Proceedings of the ASME 2014 Small Modular Reactors Symposium
SMR2014
April 15-17, 2014, Washington, D.C., USA

SMR2014-3392

INTEGRATION OF NUSCALE SMR WITH DESALINATION TECHNOLOGIES

D. T. Ingersoll
NuScale Power, LLC
Corvallis, OR, USA

Z. J. Houghton
NuScale Power, LLC
Corvallis, OR, USA

R. Bromm
Fluor Corporation
Greenville, SC, USA

C. Desportes
Aquatech International
Canonsburg, PA, USA

ABSTRACT

Nuclear energy plants are attractive energy source for large scale water desalination since the thermal energy produced in a nuclear reactor can provide both electricity and steam to desalt water without the production of greenhouse gases. A particularly attractive option is to couple a desalination plant with the new generation of nuclear plant designs: small modular reactors (SMR). This allows regions with smaller electrical grids and limited infrastructure to add new electrical and water capacity in more appropriate increments and allows countries to consider siting plants at a broader range of distributed locations. The NuScale SMR plant design is especially well suited for the co-generation of electricity and desalted water. The enhanced safety, improved affordability, and deployment flexibilities of the NuScale design provide a cost-effective approach to expanding global desalination capacity. Parametric studies have been performed to evaluate technical options for coupling a NuScale plant to a variety of different desalination technologies. An economic comparison of these options was performed for each of the different desalination technologies coupled to an appropriately sized NuScale plant capable of providing sufficient carbon-free electricity and clean water to support a city of 300,000 people.

1. INTRODUCTION

As the access to clean ground water and surface water sources dwindle, more regions are turning to water desalination as a means to meet clean water demands. Although purification of seawater is the most common use of large-scale desalination technology, accounting for approximately 60% of the global desalination capacity, desalination of brackish ground water and surface water now accounts for nearly 35% of the desalination market. According to the Global Water Intelligence data base, approximately 16,000 desalination plants exist world-wide producing roughly 75 million cubic meters per day.[1] Over 700 new plants were added in 2010-2011, which collectively increased the global capacity by 5.2 million cubic meters per day. This growth is expected to continue and is being driven by continued population growth, rapid industrialization in developing countries, urbanization and dwindling fresh water sources.

Removing the salt and impurities in seawater is energy intensive and requires either significant amounts of electricity or thermal energy, or both depending on the desalination technology. At current U.S. water use rates, 2 kWh of energy per person per day would be required to meet water needs with desalted water. The choice of desalination technology determines the balance of energy form required: primarily electrical energy for membrane-based systems and predominately thermal energy for distillation systems. Some hybrid plants combine both membrane and distillation processes in order to achieve the desired water quality.

Fossil energy sources have been the dominant source of electrical and thermal energy for desalination plants; however, there is an increasing concern regarding the environmental impact of burning fossil fuels because of the resulting emission of “greenhouse gases.” Renewable energy sources such as wind and solar are expanding in many regions; however, their variability and uncertainty of output creates reliability challenges for industrial processes such as desalination. These environmental and reliability concerns, coupled with concerns over energy supply security and an anticipated growth in energy demand, are driving a growing interest in the development and expansion of nuclear energy options for this application. To date, however, less than 15 of the 16,000 desalination plants world-wide use heat or electricity provided directly from commercial nuclear power plants, which represents less than 0.1% of the global desalination capacity.[2] In contrast to this limited amount of commercial nuclear desalination, all nuclear-powered naval vessels routinely use nuclear energy to desalinate seawater.

Despite the slow adoption of nuclear power for desalination applications, there is renewed attention to this opportunity as several reactor vendors have begun to develop new, smaller sized commercial power plants. Referred to as small modular reactors (SMR), these new designs have reactor units with power output less than 300 MWe, are substantially manufactured in a factory, and are easily transported to a site and installed with other units into a multi-unit plant.[3] Although motivated by goals of increased safety and affordability, most SMRs have additional features that lend well to their use for desalination applications.[4] These benefits include: scalability to better match the energy demands of non-electrical energy applications, expandability to allow for future growth of demand, and reduced risk to facilitate co-location with the energy consumer.

Several SMR designs are being developed world-wide, including in the U.S. One design, which is being developed by NuScale Power, LLC with the financial backing of Fluor Corporation, is the most modular of the U.S. designs with the smallest power unit size and the largest number of reactor modules in a single plant (up to 12 modules). The flexibilities afforded by the high level of modularization of the NuScale plant, coupled with a significantly enhanced level of plant safety and robustness, makes it uniquely suitable for desalination applications in a wide variety of locations and coupling with multiple desalination technologies. A description of the NuScale plant design is given in the following section, followed by a technical evaluation of options for coupling a NuScale plant to a range of different desalination technologies. The final section presents a preliminary economic comparison of the various plant coupling options.

2. NUSCALE DESIGN OVERVIEW

The fundamental building block of the NuScale plant is the NuScale power module. The power module consists of a small 160 MWt reactor core housed with other primary system components in an integral reactor pressure vessel and surrounded by a steel containment vessel, which is immersed in a large pool of water. Several power modules—as many as 12 modules—are co-located in the same pool. Models of a single power module and a multi-module plant are shown in Fig. 1. The reactor vessel is approximately 20.0 m (65 ft) tall and 2.7 m (9 ft) in diameter. The integral vessel contains the nuclear core consisting of 37 fuel assemblies and 16 control rod clusters. The fuel assemblies are shorter than traditional pressurized water reactor (PWR) fuel assemblies but use the same 17 by 17 pin array geometry, same materials, and same fuel type. Above the core is a central hot riser tube, a helical coil steam generator surrounding the hot riser tube, and a pressurizer. The helical coil steam generator consists of two independent sets of tube bundles with separate feedwater inlet and steam outlet lines. A set of pressurizer heaters and sprays is located in the upper head of the vessel to provide pressure control.

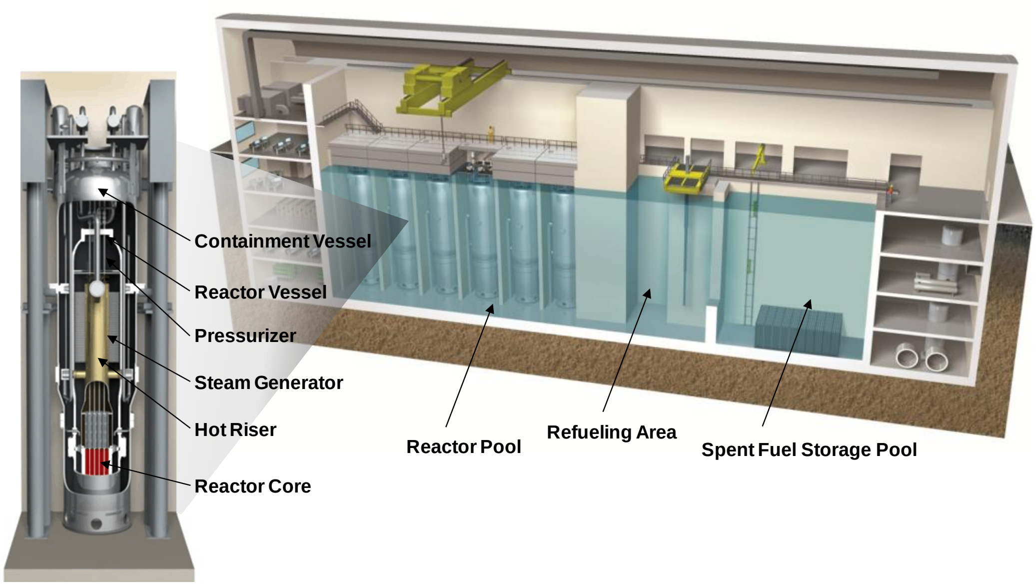

Fig. 1 Model of NuScale power module (left) and cutaway of 12-module plant (right).

Primary reactor coolant is circulated upward through the reactor core and the heated water is transported upward through the hot riser tube. The coolant flow is turned downward at the pressurizer plate and flows over the shell side of the steam generator, where it is cooled by conduction of heat to the secondary coolant and continues to flow downward until its direction is again reversed at the lower reactor vessel head and turned upward back into the core. The coolant circulation is maintained entirely by natural buoyancy forces of the lower density heated water exiting the reactor core and the higher density cooled water exiting the steam generator. On the secondary side, feedwater is pumped into the tubes where it boils to generate superheated steam, which is circulated to a dedicated turbine-generator system. Low pressure steam exiting the turbine is condensed and recirculated to the feedwater system. The entire nuclear steam supply system is enclosed in a steel containment that is 24.6 m (80 ft) tall and 4.6 m (15 ft) in diameter. The small volume, high design pressure containment vessel is a unique feature of the NuScale design and contributes significantly to the large safety margins and overall resilience of the plant design.

There are several key features of the NuScale plant that collectively distinguish it from the many other SMRs being developed today and make it especially well-suited for application to water desalination.

- *Output reliability.* Using a small integral design for each reactor module enables significant simplification of the entire power train, thus eliminating many potential failure modes and reducing plant maintenance issues. For example, natural circulation of the primary coolant eliminates several pumps, pipes, and valves. Additionally, other modules continue to produce power while one module is undergoing refueling or maintenance, which provides a high plant capacity factor. This ensures that power is always available to support the coupled desalination plant.
- *Light water reactor technology.* The NuScale plant can be licensed within the existing LWR regulatory framework, thus drawing on a vast body of operational data, proven codes and methods, and existing regulatory standards. This will facilitate expeditious licensing of the plant for near-term deployment to support the rapidly growing desalination market.
- *Nuclear modularity.* While most new nuclear builds utilize modular construction practices, the NuScale design extends this approach to the nuclear steam supply system. Each power module is contained within a compact, factory-manufactured containment vessel and provides output steam to a dedicated and independent power conversion system. Also, the scalability of the plant from 1 to 12 modules further enhances plant economics and deployment flexibility for coupling to desalination plants of varying sizes.
- *Dedicated power trains.* Because each power module, including the power conversion system, is independent of other modules, it is possible to operate the plant in such a manner that some modules produce only electricity while other modules produce only steam for thermal heat applications. This allows the plant to co-generate at the plant level without the additional complexities of steam extraction from one or more turbine stages in order to support multiple desalination technologies.

The synergy created by these unique features of output reliability, reliance on existing light water technology, and the plant-level flexibilities afforded by the multi-module configuration, all combine to position the NuScale plant for early and successful application to water desalination. Of additional importance is the high level of plant resilience afforded by the small unit size, which improves the system response to upset conditions. As stated earlier, the majority of existing desalination plants use seawater as the water source, hence they are located on coastlines and can be subjected to a tsunami. The terrible earthquake-induced tsunami that struck Japan in March 2011 destroyed four of the six nuclear reactors that comprised the Fukushima Dai-ichi nuclear power station on Japan's eastern coast. As a result of this accident, a higher level of scrutiny on new nuclear plants located on coastlines can be expected, along with a higher standard for plant resilience to such extreme events. Although not discussed in detail here, the NuScale design offers an unparalleled level of plant resilience to the type of events that happened in Japan.[5] Table 1 provides a summary of key design features and their corresponding contributions to plant safety and resilience.

Table 1 Key NuScale plant features for enhanced safety and resilience to extreme events

Reactor Building	• Deeply embedded below grade • Seismically qualified • Resistant to external impact
Emergency Core Cooling System	• No AC or DC power needed for actuation • No operator action required • No external source of water required • Unlimited cool-down capability
Containment	• Immersed in reactor pool to provide assured removal of decay heat • Vacuum precludes combustible mixture of hydrogen and oxygen
Spent Fuel Pool	• Housed in underground structure • Four times more cooling water per fuel assembly than conventional plant

3. INTEGRATION WITH DESALINATION TECHNOLOGIES

There are a number of processes that have been demonstrated for producing clean water from seawater; however, global experience is dominated by three primary processes: two distillation-based technologies [multi-effect distillation (MED) and multi-stage flash (MSF)] and one membrane-based technology [reverse osmosis (RO)].[6] A key distinction in the three methods is the way that they couple with a power source. The RO plant has the most straightforward coupling since it can operate using only electricity, which is needed to run the high-pressure pumps. Therefore, it is not essential to co-locate the desalination plant with the power plant so long as a grid connection is available. However, there may be an advantage for co-location of the power and RO desalination plant in terms of shared infrastructure and protection against grid disruption. Also, low grade steam or warm waste water from the power plant can be used to preheat the saline feedwater of the RO plant to improve its clean water production efficiency, although the quality of the distillate may be adversely impacted.

Both the MED and MSF plants require a thermal heat source such as a steam line from the secondary side of the nuclear plant. This steam is typically extracted from a low-pressure turbine stage, which results in a commensurate decrease in the electrical output of the power plant and may have implications on the reliability and flexibility of operations for both the power plant and the desalination plant. Also, the use of a tertiary heat transport loop is typically required to ensure that no radionuclides such as tritium are carried over from the reactor's secondary loop to the distillation plant.

The choice of desalination method(s) is determined primarily by the characteristics of the source water and the water quality required by the end user. For example, RO technology typically has a lower capital cost but is less effective with feedwater that contains high level of organic materials that can foul the membranes or that have high salinity levels and can only produce potable water without further treatment. The two thermal distillation processes are much more tolerant of "dirty" or "salty" feedwater and produce high purity water. Therefore, all three technologies were considered for this study. The unique energy input requirements of each desalination technology were considered, as well as the operational requirements of the NuScale power plant. The GateCycle energy system modeling software[7] developed by General Electric was used to determine heat and mass balances for all of the coupling options studied. For the thermal desalination options, consideration was given to coupling the NuScale plant via three distinct mechanisms: high pressure (HP) steam taken before admission into the turbine, medium pressure (MP) steam taken from a controlled extraction of the turbine, and low pressure (LP) steam taken from the exhaust end of the turbine.

3.1 Utilization of Main (HP) Steam for Thermal Desalination

The first integration option considered was the coupling of a NuScale module to an MED distillation cycle equipped with a thermo-compressor (TC). Main steam taken from the exit of the steam generator is split and provided both to a turbine-generator system and also to a reboiler. Clean steam from the reboiler is used to drive the MED-TC cycle, as shown in Fig. 2. The TC utilizes high pressure steam to power a steam-jet air ejector, which increases the overall efficiency of the MED process. A measure of this efficiency is the "gain to output ratio (GOR)," which is the ratio of fresh water produced to process steam used. For the case studied, use of the TC increases the GOR of the MED plant from 12 to 17. The number of MED units coupled to the NuScale secondary steam cycle can be scaled based on water output requirements, with one NuScale module capable of yielding enough steam to produce up to 88,000 m^3/d of water. The turbine-generator equipment can then be sized to accept the remaining steam flow for generating electricity.

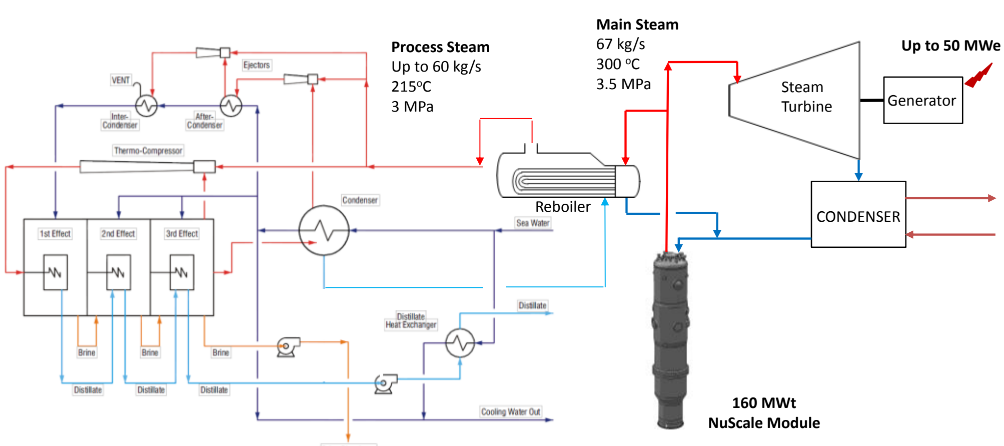

Fig. 2 Process diagram for a NuScale module coupled to an MED-TC distillation cycle.

exhaust steam is sent to the reboiler, thus maximizing the amount of steam supplied for desalination while also producing electricity. Only the MED cycle is considered here due to the low temperature and pressure of the available steam. A GOR of 12 was assumed. The power output of the steam turbine is largely dependent on the design of the exhaust section and the exhaust pressure. Therefore, the electrical and water outputs of the exhaust steam design are largely fixed at full operating power, whereas the previous cases are capable of adjusting the balance between power and water output without changing reactor power.

3.2 Utilization of Extraction (MP) or Exhaust (LP) Steam for Thermal Desalination

While the above design utilizes main steam from the NuScale power module, an alternative option is to utilize extraction steam from the steam turbine. Figure 3 shows the conceptual coupling of a NuScale module using controlled extraction to an MSF distillation plant. In this configuration extraction steam is extracted from the turbine to supply heat to a reboiler. Clean steam from the reboiler is supplied to an MSF or MED cycle at 200 kPa (30 psia). This pressure was chosen to provide a reasonable efficiency for both the MSF and MED cycles; however, the extraction steam could be supplied at virtually any pressure desired, depending on the specific application.

The use of a controlled extraction turbine introduces limitations to the amount of steam that can be supplied to the distillation process. This is due to design requirements of the steam turbine, such as minimum and maximum allowable exhaust flows. Therefore, the quantity of steam available for desalination is less than in the previous case utilizing main steam. Additionally the GOR for each design will be reduced from that used in the high pressure case. This analysis assumed a GOR of 14 for the MED cycle and 8 for the MSF cycle.

The final thermal desalination coupling option studied used a low backpressure type turbine operating with an exhaust pressure around 40 kPa (6 psia). In this variation, 100% of the exhaust steam is sent to the reboiler, thus maximizing the amount of steam supplied for desalination while also producing electricity. Only the MED cycle is considered here due to the low temperature and pressure of the available steam. A GOR of 12 was assumed.

3.3 Integration with RO Desalination Technology

The last option studied was to couple the NuScale plant to an RO desalination process, as depicted in Fig. 4. In this design, the normal power conversion systems of the NuScale plant are left virtually unaltered. Electricity output from the standard turbine-generator system is supplied to the RO plant to run the necessary high-pressure pumps and ancillary equipment. In order to increase the efficiency of the RO process, the feedwater stream to the RO units can be preheated by the hot water returning from the condenser. This design has the most flexibility in balancing electrical and water output but requires a relatively clean feedwater stream or significant amounts of water pretreatment. The calculated water output in this study is based on an electricity consumption of 4.0 kWh/m^3 for the RO plant.

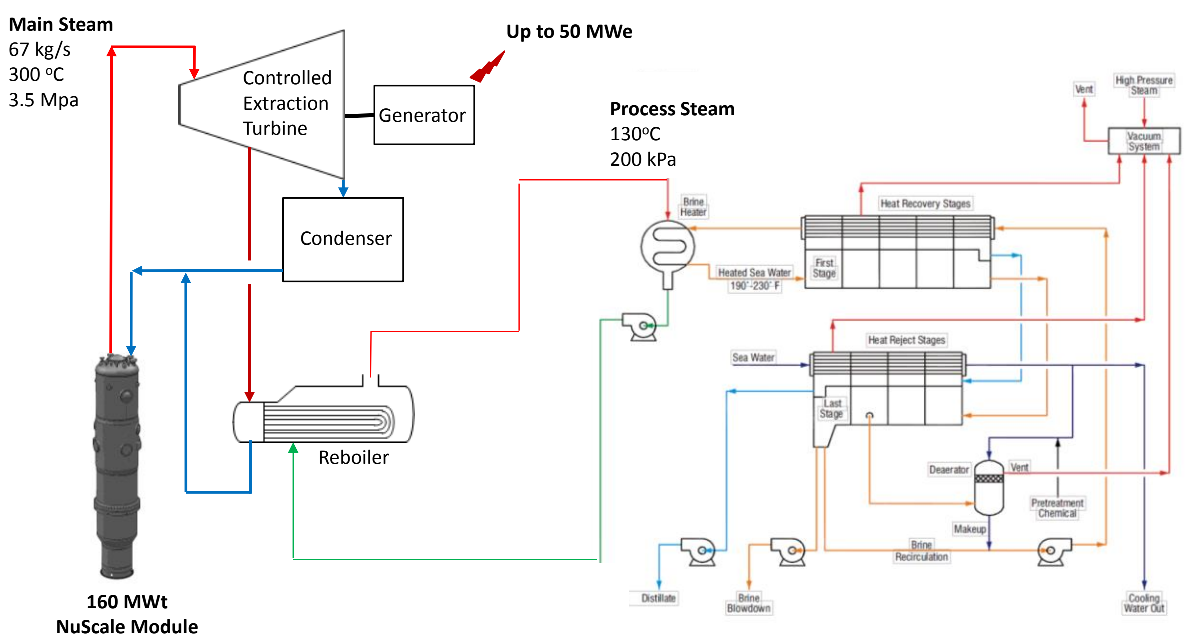

Fig. 3 Process diagram for a NuScale module coupled to an MSF cycle through a controlled extraction type turbine.

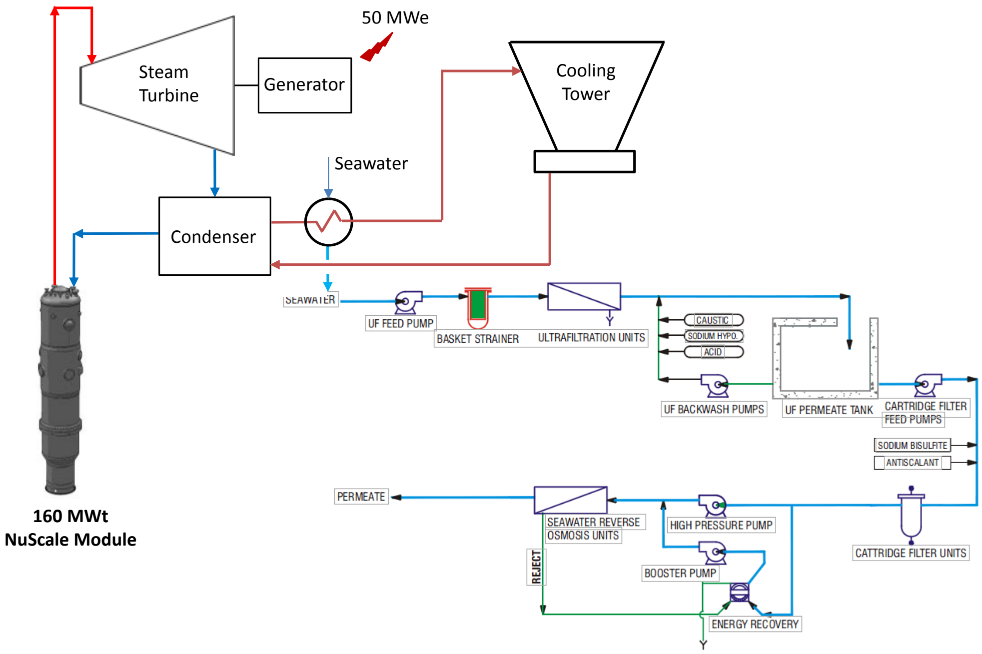

Fig. 4 NuScale plant coupled to an RO desalination cycle.

3.3 Comparison of Plant Integration Options

Figure 5 shows the relationship between electrical and water output for a NuScale module coupled to each desalination option previously discussed. The figure shows the clear advantage of the RO process in terms of water produced due to its high conversion efficiency. This comes at the expense of water quality since the RO process is typically capable of producing potable-quality water while the thermal distillation processes typically produce high purity water. Thus, installations with very low-quality feed stock or where large quantities of high purity water are required may be better suited to a thermal distillation process. For the thermal desalination processes, it is shown here that plant electrical output is higher when lower pressure steam is used. The trade-off is a successive reduction in operational flexibility as the motive source is changed from main (HP) to extraction (MP) to exhaust (LP) steam.

4. ECONOMIC COMPARISONS

The preceding results were all based on coupling a single NuScale power module to each of the desalination technologies. In order to do an economic comparison of the various options, it was useful to select specific NuScale and desalination plant sizes that are representative of an existing plant. It was decided to size the desalination plant to have a production capacity of 190,000 m^3/d (50 million gallons per day) of potable water, similar to the Carlsbad Desalination Plant,[8] which represents a large municipal desalination plant application. The Carlsbad project, which began construction in 2013, is located just north of San Diego, California. With a typical domestic water consumption rate of 0.55-0.65 m^3/d (150-170 gal/d) per person in that area, the Carlsbad Desalination Plant is estimated to support a population of 300,000.

Table 2 lists the key plant parameters for four different desalination options—each sized to produce 190,000 m^3/d of potable water. Unit consumption rates for the thermal desalination processes are based on an extraction steam driven desalination skid. For both MP-MED and MP-MSF, seven desalination units coupled to seven separate controlled extractions type steam turbines are assumed in order to achieve the target output and were based on standard available unit sizes. The LP-MED cycle uses significantly more steam flow at a lower pressure and temperature and only requires coupling to four nuclear modules to achieve the target water production rate.

Table 2 Key parameters for desalination plant options

Desalination Technology	MP-MSF	MP-MED	LP-MED	RO
Electrical consumed (kWh/m^3)	3	1	1	4
Unit steam consumed (kg/s)	39.3	22.4	45.8	N/A
GOR (kg water/kg steam)	8	14	12	N/A
Number of units required	7	7	4	N/A

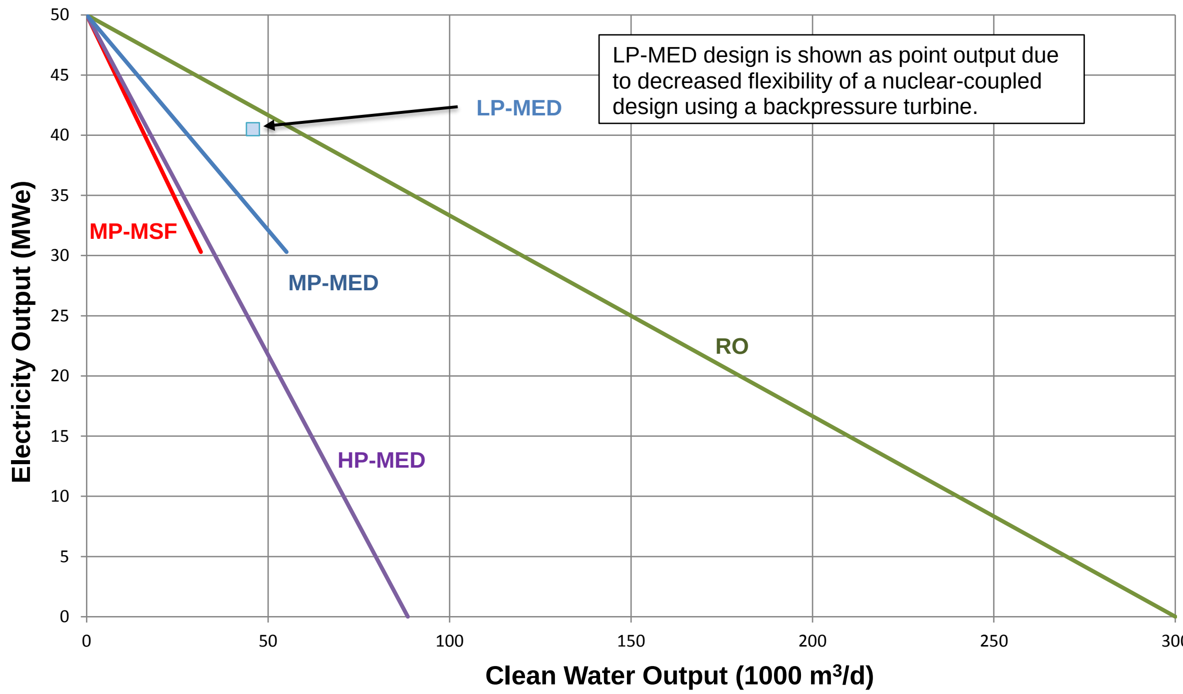

Fig. 5 Relationship between electricity and water output from a single NuScale module coupled to a variety of membrane and thermal distillation desalination processes.

Regarding the sizing of the NuScale plant, it was decided to choose a plant size that could provide: (1) sufficient energy to operate a 190,000 m^3/d desalination plant, and (2) additionally supply the electricity needs of the same 300,000 population—a population comparable to the U.S. coastal cities of Corpus Christi, Tampa or St. Petersburg. The resulting NuScale plant contained eight modules with a total thermal capacity of 1280 MWt and varying net electrical outputs depending on the desalination process used.

Table 3 summarizes the economic analysis for an 8-module NuScale plant coupled to the four most promising desalination options. In addition to the RO case, the medium pressure (or extraction steam) design cases were initially selected for the thermal desalination technologies. The low pressure (or exhaust steam) MED case was included as well to highlight the potential reduction in energy costs for this configuration.

Since the NuScale plant design is under development, capital and operating costs are still preliminary. Also, detailed cost estimates are based on a reference 12-module plant. Capital and operating costs for an 8-module plant were scaled from the 12-module estimates and were adjusted to represent nth-of-a-kind plant cost. Given the preliminary nature of the cost data for the NuScale plant and the simplistic scaling that was used for this analysis, capital and operating costs presented in Table 3 are certain to change are given only to provide a rough comparison of the cost scales between the power plant and the various desalination plant options.

Capital cost data for the desalination plant options are based on recent project data and are presented for relative comparisons only. For the purpose of this study, capital costs for the LP-MED and MP-MED cycles were assumed to be the same. Although the Desalination Economic Evaluation Program (DEEP) code[9] developed by the International Atomic Energy Agency was not used for any of the analysis results presented here, it provided useful cross-checking for some of the economic and operational parameters calculated by GateCycle and internal costing methods. Desalination plant operating and maintenance costs are estimates for a non-descript feedstock of reasonable quality and based on available industry data [10,11] and vendor input.

Simple payback results do not include financing costs, which can be significant and varies widely in different financial markets. Explicit assumptions on final site selection, feedstock quality, product quality and financing method are required to yield more accurate predictions of potential costs and profitability. Although simplistic, the analysis does provide a relatively clean comparison of the relative profitability of different desalination technologies when coupled to a NuScale plant.

Table 4: Summary of economic analysis for coupled NuScale-desalination plant

Desalination Technology	MP-MSF	MP-MED	LP-MED	RO
Coupled Plant Production Rates				
Water produced (m^3/d)	190,000	190,000	190,000	190,000
Net plant electrical output (MWe)[1]	227	293	334	348
Capital Cost ($ millions)				
NuScale plant	$1,800	$1,800	$1,800	$1,800
Desalination plant	$379	$311	$311	$256
Operation & Maintenance Cost[2] ($ millions)				
NuScale plant	$185	$185	$185	$185
Desalination plant	$15.1	$13.3	$13.3	$14.2
Annual Revenue ($ millions)				
Annual revenue from water sales (@ $1.67/$m^3$ wholesale price)	$101	$101	$101	$101
Annual revenue from electricity sales (@ $75/MWh wholesale price)	$142	$183	$209	$217
Coupled plant net annual revenue	$43	$86	$111	$119
Coupled plant simple payback (years)[2]	51	25	19	17

[1]Net electrical output available to the grid after accounting for reduced generation due to extraction steam and electricity consumed by desalination process.
[2]Does not include financing costs.

5. SUMMARY

The use of water desalination will most certainly grow as fresh water resources dwindle. Nuclear energy offers an attractive clean energy source to provide the thermal and electrical demands of desalination technologies. Nuclear power has been proven clean, safe and reliable, and can be made affordable through the adoption of smaller sized nuclear plants. The NuScale small modular reactor design is especially well suited to support water desalination due to its high degree of modularity, enhanced safety and robustness, and flexible plant design. The analysis presented here demonstrates that a NuScale plant can easily and effectively couple to a variety of desalination technologies, and can be economically competitive for simultaneously producing clean electricity and clean water.

REFERENCES

[1] Global Water Intelligence: Desalination.com, www.desalination.com/market/desal-markets, September 18, 2013.

[2] *Advanced Application of Water-Cooled Nuclear Power Plants,* International Atomic Energy Agency, TECDOC-1584 (July 2007).

[3] D. T. Ingersoll, "Deliberately Small Reactors and the Second Nuclear Era," *Progress in Nuclear Energy*, **51**, 589-603 (May 2009).

[4] *Status of Nuclear Desalination in IAEA Member States*, International Atomic Energy Agency, IAEA-TECDOC-1524 (January 2007).

[5] J. N. Reyes, Jr. "NuScale Plant Safety in Response to Extreme Events," *Nucl Tech*, **128**, 153-163 (May 2012).

[6] *Introduction of Nuclear Desalination: A Guidebook,* International Atomic Energy Agency, Technical Reports Series No. 400 (2000).

[7] GateCycle, Version 6.1.0.0, General Electic.

[8] "Desalination Plant," Carlsbad Desalination Project, carlsbaddesal.com/desalination-plant, September 24, 2013.

[9] *Desalination Economic Evaluation Program (DEEP): User's Manual,* Version 5.0, International Atomic Energy Agency, Computer Manuals Series No. 14 (2013).

[10] H.M. Ettouney, et. al., *Evaluating the Economics of Desalination*, CEP Magazine (December 2002)

[11] Desalination Industry Data and Cost Estimation Tools, *http://desaldata.com*