Economic Analysis of Co-Production Plants for Electricity and Potable Water

Ibrahim Masaoud El Azizi

elazizi2001@gmail.com

Department of Power Generation Technologies,
The Libyan Atomic Energy Establishment, Libya
*Corresponding author email: elazizi2001@gmail.com

ABSTRACT

This paper describes the detailed analyses of power and water costs for 1800 MWt Pressurised light water reactor (PWR), 330 MWt, System-Integrated Modular Advanced Reactor (SMART) and 1200 MWt gas turbine combined cycle (GTCC) power plant operating in a cogeneration mode and coupled to various desalination processes. In this study, four different desalination processes including multiple effect distillation (MED), Multi-Stage flush distillation (MSF), reverse osmosis (RO) and hybrid MED + RO are considered and compared with each other in terms of energy consumption, electricity and water costs. Detailed economic analyses of energy and water production costs for a 100,000 m^3/d desalination plant were carried out. The obtained results concluded that the water production cost (at 5% discount rate) with the GTCC power plant and nuclear reactors coupled with RO desalination plant is 0.86 \$/m^3 and 0.79 \$/m^3, respectively. In case of MED and MSF desalination processes coupled with GTCC, the water costs are 1.23 \$/m^3 and 1.83 \$/m^3, respectively. Lower water costs were obtained when nuclear reactors coupled to MED and MSF desalination plants and found to be 1.06 \$/m^3 and 1.53 \$/m^3, respectively. Results concluded that coupling nuclear reactor to desalination plants is an attractive solution for energy demand and fresh water supply.

Keywords: Nuclear Desalination. Co-production, Reverse Osmosis, Multi-Effect Distillation, Water Cost.

1. Introduction

Libya is located in an arid area with limited water sources and the best choice for providing potable water is through seawater desalination. Seawater desalination is considered as energy intensive process in which energy cost is a major controlling parameter in the overall cost of desalination [1]. The desalination of seawater using nuclear energy is a feasible option to meet the growing demand for electricity and potable water. Nuclear desalination can be defined as the production of potable water from seawater in a facility in which a nuclear reactor is used as the source of energy for the desalination process [2]. An isolation loop is provided between the nuclear reactor and the desalination plant to ensure no radioactive contamination and high protection of desalinated water. Co-location of desalination and power plants has benefits of sharing the infrastructural facilities as in the case of hybrid plants. Interest in using nuclear energy for the production of desalinated water is growing worldwide [3]. Coupling of fossil and nuclear power plants with commercially large desalination plants can be classified into two groups, based on the kind of supplied energy to the plant. Electrical energy is supplied for RO and heat energy for distillation processes; MSF and MED [4]. Coupling RO, MED, MSF and hybrid systems with nuclear reactor has economical and technical advantages such as a low power demand, good water quality and possible lower running cost compared to stand-alone RO MSF or MED plants. Coupling of a nuclear power plant to hybrid desalination system consists of MED and/or MSF plant followed by a RO plant, where the rejected cooling water from the last effect of the MSF system used as feedwater to the RO system [5]. In the hybrid desalination systems both thermal and membrane desalination processes are combining with power generation systems. Hybrid configurations are flexibile in operation, less specific energy consumption, low construction cost, high plant availability and better power and water matching. The main advantages of hybrid systems are reducing the seawater intake and reject disposal systems, reducing the RO membrane replacement and blending the products of the desalination processes. There is no technical impediment to the use of nuclear reactors for supply of either heat of electricity or both to a desalination plant. There are no specific nuclear reactors for desalination and any nuclear reactor capable for providing electrical and/or thermal energy can be coupled to an appropriate desalination process. The past experience and information on reactor type, location, desalination process and status for nuclear desalination are given in Table 1 [6].

Table 1. Nuclear desalination systems including reactor types and desalination processes

Reactor Type	Location	Desalination Process	Status
LMFR	Kazakhstan (Aktau)	MSF, MED	In service till 1999
PWRs	Japan (Ohi, Takahama, Ikata, Genkai)	MSF, MED, RO	in service with operating experience of over 125 reactor-years.
	Republic of Korea and Argentina	MED, RO	Under Design
	Russia	MED, RO	Under Design (Floating unit)
PHWR	India (Kalpakkam)	MSF, RO	Never in-service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999.
	Pakistan (KANUPP)	MED	Under commissioning
	Canda	RO (Preheat)	Under design
BWR	Japan (Kashiwazaki)	MSF	Under design
NHR	China	MED	Under design
HTGR	South Africa, France, The Netherlands	MSF, MED, RO	under consideration

All nuclear reactor types can provide the energy required by the various desalination processes. However, Small and Medium Reactors (SMRs) may offer large potential for nuclear desalination systems in developing countries. Small and medium sized nuclear reactors (SMRs) are defined as power reactors that have power outputs in the range of 100–400 MW(e). SMRs are suitable for seawater desalination, often with cogeneration of electricity using low-pressure steam from the turbine and hot seawater feed from the final cooling system. The development of cost competitive small and medium size nuclear power reactors is more suitable for grid sizes in developing countries as well as for coupling with desalination plants of 10,000 m^3/d to 100,000 m^3/d capacities. About one-third of the SMRs under construction are expected to supply heat or electricity or both to integrated seawater desalination plants [7]. The International Atomic Energy Agency (IAEA) has studies the feasibility of using nuclear energy for seawater desalination and has published reports on the technical and economical evaluation of nuclear energy sources for seawater desalination [8]. In this study the economic analysis of coupling of nuclear reactors with desalination processes will presented.

2. Materials and Methods

2.1 Site Specifications

The geographical area chosen for the nuclear power plant and desalination plant has its own characteristics. The seawater temperature and feed water TDS in this site are 21^{o}C and 37500 mg/l, respectively.

2.2 Coupling of Desalination Plants with Combined Cycle Gas Power Plant

Heat and/or electricity to be used for desalination processes can be produced by burning conventional fuels. In Libya Oil/Gas power plants are presently used to produce the desalted water in many cities. In this study CC1200 MWe combined cycle gas power plant was coupled with various desalination processes, Reverse Osmosis (RO), Multi-Effect Distillation (MED) and hybrid MED+RO desalination plants. Discount and interest rates of 5% and fuel escalation at 3% were used.

2.3 Coupling of Desalination Plants with Pressurised Water Reactor (PWR)

Nowadays, pressurized water reactor (PWR) is the most common reactor type in operation. There are many different design configurations, where the light water is used as a coolant and moderator for the reactor core [8]. The PWR coupled with various desalination processes (RO, MED, and hybrid MED+RO) and both energy and water costs were determined.

2.4 Coupling of Desalination Plants with Small Modular Reactor (SMR)

Small Modular Reactors (SMRs) have been indicated as the most suitable size for the majority of nuclear desalination applications. SMRs is very flexible and appears to be particularly suitable for cogeneration of electricity and potable water. System-Integrated Modular Advanced Reactor (SMART) is a small PWR with a rated thermal power of 330 MW, developed by KAERI (Korea Atomic Energy Research Institute) coupled to various desalination processes because it can serve as a safe and economic energy source for seawater desalination.

2.5 The Power Plants Performance Data.

The performance data associated with the design, construction, operation, maintenance, fueling of GTCC power plant and both nuclear reactors as well as the all technical and economic data associated with the desalination processes were collected and calculated using DEEP software. The calculations of the levelised water cost for various desalination processes were performed and the obtained results are summarised in Table 2.

Table 2. Power plants performance data.

Thermal-Hydraulic Parameters	Unit	Type of power plant		
		GTCC	PWR	SMART
Reference thermal power output	MWt	1200	1800	330
Reference electrical output	MWe	639	617	105.6
Total capital cost	($/kW)	982	5571	5571
Annual operation and maintenance costs	($/kWh)	0.079	0.021	0.021
Efficiency	(%)	51	34.9	42.1
Availability	(%)	85	90	90
Plant life time	Year	25	60	40
Construction lead time	Month	24	60	50

2.6 Cost Evaluation Methods

Calculations are performed using the desalination economic evaluation program software (DEEP-5.1), which has been developed originally by IAEA. For the economic evaluation, the technical and economic data for the power plants and desalination plants were determined used as the input data into the DEEP software. DEEP output includes the levelized cost of water and power, a breakdown of cost components, energy consumption and net saleable power for each selected option. DEEP uses the power credit method for desalination cost evaluation to treat two products, namely water and electricity [9, 10]. Cost calculations were done for both power plants and water desalination plants. The DEEP model allows different power plants to be coupled with various desalination plants.

2.6.1. The Power and Water Credit Methods

Power credit is calculated on the basis of the cost of producing the same amount of electricity in a power-only plant. In the power credit method, the energy cost is set to be the cost obtained from an imaginary single purpose power plant, generating net energy ***E*** with total expenses, ***C***. One can thus determine the net levelized power cost using the following equation [10]:

$$C_{kWh} = \frac{C}{E} \tag{1}$$

The principle of water credit is to evaluate a water value produced and to determine the cost of the power generation by the power plants. The water credit depends on the water cost, C_w which can be calculated using the following equation [10]:

$$Water\ Credit = \frac{C_w}{E_w} \tag{2}$$

3. Results and Discussion

3.1 Comparison of Energy and Potable Water Costs produced by Different Power Plants.

In this study one conventional GTCC power plant ant two nuclear reactors (PWR and SMART) coupled with MED, MSF, RO and hybrid MED+RO have been taken into consideration. Results of DEEP calculation for energy and desalinated water production costs are presented in Table 3.

Table. 3 Comparison of energy and water costs produced by different power and desalination plants.

Parameter	Desalination plant size (m^3/d)	Levelized electricity cost ($/kwh)	Desalinated water Cost ($/$m^3$)			
			MED	MSF	RO	MED+RO
GTCC power plant	100,000	0.09	1.23	1.83	0.85	1.03
PWR nuclear reactor	100,000	0.067	1.06	1.53	0.79	0.91
SMART nuclear reactor	100,000	0.067	1.06	1.53	0.79	0.91
Permeate water TDS (mg/l)			25	25	199	108

From the obtained results, the desalinated water cost in case of GTCC power plant is found to be 1.23 $/$m^3$ for MED, 1.83 $/$m^3$ for MSF and 0.85 $/$m^3$ for RO, respectively. In case of nuclear reactors, less desalinated water cost obtained and found to be 1.06 $/$m^3$ for MED, 1.53 $/$m^3$ for MSF and 0.79 $/$m^3$ for RO, respectively. Desalinated water cost in case of nuclear reactors coupled with desalination processes is about 31% to 53% lower than the corresponding water cost by the same desalination processes coupled with the conventional GTCC power plant. Desalinated water cost in case of nuclear reactors coupled to RO is about 15 and 48% lower than the corresponding cost by the nuclear reactors coupled to MED and MSF desalination plants, respectively. Desalinated water cost in case of GTCC power plant coupled with MED and MSF is 16% - 44% higher than the corresponding desalinated water cost produced from hybrid MED+RO processes. The water desalination cost in case of nuclear reactors coupled with hybrid MED+RO desalination process is 13% - 41% lower than the corresponding water cost by the nuclear reactors coupled to MED and MSF, respectively.

This means that the coupling of RO desalination plants with GTCC power plants and/or nuclear power plants have lower water cost compared to MED, MSF and hybrid MED+RO desalination processes. Similar results reported by the IAEA based on country case studies showed that costs of desalinated water would be in the range 0.60 – 0.74 $/$m^3$ for RO, 0.75 – 0.86 $/$m^3$ for MED, 1.2 – 1.50 $/$m^3$ for MSF and 0.91 – 1,10 $/$m^3$ for MED+RO desalination processes respectively [11]. Elaskary [3] studied the coupling of PWR reactors with different desalination plants and found that the water cost is 1.04 $/$m^3$ for MED, 1.41 $/$m^3$ for MSF and 0.74 $/$m^3$ for RO respectively.

The product water TDS produced by MED and MSF are very low because it is used for industrial applications, however, the water TDS is increased in hybrid MED+RO desalination process after blending both products together. The RO water product TDS is high compared to MED and MSF processes and can be reduced by using high rejection seawater reverse osmosis membranes.

Results detected from DEEP software for specific energy consumption (Table 4) showed that the MED and MSF desalination processes uses about 6.21 kWh/m^3 and 12.20 kWh/m^3, respectively, while the RO and MED+RO use 3.23 kWh/m^3 and 4.56 kWh/m^3, respectively.

Table 4. Total equivalent energy consumption by different desalination processes.

Parameter	UNIT	MED	MSF	RO	MED+RO
Specific energy consumption (SEC)	(kWh/m^3)	6.21	12.20	3.23	4.56

The specific energy consumption by RO desalination process is lower by 48% and 74% compared to MED and MSF desalination process, respectively, whereas, the Specific energy consumption in case of hybrid MED+RO desalination process is 27% and 63% lower than the stand-alone MED and MSF desalination plant, respectively. These results are similar to the results obtained by Elaskary [4] and Nisan and Dardour [12]. They carried out studies where, different nuclear power reactors (PWR, PHWR and SMR) operating in cogeneration mode coupled to various desalination processes. They used DEEP software for calculating the energy and desalinated water cost and found that the specific energy consumption values are 6.38 kWh/m^3 for MED, 12.56 kWh/m^3 for MSF, 3.17 kWh/m^3 for RO and 4.73 kWh/m^3 for hybrid MED+RO, respectively.

4.0 Conclusions

Nuclear desalination systems are technically feasible and economically attractive options with a variety of nuclear reactor concepts. From the obtained results it can be concluded that, water desalination cost in case of nuclear reactors coupled to MED and RO desalination plants is lower than the water cost produced by CC gas power plant. Coupling of RO desalination process with GTCC power plants and/or nuclear power plants have lower water cost compared to MED, MSF and hybrid MED+RO desalination processes. The specific energy consumption by RO desalination process is lower by 48% and 74% compared to MED and MSF desalination process, respectively. DEEP software analysis showed that the intermediate loop between the nuclear power plant and thermal desalination plant is essential, however it adds cost to the water price. Taken in consideration the environmental impacts, nuclear desalination over fossil fuel desalination is more attractive and more feasible and SMR reactors are more favored choice for seawater desalination.

References

[1] K. V. Reddy and N. Ghaffour, "Overview of the Cost of Desalinated Water and Costing Methodologies," *Desalination*, Vol. 205, No. 1-3, 2007, pp. 340-353.

[2] P. Asiedu-Boateng, B. J. B. Nyarko, S. Yamoah, F. Ameyaw, K. Tuffour-Acheampong "Comparison of the Cost of Co-Production of Power and Desalinated Water from Different Power Cycles" *Energy and Power Engineering*, Vol. 5, 2013, pp. 26-35.

[3] A. M. Elaskary, "System Simulation for Coupling Nuclear Power Plants and Desalination in Different Scenarios-" *Int. Jo. of Sci. & Eng. Rese*., Vol. 4, Issue 4, (2013). pp. 1116-1122.

[4] International Atomic Energy Agency "New Technologies for Seawater Desalination Using Nuclear Energy" IAEA-TECDOC-1753, IAEA, Vienna, 2015.

[5 I. S. El-Mutaz, "Coupling nuclear reactor to hybrid RO+MSF desalination plants", *Desalination*, Vol. 157, 2003, pp. 259-269.

[6] I. Khamis, "A global overview on nuclear desalination" *Int. J. Nuclear Desalination*, Vol. 3, No. 4, 2009, pp. 311 – 328.

[7 I. S. El-Mutaz,"Hybrid RO MSF:a practical option for nuclear desalination" *Int. J. of Nuclear Desalination*, Vol.1, No. 1, 2003, pp. 1-10.

[8] Technical and Economic Evaluation of Potable Water Production Through Desalination of Seawater by Using Nuclear Energy and Other Means. IAEA-TECDOC-666, IAEA, Vienna, 1992.

[9] S. Nisan and S. Dardour, "Economic Evaluation of Nuclear Desalination Systems," *Desalination*, Vol. 205, No. 1, 2007, pp. 231-242.

[10] International Atomic Energy Agency, "Examining the Economics of Seawater Desalination Using the DEEP Code", IAEA-TECDOC-1186, IAEA, Vienna (2000).

[11] International Atomic Energy Agency, "Economics of Nuclear Desalination: Developments and Site-Specific Studies" IAEA-TECDOC-1561, IAEA, Vienna (2006).

[12] S. Nisan, S. Dardour, "Economic evaluation of nuclear desalination systems" *Desalination*, Vol. 205, (2007), pp. 231–242,