The 19th Pacific Basin Nuclear Conference (PBNC 2014)
Hyatt Regency Hotel, Vancouver, British Columbia, Canada, August 24-28, 2014.

PBNC2014-209

EXTENDING NUCLEAR ENERGY TO NON-ELECTRICAL APPLICATIONS

D. Ingersoll[1], Z. Houghton[1], R. Bromm[2], C. Desportes[3], M. McKellar[4], and R. Boardman[4]
[1] NuScale Power, LLC, Corvallis, Oregon USA
[2] Fluor Corporation, Greenville, SC, USA
[3] Aquatech International, Canonsburg, PA, USA
[4] Idaho National Laboratory, Idaho Falls, ID, USA

Abstract

Electricity represents less than half of all energy consumed in the United States and globally. Although a few commercial nuclear power plants world-wide provide energy to non-electrical applications such as district heating and water desalination, nuclear energy has been largely relegated to base-load electricity production. A new generation of smaller-sized nuclear power plants offers significant promise for extending nuclear energy to many non-electrical applications. The NuScale small modular reactor design is especially well suited for these non-traditional customers due to its small unit size, very robust reactor protection features and a highly flexible and scalable plant design. A series of technical and economic evaluation studies have been conducted to assess the practicality of using a NuScale plant to provide electricity and heat to a variety of non-electrical applications, including water desalination, oil refining, and hydrogen production. The studies serve to highlight the unique design features of the NuScale plant for these applications and provide encouraging conclusions regarding the technical and economic viability of extending clean nuclear energy to a broad range of non-electrical energy consumers.

Introduction

Economic growth and human well-being are inextricably connected to energy consumption.[1] The Energy Information Administration (EIA) projects that there will be a 56% growth in global energy consumption between 2010 and 2040, with more than two-thirds of that growth occurring in countries with emerging economies.[2] The EIA also expects that over half of the energy consumed in 2040 will be by the industrial sector, as will the associated emission of greenhouse gases (GHG).

Whether driven by the climate change debate or clean air considerations, it is reasonable to expect a future emphasis on non-emitting energy sources. Early in his first term of office, President Obama declared a national goal of reducing GHG emissions by 80% by 2050 relative to our 2005 emissions. Figure 1 characterizes this challenge by showing the 2005 emission values by energy sector and the 2050 target. One key point of interest is that the 2050 target is extremely aggressive. To emphasize this point: the last time that the U.S. had a CO_2 emission level comparable to the 1000 Tg (million metric ton) target level was 1906—very early in our country's industrialization. The second key point is that moving to entirely clean electricity solves only part of the problem, i.e. clean energy options must also address the transportation and industrial sectors' needs.

Wind and solar power capacities are on the rise globally and will be important contributors to the global clean energy portfolio; however, supply intermittency and land use issues will limit the ultimate level of contributions from these sources. Nuclear power capacity also is growing globally and can provide abundant clean energy in a highly reliable, dispatchable manner. Currently, nuclear power plants provide nearly 20% of the electricity and roughly 70% of the clean electricity generated in the United States. Yet as shown in Fig. 1, electricity represents only 40% of all energy consumed in the U.S., with another 50% being by industrial and transportation consumers. Hence, the challenge is how to move nuclear energy into these sectors in a way that meets their different energy demands and is competitive with existing and alternative energy sources.

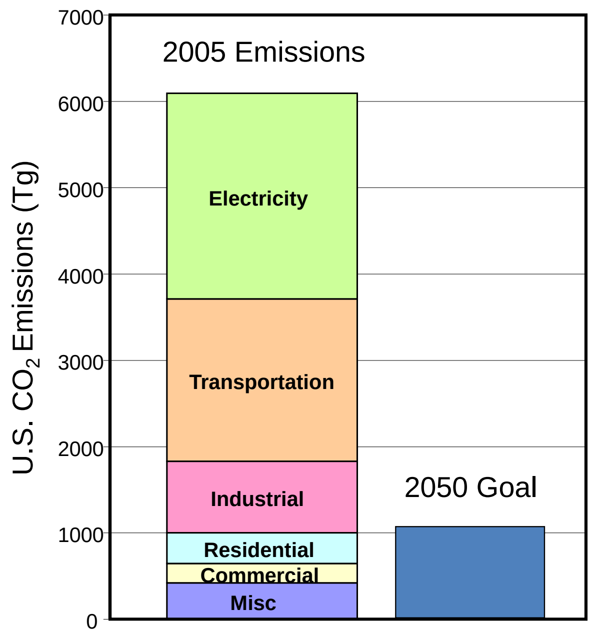


Figure 1. Contributors to the 2005 U.S. carbon dioxide emissions and the 2050 target level.

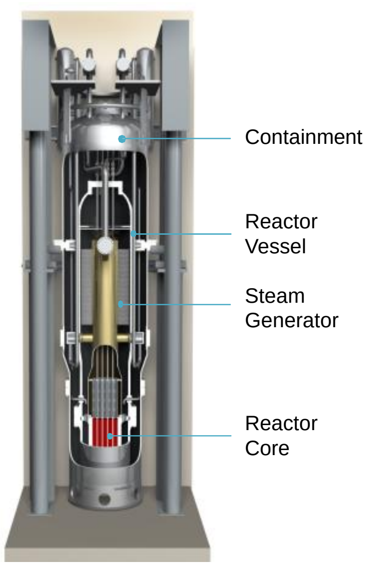
Although a few commercial nuclear power plants world-wide provide energy to non-electrical applications, nuclear energy is primarily used only for base-load electricity production. Of the nominally 440 commercial nuclear plants operational world-wide, 59 units in 9 different countries (Bulgaria, Czech Republic, Hungary, India, Romania, Russia, Slovakia, Switzerland, Ukraine) are being used for district heating and 12 units in 3 countries (India, Japan, Pakistan) are being used for water desalination.[3] To date, no commercial reactor plant has been used to provide process heat directly to industrial applications such as oil refining or chemical production.

A new generation of smaller-sized nuclear power plants is emerging that offers significant promise for extending nuclear energy to many non-electrical applications. The NuScale small modular reactor design, which is being developed in the U.S. by NuScale Power, LLC, is one of those new designs and is especially well suited for non-traditional applications. In particular, its small unit size, very robust reactor protection features, and highly flexible and scalable plant design allow it to address many of the different and diverse energy requirements of those users.

A series of technical and economic evaluation studies have been conducted to assess the practicality of using a NuScale plant to provide electricity and heat to a variety of non-electrical applications, including water desalination, oil refining, and hydrogen production. The studies serve to highlight the unique design features of the NuScale plant for these applications and provide an initial assessment of the technical and economic considerations for extending clean nuclear energy to a broad range of non-electrical energy consumers. An overview of the NuScale plant design and its differentiating features is given in the next section, followed by brief descriptions and results for the three non-traditional application studies recently conducted. The collective results are summarized in the final section.

Overview of NuScale SMR Design

A NuScale plant consists of up to 12 independent power modules, each capable of producing a net electric power of greater than 45 MWe, operating within a single reactor building. Each module includes an integral pressurized light water reactor (LWR) operated using natural circulation of the primary coolant flow and housed within its own small-volume, high-pressure containment vessel that is submerged underwater in a stainless steel lined concrete pool. A model of a single NuScale power module is shown in Figure 2 along with a cut-away view of a 12-module NuScale plant.



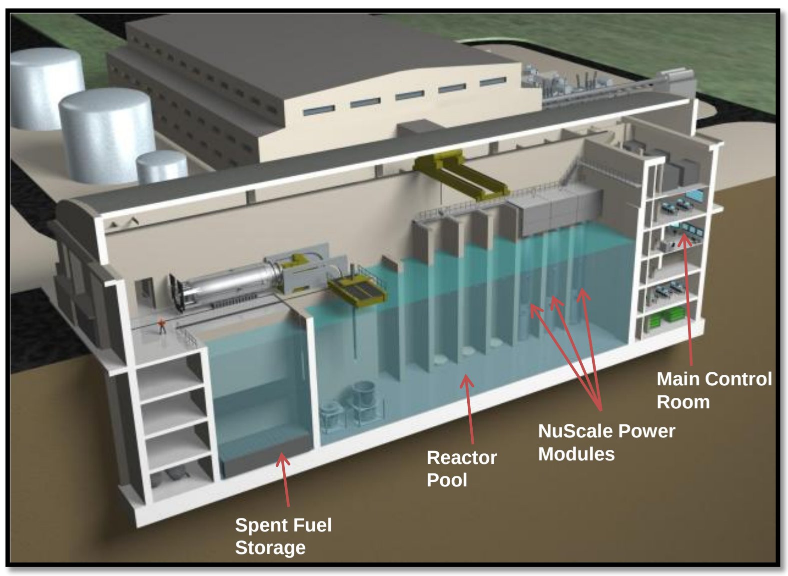


Figure 2. Cut-away views of a NuScale power module (left) and 12-module plant (right).

The integral reactor pressure vessel contains the nuclear core, a helical coil steam generator, and a pressurizer. Although the integral design is a significant departure from traditional commercial plants, the design incorporates the same fuel, materials, and coolant chemistry used in most existing plants. The entire nuclear steam supply system is enclosed in a unique low-volume, high-pressure steel containment vessel that is nominally 24.6 m (80 ft) tall by 4.6 m (15 ft) in diameter.

There are several features of the NuScale plant that distinguish it from the many other small nuclear plants being developed today and make the design well suited for non-electrical applications. The first is its compact size. The power module can be entirely prefabricated in a factory and shipped to the site by rail, truck or barge. This feature provides a number of cost efficiencies and reduces total construction time due to the parallel fabrication and minimal on-site safety grade construction. Also, each power module and power conversion systems is designed to be independent of other power trains, which allows modules to be added to the plant incrementally as demand grows and also allows modules to operate and produce power while one of the modules is being refueled or serviced. This latter feature is especially important to non-electrical applications that may require continuous power for efficient operation.

The design relies on well-established LWR technology. Therefore, the NuScale plant can be licensed within the existing LWR regulatory framework, drawing on a vast body of established experience, proven codes and methods, and existing regulatory standards. This will enable timely licensing of the first plants to better respond to the rapidly growing market of non-electrical energy customers. Also, as can be seen in Fig. 2, the NuScale module is located below grade in a large pool of water. The water provides passive containment cooling and decay heat removal, i.e. the pool provides a heat sink with a capacity to absorb all the decay heat produced by a full complement of mature cores for greater than 30 days. Also, the below grade pool provides enhanced physical security. The design yields a high level of safety and asset production, which should help to address regulatory challenges related to siting the plant near industrial users. Additional benefits of the NuScale plant design are discussed in the following sections with respect to specific non-electrical applications.

Water Desalination

Removing the salt and impurities in seawater is energy intensive and requires either significant amounts of electricity or thermal energy. 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 GHG. Renewable energy sources such as wind and solar are expanding in many regions but their variability and uncertainty of output creates reliability challenges for industrial processes such as desalination. These considerations are driving a growing interest in the development and expansion of nuclear energy options for this application. Although nuclear desalination has been demonstrated, less than 15 of the 16,000 desalination plants world-wide use heat or electricity provided directly from commercial nuclear power plants. Hence it is a largely untapped market for nuclear energy.

The flexibilities afforded by the high level of modularization of the NuScale plant makes it uniquely suitable for desalination applications in a wide variety of locations and coupling with multiple desalination technologies. Of additional importance is the high level of plant resilience afforded by the small unit size, which improves the system response to upset conditions. Since the majority of existing desalination plants use seawater as the feed water source, they are typically 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 Daiichi 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.[4]

A technical and economic evaluation was performed of options for coupling a NuScale plant to a range of different desalination technologies. Three technologies were investigated: multi-effect distillation (MED), multi-stage flash (MSF), and reverse osmosis (RO). 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. However, 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. Both the MED and MSF technologies require a thermal heat source, although a modest amount of electricity is needed for normal plant house load. The thermal heat is typically provided by steam 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.

All three technologies were considered for the 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 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. In the case of coupling with an MED plant, a variation to the typical steam extraction approach was considered whereby steam taken directly from the output of the NuScale module steam generator was used to drive a thermo-compressor (TC) on the MED cycle.

Figure 3 shows the relationship between electrical and water output for a single co-generation NuScale module coupled to each desalination option considered. 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 only potable-quality water while the thermal distillation processes typically produce high purity water. Thus, installations with very low-quality feed water or where large quantities of high purity water are required may be better suited to a thermal distillation process. For the thermal desalination processes, 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.

In order to evaluate the economic factors related to the co-generation option, it was necessary to choose a specific plant size for both the NuScale plant and the desalination plant. It was decided to choose a plant size that could provide: (1) sufficient thermal and electrical power to operate a 190,000 m^3/d desalination plant, which can supply sufficient clean water for a community of 300,000 people, and (2) additionally supply sufficient electricity to the grid to support the electrical demand of the same 300,000 population—a population comparable to the U.S. coastal cities of Corpus Christi or Tampa.

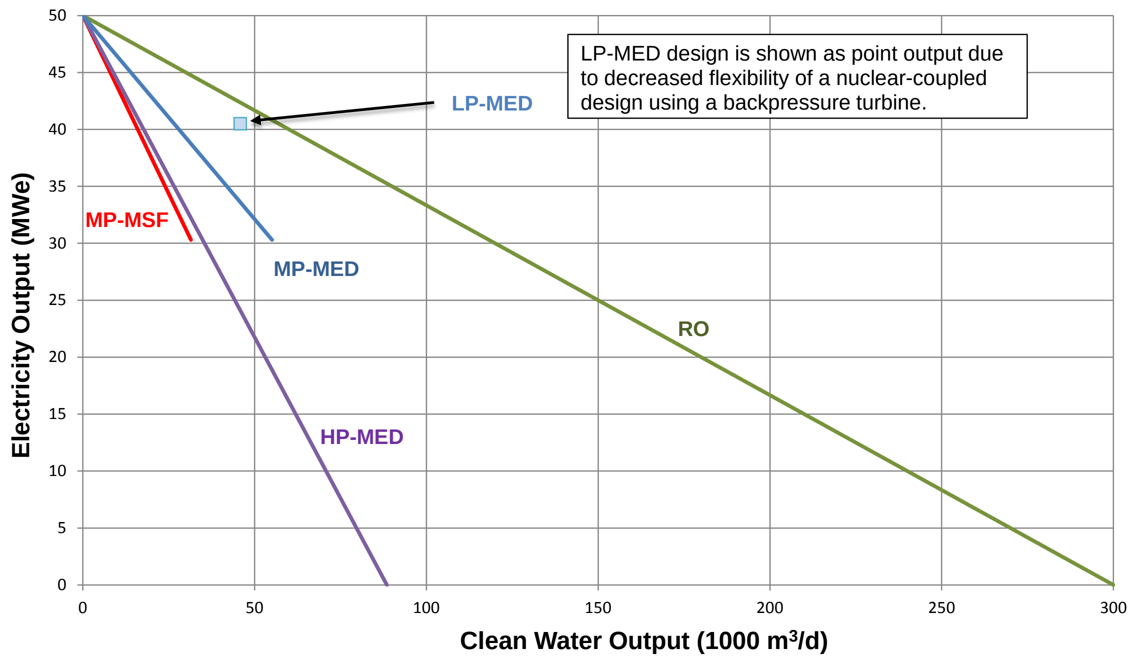


Figure 3. Relationship between electricity and water output from a single NuScale module coupled to a variety of membrane and thermal distillation desalination processes.

Table 1. Summary of economic factors 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
Capital Payback[2] (years)				
Coupled plant simple payback	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.

Table 1 summarizes the economic analysis for an 8-module NuScale plant coupled to four different desalination options. In addition to the RO case, the medium pressure (or extraction steam) design cases were selected for the thermal desalination technologies. The low pressure (or exhaust steam) MED case was also included to highlight the potential reduction in energy costs for this configuration. The thermal energy produced by the NuScale plant was fixed at 1280 MWt (6 x 160 MWt/module), while the electricity provided to the grid depended on the amount of electricity and thermal energy used to produce a fixed 190,000 m^3/d of water product from each of the desalination options. Although simplistic, the analysis provides a reasonably clean comparison of the potential relative profitability of different desalination technologies when coupled to a NuScale plant.

Oil Refining

The production of refined petroleum products is highly energy intensive with most of the energy being used either in the field for crude oil recovery processes or at a refinery for processing of the crude oil into end-use products such as transportation fuels or petrochemicals. Over the past decade, roughly 7% of the total U.S. energy consumption is by oil refineries, which represents roughly 1800 TWhr (6,140 TBtu) annually, or an average power demand of 200 GWt. Older refineries can consume up to 15-20% of the energy value of their feedstock for supplying process heat,[5] although modern refineries average closer to 6% and use almost entirely natural gas feedstock or refinery fuel gas to produce the required heat.[6] Depending on the actual process, energy may be needed in the form of steam, electricity or direct fired heat as discussed below.

The energy demands in the field and at the refinery are quite different and have different implications on the types of energy sources used for these applications. Nuclear energy represents an attractive technology because of its abundant, reliable and clean energy characteristics. As with the case of water desalination, the NuScale nuclear plant design is well suited for oil recovery and refining applications due to its small unit size, which provides enhanced safety and plant resilience, affordability through incremental capacity growth, and reliability through continuous power output from a multi-module plant. While the small unit size of the NuScale design could create a unique opportunity for oil recovery operations, the focus of the recent study was on oil refining applications.

A multi-module, multi-output NuScale plant can be easily customized to the needs of a specific refinery while maintaining a highly standardized nuclear power module design. A single NuScale power module produces roughly 245,000 kg/hr of superheated steam with an outlet temperature of approximately 300°C. To accommodate the superheated steam and buffer the reactor from the refinery processes, a secondary heat transport medium can be used such as high pressure water or a specially designed heat transfer fluid such as DOWTHERM™. An intermediate heat exchanger transfers heat to the secondary fluid stream for use in pre-heating refinery process inputs and provides additional isolation between the reactor and refinery. The end-use heated fluid characteristics can be adjusted as needed to match the requirements of a specific process. An initial estimate is that a single 160 MWt module can provide for pre-heating of several refinery process input streams to 288°C (550°F). A schematic of a potential coupling between a NuScale module and an oil refinery is given in Figure 4. An economic assessment for this type of coupled operation is discussed below for a representative refinery.

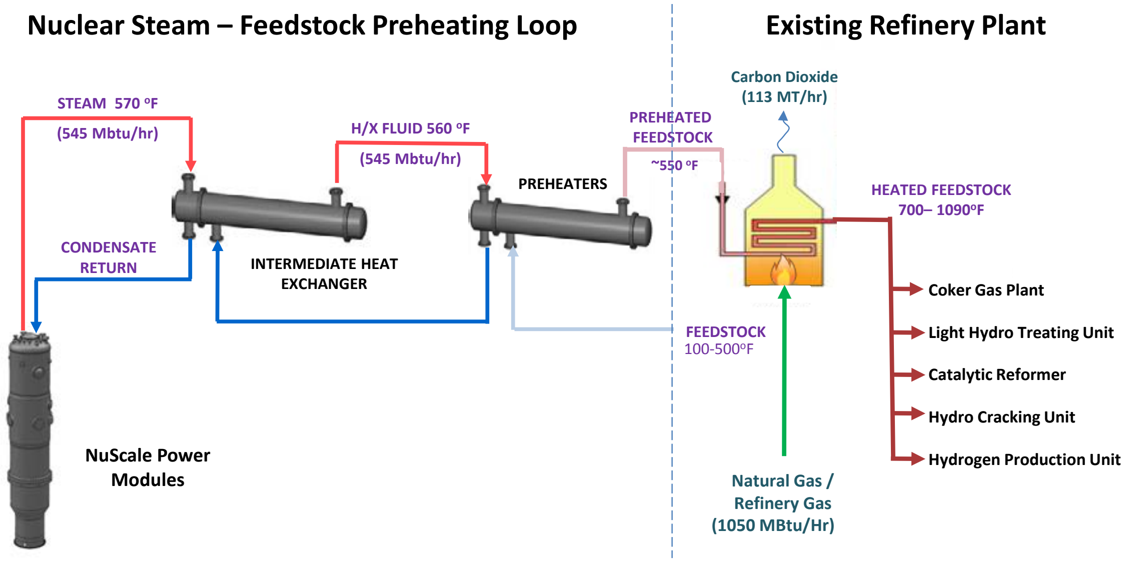


Figure 4. Simplified arrangement of a NuScale plant coupled to an oil refinery.

Another attractive feature of the NuScale plant design for this application is the staggered refueling of modules. The plant is designed with a high level of independence between modules, including the power conversion systems, so that other modules can continue to produce electricity (or steam) while one of the modules is off-line for refueling. Many refinery processes become very inefficient if disrupted and therefore have a high reliability requirement. A multi-module NuScale plant uniquely provides for redundancy and availability of energy supply. Although the output of a NuScale module is in the lower range of process temperature requirements, a variety of hybrid cycles have been suggested in the literature that could be used to boost the end-use steam temperature.

To understand the economic viability of supporting a refinery with a NuScale plant, a typical large-size refinery was selected capable of processing 250,000 barrels/day of crude oil to produce diesel fuel, gasoline, petroleum coke and other petroleum products. Anticipated energy demands for this scale of refinery are listed in Table 2.

Table 2. Primary energy demands for typical 250,000 barrels/day refinery

Traditional Energy Source	Energy Demand (MBtu/hr)	Replaceable by NuScale
Natural Gas		
For 250 MW of electricity	1,900	1,900
For H_2 production	4,100	No
For fired heaters	1,800	1,660
For pilot lights	140	No
Refinery Fuel Gas		
For fired heaters	2,000	No

Six NuScale modules are sufficient to provide the required 250 MWe of electricity for the refinery, as well as the house load for the NuScale plant. To determine how many modules are needed to meet the non-electrical energy demands requires a better understanding of the detailed process flow characteristics of the refinery. For example, although steam output from NuScale modules could be used to replace the refinery fuel gas (RFG) for some of the fired heaters, the RFG is a by-product of refinery processes and it is more cost-effective to consume it internally than to process it further for external use. Also, the use of natural gas (NG) in a methane reforming process is currently the most efficient process for hydrogen production. However, the technical and economic suitability of using a NuScale plant to produce hydrogen through a high-temperature steam electrolysis method is being evaluated, as discussed in the next section. Of the 1,800 MBtu/hr energy demand listed for NG-supplied fired heaters, it appears that NuScale-supplied steam can provide approximately 1,660 MBtu/hr. This requires four NuScale modules in addition to the six modules needed to supply the electrical demand. Hence, a 10-module NuScale plant can meet the selected energy needs indicated in Table 2.

Table 3 summarizes the economic assessment of a 10-module NuScale plant coupled to the refinery. The capital cost for the refinery assumes a typical 250 MWe gas-turbine combined cycle plant is used to produce electricity from the NG. The estimated NuScale capital cost is for an nth-of-a-kind 10-module plant. The estimated operating cost for the NuScale plant includes annual operations and maintenance costs, nuclear waste fee, and decommissioning fund contributions. The fuel cost for the NuScale plant is assumed to be fixed at $48 million/yr, while the NG cost is treated as a variable ranging from $4 to $14/MBtu.

Table 3. Economic factors for 10-module NuScale plant coupled to 250,000 bbl/d refinery

	Fossil Heat	With NuScale	Savings
NG Consumption (MBtu/hr)	7,960	4,366	3,594
CO_2 Production (MT/hr)	525	336	189
Capital Cost (million)	$ 290	$ 2,100	($ 1,810)
Owner's Cost (million)	$ 70	$ 310	($ 240)
Annual Operating Cost* (million)	$ 6.8	$ 104.6	($ 97.8)
Annual Fuel Cost (million)	$ 280 - $ 980	$ 48	$ 232 - $ 932

*Does not include financing fees, taxes or fuel costs

A series of sensitivity studies was conducted for both O&M costs and capital cost payback with a $4-14/MBtu range for NG price and a range of $0-60/MT for carbon emission tax. The results indicate that the NuScale-coupled refinery O&M costs become favorable with an NG price of about $5/MBtu and no carbon tax. The annual savings, due largely to fuel costs, becomes significantly larger as NG prices increase or carbon emission taxes are added. A NG price of $9.5/MBtu allows a 25-year payback of the total capital investment, which drops to $7.5/MBtu if a $40/MT carbon tax is imposed.

Based on a simple analysis, the NuScale economics look viable for supporting large refinery applications, even in the absence of emission penalties. This is particularly true in countries or regions of the U.S. where low-cost natural gas is not available. Given regional differences in energy costs, a more refined study may identify domestic and international locations with more favorable economics. Also, given the uncertainties in emission penalties, it may be possible to develop a long-term electricity (and steam) purchase agreement structure that is mutually attractive and allow the oil companies to hedge against future emission restrictions and costs.

Hydrogen Production

As demonstrated in the previous two studies, the thermal energy produced by an LWR may be used for low-to-moderate temperature processes such as water desalination and petroleum refining. It can also be used to produce hydrogen and oxygen via steam electrolysis. The U.S. currently uses over 12 million tons of hydrogen each year for fertilizer production, petroleum and metals refining, and the food industry. Additionally, the build-out of an unconventional hydrocarbon fuels industry in the U.S. and China, in which coal is converted to advanced liquid fuels, will need millions of tons of clean hydrogen per year to avoid excessive carbon emissions and to better steward fossil fuels and biomass resources. The anticipated eventual penetration of fuel cell technology into the transportation sector will create a substantial additional demand for hydrogen but will only have a significant impact on GHG reduction in this energy sector if the hydrogen is produced using carbon-free sources of energy.

In general, hydrogen can be produced by stripping it from a hydrocarbon fuel such as methane or by splitting water. Given the low cost of natural gas, steam-methane reforming is the most common method of producing hydrogen in the U.S. It requires combustion of roughly 10-15% of the methane in the feed stream to generate the heat and steam necessary to split the remainder of the methane; consequently, the resulting emission of CO_2 is a concern. Alternatively, electrolysis can dissociate water or steam into a clean source of hydrogen and oxygen. High-temperature steam electrolysis (HTSE) is an emerging technology and is ~40% more efficient than conventional water electrolysis.

A study was conducted to establish a cost baseline for producing hydrogen when supplying heat and electricity to an HTSE process. The results of the study help evaluate the market case for producing hydrogen, either as a standalone hydrogen/oxygen plant or with load management within a hybrid energy system. The ASPEN HYSYS code was used to model integration of a NuScale reactor module with a Rankine power cycle and a co-located HTSE plant. HYSYS allows for accurate mass and energy balances and contains all of the fundamental process components in the plant, e.g., compressors, turbines, pumps, valves, and heat exchangers.

In this case study, heat and electrical power produced by a NuScale power module (NPM) was directly routed to a proportionally scaled HTSE unit operating at 800°C. A tertiary steam loop by-pass was added to the NPM power cycle steam delivery loop to transfer heat to the HTSE plant. Condensate produced in the HTSE loop was recombined with the turbine condensate in the reactor feed water loop. All of the electricity produced by the NPM was directly supplied to the HTSE block. Figure 5 provides a simplified process flow diagram of a NuScale module coupled to an HTSE unit.

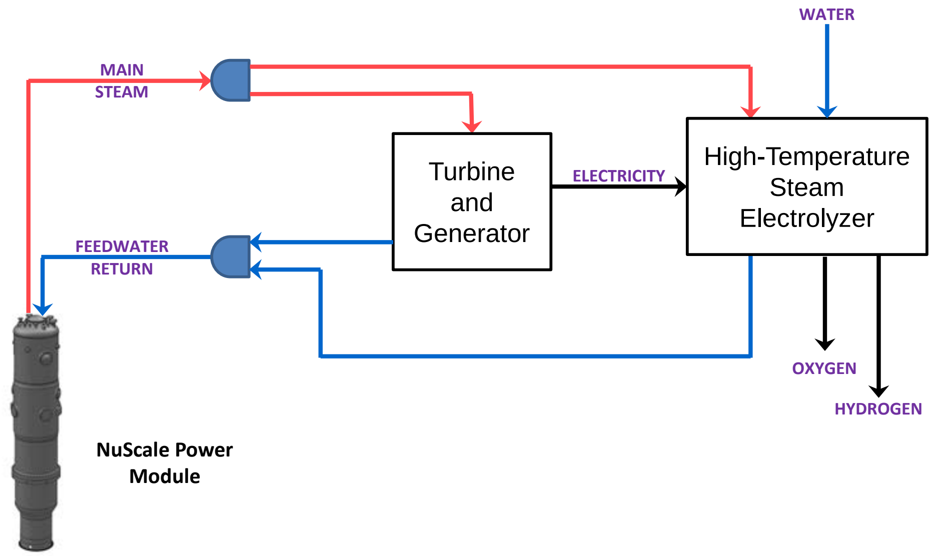


Figure 5. Simplified process flow for single NuScale module and HTSE unit hydrogen plant.

Within the HTSE block, a custom heat recovery scheme was used to cool the hot hydrogen and oxygen product streams in order to preheat the HTSE feed water and then to superheat the inlet steam and gas recycle flows. The HTSE steam loop delivered the heat necessary to boil and flash the preheated HTSE feed water and to partially superheat the high-pressure steam. A small amount of electrical power (1.15 MWe) from the NPM was needed to boost the inlet temperature of the HTSE feed steam and recycle gases to approximately 800°C and the balance of electricity was used to electrolyze the high-pressure steam/hydrogen mixture. Table 4 provides a summary of the key mass/energy parameters.

Table 4. Key parameters for hydrogen production.

Parameter	Value
Number of NuScale modules	1
Power Cycle Efficiency	31.8%
Electricity Generation (MWe)	46.2
- HTSE Electrolyzer	44.9
- HTSE Pumps and Circulator	0.11
- HTSE Topping Heaters	1.15
Process Heat Generation (MWt)	12.3
Number of HTSE units	1
Hydrogen Production Efficiency	32.0%
Water Consumption (kg/hr)	11,900
Water Consumed/Hydrogen Produced	9.04
Gas Production Rates	
Hydrogen (kg/hr)	1,310
Oxygen (kg/hr)	10,400

The study showed that one 160-MWt NuScale module can optimally produce about 1,310 kg/hr (2,900 lb/hr) hydrogen and 10,400 kg/hr (23,000 lb/hr) oxygen using one matched-scale HTSE module. The hydrogen and oxygen product are 99% pure and no GHG are produced with this method of hydrogen/oxygen production. A medium-scale hydrogen production plant of about 200 tons/d hydrogen would require six NuScale modules. This scale of plant would readily produce sufficient hydrogen for a mid-size commercial ammonia production plant of approximately 1,150 tons/d,[7] a typical distributed-scale petroleum refinery of 40,000 to 50,000 barrels/d,[8] or a cluster of steel refining mills.

A standard parametric evaluation of the process economics was completed to determine the sensitivity of hydrogen/oxygen product costs to: hydrogen plant size, HTSE configuration, cost of electricity, capital costs, and internal rate of return on capital investment. The results of the economic assessment favor traditional natural gas reforming due to current U.S. natural gas costs and the mature reforming technology. A coupled NuScale-HTSE plant for hydrogen production may become competitive depending on several economic factors, including increased natural gas prices, carbon emission penalties, and optimization of the HTSE process. Also, a NuScale-HTSE plant can be coupled with wind and solar energy generators in a hybrid energy system that can allow greater penetration of the renewable sources while providing a carbon-free solution to large-scale electricity and hydrogen production.

Summary

The NuScale SMR plant design has been demonstrated to be well suited for expanding nuclear energy to a variety of non-electrical applications, including water desalination, oil refining, and hydrogen production. In all cases, the co-generation of electricity and process steam can be easily accommodated by the modular nature of the NuScale plant. The economic competitiveness of using a NuScale plant for these applications appears promising, but depends on many economic factors—most importantly the cost of natural gas and the penalty for carbon emissions. What is clear is that the NuScale plant design provides an attractive solution for clean, abundant and reliable energy for a wide range of energy customers.

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