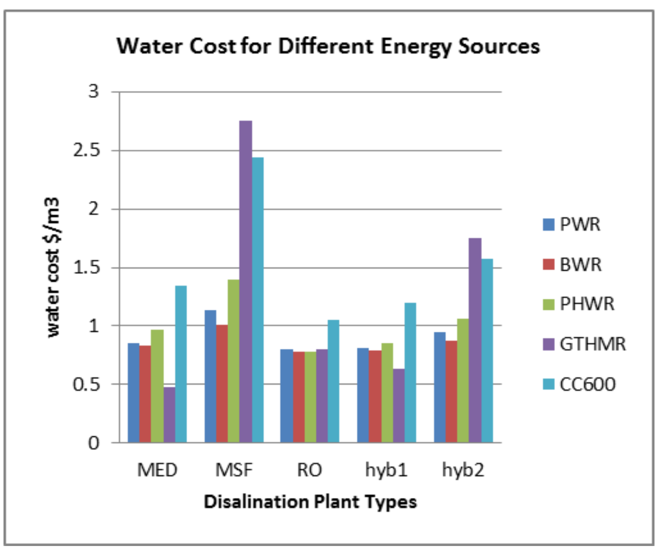

Fig. 4. Water cost comparison for different energy sources

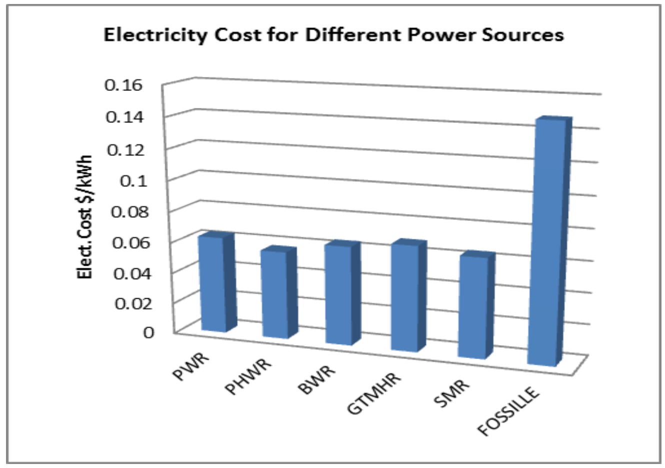

Fig. 5. Electricity cost comparison for different energy sources

4.2 Desalination Plant Type and Size

The results from DEEP simulation verified that as the water plant capacity increases water cost decreases for all type of desalination. Figures 6 to 8 are samples for these results.

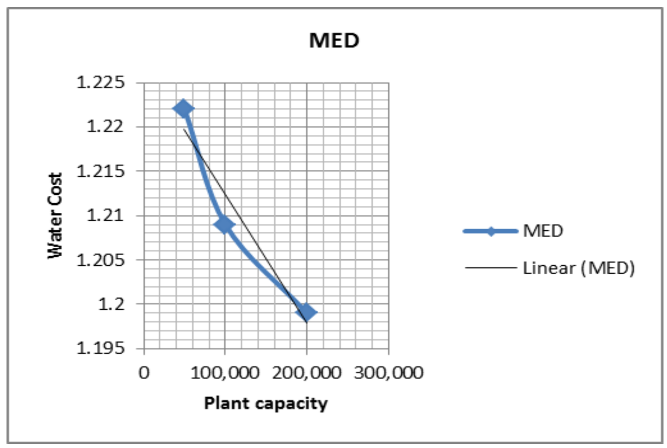

Fig. 6. Change in water costs for 50,000 - 200,000 m3/d in MED plant

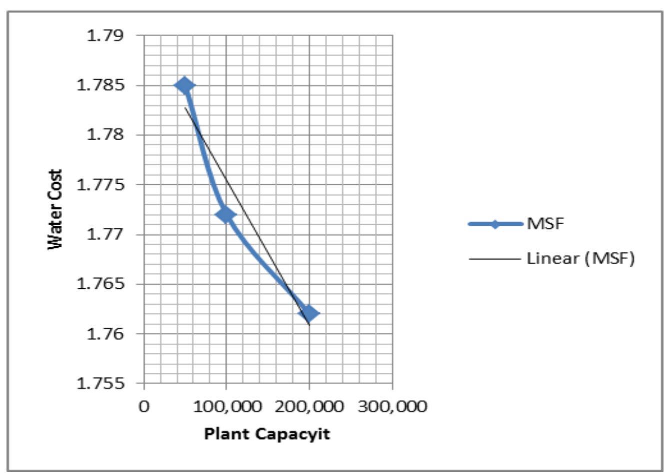

Fig. 7. Changes in water costs for 50,000 - 200,000 m3/d in MSF plant

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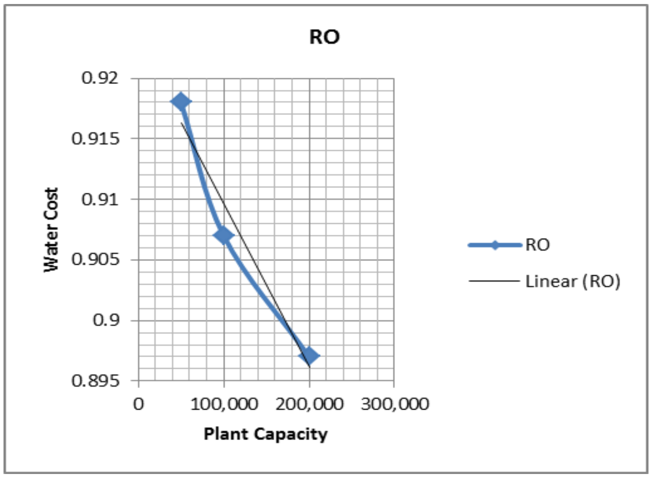

Fig. 8. Change in water costs for 50,000 - 200,000 m3/d in RO plant

Figure 9 shows the difference in water cost for different desalination plants type, and figure 10 explains the effect of NPP energy levels on water cost for the same desalination plant. Table 9 is a registered outcome for energy consumption while DEEP operations for all desalination types. MED thermal desalination uses 6.38 KWh per cubic meter electrical energy; whereas MSF uses about double the electrical consumption than MED does and RO uses 3.17kWh/m3 as it is detected from DEEP simulation models.

TABLE 9

Energy Requirements for Different Desalination Processes

Process/energy type	MED	MED+RO	MSF	MSF+RO	RO
Electric energy equivalent kwhr/m3	4.75	2.33	10.46	5.3	0
Electric energy consumption kwhr/m3	1.63	2.4	2.1	4.8	3.17
Total electric energy equivalent kwhr/m3	6.38	4.73	12.56	10.1	3.17

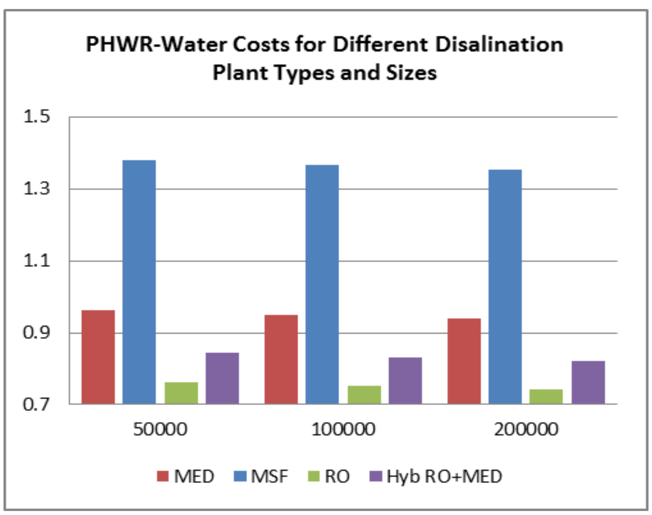

Fig. 9. Water cost for different plant capacity

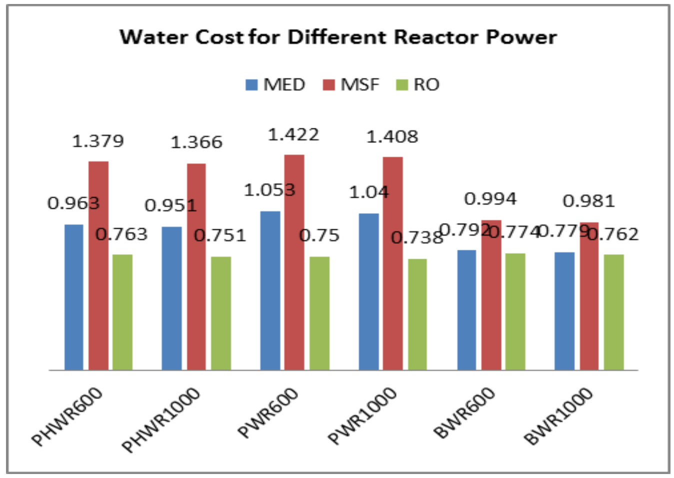

Fig. 10. Water cost for different desalination plant type in different plant energy

4.3 Discount/Interest Rate

As a test case for discount/interest rate (DR) effect on electricity and water price DEEP cost analysis for PHWR model at 50,000 m3/d water capacity has been run for three DR values (5%, 8%, 10%), the results are in figures 11, 12. The results explained the behavior of such economic sample but it can be generalized to study all coupling configurations.

Electricity cost versus water cost for different discount rates for the PHWR are concluded from DEEP results in figure 11. Electricity cost at 10% discount rate is about 63% higher than the corresponding cost at 5%DR for fixed plant power.

Figure 12 explains the effect of DR increases on water price for different desalination processes. Water cost at 10% discount rate is about 53% higher than the corresponding cost at 5%DR in MSF, and 51% in MED and 36% in RO.

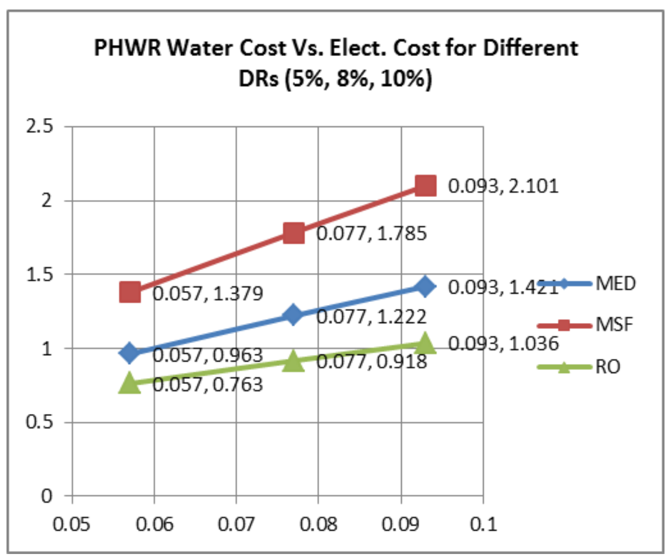

Fig. 11. Effects of Discount Rate in electricity and water price for PHWR at 50,000 capacity

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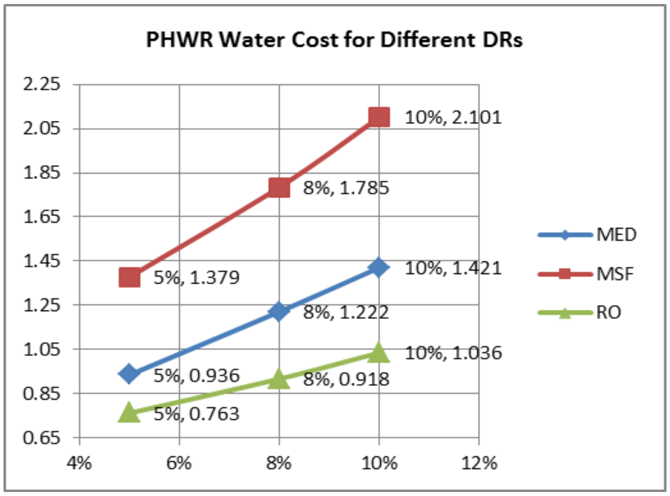

Fig. 12. Effects of Discount Rate in water price for PHWR at 50,000 capacity and different Desalination types

4.4 Fixed and Transportable Water

An energy and water plant is designed to answer a specific demand requirement that varies between winter and summer at that plant's location. In North African countries summer electricity demand is much higher than winter demand, while water demand is almost stable all year long. For this reason and for high efficient NPP consideration there is a large potential for medium- to high capacity plant (50,000 – 200,000 m3/day) fixed / transportable desalination plants coupled to nuclear plants in this area. Figure 13 concludes a test model for verifying water transmission effect on water price for different desalination plant capacity. As it is expected from results water transmission adds cost to the produced water price, also as capacity increases transportable water cost decreases (water cost for 200,000 m3/d transportable water plant is almost the same as 50,000 m3/d fixed water plant).

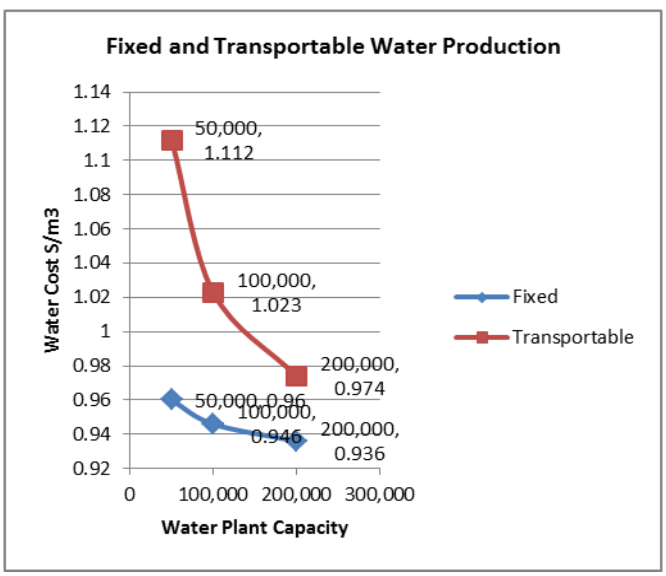

Fig. 13. Desalination plant in fixed and transportable water production

5 Results Analysis

- Water Desalination cost in case of nuclear reactors coupled to MED is 32% to 45% lower than the corresponding cost by the conventional power + MED systems.
- Water Desalination cost in case of nuclear reactors coupled to RO 28% to 35% lower than the corresponding cost by the conventional power + RO systems.
- Water Desalination cost in case of nuclear reactors coupled to MSF 15% to 42% lower than the corresponding cost by the conventional power + MSF systems.
- The combination of RO and MED or MSF technologies in the tested hybridized desalination plants provide several important advantages:
- Hybrid RO + MED and RO + MSF plants produce cheaper water than MED or MSF thermal desalination-only plants
- Water Desalination cost in case of nuclear reactors coupled to hybrid plant (MED + RO) is 28% to 43% lower than the corresponding cost by the conventional power coupled to hybrid (MED + RO) systems.
- The desalination cost of nuclear reactors coupled to hybrid plant (MSF + RO) is 24% to 33.5% lower than the corresponding cost by the conventional power coupled to hybrid (MSF + RO) systems.
- This cost is likely to be further reduced as a system capacity is increased.
- Plant management economic aspects details- such as discount/interest rate are essential for cost calculations.
- Intermediate loop is essential for NPP coupling to desalination plant but it adds cost to water price
- Fixed or portable water production is an important choice and should be optimized with plant capacity.
- The lowest costs with the MED plants are obtained by the GT-MHR, utilizing virtually free waste heat give desalination costs which are respectively 62% and 44% lower.

6 Conclusion

Reactor types and sizes that are commercially available offering wide range of technical specifications which have to be verified for most suitable for each specific case and site. The choice of a reactor type for a dual purpose or co-generation plant should also be carefully chosen as a possible long-term investment project. Analysis results indicate that the discount rate has a great effect on water cost especially for nuclear energy source than for conventional energy source based desalination because of the high capital cost and relatively long construction periods in NPP. Fuel price changes affect water price in fossil plant rather than in nuclear options. If the economic performances of the GTMHR as one of the high temperature reactors for 4G generation, as announced by their respective developers, are indeed true that the GT-MHR would lead to the lowest water costs of all options considered. For high efficient NPP consideration there is a large potential for medium- to high capacity plant fixed / transportable desalination plants coupled to nuclear plants especially for North Africa Cost area.

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