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Nuclear desalination in Chile: a competitive solution

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ABSTRACT

Renewable energy sources are considered the main drive for developing at least 70% of the total energy in Chile by 2050. All major international greenhouse gases reduction agreements include growth of renewable energy sources and nuclear power as the only ways to significantly reduce emissions by the decade 2040–50. Chile's energy production matrix still relies heavily on fossil fuels, making very difficult to match the goal targeted by international agreements. For these reasons, the possibility of using nuclear power plants is considered. Small modular reactors (SMRs) in particular seems particularly suitable for a country like Chile for many reasons: SMRs are scalable and can provide energy in remote locations with no or limited grids (Atacama desert); SMRs can cope easily with future demands for expansion, thanks to their modularity; SMRs are cost effective and use all the latest developments in safety. This paper examines, using IAEA DEEP 5 economic software, the costs of nuclear desalinated water produced for the Chilean mining industry. Comparisons with respect to existing fossil fuels solutions show that the final cost is very competitive and allow for significant reduction of CO_2 emissions.

Keywords: Small modular reactors; Chile 2050 energy policy; Nuclear desalination; IAEA DEEP 5 software

1. Introduction

The last decade has seen an incredible development of small/medium modular reactors capable of electrical power between 300 and 700 MWe [1]. The International Atomic Energy Agency (IAEA) has been promoting small modular reactors (SMRs) development for their predicted capabilities of enhanced safety and ability to provide energy in remote locations, offering abundant power with virtually no greenhouse gases (GHG) [2]. The small footprint and the limited costs compared with large, full-scale reactors, make SMRs a very favorable option particularly suitable for regions suffering from desertification, in need of large quantities of reliable energy for desalination purposes and with limited electrical grid. The demands for clean, abundant power in a broader range of energy markets cannot be met without the use of nuclear power [2,3]. SMRs are factory built and will provide scalable power where needed. This flexible approach of deploying modular nuclear power allows communities to evaluate all the risks connected and provide the possibility of future expansions if necessary.

Many highly innovative designs have been proposed around the world with all major countries involved: USA, Russian Federation, China, Korea, India, South Africa and Argentina [4,5]. Even though each design is not identical to the other, few common characteristics can be identified. Advanced SMR designs include water-cooled reactors, high temperature gas reactors as well as liquid metals cooled reactors. All SMRs proposed adopt modularization with systems and components that are shop-fabricated similarly to typical industrial plant, then shipped and assembled onsite. Using

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this approach, production costs are substantially reduced and modern quality control processes are used providing high reliability and much greater simplicity [6]. Modern SMR designs use a different approach from large reactors with respect to safety: all systems are passively controlled in case of accident and reach higher levels of safety than ever in the past.

Chile has not excluded in the 2050 energy policy the possibility to use in the future nuclear power as part of the mix of energy sources used to grow the country's economy [7]. Chile is a country poor of primary resources [8]. It depends heavily on foreign imports to satisfy the internal energy demands and it has seen a recent economic boom, which has no rivals in South America: its GDP per capita is among the highest in 2017 [9]. As the country continues to develop economically, energy demand in Chile is expected to grow from about 65 TWh in 2012 to 100 TWh by 2020 [10]. Installed capacity has grown consistently as well as projects under construction. In 2017, 46 plants were under construction for a total over 2,400 MW [11] with significant increases in hydropower and solar plants. Chile has come a long way in the last 25 years to accommodate increasing power demands from both population and industry: recently it has started a process to diversify its energy matrix trying to rely less on polluting coal power plants. Natural gas and solar power have been augmented significantly and hydropower installed capacity is still far from accomplishing the available estimated potential [12]. However, recent trends in the management of the energy policy have increased controversy and public contestation, in some cases bringing to full halt some very important projects [13]. Many barriers including economical, technical and regulatory [14] hinder massive deployment of solar systems and limit market penetration.

Between 1990 and 2013, Chile's total emissions increased by 113.4%, from 51.5 $MtCO_2e$ to 109.9 $MtCO_2e$ [15] and for fuel combustion only from 29.43 $MtCO_2$ to 82.02 $MtCO_2$ [16]: this is an increment of 272%. The main green house gas emitted by Chile was CO_2 (78.4%), followed by CH_4 (10.7%), N_2O (10.0%), and fluorinated gases (0.9%). In general, increased GHG emissions are mainly due to increase in energy consumption in the country, including the consumption of coal and natural gas for electricity generation and consumption of liquid fuels, mostly diesel and gasoline, for road transportation. Electricity and heat production are the leading sources of GHG emissions: in late 2016, 29% of electrical energy production was produced by hydropower plants, while 43% of electricity generation was still produced by coal and natural gas plants. Solar and biomass contribute for only 6% of the total. Coal will still continue to play a role in Chile's energy future for many years to come; coal will have over a 45% share in electricity generation in 2030. Under business as usual (BAU) conditions [17], Chile would fail to reach its commitment of greenhouse gas reduction by 2020 [18], becoming the largest polluter per capita of South America and being already above world average for producing energy from fossil fuels. Coal and natural gas provide both technical and economic stability to the Chilean energy matrix, contributing, though, largely to gas emissions without being compensated adequately by the current effort to promote both CRE (Conventional Renewable Energies) and NCRE (Non-conventional Renewable Energies) [19].

The Chilean mining industry is aging requiring more and more energy [20], while solar desalination systems offer clean water typically at much higher costs and lower productivity than those provided by conventional fossil fuels plants [21]. Then, a deeper reflection must be done for ensuring both long-term sustainable policies and energy security [22,23]. Since de-carbonization efforts so far seem insufficient to reach a substantial GHG emission reduction [24], the nuclear energy option must be reconsidered taking into account the events that shaped recently in Chile policy-making in this area: the 2010 earthquake and 2011 Fukushima Daiichi nuclear accident in Japan [25,26]. Chile could benefit largely from nuclear power advancements (SMRs) using a mature technology able to drastically reduce emissions so changing significantly the present and future dependence from fossil fuels [27].

The purpose of this paper is to provide elements for discussing whether or not nuclear power should be considered in Chile at the light of these considerations and the need to provide clean, stable energy in areas such as the Atacama desert where most of the mining industry is present. Analyzing the specific case of the Escondida mine in the Antofagasta region, economic indications on how SMRs could help, are provided comparing existing fossil fuels solutions.

2. Nuclear SMRs in Chile: desalinated seawater for the mining industry

Given the history of nuclear energy development in Chile [28] and the well-known possible extreme natural events that can affect the country anytime, it is suggested at this stage, the implementation and approval of SMRs in high development state and that rely heavily on the industrial experience matured in decades of free-accident nuclear industry around the world. For this reasons, only water-cooled reactors are considered. Some of these reactors are in advanced state of certification (NuScale in USA), some are fully certified (such as the Korean SMART) or in construction (such as the Argentinian CAREM). These reactors could be fully adopted in Chile to help reducing drastically the GHG emissions, providing electrical power to the grid and help the mining industry to acquire desalinated water useful for their operations. Nuclear desalination in fact seems particularly suitable and attractive for a country like Chile where most of the needs are located in remote areas [29]. Nuclear power can provide safe, reliable and clean power both for electrical and thermal applications. Desalination costs are in fact variable depending on the process used and might change with time. The flexibility of SMRs with enhanced safety features is ideal for providing both forms of energy (thermal and electrical) in a flexible manner. Removing the salt and impurities present in ocean seawaters is a very energy intensive process, typically requiring significant amounts of thermal energy, electricity or both depending on the technique used to process the water. Even with current improvements [30], the typical cost for desalination plants sets at almost 50% the cost of energy to be provided over the total cost even using the most cost-effective technique (reverse osmosis or RO [31]). Traditionally, fossil fuels have provided the energy needed to run desalination plants, but this needs to change if there is any hope to respect GHG emissions limitations internationally agreed. As renewable energy-based desalination can reduce this dependence, its overall impact and its extent are still being debated [32–35], so that the nuclear option remains wide open [36–38].

Given the adverse geographical conditions of the most important mines in Chile (more than 150 km from the coast and with difference in altitude up to 3,000 m with respect to the sea level), a dedicated power source to produce desalinated water seems unavoidable: this is potentially a big issue because the construction of a new mine is short compared with the time typically dedicated to the construction of a desalination plant and pipeline [39]. Besides, most of the mining industrial activities in Chile are in remote locations across deserted areas (Antofagasta region), which are characterized by very low humidity and lack of fresh waters. Most of these activities are not just water intensive, but also energy intensive. BHP Billiton and Rio Tinto have built a 220,000 m^3/d RO seawater desalination plant connected with an internal reservoir at 3,200 m above sea level, which absorbs 1,000 MWe from the grid only for desalination. Many projects are under way and it is estimated that by 2026 seawater consumption in the northern Chile will more than quadruple from today's volume to 924 Ml/d, while freshwater consumption will fall to 933 Ml/d by the same time. Providing large water quantities from seawater to the local mining industry needs to be matched by a safe, reliable and flexible source of power. SMRs can provide both thermal and electrical power according to the demand and possess the flexibility for future expected expansions [5,38] thanks to their modularity. Taking into consideration for example NuScale SMR design, several desalination technologies can be taken into consideration and coupled with this reactor [37,38].

Multi-effect distillation (MED) and multi-stage flash (MSF) require typically a heat source such as hot steam taken from the secondary side of the nuclear plant. RO instead requires only electricity to run the high-pressure pumps and ancillary equipment. Pre-water treatment might be needed, but the calculated electrical consumption is assumed to be around 4.0 kWh/m^3 for RO vs. a 3.0 kWh/m^3 required for MSF and 1.0 kWh/m^3 (Table 1) required for MED, respectively [38].

The combined plant proposed is then constituted by a small NuScale modular reactor coupled with an advanced desalination plant. This plant would be very flexible due to its power scalability: more nuclear cores can be added with the final power ranging from 50 MWe (1 core) up to 600 MWe (12 cores). The plant would be able to produce alternatively only fresh desalinated water, only electricity to be sold to the grid or both with a pretty good tuning based on the market/industry request. Depending on the type of desalination plant coupled with the NuScale reactor, a different number of cores might be required. Taking into consideration as reference case the Escondida mine located approximately at 3,050 m of altitude and the approximate distance to the Pacific Ocean of 170 km for a water flow of roughly 216,000 m^3/d, it is easy to calculate the needed pumping power and desalination power using the following equations suggested in [40]:

$$P_{\text{hydraulic}} = \frac{Q\rho g h}{\eta_{\text{mechanical}}\eta_{\text{electric}}3.6\times 10^6}[\text{kW}] \tag{1}$$

$$P_{\text{hydraulic horizontal losses}} = 0.03\ [\text{kWh}]/\left(\text{m}^3/\text{km}\right) \tag{2}$$

$$P_{\text{altitude hydraulic losses}} = 0.003\ [\text{kWh}]/\left(\text{m}^3/\text{m}_{\text{altitude}}\right) \tag{3}$$

Pumping power is calculated at 96.185 MWe assuming mechanical and electrical efficiency of 0.85 and 0.97, respectively, while horizontal pumping losses due to the length of the pipe are evaluated at 45.9 MWe. Vertical losses, due to difference in altitude, are calculated at 82.35 MWe for a total power requested for transportation and pumping of 224.4 MWe.

The economic aspects of the different plant configurations (NuScale nuclear reactor coupled with RO, MSF or MED desalination technologies as well as other carbon-based solutions) are studied using the IAEA DEEP 5.1 (Desalination Economic Evaluation Program) software [41,42]. This software has been used worldwide to evaluate in detail the economics of different desalination technologies and combinations of energy plants [43]. DEEP 5.1 calculates desalination electrical power needed for RO at 30.2 MWe, while it is evaluated at 18.0 MWe for MED (gained output ratio [GOR] is 14 for 17 stages with a flow of steam at 184 kg/s at 78°C) and at 29.5 MWe for MSF (GOR is calculated at 10 with 33 stages with a flow of steam at 252 kg/s at 117.5°C) as shown, respectively, in Figs. 1–3.

In all three cases, studied the annual average temperature and salinity of the Pacific Ocean corresponding to Antofagasta region in Chile have been used: respectively, 17.3°C and 35,000 ppm as provided by Davila and Vlades [44]. Both levelized energy costs (LEC) and levelized water costs (LWC) are calculated in DEEP using a two-step process

Table 1
Key parameters for desalination plant options/full-scale plant, eight cores

Desalination technology	Reverse osmosis (RO)	Multi-effect distillation (MED)	Multi-stage flash (MSF)
Electrical consumption (kWh/m^3)	4.0	1.0	3.0
Unit steam consumed (kg/s)	N/A	184 at 78°C	252 at 117.5°C
GOR (kg water/kg steam)	N/A	14	10
Number of units/stages required	N/A	17	33
Water production (per core in m^3)	27,000	27,000	27,000
Net electrical output (per core in MWe)	45.37	42.1	33.8

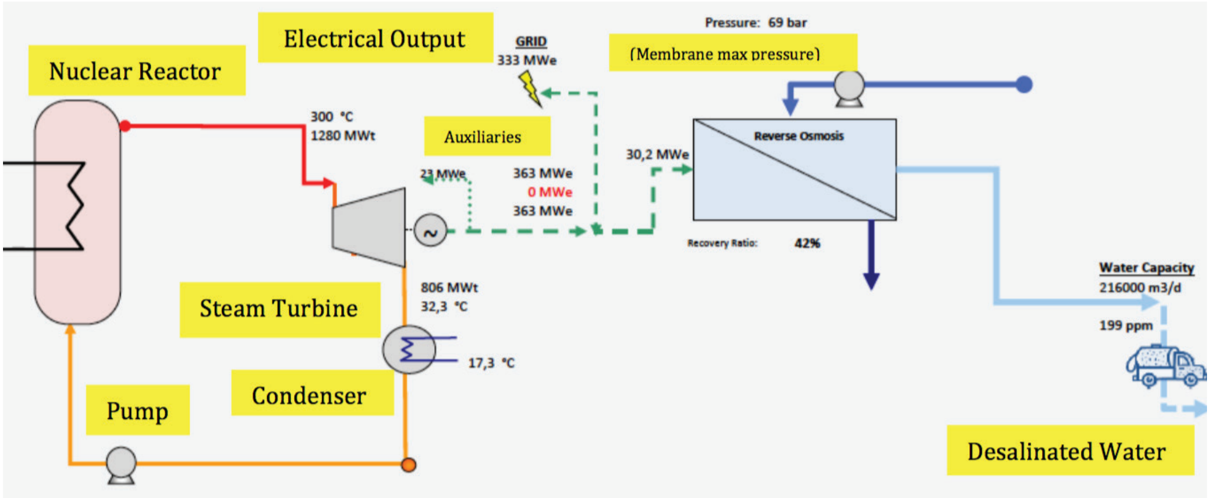

Fig. 1. Schematics of NuScale plant coupled with RO desalination system based on DEEP 5.1 [41].

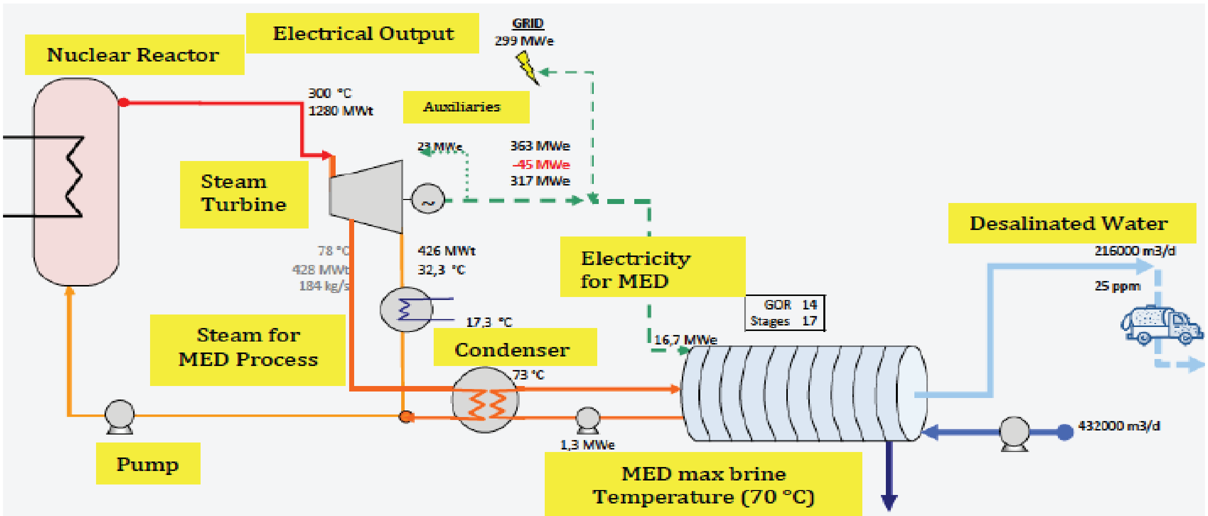

Fig. 2. Schematics of NuScale plant coupled with MED desalination system based on DEEP 5.1 [41].

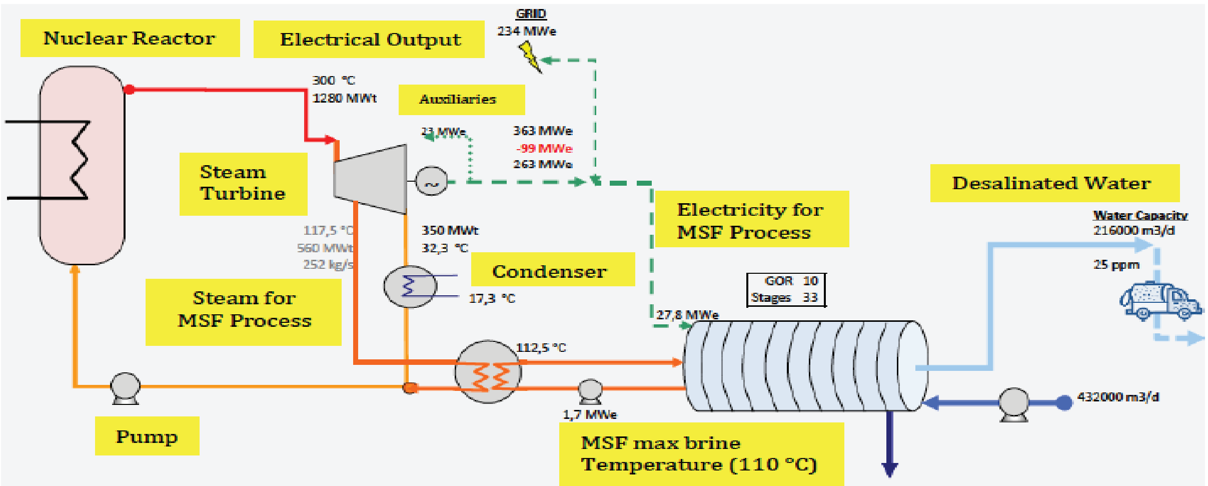

Fig. 3. Schematics of NuScale plant coupled with MSF desalination system based on DEEP 5.1 [41].

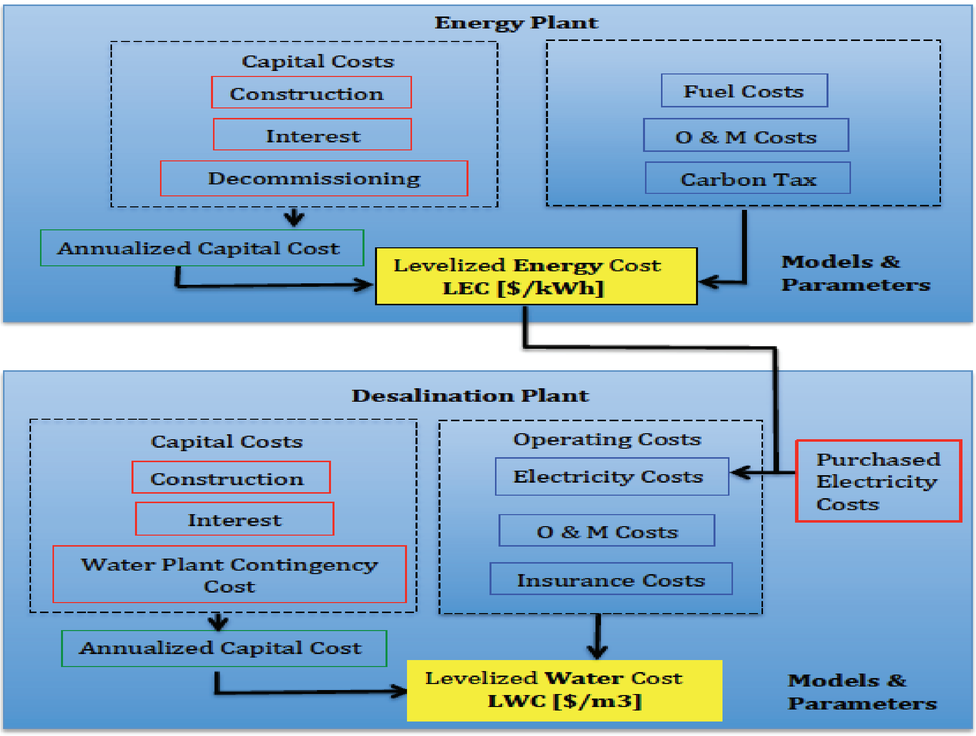

Fig. 4. Schematics (own elaboration) of water cost estimation process in DEEP 5.1 [41].

as schematically summarized in Fig. 4. DEEP evaluates LEC in $/kWh using parameters and models to describe the steam cycle, gas cycle or combined cycle.

Four major parts compose LEC costs in DEEP: capital cost, O&M, fuel cost for the energy plant and added cost (if any) for carbon tax. Similarly LWC is also composed by capital, O&M and energy costs components pertinent to the desalination plant.

Several types of desalination technologies are included: RO, MED and MSF are the cases used in this study. It is also possible to consider a hybrid desalination plant encompassing both RO and distillation processes. DEEP considers also missing revenues from lost electricity generation when heat is produced by an electricity generation plant. DEEP has a wide database of used standard data in the field for both LWC and LEC. The user, at any time, can modify default values used for the calculation to satisfy specific conditions. All data used for simulating the use of a SMR coupled with different desalination plants are summarized in Table 2 and have been used to satisfy both the conditions of NuScale SMR plant and actual costs in 2017. In particular five scenarios are taken into consideration: (1) nuclear power (SMR) coupled with reverse osmosis desalination plant (Nu-RO, NuScale with eight cores); (2) nuclear power coupled with MSF desalination plant (Nu-MSF, NuScale with eight cores); (3) nuclear power coupled with MED desalination plant (Nu-MED, NuScale with eight cores); (4) cogenerative power plant coupled with RO desalination (GAS-RO) and (5) coal power plant coupled with RO desalination. For these last two options, only reverse osmosis is considered because it allows larger production of desalinated water at lower quality and lower cost, but still sufficient for the mining industry in Chile. These calculations performed with DEEP 5 show that in order to accomplish the minimum goal set for desalinated water and full power production for all pumping and transportation needs for the Escondida mine case, eight cores minimum are needed for MSF, seven cores minimum for MED and only six cores for RO. As already predicted by Ingersoll et al. [37,38], RO allows more flexibility between water and electricity produced and sufficient water quality for mining processes. Using eight cores per each desalination system, almost no residual electrical power would be available for the grid using MSF (Fig. 3), while for MED (Fig. 2) or RO (Fig. 1) there would be, respectively, a residual electrical capacity of 75.6 or 109.6 MWe available to the grid and with large margins of flexible operations for reduced water loads. Three more considerations are needed. First of all, it has been proven that the economy of scale improves final price for desalinated water [45]. Second, based on calculation with parameters in the IAEA DEEP 5 models, an increase in the desalination plant capacity tend to reduce water prices, regardless of the power source used (oil, gas, coal and nuclear energy), but become almost constant for a capacity range between 50,000–150,000 m^3/d using nuclear coupled with RO [46].

This makes the nuclear solution particularly interesting for mixed types of production considering both water and electricity. Third, as expected, increased levels of salinity have a direct impact on the amount of energy used and final cost of the water unit. In time, when the request of water will decrease due to reduced mining activities, the same infrastructure created in the northern Chile would still be able to produce only some desalinated water in addition to electricity available for the grid. So using RO, only six NuScale core units would be needed to satisfy 36,000 m^3/d per core

Table 2
Main parameters of DEEP 5 to analyze the economics of combined power plant coupled with RO vs. coal with RO with respect to NuScale nuclear option with RO, MED, MSF technology

General case-specific parameters					Values
Annual average seawater temperature Tsw					17.3°C
Total dissolved solids (TDS)					35,000 ppm
Interest rate ir					5.0%
Discount rate *i*					5.0%
Annual fuel real escalation rate eff					3.0%
Energy plant parameters	Values for				
	SMR with RO	SMR with MED	SMR with MSF	COAL with RO	GT/cogenerative with RO
Total thermal power Qtp	1,280 MW(th)	1,280 MW(th)	1,280 MW(th)	1,280 MW(th)	1,280 MW(th)
Reference efficiency Eb	28.0%	28.0%	28.0%	39.0%	53.25%
Main steam temperature Tms	300.0°C	300.0°C	300.0°C	300.0°C	130.0°C (in S. Turbine)
Operating availability App	95.0%	95.0%	95.0%	85.0%	85.0%
Plant lifetime Lep	60 years	60 years	60 years	35 years	25 years
Construction lead time Le	51 months	51 months	51 months	48 months	24 months
Specific construction cost (EPC) Ce[a]	5,078 $/kW(e)	5,078 $/kW(e)	5,078 $/kW(e)	2,400 $/kW(e)	850 $/kW(e)
Specific O&M cost Ceom	9.0 $/MW(e)*h	9.0 $/MW(e)*h	9.0 $/MW(e)*h	3.5 $/MW(e)*h	5.5 $/MW(e)*h
Specific fuel cost Csf[b]	3.9 $/MW*h	3.9 $/MW(e)*h	3.9 $/MW(e)*h	8 $/MW*h	10.24 $/MW*h
Additional site-related costs factor Dcr	10.0%	10.0%	10.0%	10.0%	10.0%
Contingency factor kec	5.0%	5.0%	5.0%	0.0%	0.0%
Decommissioning cost factor kdcopp	10.0%	10.0%	10.0%	0.0%	0.0%
Desalination plant parameters	Values for				
	RO pressure membrane 69 bar	Max brine temperature 70°C	Max brine temperature 110°C	RO pressure membrane 69 bar	RO pressure membrane 69 bar
Total desalination plant capacity Wdc	216,000 m^3/d	216,000 m^3/d	216,000 m^3/d	216,000 m^3/d	216,000 m^3/d
RO recovery ratio	42%	14 (17 stages)	10 (33 stages)	42%	42%
Specific power use Qsdp	3.355 kW(e)*h/m^3	7.00 kW(e)*h/m^3	14.33 kW(e)*h/m^3	3.355 kW(e)*h/m^3	3.355 kW(e)*h/m^3
Operating availability Amp	90.0%	90.0%	90.0%	90.0%	90.0%
Plant lifetime Lwp	20 years	20 years	20 years	20 years	20 years
Construction lead time Lm	12 months	12 months	12 months	12 months	12 months
Base unit cost Cdu	1,100 $/($m^3$/d)	1,100 $/($m^3$/d)	1,100 $/($m^3$/d)	1,100 $/($m^3$/d)	1,100 $/($m^3$/d)
Management salary sdm	60,000 $/year	66,000 $/year	66,000 $/year	60,000 $/year	66,000 $/year
Labor salary sdl	29,700 $/year	29,700 $/year	29,700 $/year	29,700 $/year	29,700 $/year

(*continued*)

Table 2 (*continued*)

Desalination plant parameters	Values for				
	RO pressure membrane 69 bar	Max brine temperature 70°C	Max brine temperature 110°C	RO pressure membrane 69 bar	RO pressure membrane 69 bar
Specific O&M material cost[c]	0.19 $/m^3$	0.07 $/m^3$	0.07 $/m^3$	0.19 $/m^3$	0.19 $/m^3$
In/outfall specific cost factor Csdo	7.0%	7.0%	7.0%	7.0%	7.0%
Water owners cost factor kdo	5.0%	5.0%	5.0%	5.0%	5.0%
Contingency factor kdc	10.0%	10.0%	10.0%	10.0%	10.0%
O&M insurance cost kdi	0.5%	0.5%	0.5%	0.5%	0.5%
IL specific cost Cinl	N/A	92/84 $/(m^3/d)$	92/84 $/(m^3/d)$	N/A	N/A
IL temperature difference DTmcr	30°C	30°C	30°C	10°C	10°C
IL pressure drop DPip	2 bar	3 bar	3 bar	1 bar	1 bar
Purchased electricity cost Cpe	0.02 $/m^3$	0.02 $/m^3$	0.02 $/m^3$	0.02 $/m^3$	0.02 $/m^3$
Other DATA and water transportation					
Carbon TAX ct[d]	N/A	N/A	N/A	5 $/ton	5 $/ton
Specific CO_2 emissions	0.029 kg/kWh	0.029 kg/kWh	0.029 kg/kWh	1,1 kg/kWh	0.4 kg/kWh
Auxiliary loads (% of total produced)	6%	6%	6%	6%	6%
Length of the pipe	170 km	170 km	170 km	170 km	170 km
Pipe life-time	25 years	25 years	25 years	25 years	25 years
Construction time	60 months	60 months	60 months	60 months	60 months
System pumping requirements	224.4 MWe	224.4 MWe	224.4 MWe	224.4 MWe	224.4 MWe
Cost of pipe	0.7 M$/km	0.7 M$/km	0.7 M$/km	0.7 M$/km	0.7 M$/km
System O&M cost (% of the capital)	7%	7%	7%	7%	7%

[a]Data provided by NuScale Power as in [47].
[b]Based on average cost data of fuels in Chile in 2017 (coal at 60 $/t and natural gas at 3.0 $/MMBTU).
[c]Specific O&M material cost was defined for convenience as the total sum of the four corresponding costs provided in DEEP 5.1 including the RO membrane replacement cost, specific O&M parts cost, tubing replacement cost for MED and MSF, chemical cost for pre- and post-treatment.
[d]Starting 2018, Chile is applying a carbon tax for power plant equal or larger than 50 MW.

and a production of 44.5 MWe per core of electricity, with a net total of 42.6 MWe (=44.5 × 6 – 224.4 MWe) to be sold to the grid [37]. The electricity produced would satisfy entirely the request for pumping power (224.4 MWe) with a thermal efficiency of the nuclear plant at 28%.

Table 2 shows a summary of the principal data used to run DEEP simulations. The economic analysis using the DEEP software allows comparing different possible solutions for the Chilean mining desalination problem. Fig. 5 describes the relationship between electric and water output from a single NuScale SMR module as provided by Ingersoll et al. [37,38] and used into DEEP software.

The LWC and LEC are compared with each other and key parameters were identified. DEEP allows also evaluating costs for transportation, which in the simulation for the Chile mining industry represents a high portion of the total costs. Nuclear/steam cycle model has been used to represent NuScale SMR. Selected values were specified to reflect the NuScale plant, while most of the others were kept at default value provided by the software. DEEP modules for cogeneration and coal power plants have been used to run a comparative study with the nuclear solution: main data used into DEEP for these cases are also summarized in Table 2.

Fig. 6 shows schematics of the combined power plant coupled with RO, while the coal power plant coupled with RO desalination technology would have an identical configuration to Fig. 1 with the nuclear reactor substituted by a coal furnace. The cogenerative power plant has a final electrical capacity of 583 MWe from the turbogas and 189 MWe from the heat recovery steam generator (HRSG). RO process

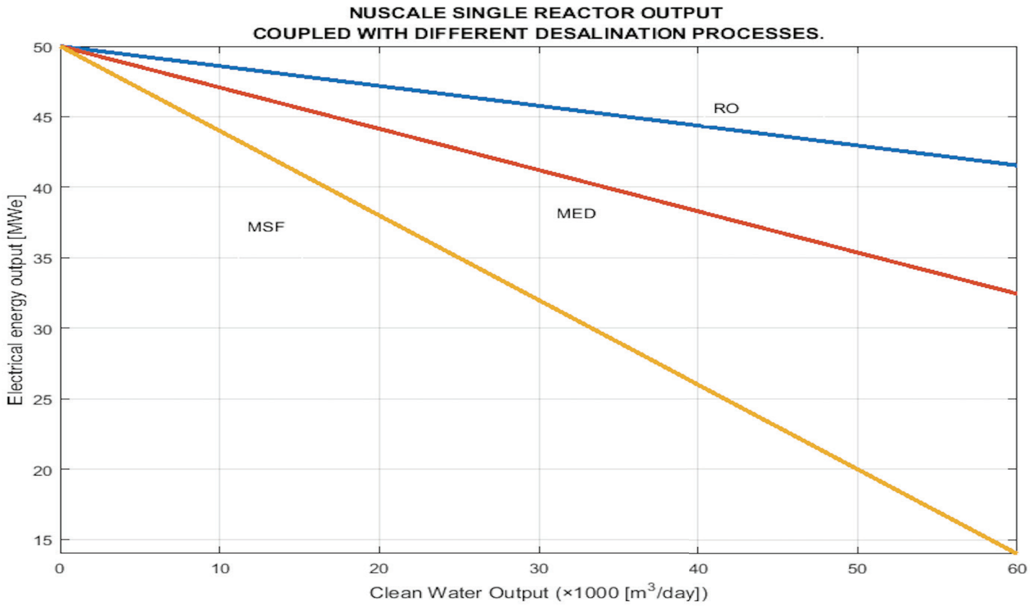

Fig. 5. NuScale single reactor output coupled with different thermal and membrane distillation desalination processes.

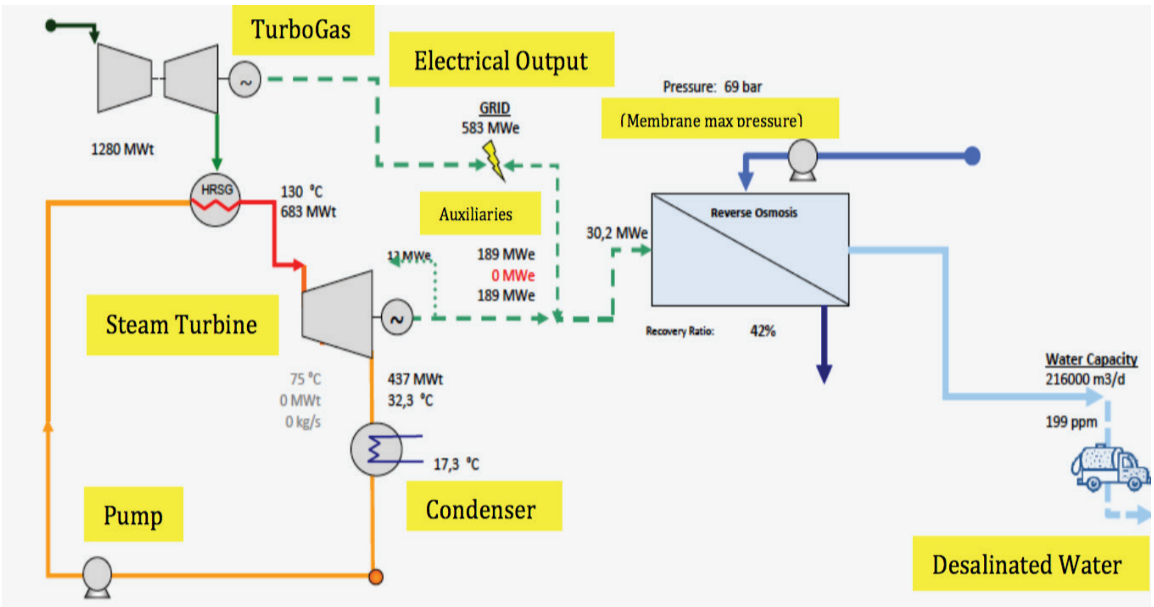

Fig. 6. Schematics of cogenerative plant coupled with RO desalination system based on DEEP 5.1 [41].

absorbs 30.2 MWe while water transport needs 224.4 MWe setting the net electricity production at 517.4 MWe. Coal power plant coupled with RO desalination technology produced instead 323 MWe of which 224.4 MWe are to be used for water transportation.

3. Results and discussion

The total costs for producing desalinated water, LEC and LWC breakdowns of the NuScale coupled with three different desalination systems are evaluated using DEEP software and presented in Figs. 7, 8(a) and (b). As expected RO is the most competitive in terms of cost and the most flexible needing only electricity for producing desalinated water.

The resulting total water cost including the costs for water transportation was evaluated at 2.995 $/m^3 for NuScale SMR coupled with RO, of 3.326 $/m^3 for NuScale coupled with MED and of 3.739 $/m^3 for MSF. The most convenient of the five scenarios under investigations is the cogenerative power plant whose final cost is evaluated at 2.715 $/m^3 while for coal power plant it was calculated at 2.798 $/m^3 as shown in Fig. 7. Main results from DEEP simulations are summarized in Table 3.

In a similar way, if water transportation costs are excluded, NuScale with RO is more competitive than coal

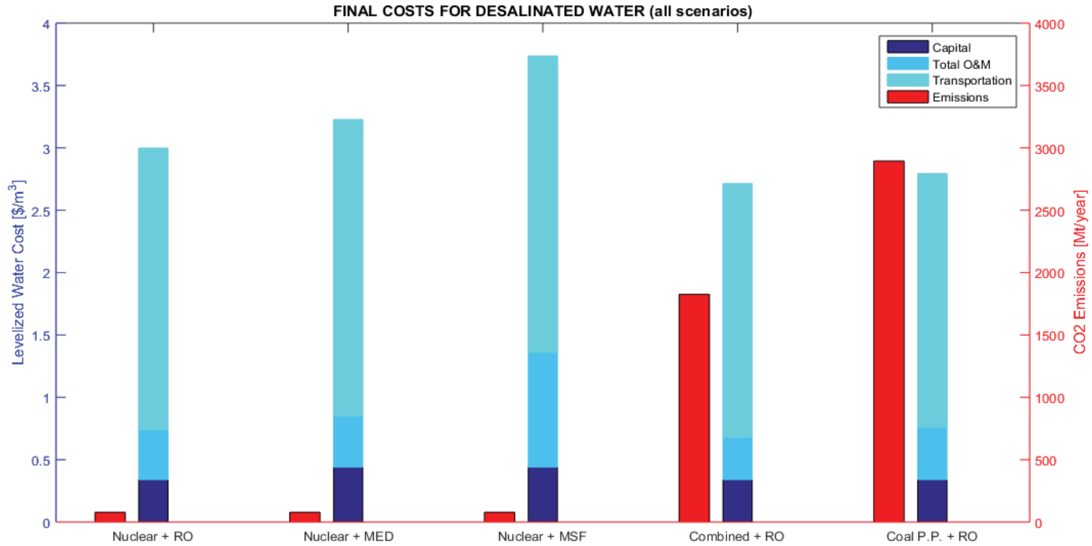

Fig. 7. Levelized total cost desalinated water breakdowns using DEEP 5 simulations (all scenarios).

Table 3
Costs for desalination plant and power plant summary

Outputs summary (all scenarios)	NuScale with RO	NuScale with MED	NuScale with MSF	Combined with RO	Coal with RO
Levelized capital costs/desalination plant ($/m^3)	0.34	0.44	0.44	0.34	0.34
Total energy cost ($/m^3)	0.20	0.40	0.81	0.14	0.22
Levelized operating costs/desalination plant ($/m^3)	0.20	0.11	0.11	0.20	0.20
Heat cost per unit ($/m^3)	0.0	0.29	0.63	0.0	0.0
Electricity ($/m^3) (produced + purchased)	0.18+0.02	0.11+0.0	0.19+0.0	0.09+0.05	0.18+0.04
Total O&M ($/m^3) (energy + O&M)	0.40	0.51	0.92	0.34	0.42
Transport ($/m^3)	**2.257**	**2.376**	**2.376**	**2.033**	**2.033**
Lifecycle emissions (Mt/year)	**79**	**79**	**79**	**1,826**	**2,895**
Power lost (MWe)	0	45.4	99.5	0	0
Power used for desalination (MWe)	30.2	16.7	27.8	30.2	30.2
Total water production cost ($/m^3)	**0.738**	**0.951**	**1.363**	**0.681**	**0.764**
Levelized capital costs/power plant ($/kWh)	0.044	0.044	0.044	0.010	0.035
O&M ($/kWh)	0.009	0.009	0.009	0.006	0.004
Fuel costs ($/kWh)	0.004	0.004	0.004	0.015	0.018
Carbon tax ($/kWh)	0.0	0.0	0.0	0.002	0.006
Reference thermal efficiency (%)	28%	28%	28%	53.25%	39%
Total power cost ($/kWh)	**0.057**	**0.057**	**0.057**	**0.033**	**0.063**
Total water production + transport ($/m^3)	**2.995**	**3.326**	**3.739**	**2.715**	**2.798**

Values in bold are plotted in Fig. 7 (Levelized total costs and emissions) and Figs. 8(a) and (b) (Levelized energy and water costs).

with an LWC of 0.738 $/m^3 vs. 0.764 $/m^3. Among all examined cases, the cogenerative cost is evaluated at 0.681 $/m^3 as shown in Fig. 7 and it is still the cheapest solution. Fig. 8(a) shows levelized energy and water costs breakdowns for the five scenarios. Analyzing the three nuclear cases, it is evident that capital costs + decommissioning are the biggest part being 77% of the total energy cost.

With the implementation of SMR in full scale, these costs will become even smaller. Fig. 8(b) shows that MSF and MED are less competitive needing electricity and heat for achieving the desalination flow and quality requested. Among the reverse osmosis solutions, differences in costs between nuclear and other fossil fuels are very small with differences below 10%. It is also evident from the results that the nuclear option is absolutely competitive with both the combined/cogenerative power plant and the coal power plant. Large differences of CO_2 emissions exist and are, as expected, much larger in the coal plant. According to DEEP calculations, emissions of CO_2 for the nuclear modular reactor coupled with RO would be, respectively, 23 times and 36 times less with respect to combined power plant and coal power plant as shown in Fig. 7. It would also

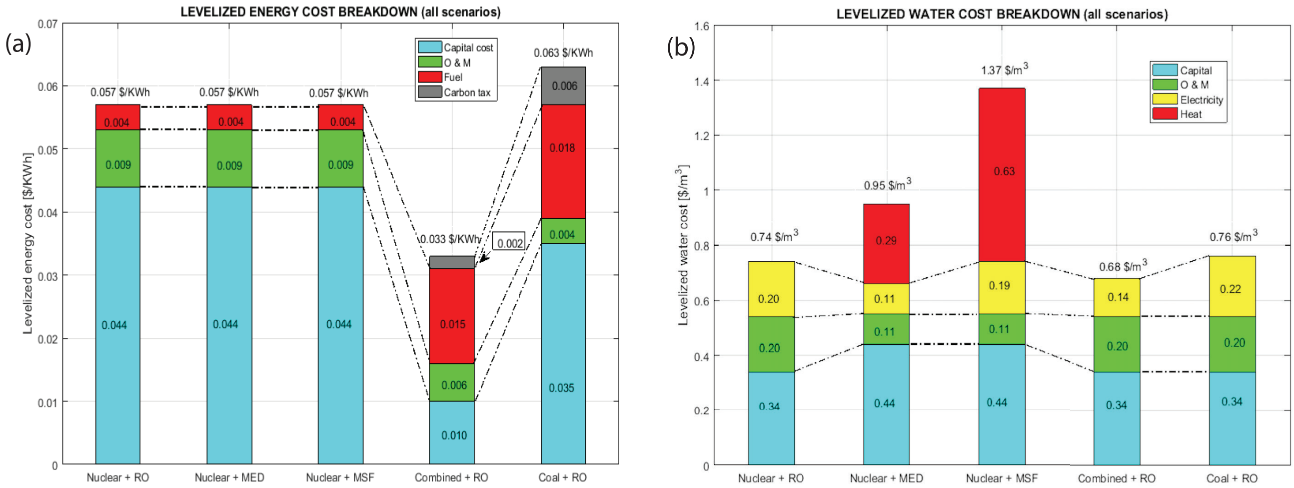

Fig. 8. Levelized energy costs (a) and water costs (b) breakdown of nuclear SMR with desalination plants (all scenarios).

appear that the carbon tax operative from early 2018 and introduced by the Chilean Government (5 $/ton for power production over 50 MW), does not really affect much both fossil fuels options: differences over the final price of energy to be produced for desalinated water range from 0.2/kWh cents to 0.6 cents/kWh for combined and coal power plant, respectively.

DEEP calculations confirm what found in the research by Benavente [48], and Mardones and Flores [49] setting the possible value to produce any visible effect for the carbon tax at a much higher level (i.e., higher than 20–25 $/ton of produced emissions). Water transportation costs to the mining area of northern Chile represent the biggest cost for the desalinated water with very limited differences among the scenarios studied: for the cogenerative power plant (cheapest solution) the cost is almost 75% of the total. The results are in line with those provided by Zhou and Tol [50] and suggest an increased energy cost for both the mining industry and Chile as a whole country. While some neighboring country such as Brazil have already recognized and embraced fully a change in energy policy, integrating nuclear power in the Chilean energy matrix still appear uncertain [51].

4. Conclusions

In this study, the use of a small nuclear reactor is proposed and compared with available options for desalination and energy production applied to a specific mine in the northern part of Chile. SMR provide unprecedented level of safety, affordability and flexibility thanks to the new designs and modularity. The American NuScale in particular is considered thanks to its advanced licensing state and innovative design in both passive safety and earthquake resistance. This study provides economic insights for policy makers with the aim of reducing CO_2 emissions in the near term future while still providing desalinated water in the most remote and desertic areas of Chile. The most effective design is reverse osmosis with NuScale SMR Design. Comparisons with available cogenerative and coal technologies have been performed using the IAEA DEEP software showing that the nuclear option is very competitive from a cost point of view.

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