Coupling pressurised water reactor to large scale SWRO desalination plants: an economic assessment

Ghada A. Al Bazedi, Mohamed H. Sorour, Shadia R. Tewfik*, Abdelghani M.G. Abulnour and Heba A. Hani

Chemical Engineering and Pilot Plant Department,
National Research Centre, El-Bohouth Street,
Dokki, P.O. Box 12622,
Giza, Egypt
Email: bazedi@yahoo.com
Email: mhsorour12@yahoo.com
Email: shadiatewfik@yahoo.com
Email: dr_agaboelnour@yahoo.com
Email: hi_heba2@yahoo.com
*Corresponding author

Abstract: Water management via rational use, reuse practices and water desalination is the key element for mitigation of water shortage. This paper addresses small-scale nuclear systems as a cost-effective energy alternative for large-scale desalination plants. An empirical cost model has been derived and validated based on reported cost indicators and selected cases. The capital cost of 150,000 m^3/d seawater desalination plant coupled to small nuclear reactors has been estimated to be between 3 and 11 M$/MWe, respectively. In addition, specific cost of nuclear desalination-steam cycle system SWRO (conventional pre-treatment), ranges between 0.046–0.064 $/kWh and 0.62–0.667 $/$m^3$ for energy and water, respectively. Cost indicators of different desalination systems show that product water cost ranges between 0.62 and 0.779 $/$m^3$ when applying nuclear power as an energy source for RO, RO/MED, MED while when applying oil/gas as an energy source the product water cost ranges between 1.12 and 1.89 $/$m^3$.

Keywords: nuclear desalination; reverse osmosis; SMRs; PWR; cost function.

Reference to this paper should be made as follows: Al Bazedi, G.A., Sorour, M.H., Tewfik, S.R., Abulnour, A.M.G. and Hani, H.A. (2019) 'Coupling pressurised water reactor to large scale SWRO desalination plants: an economic assessment', *Int. J. Nuclear Governance, Economy and Ecology*, Vol. 4, No. 3, pp.198–211.

Biographical notes: Ghada A. Al Bazedi is an Associate Research Professor at the Engineering Research Division of the National Research Centre, Egypt. She has a PhD degree in Chemical Engineering from Cairo University, 2012. Her PhD was about modelling, simulation and optimisation of large scale reverse osmosis desalination plants. She is interested in membrane science, environmental engineering as well as separation technology. She participated in several relevant research projects as Co-PI or team member. She has several publications in desalination and waste management and is a member of different engineering societies.

Copyright © 2019 Inderscience Enterprises Ltd.

Mohamed H. Sorour received BSc, MSc and PhD in Chemical Engineering from Alexandria University. He has been working at the Chemical Engineering and Pilot Plant Dept. at National Research Centre, Egypt, since his graduation in 1972. He has been a Research Professor since 1994. His main experience is in membrane science, fabrication-separation technology, desalination, waste management and techno-economic studies in the field of chemical and allied industries. He provided consultancy services to several national organisations. He has participated in several international and national projects and has several publications and granted patents.

Shadia R. Tewfik received BSc and MSc from Cairo University and PhD in Chemical Engineering from Czechoslovak Academy of Science. She has been working at the Chemical Engineering and Pilot Plant Dept. at National Research Centre, Egypt, since her graduation in 1967. She has been a Research Professor since 1987. Her main experience is in simulation and optimisation, membrane fabrication-separation technology, waste management and techno-economic studies in the field of chemical and allied industries. She is currently principal investigator of a national and an international FP7 ERANETMED project for the technological and engineering development of hollow fibres for desalination.

Abdelghani M.G. Abulnour received BSc from Cairo University and his MSc and PhD in Chemical Engineering from Alexandria University. He has been working at the Chemical Engineering and Pilot Plant Dept.at National Research Centre, Egypt, since his graduation in 1972. He has been a Research Professor since 1994. His main experience is in process engineering, membrane science fabrication-separation technology, desalination, waste management and techno-economic studies in the fields of chemical and allied industries. He is a consultant of several national organisations. He has participated in several international and national projects and has several publications and granted patents.

Heba A. Hani is Associate Professor in the Engineering Research Division at the National Research Centre, Egypt. She has received her BSc from chemical Engineering Department from Alexandria University with honours degree in 1999. She has a PhD degree in Chemical Engineering from Cairo University, 2010. Her PhD was on zeolites for heavy metals removal. She won Prize of Best PhD Thesis in 2011. She worked as a research assistant, assistant researcher, researcher and associate professor in the Chemical Engineering and Pilot Plant Department. Her research activities centre mostly in separation technologies and modelling and simulation in chemical engineering.

1 Introduction

Seawater desalination is an energy intensive process compared to conventional water purification technologies for fresh water supplies, requiring about 0.2 kWh/m^3 or less (CAPMAS, 2012). Reverse Osmosis (RO) desalination consumes about 3–5 kWh/m^3, which is comparative to the energy consumption of fresh water transported over large distances (Ahmed et al., 2013). Concerning thermal technologies, total equivalent electrical energy consumption has been estimated to be about (13.5–25.5), (6.5–11), and (7–12) kWh/m^3 for: Multistage Flash Distillation (MSF), Multiple Effect Distillation (MED) and Mechanical Vapour Compression (MVC), respectively (WRA, 2011).

According to International Atomic Energy Agency (IAEA) “SMRs” are reactors with electrical output less than 700 MWe (WNA, 2016; Rosner et al, 2011; Carelli et al., 2010). Comparing to large reactors (gigawatt reactors) SMR technology shows significant enhancements in the reactor design and safety environment. There are several proven designs currently available for commercial application; these include the Canadian “CANDU-6” and “EC6” , the three Indian “PHWR” (220, 540 and 700) that are pressure tube type “heavy water reactors”, the Russian “KLT-40S” (barge-mounted plant), and the Chinese “QP-300” and “CNP-600” that are “pressurised water reactors” (OKBM, 2009a). The “CANDU-6” and the “QP-300”, have already been applied in Europe and Asia (WNA, 2016; NEA, 2011).

Small reactor technology manifests a rapid development and commercialisation; these small reactors include but are not limited to: “CAREM (PWR, 25 MWe”) in Argentina, “NH-200 (PWR, 200 MWh)” in China, SMART (PWR, l00 MWe) in Korea, “KLT-40S (PWR, cogeneration, 40 MWe)” in Russia, “PHWR-200” (PHWR, 200 MWe) in India. Currently, the “plug and play” small reactors 5 to 10 MWe that belong to High Temperature Reactor (HTR) “graphite-moderated type” are under development. They are claimed to be much safer, and could run for 5–10 years before requiring refuelling or servicing (Rosner et al., 2011; Subki, 2011).

Table 1 shows a concise comparison between SMRs and large gigawatt reactors (ARIS, 2012; Ingersoll, 2011; Fath et al., 2005; BERR, 2008). By 2013 there were about 131 SMRs operating with total capacity around 59 GWe (ARIS, 2012; IAEA, 2006). SMRs offer numerous advantages including safety enhancement, design flexibility, relatively shorter construction time and cogeneration operation mode (desalinated water, process steam and energy carrier).

Table 1 Comparison between SMRs and large reactors (ARIS, 2012; Ingersoll, 2011; Fath et al., 2005; BERR, 2008)

Indicators	*SMRs*	*large reactors*
Capacity	Up to 700 MWe	> 1000 MWe
Safety	• Passive safety in the event of malfunction and enhanced resistance to seismic events. • Safety related pumps or sumps and emergency alternating-current (ac) power are not required.	• Active containment heat systems. • High and low -pressure injection system • Emergency sump and associated (NPSH)[a] are required.
Construction time	2–3 years	5–10 years
Flexibility	More flexible range of roles for nuclear energy including desalination, district heating and energy production.	Less flexible range of roles.
Design	Modular design provides economy of mass and series production, greater simplicity that offers variety of energy products, and fuel cycle options.	More complex.

Table 1 Comparison between SMRs and large reactors (ARIS, 2012; Ingersoll, 2011; Fath et al., 2005; BERR, 2008) (continued)

Indicators	*SMRs*	*large reactors*
Footprint	Could be used as land-based or barge-mounted plant. Small space example: Toshiba 22 × 16 × 11 m	Extra spaces for cooling system and multiple accessories units, example: Clinton, Illinois Reactor's cooling reservoir, covers over 5000 acres.
Connection to grid	Can be accommodated into small electricity grids; allowing an option of autonomous operation.	Relatively harder.
Capital cost	Represents about two thirds of nuclear energy costs while fuel and other operating expenses are about one third.	Represents about 73% of the total cost.
Overnight specific cost	Relatively higher cost per MWe of installed capacity.	Lower specific cost per MWe of installed capacity. This is due to saving and optimization of raw materials.
Financial risk	Lower financial risk, because of the option of incremental capacity to meet the incremental increase of demand.	Relatively higher financial risk that requires high investment.

Note: [a]Net Positive Suction Head

In view of the excessive demand for fresh water and the need to adopt large desalination plants (e.g., >100,000 m^3/d) and taking into consideration the massive energy requirements, SMRs present a reliable source for energy. The world-wide experience of SMRs-based desalination plants is presented in Table 2 (WNA, 2016; Rosner et al., 2011; BERR, 2008; IAEA, 2006; IAEA, 2010; IAEA, 2009; Kuptiz, 2000; IAEA, 2007; Thakur, 2007). Majority of world experience in small nuclear desalination is directed to "PWR" type (58%) followed by "HTGR" (17%) and others (25%) (Misra, 2011; Zhu et al., 2007).

Table 2 World experience of SMRs adopted in desalination (WNA, 2016; Rosner et al. 2011; BERR, 2008; IAEA, 2006; IAEA, 2010; IAEA, 2009; KAERI, 2009; Kuptiz, 2000; OKBM, 2009a; OKBM, 2009b; Thakur, 2007)

Reactor type	*Reactor design*	*Power MWe*	
BWR	VK-300	150	Russia
PWR	CAREM-25	27	Argentina[a]
PWR	SMART	100	South Korea
PWR	NP-300	100–300	France
PWR	ABV	8.5	Russia
PWR	KLT-40S	35	Russia

Table 2 World experience of SMRs adopted in desalination (WNA, 2016; Rosner et al. 2011; BERR, 2008; IAEA, 2006; IAEA, 2010; IAEA, 2009; Kuptiz, 2000; OKBM, 2009a; Thakur, 2007) (continued)

Reactor type	*Reactor design*	*Power MWe*	
HWR	PHWR-220 PHWR	220	India [b] Pakistan [c]
GCR	HTGR	15–40	South Africa, France, Netherlands [d]
HTGR	GT-MHR	600	Russia
HTGR	MHTGR	250	China
LMFR	LWR	250	Kazakhstan [e]

Note: [a]a: 12,000 m^3/d under design, b: 6300 m^3/d under commissioning, c: 4800 m^3/d under design, d: under consideration, e: 80,000 m^3/d in service till 1999

This paper addresses techno economic aspects of SMR nuclear powered large scale desalination plants. Cost model for prediction of cost indicators concerning (PWR) reactor type has been developed. Cost indicators of a proposed nuclear desalination have been assessed according to specific technical and financial merits.

2 Approach and methodology

The adopted methodology to come up with the performance and cost indicators of gearing SMRs to power large scale desalination units is as follows:

- Large scale Reverse Osmosis (RO) desalination plants have been assumed as a model for emerging new plants. The energy requirements have been estimated based on typical conservative measures following current practice in the region.
- Actual reported capital costs of independent SMRs up to gigawatt design concerning PWR design category have been compiled and analysed.
- A mathematical equation for unit capital cost estimate has been numerically derived and validated according to published cases.
- Further, mathematical models for specific operating and energy costs have been also formulated.
- SWRO technical parameters assumed include 42% recovery ratio, 69 bar operating pressure, unit capacity 150,000 m^3/d with feed water salinity 35,000 ppm.
- Two pre-treatment alternatives are considered for the desalination process comprising
  - "Conventional pre-treatment"
  - "MF-UF" pre-treatment
- Capital cost of the proposed SWRO unit using has been assessed and compared via "WT-CostII" simulator (Moch, 2008; Al Bazedi, 2012; Li et al., 2011).

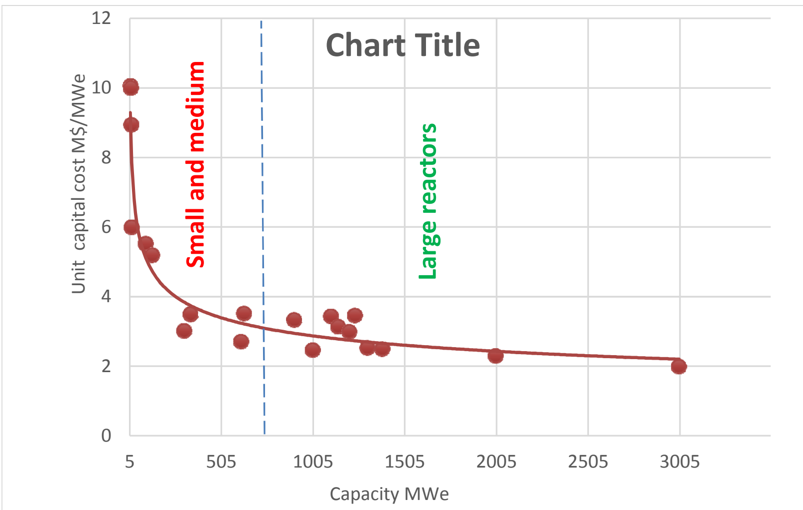
- The estimated capital costs have been implemented within Desalination Economic Evaluation Program "DEEP4" (IAEA, 2011) for simulation and cost assessment of nuclear desalination units.
- Three Pressurised Water Reactors "PWR" SMRs with different output capacities ranging from 300 to 1000 MWth, have been selected and compared to power the proposed SWRO according to overnight capital costs and safety criteria.
- Typical technical and financial indicators of the selected nuclear modules are fed as inputs to DEEP approach forming modified spread sheet of DEEP code.
- Further, cost indicators of the proposed nuclear desalinations have been evaluated and compared with traditional energy source. All cost indicators have been assessed and updated according to 2015 prices (ENR, 2016) using ENR cost index, based on 5% interest and discount rates.

3 Results and discussion

3.1 Financial considerations

Application of SMRs enables reduced operational risk and environmental advantage. However, there is a controversial issue regarding the financial indicators of SMRs versus gigawatt reactors. Investigation of the available updated financial data of nuclear reactors as depicted in Figure 1, it reveals somewhat cost benefits related to large (gigawatt) scale. A more refined data analysis using cost data of around (25) records of PWR category, based on electricity output, yields two zones of data for SMRs and large reactors.

Figure 1 Unit capital cost of PWR nuclear reactor



The following mathematical equation has been formulated and validated to be used for quick cost estimate for both ranges of PWR reactors (SMRs and large reactors). It should be emphasised for simplicity, the characteristics difference between reactors design has been neglected. Higher and lower cost indicator values in each range have been excluded.

$$\text{Unit capital cost} = 15.32 * \text{capacity}^{\wedge}{-0.242} \tag{1}$$

where:

Unit capital cost in: M$

Capacity in: MWe

The reliability of the developed cost equation can be perceived by investigating the data presented in Table 3, for actual and predicted cost data. However, a general trend could be extracted and rather crude financial indicators for SMRs and large reactors (gigawatt range) for PWR category are shown in Figures 2 and 3.

The advantages of using SMRs are better level of safety, construction time is reduced as their major components could be fabricated in a permanently located factory and then shipped to be assembled onsite, in addition to being simpler and with longer operation before refuelling (EPI and CAES, 2010).

Table 3 Deviation of predicted unit capital cost (Al Bazedi, 2014; IEA/NEA, 2010; IAEA, 2008)

Capacity MWe	*Actual unit [a] capital M$/MWe*	*Predicted unit capital M$/MWe*	*Squares of errors*	*Abs deviation %*
7.9	10.1	9.3	0.59	8
8.5	10.0	9.1	0.76	9
12	8.9	8.4	0.30	6
14	6.0	8.1	4.37	35
90	5.5	5.2	0.14	7
125	5.2	4.8	0.19	8
125	5.2	4.8	0.19	8
300	3.0	3.9	0.69	28
335	3.5	3.8	0.07	8
335	3.5	3.8	0.06	7
610	2.7	3.2	0.29	20
626	3.5	3.2	0.09	8
900	3.3	3.0	0.15	12
1000	2.5	2.9	0.17	17
1100	3.4	2.8	0.40	18
1139	3.1	2.8	0.12	11
1200	3.0	2.8	0.06	8

Table 3 Deviation of predicted unit capital cost (Al Bazedi, 2014; IEA/NEA, 2010; IAEA, 2008) (continued)

Capacity MWe	*Actual unit [a] capital M$/MWe*	*Predicted unit capital M$/MWe*	*Squares of errors*	*Abs deviation %*
1230	3.5	2.7	0.53	21
1300	2.5	2.7	0.03	7
1300	2.5	2.7	0.03	7
1380	2.5	2.7	0.03	7
2000	2.3	2.4	0.02	6
3000	2.0	2.2	0.05	11

Figure 2 Annual operating cost of SMRs-large reactors

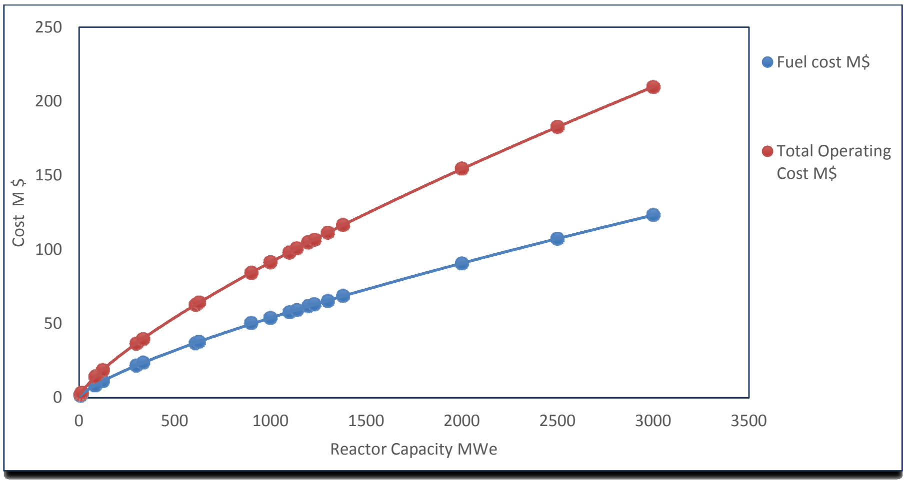
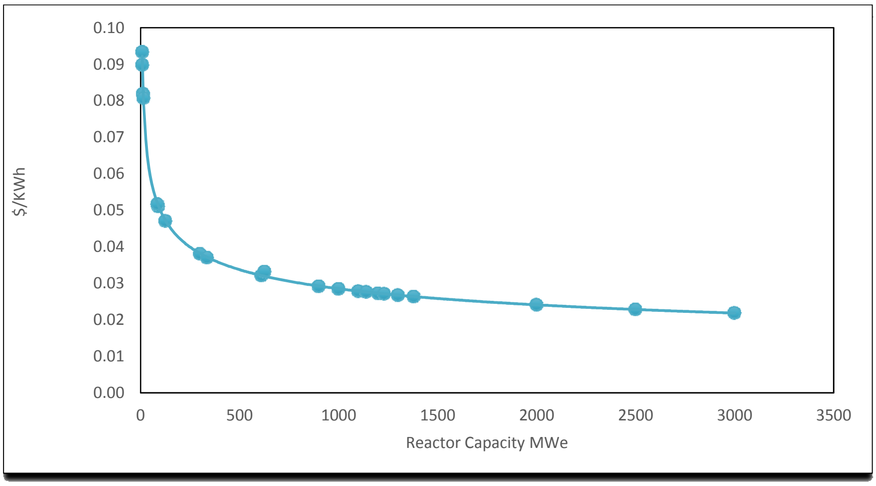


Figure 3 Energy cost of SMRs- SMRs-large reactors



Two different pre-treatment alternatives have been assessed.

- “MF/UF/RO”
- “Conventional pre-treatment/RO”

Capital cost for the same capacity SWRO plant using MF/UF and conventional pre-treatment have been estimated as 192 M$ and 168 M$, respectively while the average specific water costs are 0.61 $/m^3$ and 0.59 $/m^3$ and average specific power costs are 0.033 and 0.03 $/kWh according to 2015 price by simulating using “WT-CostII”.

Cost indicator matrix of coupling selected SMRs of specific energy outputs with desalination plant, capital and operating cost according to DEEP by implementing the water plant cost according to “WT-CostII”, as well as updated levelised reactor costs are depicted in Table 4. The nuclear system selected is nuclear reactor-steam cycle. As indicated in Table 4, water cost increases linearly with the power cost, the lowest water cost is $ 0.62/m^3$ in the case of using conventional pre-treatment with steam cycle-nuclear power plant with output electricity of 310 MWe respectively.

Table 4 Cost indicators of nuclear desalination-steam cycle system SWRO (conventional pre-treatment)

PWR Reactor with different power output	*Power output*		*Water and power cost*			
	Reference thermal output MW(th)	*Reference electricity output MW(e)*	*Unit capital cost M$*	*Total annual cost M$*	*Power $/kWh*	*Water $/m^3$*
I	1000	310	1176	55	0.046	0.62
II	400	125	812	22	0.063	0.664
III	300	90	622	49	0.064	0.667

By comparing the desalination (conventional pre-treatment) cost coupled with different power sources including nuclear power and gas and oil as power source, the following results have been obtained (Table 5). These results are in rather good agreement with those obtained by the National Nuclear Laboratory (NNL, 2014) for both the levelised capital cost and the unit power cost. The produced water cost using nuclear power is much lower than that produced using oil/gas as an alternative as it represents about 50% only. RO and combined RO/MED are of lower production cost than for MED water production cost. Cost indicators of different desalination systems powered by different energy alternatives shows that product water cost ranges between 0.62 $/m^3$ and 0.779 $/m^3$ when applying nuclear power as an energy source for RO, RO/MED, MED while when applying oil/gas as an energy source the product water cost ranges between 1.12 $/m^3$ and 1.89 $/m^3$.

Table 5 Cost indicators of different desalination systems powered by different energy alternative

		Power plant capacity	*Power plant cost*		*Water plant cost*		*Specific Cost*	
		Thermal/ electric MW	*Total capital cost M$*	*Annual operating cost M$*	*Total capital cost M$*	*Annual operating cost M$*	*Power $/kWh*	*Water $/m^3$*
	RO desalination unit							
I	Nuclear reactor	900/310	1176	55	168	30	0.046	0.62
	Gas/Oil		980	440	168	30	0.229	1.12
	Hybrid desalination unit "RO/ (MED)1:1"							
II	Nuclear reactor	900/310	1176	55	168	30	0.046	0.62
	Gas/Oil		980	440	162	55	0.229	1.47
	Thermal desalination unit MED							
II	Nuclear reactor	900/310	1088	49	167	22	0.046	0.779
	Gas/Oil		980	440	167	67	0.229	1.89

4 Conclusions

Nuclear energy systems in general and SMRs in particular provide competitive sustainable power demand for large scale desalination plants and the served communities. SMRs are particularly compatible with the emerging short-term needs of such desalination plants because of relatively short construction time, inherent safety features, and small footprint down to the scale of barge mounted units. Thorough investigation of application of SMRs as compared to gigawatt nuclear reactors realised the following conclusions.

Capital cost for two pre-treatment scenarios for SWRO plant using MF/UF and conventional pre-treatment have been estimated as 192 M$ and 168 M$, respectively with average specific water costs of 0.61 $\$/m^3$ and 0.59 $\$/m^3$ according to 2015 price by simulating using WT-CostII. Cost indicator matrix of coupling selected SMRs with specific energy outputs with desalination plant, capital and operating cost according to DEEP by implementing the water plant cost according to Wt-CostII, as well as updated levelised reactor costs shows that water cost increases linearly with the power cost. The lowest water cost is $\$ 0.62/m^3$ in the case of using conventional pre-treatment with steam cycle-nuclear power plant of output electricity 900 MWth and 310 MWe, respectively.

Cost indicator matrix of coupling selected SMRs of specific energy outputs with desalination plant, shows that the produced water cost using nuclear power is lower than that produced from using an oil/gas as an alternative, corresponding to almost half the cost. It has been concluded that RO and combined RO/MED desalination plants are of lower production cost than for MED water production cost. By comparing the desalination (conventional pre-treatment) cost coupled with different power sources including gas and oil, nuclear power, cost indicators show that product water cost ranges between 0.62 $\$/m^3$ and 0.779 $\$/m^3$ when applying nuclear power as an energy source for RO, RO/MED, MED while when applying oil/gas as an energy source the product water cost ranges between 1.12 $\$/m^3$ and 1.89 $\$/m^3$.

Acknowledgement

This work was financially supported by the Science and Technology Development Fund (STDF) of Egypt, under grant number STDF/1689. The authors would like to express their acknowledgement to the late Dr. Safaa Abd El Raouf Ahmed, who was the team leader of this project and had passed away before finalisation of this article.

References

Ahmed, S.A., Sorour, M.H., Abulnour, A.G., Talaat, H.A., El-Sayed, M.M.H. (2013) 'Comparative assessment of feasible options for delivery of potable water to remote coaster locations: North-west Egypt', *Journal of Desalination and Water Treatment*, Vol. 52, Nos. 7/9, pp.1350–1356.

Al Bazedi, G., Ettouney, R., Tewfik, S., Sorour, M. and El Refaie, M. (2012) 'Simulation and optimization of large scale desalination plants: a case study for South Mediterranean coast', *Journal of Indian Water Works Association.*

Al Bazedi, G.A., Ahmed, S.A., Hani, H.A., El-Sayed, M.M.H. and Abulnour, A.M.G. (2014) 'Small/medium nuclear reactors for potential desalination applications: Mini review', *Korean Journal of Chemical Engineering*, Vol. 31, No. 6, pp.924–929.

ARIS (2012*) Advanced Reactors Information System*, *Status of Small and Medium Sized Reactor Designs, A Supplement to the IAEA*, Available online at: http://aris.iaea.org

BERR (2008) *Department for Business Enterprise and Regulatory Reform, Consultation on the Strategic Siting Assessment Process and Siting*, Criteria for New Nuclear Power Stations in the UK, London.

CAES (2010) *The Energy Policy Institute (EPI) and Center of Advanced Energy Studies Economic and Employment Impacts of Small Modular Reactors Report*.

CAPMAS (2012) *Central Agency for Public Mobilization and Statistics*, Egypt.

Carelli, M.D., Garrone, P., Locatelli, G., Mancini, M., Mycoff, C., Trucco, P., Ricotti, M.E. (2010) 'Economic features of integral, modular, small-to-medium size reactors', *Progress in Nuclear Energy*, Vol. 52, pp.403–414.

ENR (2016) *CCI Cost Index*. Available online at: www. enrcci.com

Fath, H.E.S., El-Shall, F.M. and Seibert, U. and Vogt, G. (2005) 'A stand-alone complex for the production of water, food, electricity and salts for the sustainable development of small communities in remote areas', *Ninth International Water Technology Conference*, Sharm El-Sheikh, Egypt.

IAEA (2006) *Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refuelling Schemes*, IAEA-TECDOC-1485, Vienna, Austria.

IAEA (2007) *Status of Small Reactor Designs Without on-Site Refuelling*, IAEA-TECDOC-1536, Vienna, Austria.

IAEA (2008) *Energy, Electricity and Nuclear Power for the Period up to 2030*, Reference Data Series No. 1, Vienna, Austria.

IAEA (2009) *Annual Report*. Available online at: https://www.iaea.org/sites/default/files/publications/reports/2009/anrep2009_full.pdf

IAEA (2010) *International Status and Prospects of Nuclear Power*, 2010 edition.

IAEA (2011) *DEEP Desalination Economic Evaluation Program 2011*. Available online at: http://www.iaea.org/NuclearPower/Desalination/

IEA/NEA (2010) *Projected Costs of Generating Electricity,* 2010 edition, OECD Publications, Paris, France.

Ingersoll, D.T. (2011) 'An overview of the safety case for small modular reactors', *ASME Small Reactors Symposium*, Washington, DC, USA, doi: 10.1115/SMR2011-6586.

KAERI (2009) *Update on the SMART Design Description in IAEA-TECDOC-1485*, KAERI, Republic of Korea.

Kuptiz, J. (2000) 'Small and medium reactors: development status and application aspects', *Lectures Given at the Workshop on Nuclear Data and Nuclear Reactors: Physics, Design and Safety*, IAEA, Austria.

Li, N.N., Fane, A.G., Winston Ho, W.S. and Matsuura, T. (2011) *Advanced Membrane Technology and Applications*, Section 7.3, John Wiley & Sons.

Misra, B.M. (2011) 'Status and prospects of nuclear desalination', *International Desalination Association World Congress: SP05-041*, Austria.

Moch, I. Jr., Moch, I.A., Querns, W.R. and Darlene Steward, W.T. (2008) *Cost II Modeling the Capital and Operating Costs of Thermal Desalination Processes Utilizing a Recently Developed Computer Program that Evaluates Membrane Desalting, Electrodialysis, and Ion Exchange Plants*, Desalination and Water Purification Research and Development Program Report No. 130, USBR.

National Nuclear Laboratory (2014) *Small Modular Reactors-Feasibility Study*, Available online at: http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

NEA (2011) *Nuclear Energy Agency, Current Status, Technical, Feasibility and Economics of Small Nuclear Reactors*, Nuclear Developments.

OKBM (2009a) *Update on the ABV Design Descriptions in IAEA-TECDOC-1536*, OKBM Afrikantov, the Russian Federation.

OKBM (2009b) *Update on the KLT-40S Design Descriptions in IAEA-TECDOC-1391 and IAEA Nuclear Energy Series Report NP-T-2.2*, OKBM Afrikantov, the Russian Federation.

Rosner, R. et al. (2011) *Small Modular Reactors – Key to Future Nuclear Power Generation in the US Energy Policy Institute at Chicago*, Technical Paper, Revision 1, November, pp.1–73.

Subki, M.H. (2011) *Update on SMR Technology Status and IAEA Programme on Common Technology and Issues for SMRs*, INPRO Dialogue Forum on NE Innovations: CUC for SMR, 10–14 October.

Thakur, S. (2007) *Positive Experience with SMRs in India, Lessons Learned in Previous Two Decades and Future Plants*, NPCIL, India.

WNA (2016) *World Nuclear Association report, Small Nuclear Power Reactors*, Available online at: http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

WRA (2011) *Seawater Desalination Power Consumption*, White Paper.

Zhu, S., Tang, Y., Qi, W., Zhu, J. and Yu, S. (2007) 'Co-generation of electricity and desalted water by gas turbine MHTGR', *Transactions*, SmiRT 19, Toronto.

Notation

BWR	Boiling Water Reactor
DR	Discount Rate
FOAK	First Of A Kind
GT-MHR	Gas Turbine Modular Helium Reactor
GWe	Gigawatt electrical
HTGR	High Temperature Gas Reactor
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IR	Interest Rate
LFTR	Liquid Fluoride Thorium Reactor
LWR	Light Water Reactor
MED	Multiple Effect Distillation
MSF	Multistage Flash Distillation
MSR	Molten Salt Reactor
MVC	Mechanical Vapour Compression
MWe	Mega Watt electrical
MWh	Mega Watt thermal
NF	Nano Filtration
PBMR	Pebble Bed Modular Reactor
PWR	Pressurised Water Reactor
RO	Reverse Osmosis
RPV	Reactor Pressure Vessel
SMR	Small Medium/Modular Reactor
SWRO	Sea Water Reverse Osmosis
UF	Ultra-Filtration