NuScale Small Modular Reactor for Co-Generation of Electricity and Water

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ABSTRACT

The worldwide demand for potable water has been steadily growing and is projected to accelerate while natural reserves of fresh water are generally flat or diminishing. Desalination of seawater or brackish groundwater is expected to make up the difference; however, the desalination of water is energy intensive, requiring large amounts of electricity and/or thermal energy. Nuclear energy is an attractive option for large scale desalination application since the thermal energy produced in a nuclear plant can provide both electricity and heat for clean water production without the emission of greenhouse gases or the variability of renewable sources. A particularly attractive option for nuclear desalination is to couple a desalination plant with a new generation of designs—small modular reactors. The NuScale small modular reactor design is especially well suited for the cogeneration of electricity and clean water because of the enhanced safety, improved affordability, and deployment flexibilities of the plant design, which provides a cost-effective approach to expanding global desalination capacity. Parametric studies were performed to evaluate the technical and economic considerations of coupling a NuScale plant to a variety of different desalination technologies. The study concludes that although a NuScale plant coupled to a reverse osmosis desalination plant provides the most favorable economics, NuScale design features offer several flexibilities for coupling to thermal distillation plants and hybrid plant configurations.

Keywords: NuScale Power, small modular reactors, nuclear desalination

1. INTRODUCTION

There has been an increasing concern in recent years regarding the energy-water nexus, i.e. the intimate co-dependence of energy and water and the impending shortfall of both. In short: it takes water to produce energy and vice versa. In 2005, for example, 41% of the U.S. fresh water withdrawal was for cooling of thermoelectric power stations.[1] That same year, an average of 7,300 MW of power was used globally to produce 35 million cubic meters per day of clean water. Although the importance of access to abundant, clean and affordable electricity has been broadly recognized for many years, the equal importance of abundant, clean and affordable water and its interdependence with energy is a rapidly emerging concern. An increasing number of countries throughout the world are striving to reduce or eliminate their import of energy sources, i.e. meet more of their growing energy demand with domestically produced power, while also facing challenges regarding the availability of clean, potable water. Scores of countries are considered to be “water stressed,” i.e. their

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availability of fresh water is less than 2000 m^3 per person per year. Even in countries that have adequate water resources nationally, the geographic distribution of water typically is not uniform and selected regions may be even "water scarce," i.e. they have a renewable water supply less than 1000 m^3 per person per year. An example of this is the southwestern region of the United States, where annual consumption of water has been exceeding water production in recent years.[2] Even in the normally precipitation-rich southeastern region of the U.S., recent droughts have created severe water shortages in some locations and resulted in regional tensions. For example, the State Legislature in the U.S. state of Georgia is now disputing the location of the long-standing boundary between their state and the neighboring state of Tennessee. The current boundary, which denies Georgia's access to the Tennessee River, is claimed to be a surveyor's mistake.[3]

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 organization, approximately 16,000 desalination plants exist world-wide producing roughly 75 million cubic meters per day.[4] 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 the 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.

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 create 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.[5] For example, Kazakhstan operated a distillation-type desalination plant at the Aktau site for over 27 years until the reactor was shut down in 1999. India coupled a desalination plant to the Madras Atomic Power Station in 2002 and at the Kudankulam site in 2009. Japan has accumulated the greatest amount of experience with nuclear-driven desalination plants, having operated 10 desalination units at four nuclear plant sites before the country-wide shut down of their nuclear plants in 2011.[6] 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 has been 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.[7] Although motivated by goals of increased safety and affordability, most SMRs have additional features that lend well to their use for desalination applications.[8] 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. Although many of the designs are still under development, two SMRs have already received design approval from their regulator: the SMART reactor developed in the Republic of Korea and the barge-mounted KLT-40S reactor developed in the Russian Federation. Both designs are being marketed as co-generation plants for producing electricity and water.

Several SMR designs are being developed in the U.S. and most of them advertise their applicability to water desalination. One design, which is being developed by NuScale Power, LLC, 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, make 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 Section 2 followed by a brief discussion of desalination technologies considered in the study. Section 4 provides a technical evaluation of options for coupling a NuScale plant to a range of different desalination technologies. The final section presents a preliminary economic evaluation of the various plant coupling options.

2. NUSCALE PLANT OVERVIEW

The NuScale SMR plant is an innovative design that builds on 50 years of world-wide experience with the commercial application of pressurized, light-water-cooled reactor (LWR) technology. The design incorporates several features that reduce complexity, improve safety, enhance operability, and reduce costs. From the outset, the top level design goals for the NuScale plant have been to achieve a high level of safety and asset protection while providing an affordable approach to nuclear power that gives the plant owner the maximum flexibility in construction, operation and application of the plant.

2.1. Design Description

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.

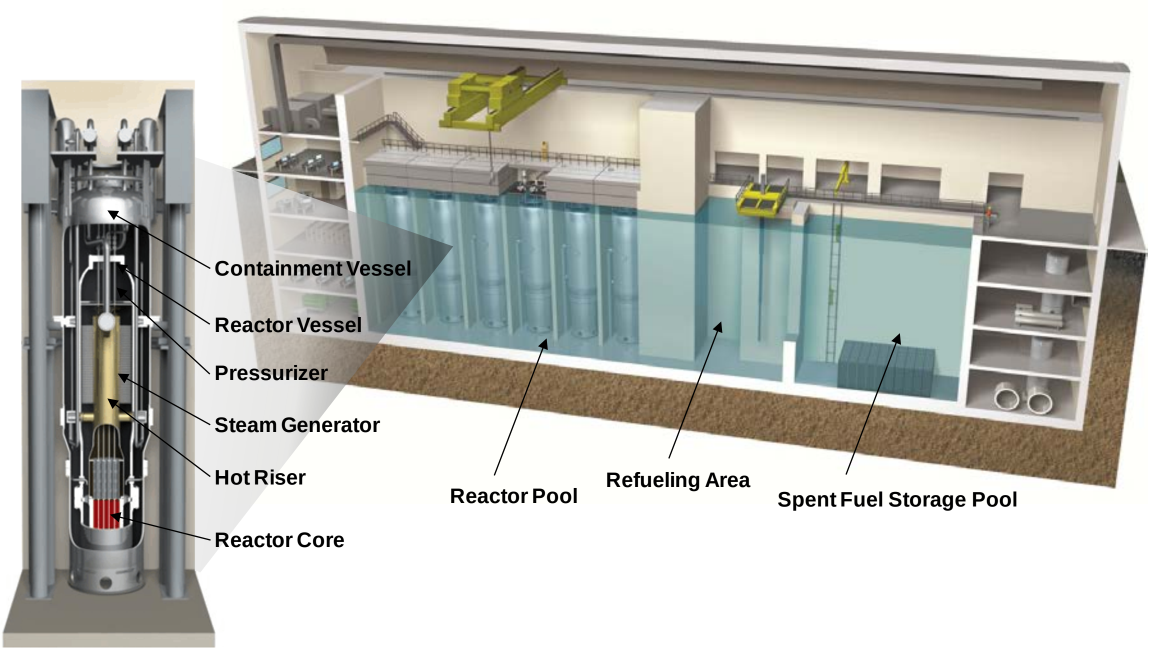

Figure 1. Model of NuScale power module (left) and cutaway of 12-module plant (right).

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.

As can be seen in Fig. 1, the NuScale module is located below grade in a pool of water. The reactor pool provides passive containment cooling and decay heat removal. Specifically, the pool provides an assured heat sink with a capacity to absorb all the decay heat produced by up to 12 fully mature cores for greater than 30 days, after which air cooling of the vessel is sufficient to avoid fuel damage. The pool also provides an additional fission product barrier in the unlikely event of fuel failure and provides radiation shielding outside containment to reduce operational exposure. Finally, the below grade pool provides enhanced physical security by adding an additional barrier to fuel access.

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

- *Compact size.* The nuclear steam supply system can be entirely prefabricated off site and shipped by rail, truck or barge. This reduces construction time due to parallel fabrication considerations and reduces overall schedule uncertainty due to the reduced amount of on-site construction activities. This will help to bring the construction duration for a NuScale plant more in line with the construction time for a desalination plant.

- *Natural circulation cooling.* Natural circulation operation provides a significant advantage since it eliminates pumps, pipes, and valves and hence the maintenance and potential failures associated with those components. It also reduces in-house plant loads. This added simplicity enhances overall plant safety as well as improving economics.
- *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 reduce uncertainties in the plant's performance and 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 to couple 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 applications.

The synergy created by these unique features, especially plant simplicity, 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.

2.2. Resilience against Fukushima-type Events

An important characteristic of the NuScale design that enhances its attractiveness for desalination application 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.

2.2.1. Compact Containment System

The NuScale design offers an unparalleled level of plant resilience to the type of events that happened in Japan.[9] A key feature in achieving this level of resilience is the containment vessel, which has several features that distinguish it from existing containment designs. It has been designed to a rated pressure of 5.5 MPa (800 psia), which is approximately 12 times higher than traditional containments. As a result, it can withstand all loss-of-coolant accidents (LOCA) that can occur inside containment. The high design pressure is achieved by reducing the diameter of the containment vessel rather than the more costly approach of increasing the wall thickness. During normal power operation, the containment atmosphere is evacuated to provide an insulating vacuum that significantly reduces parasitic heat loss from the reactor vessel. As a result, the reactor vessel does not require surface insulation. This eliminates the potential for sump screen blockage, which has been an issue for many large LWRs. Furthermore, the deep vacuum improves steam condensation rates during any sequence where safety valves vent steam into this space. In addition, by eliminating containment air, it prevents the creation of a combustible hydrogen-air mixture in the unlikely event of a severe accident (i.e., little or no oxygen), and eliminates corrosion and humidity problems inside containment.

A closely coupled innovation is the immersion of the containment vessel in a large reactor pool. The pool provides the heat capacity needed to absorb and remove decay heat from each of the reactor cores during off-normal events. Conventional designs provide this “ultimate heat sink” in large external tanks that must be accessed through a network of pipes, valves and heat exchangers when needed. The NuScale design simplifies heat transfer to the ultimate heat sink by immersing the containment in it, thereby assuring its availability and eliminating the cost and maintenance issues associated with those additional heat transfer systems.

2.2.2. Emergency Core Cooling System

The unique design of the NuScale containment vessel and its immersion in the ultimate heat sink allows the emergency core cooling system (ECCS) to be simplified considerably compared to other reactor designs. As shown in Fig. 2, the ECCS consists of just two independent reactor vent valves (RVV) and two independent reactor recirculation valves (RRVs). The ECCS provides a means of long-term decay heat removal in the event of a LOCA.

The ECCS removes heat and limits containment pressure by steam condensation on the inside surface of the cold containment vessel. It also allows heat conduction through the containment vessel walls to the water in the reactor pool. Long-term cooling of the reactor core is established via recirculation of steam condensate back into the reactor pressure vessel via the RRVs.

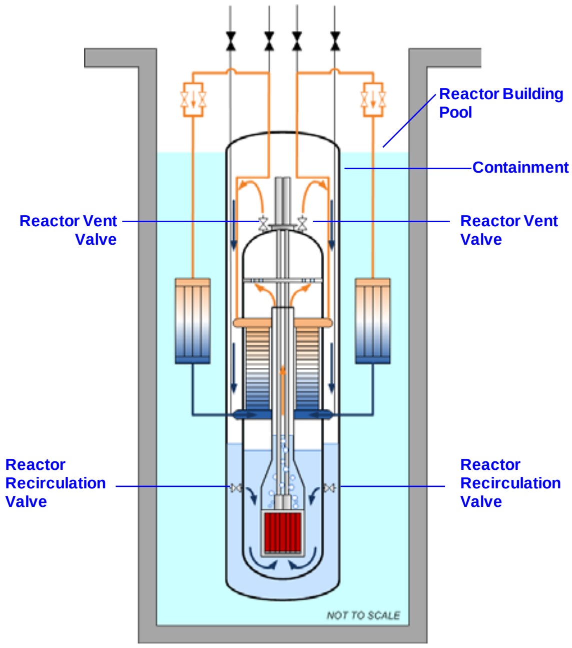

Figure 2. Key features of NuScale power module (left) and features specific to the emergency core cooling system (right).

Following a LOCA or other condition resulting in an actuation of the ECCS, heat removal through the containment vessel rapidly reduces the containment pressure and temperature and maintains them at acceptably low levels for extended periods of time. Steam is condensed on the inside surface of the containment vessel, which is passively cooled by conduction and convection of heat to the reactor pool water.

2.2.3. Response to Complete Station Blackout

In the event of a complete station blackout, as experienced at the Fukushima Daiichi plants, heat is removed from the reactor modules by fail-safe actuation of the ECCS and allowing the reactor building pool to heat up and boil. Water inventory in the reactor pool is sufficiently large to cool all of the reactors and prevent fuel damage for at least 30 days without any source of power, operator action, or makeup water. After 30 days, water boil-off and passive air cooling of the containment vessel provide adequate cooling for an unlimited period of time. The stages of passive removal of the reactor decay heat for a long-term cool-down of the reactor module is depicted in Fig. 3. The key to ensuring the transition from water cooling to air cooling is the very small decay heat and the large containment surface area. As shown in Fig. 3, one second after reactor shutdown, the power has decayed to 10 MWt and after one day, the power has decayed down to 1.1 MWt. After 30 days, the decay heat being generated per module is less than 400 kW—equivalent to about 250 hair dryers.

This extremely robust safety feature is a direct consequence of the unique design of the compact containment vessel, the assured supply of long-term cooling afforded by the reactor pool, and the relatively low power output of each module.

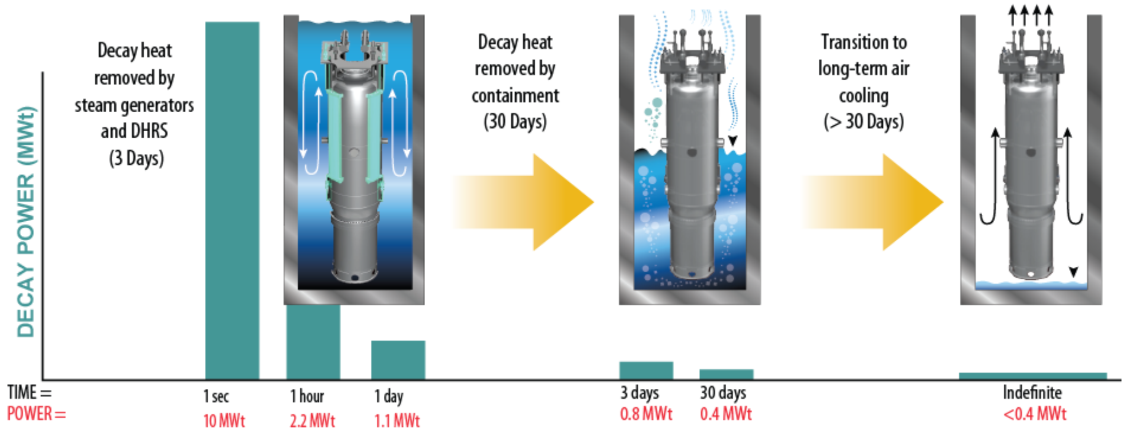

Figure 3. NuScale Power Module heat removal during a prolonged station blackout event.

2.2.4. Validation of Long-term Cooldown Performance

The performance of the NuScale ECCS and its long-term cool-down capability has been validated using the NuScale Integral System Test (NIST) facility. NIST is a full pressure, full temperature, 1/3rd height scaled model of the NuScale reactor vessel, containment and reactor building cooling pool. Figure 4 presents the results from a small break LOCA test conducted in NIST. The initiating event for this test, a simulated stuck-open vent valve, was essentially identical to that for the accident at Three Mile Island. However, the outcome was quite different and the accident was completely mitigated without requiring external power or operator actions. The left-hand graph in Fig. 4 shows the normalized reactor pressure and containment pressure reaching equilibrium quickly followed by continual pressure drop as heat is removed by the pool. Long-term cooling was achieved using the ECCS alone. As expected, water accumulated in the space between the pressure vessel and the containment vessel, and was recirculated back into the reactor vessel. This is validated in the right-hand graph in Fig. 4, which shows that the normalized collapsed liquid level in the reactor vessel remained well above the top of the core throughout the entire transient. These tests, in combination with an extensive program of other integral and separate effects tests, serve to validate the NuScale plant design for resilience against extreme events.

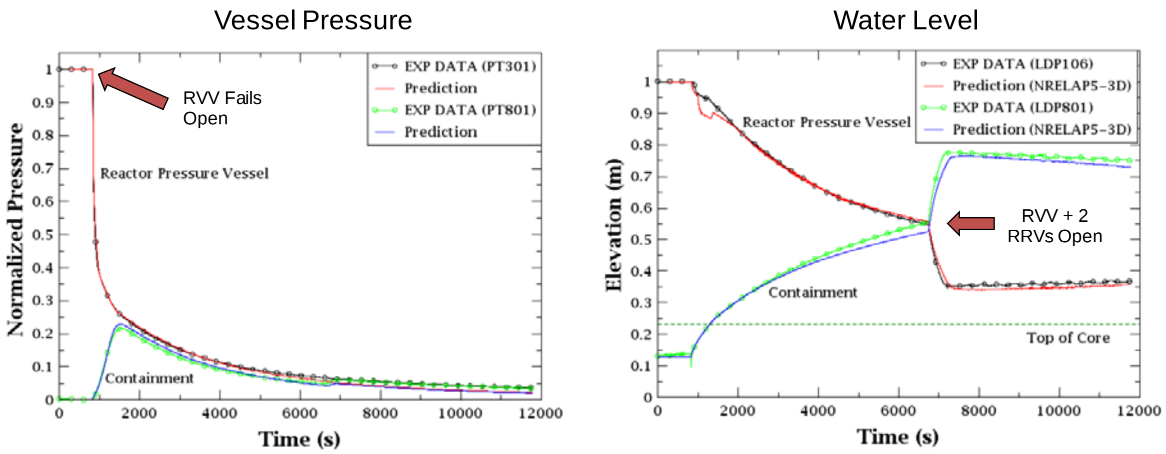

Figure 4. Comparison of test results and analytic predictions for vessel pressure (left) and water level (right) after a small break loss-of-coolant-accident.

3. DESALINATION TECHNOLOGY OPTIONS

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 and one membrane-based technology.[10] These are described briefly below:

1. *Multi-Effect Distillation (MED):* In each MED "effect" (stage), heat is transferred from condensing water vapor on one side of a tube bundle to the evaporating brine on the other side of the tubes. This process is repeated successively in each of the successive effects at progressively lower pressure and temperature, driven by the vapor from the preceding stage. In the last effect, the water vapor condenses in the heat rejection heat exchanger, which is cooled by incoming seawater. The condensed distillate is collected from each effect and some of the heat may be recovered by flash evaporation at a lower pressure. Low pressure saturated steam is used as a heat source, which is supplied by steam boilers or dual-purpose plants (co-generation of electricity and steam). Thermal compression is sometimes used where higher pressure steam is directed to a steam jet ejector that is used to pull low pressure steam from one of the colder effects and send it to the first effect. This provides a higher efficiency in the MED. A small amount of medium pressure steam is also used in ejectors to maintain the vacuum in the unit.

2. *Multi-Stage Flash Distillation (MSF):* Seawater passes through tubes in each evaporation stage where it is progressively heated. Final seawater heating occurs in the brine heater by the heat source (steam heat exchanger). The heated brine flows through nozzles into the first stage, which is maintained at a pressure slightly lower than the saturation pressure of the incoming stream. As a result, a small fraction of the brine flashes to steam. The heat used to

flash the vapor comes from cooling of the remaining brine flow, which lowers the brine temperature. Subsequently, the produced vapor passes through a mesh demister in the upper chamber of the evaporation stage where it condenses on the outside of the condensing brine tubes and is collected in a distillate tray. The heat transferred by the condensation warms the incoming seawater as it passes in counter-flow through the stage. The remaining brine passes successively through all of the stages at progressively lower pressures, where the process is repeated. The hot distillate also flows from stage to stage and cools itself by flashing a portion into steam which is recondensed on the outside of the tube bundles.

3. *Reverse Osmosis (RO):* Reverse osmosis is a membrane separation process in which pure water is “forced” out of a concentrated saline solution by flowing through a membrane using a high static transmembrane pressure difference. This pressure difference has to be higher than the osmotic pressure between the solution and the pure water (about 6 MPa). The saline feed is pumped into a closed vessel where it is pressurized against the membrane to 7-8 MPa. As a portion of the water passes through the membrane, the salt content in the remaining feed water increases, therefore a portion of this solution is constantly discharged without passing through the membrane. A pure RO process requires only electricity to power the pumps needed to create the pressure head. RO systems typically require pretreatment of the inlet water to prevent fouling of the RO membranes by organics and suspended solids.

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 will be adversely impacted.

Both 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 and will result in a commensurate decrease in the electrical output of the power plant. This steam extraction approach to co-generation may have implications on the reliability and flexibility of operations for both power and desalination plants. 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.

Although thermal distillation processes have traditionally dominated the global desalination market, over 60% of the current global installed capacity is based on RO, and represents an even higher percentage of new capacity added in the past 10 years. Figure 5 (from Ref. 4) shows the global trend in membrane and thermal-based desalination capacity from 1980 to 2010. This trend is driven by a number of parallel research efforts that support improved membrane performance and lower cost. Some of the more notable recent advances in membrane technology have been enabled by the development of new polymer materials and continued improvement in the fundamental tools for designing new membranes, such as atom-level imaging microscopes and high-fidelity dynamic simulation methods.[11] These advancements are likely to continue to allow RO technology development to outpace distillation technology for the foreseeable future, spurred by increasing attention to nano-scale sciences and the broad use of membrane technology for several applications beyond desalination.

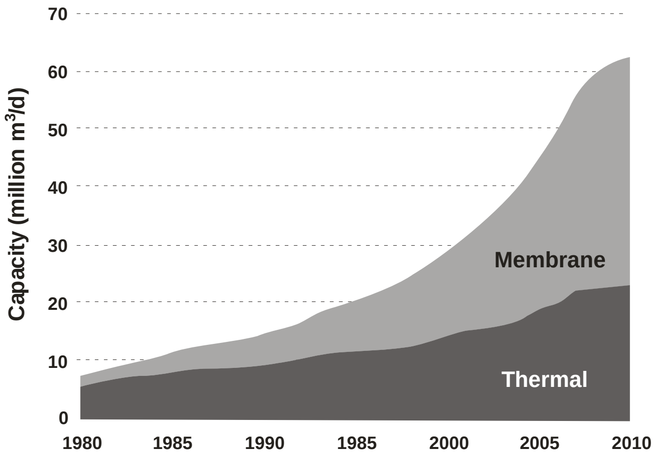

Figure 5. Global installed desalination capacity from 1980 to 2010.[4]

4. NUSCALE INTEGRATION WITH DESALINATION TECHNOLOGIES

The small size and high degree of modularity of the NuScale design facilitate coupling the output of the power module to a desalination process in a variety of ways to best meet the needs of the user. Specifically, the design allows each module to support both membrane separation and thermal distillation technologies. As demonstrated below, the coupled plant configuration can be modified to provide the most flexible operation based on the unique requirements for a given installation.

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[12] 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.

4.1. Utilization of Main (High Pressure) 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 set and also to a reboiler. Clean steam from the reboiler is used to drive the MED-TC cycle, as shown in Fig. 6. 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 clean water produced to steam used to provide process heat. For the case studied, use of the TC increases the GOR of the MED plant output 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 producing enough steam for up to 88,000 m^3/d. The turbine-generator equipment can then be sized to accept the remaining steam flow for generating electricity. A variation of this design is to utilize high pressure extraction steam from the turbine or expand the steam through a high backpressure turbine. This results in a small increase in power output with minor impact on the distillation plant GOR.

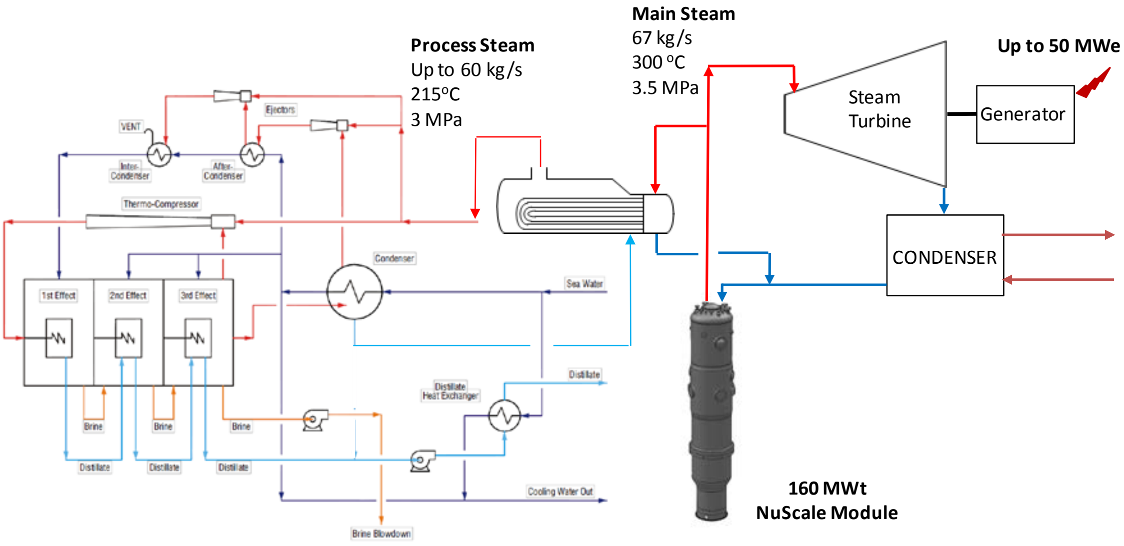

Figure 6. Process diagram for a NuScale module coupled to an MED-TC distillation cycle.

Figure 7 shows the relationship between electricity output and product water for a NuScale plant coupled to an MED-TC distillation plant. Although the curve shows as continuous from full electrical output to zero electrical output, there are practical minimum steam flow requirements for the turbine. Operation below that rate (10-15% of full flow) is not recommended except for the case of zero flow, i.e. full turbine bypass. This approach of splitting the main steam flow allows maximum flexibility in balancing water versus electrical output and yields the maximum possible water output of a single NuScale module for all of the thermal distillation cycles considered in the study. However, the output steam pressure from the NuScale module is greater than what can be used effectively by the MED-TC plant. The remaining thermal distillation configurations discussed below benefit from partial depressurization of the steam as it passes through the turbine, which generates a commensurate amount of electricity and enhances the overall economics of the combined electrical and distillate output.

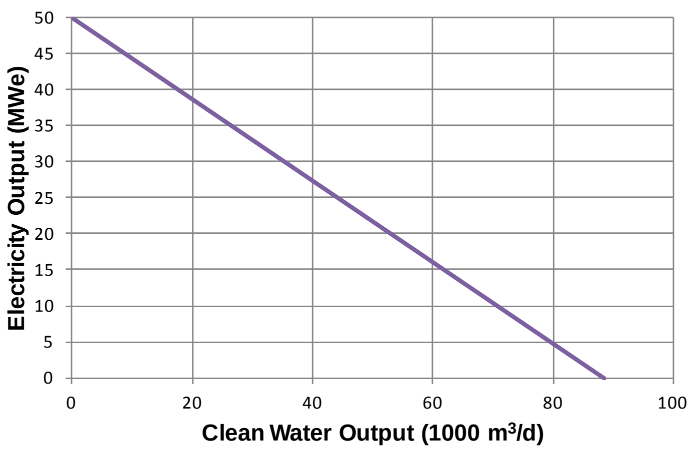

Figure 7. Relationship between electricity and water output from a single NuScale module coupled to an MED-TC distillation cycle.

4.2. Utilization of Extraction (Medium Pressure) 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 8 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. Saturated 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 MSF and MED cycles; however, the extraction steam could be supplied at virtually any pressure desired, depending on the specific application.

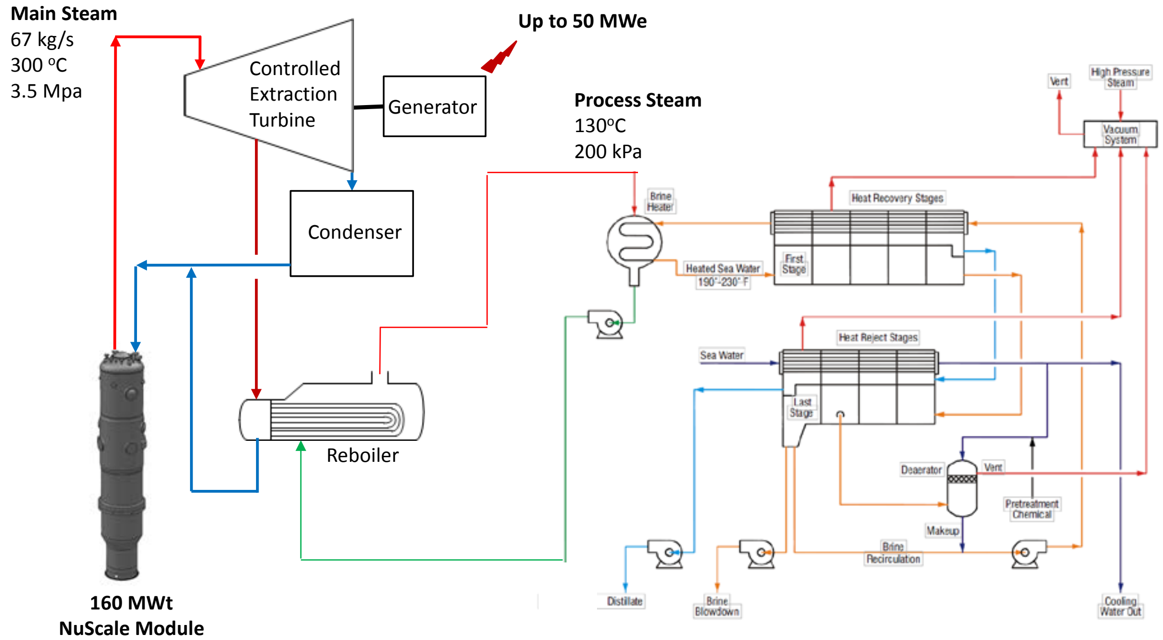

Figure 8. Process diagram for a NuScale module coupled to an MSF desalination cycle through a controlled extraction type turbine.

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. Figure 9 shows the relationship between electricity and water output for a controlled extraction type turbine coupled to either an MSF or an MED cycle. The lower GOR for the MSF cycle results in less clean water produced for a fixed amount of steam supplied, or conversely, for a fixed amount of clear water produced, the MED cycle allows the NuScale module to provide more electricity to the grid.

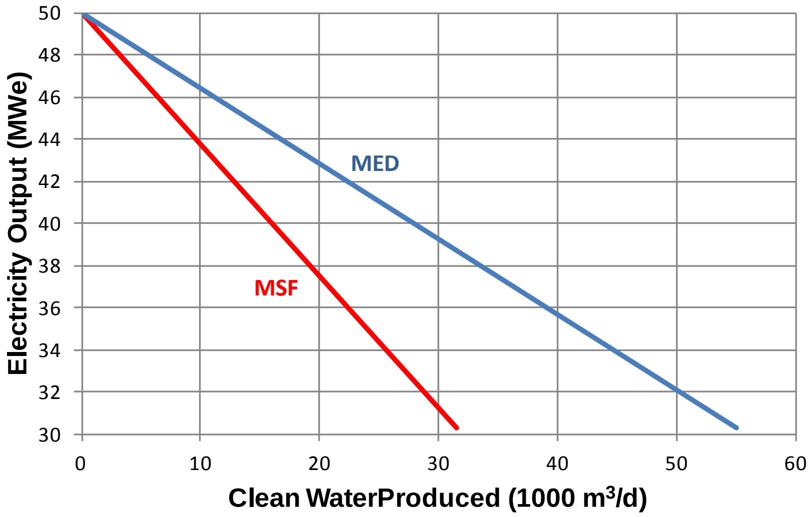

Figure 9. Relationship between electric and water output from a single NuScale module coupled to an MED or MSF distillation cycle using a controlled extraction type turbine.

4.3. Utilization of Exhaust (Low Pressure) Steam for Thermal Desalination

The final thermal desalination coupling option studied uses 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. This configuration is assumed to be coupled to an MED cycle since this technology more readily accommodates low pressure steam as the driving energy source. Table 1 summarizes the estimated water production rates with this plant coupling approach.

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 between power and water output without changing reactor power. This impact could be mitigated through the use of various design options, such as providing a steam bypass around the turbine to supply an alternate desalination stream or utilizing multiple turbines; however, the details of such arrangements were not considered here. Nuclear power plants are typically designed for baseload operation, therefore any unique design options used with a backpressure-desalination coupled unit would require in-depth analysis. Despite this, the use of lower pressure steam allows for increased electricity production for the same amount of water production when compared to the extraction or main steam cases (see section 4.5).

Table 1: Key parameters for exhaust steam-driven thermal desalination

Steam flow available for desalination	48 kg/s at 40 kPa (380,000 lb/h @ 5.8 psia)
Electrical output (gross, per module)	33.8 MWe
Water production (MED w/ GOR of 12)	51,000 m^3/d

4.4. Integration with RO technology

The last option studied was to couple the NuScale plant to an RO desalination process, as depicted in Fig. 10. 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 outputs 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.[4] For a given plant, the actual electric usage will be influenced by feedstock quality and the product quality requirements of the end user. A range of electricity consumption rates (3-6 kWh/m^3) was evaluated but did not significantly change the relative comparisons with other desalination technologies.

A variation of the RO option would be to combine it with a thermal distillation process. This hybrid scheme allows for maximizing water output and allows increased flexibility in water product quality. In particular, the high purity distillate from the thermal process can be blended with the RO permeate in whatever ratio is needed to achieve the desired final water quality. Such a system would also allow for more flexible management of the electrical output of the co-generation NuScale plant by balancing electricity and steam feeds to the RO and thermal processes. A detailed assessment of this hybrid option was beyond the scope of the present study.

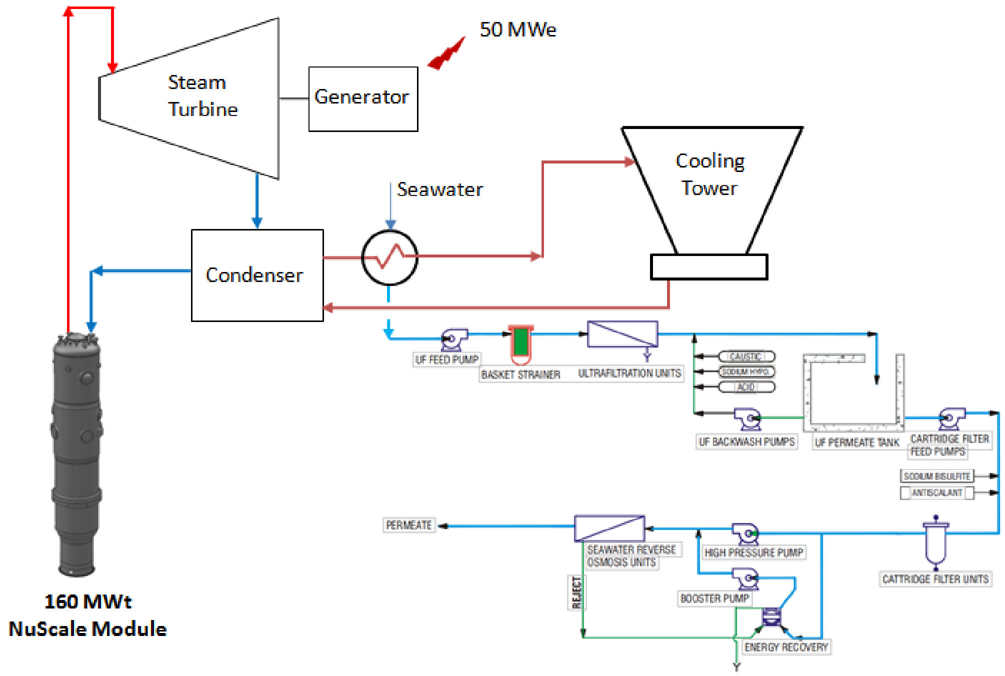

Figure 10. NuScale plant coupled to an RO desalination cycle.

4.5. Comparison of Plant Integration Options

Figure 11 shows the relationship between electrical and water outputs for a NuScale module coupled to an RO plant and is compared to the results from 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 the MED distillation processes. 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.

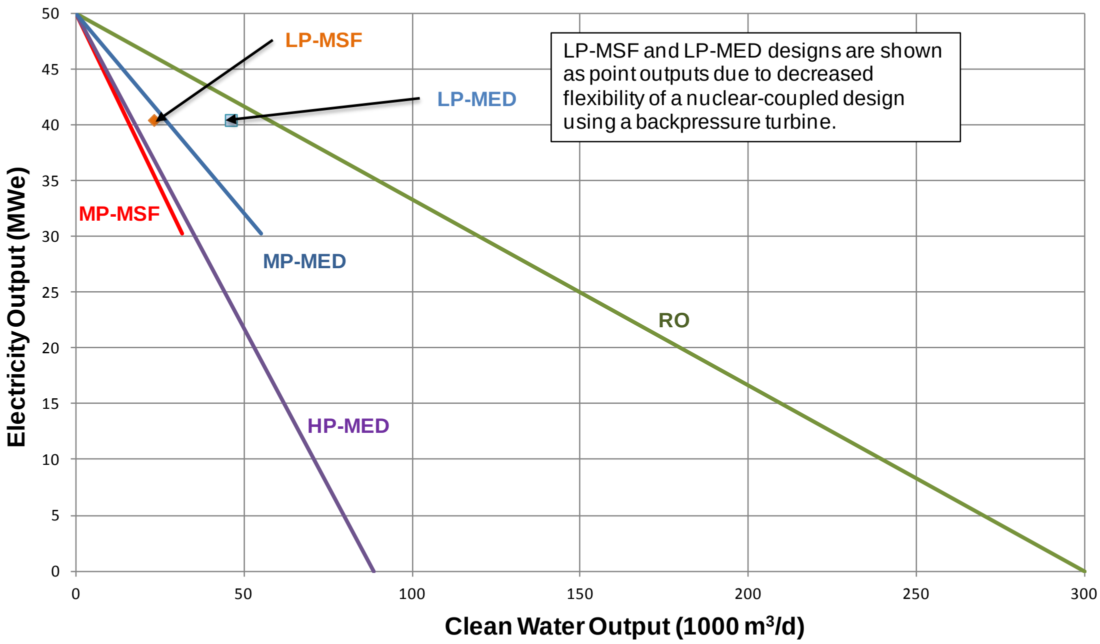

Figure 11. Relationship between electric and water output from a single NuScale module coupled to a variety of desalination processes.

5. Economic Analysis for Large Municipal Desalination Plant

The preceding results were all based on coupling a single NuScale power module to the various 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 the same water production rate as the Carlsbad Desalination Plant,[13] which represents a large municipal desalination plant application. The Carlsbad project is located in Carlsbad, California, just north of San Diego. It began construction in 2013 and when completed, is claimed to be the largest RO desalination plant in the western hemisphere,[14] producing 190,000 m^3/d (50 million gallons per day) of potable water. 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 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 extraction type steam turbines are assumed in order to achieve the target output and were based on standard available unit sizes. The MP-MED cycle could be configured to use more steam flow and fewer units; however, the impact to the results is negligible. 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 190,000 m^3/d Desalination Plant Options

Desalination Technology	MP-MSF	MP-MED	LP-MED	RO
Electrical consumption (kWh/m^3)	3	1	1	4
Unit steam consumption (kg/s)	39.3	22.4	45.8	N/A
GOR (kg water/kg steam)	8	14	12	N/A
Top brine temperature	90	70	70	N/A
Number of units required	7	7	4	N/A

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 contains eight modules with a total thermal capacity of 1280 MWt and varying net electrical outputs depending on the desalination process used. Table 3 lists the key plant parameters for the 8-module NuScale Power Plant.

Table 3. Key Parameters for NuScale 8-Module Power Plant

Power Plant Parameters	
Total plant thermal power	1280 MWt
Number of power modules	8
Thermal power per module	160 MWt
Thermal efficiency	>30%
Capacity factor	>95%
Primary system pressure	12.8 MPa (1850 psia)
Main steam supply pressure	3.5 MPa (500 psia)
Main steam temperature	302°C (575°F)
Final feedwater temperature	149°C (300°F)
Power plant footprint	40-45 acres

Table 4 summarizes the economic analysis for an 8-module NuScale plant coupled to the four primary desalination options studied. 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 very preliminary. Detailed, best-estimate costs are based on a reference 12-module plant. Capital and operating costs for an 8-module plant were scaled from the 12-module estimates using both a system-by-system approach and a simple top-down approach. Both methods gave reasonably consistent results. Also, the capital cost estimate was adjusted to represent nth-of-a-kind plant cost. The adjustment from first-of-a-kind to nth-of-a-kind costs required the application of a standard learning curve on a system-level basis due to the modularity of the plant. For example, modules were “learned” at a rate of eight per plant while turbine buildings were learned at two per plant and the control room at a rate of one per plant. Given the preliminary nature of the cost data for the NuScale plant and the simplistic scalings that were used for this analysis, capital and operating costs presented below are certain to change. However, they allow a rough comparison of the cost scales between the power plant and the various desalination plant options.

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)[a]	227	293	334	348
Capital Cost ($ millions)				
NuScale plant	$1,800	$1,800	$1,800	$1,800
Desalination plant	$379	$311	$311	$256
Operation & Maintenance Cost[b] ($ 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 (at $1.67/$m^3$ wholesale price)	$101	$101	$101	$101
Annual revenue from electricity sales (at $75/MWh wholesale price)	$142	$183	$209	$217
Coupled plant net annual revenue	$43	$86	$111	$119
Coupled plant simple payback (years)[b]	51	25	19	17

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

Capital cost data for the desalination plant options are based on Ref. 4 and recent project data where available. They 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[15] 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 [16,17] and vendor input.

It was beyond the scope of the current study to develop conclusions regarding the economic competitiveness of a NuScale co-generation plant for electricity and water. For this to be meaningful, a specific site and project definition would be required. For example, the simple payback results listed in Table 4 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 also required to yield more accurate predictions of potential costs and profitability. Furthermore, economic competitiveness requires knowledge of the prevailing cost of energy alternatives at the specific site. For example, it is very difficult for any energy source to be competitive with the abundant shale gas now being produced in the U.S., while in areas of Europe and

Asia, nuclear power is very competitive. Although simplistic, the analysis from this study does provide a relatively clean comparison of the relative profitability of different desalination technologies when coupled to a NuScale plant.

6. SUMMARY

Experts will continue to endlessly argue over highly precise predictions of the future—always to be proven wrong by history. We offer no precise prediction here, only the conjecture that the world population will continue to grow and people will strive to improve their quality of life. With that growth and progress will come an increase in demand for affordable and abundant energy and water. 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 provides a relative comparison of the economic considerations. More detailed analysis for a specific plant at a specific site is needed to fully assess the economic competitiveness of the NuScale co-generation plant.

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