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Can Nuclear Power and Renewables be Friends?

D. T. Ingersoll,[a] C. Colbert,[a] Z. Houghton,[a] R. Snuggerud,[a] J. W. Gaston[b] and M. Empey[c]
[a]NuScale Power, LLC
1100 NE Circle Blvd, Suite 200, Corvallis, OR 97330
[b]Energy Northwest
P. O. Box 968, Richland WA 99352-0968
[c]Utah Associated Municipal Power Systems
155 North 400 west, Suite 480, Salt Lake City, UT 84103
Tel: 541-360-0585, Email: dingersoll@nuscalepower.com

Abstract – *The increasing penetration of renewables, especially wind generation, have dramatically changed the economics and realities of grid management in ways that now encourage some level of load-following capabilities for historically baseload plants, including nuclear. The NuScale small modular reactor design currently under development in the United States is well suited for integration with renewables because of several design features related to the nuclear steam supply system, the power conversion system, and the overall plant architecture. The multi-module nature of a NuScale plant allows the plant output to be varied in three ways spanning a wide range of different time frames: (1) taking one or more modules offline for extended periods of sustained wind output, (2) adjusting reactor power for one or more modules for intermediate periods to compensate for hourly changes in wind generation, or (3) bypassing the steam turbine for rapid responses to wind generation variations. Results are presented from a recent analysis of nuclear-wind integration that utilized historical wind generation data from the Horse Butte wind farm in Idaho. Also discussed is the experience of Energy Northwest in their implementation of limited load-shaping at the Columbia Generating Station.*

I. INTRODUCTION

Competition for constrained federal funding and ideological biases have tended to pit various energy technologies against each other, especially between renewable sources, typically wind and solar, and traditional sources, including hydro, coal, natural gas, and nuclear. Of the traditional sources, only hydro and nuclear offer abundant power with virtually no emission of greenhouse gases (GHG). However, new sites for large hydroelectric plants are very limited and have their own environmental issues. As such, nuclear appears to be the only resource that has the potential to not only add to the “clean” energy provided by wind and solar technologies, but actually enable larger contributions of these renewable sources without jeopardizing grid stability or risking unmet electricity demand. However, doing so may require nuclear plant designs to incorporate features that enhance their load-following capabilities.

Conventional wisdom suggests that nuclear power plants should be operated continuously at full capacity and that natural gas plants are best suited to provide “peaking” capability to meet excess demand. This historical strategy has been driven mostly by economic considerations since nuclear plants have relatively high capital cost and low fuel cost compared to natural gas plants. Because of the low fuel cost in a nuclear plant, running the plant at 50% power has minimal impact on operations costs but reduces revenue by one-half. The increasing penetration of renewable sources, especially wind, has altered this economic argument since wind turbines are also capital-intensive (per unit of power produced) and their fuel cost is zero. Also, wind generation tax credits encourage their full-out operation. Finally, some regional policies require grid dispatchers to preferentially use renewable energy first, which exacerbates the economic challenges of operating base-load plants and are driving plant owners to change their concepts of economic dispatch.

Many nuclear plants currently operating were designed to load-follow and were originally outfitted with automatic grid control (AGC) features. However, the U.S. Nuclear Regulatory Commission established a policy that precluded the use of automatic dispatching for true load following, although they allow manual load-shaping if conducted by a licensed reactor operator. Globally, France’s pressurized water reactors routinely load-follow due to the high percentage of nuclear-generated electricity on their grid (nominally 75%). Canadian reactor units are also required to load-follow due to the percentage of nuclear power there and German reactors load-follow primarily because of a relatively high contribution of intermittent wind generation on their grid.[1]

Load-following with nuclear plants, especially larger plants, requires complicated power maneuvering procedures and plant components that can tolerate thermal cycling. The 1,170 MWe Columbia Generating Station (CGS) in Richland, Washington, is the only commercial nuclear plant in the United States that performs routine power maneuvering in response to anticipated load variations—a process that they refer to as load shaping. The load-shaping capability is required during the spring season to avoid excessive spill-over at the hydroelectric plants in the Bonneville Power Authority (BPA) network. An increasing wind generating capacity in the BPA network may also introduce new load-shaping requirements at the CGS. Case in point: a record-breaking 4,289 MWe of wind generation was produced on the BPA transmission network on October 16, 2012, which was the first time in history that wind generation surpassed the output of the region's hydroelectric generation.[2]

The CGS performs short-term load shaping according to guidelines agreed to by the BPA and approved by the US NRC. Generally, operators adjust reactor recirculation flow to maneuver the plant to 85% of full power and adjust control rods to drop power to 65% power. The maneuvers are performed in response to down-power requests from BPA, which must be received at least 12 hours prior for reduction to 85% power, 48 hours for reduction to 65% power and 72 hours for full shutdown. Power maneuvers between 100% and 85% using reactor recirculation flow adjustments are relatively straight forward but can require many small adjustments due to the buildup and decay of xenon in the fuel, which is a strong neutron absorber. As an example, a single step-change cycle to 85% power, return to 100% power and subsequent reduction back to 85% power can require as many as 17 different reactivity manipulations using recirculation flow and control rod movement.

II. SMALL MODULAR REACTORS

There has been a growing interest in the United States and internationally for the development and deployment of smaller sized commercial nuclear power plants to meet the expanding need for clean, abundant power in a broader range of energy markets. These small modular reactors (SMRs) are characterized by having power ratings generally below 300 MWe and are substantially factory manufactured and installed into the plant rather than stick-built on the site. Multi-module deployments use multiple identical SMRs in a single plant to provide a scalable, flexible approach to deploying nuclear power. Because of their scalable and flexible plant features, these designs are expected to be more readily adaptable to integration with inherently variable generating sources such as wind.

A highly innovative SMR design has been under development in the United States since 2000 and is being commercialized by NuScale Power with the strong financial backing of Fluor Corporation and the US Department of Energy. The robust and scalable nature of the NuScale plant design, which is based on well-established light-water reactor (LWR) technology, creates a unique solution to provide affordable, clean and abundant energy to the grid in the near-term with the opportunity to complement the increasing generation from renewable sources, especially wind turbines. The coupling of emissions-free renewables and nuclear power can reduce the overall greenhouse gas (GHG) emissions in the United States to help achieve our desired air quality standards and meet evolving GHG emission policies in response to climate change concerns.

The NuScale plant features are especially well suited for the energy demographics in the northwestern United States and considerable interest has emerged in deploying NuScale plants in this region. The Utah Associated Municipal Power Systems (UAMPS) recently announced the establishment of a Carbon Free Power Project to pursue the construction of a NuScale plant within their operating region, potentially on or near the Idaho National Laboratory Site outside Idaho Falls, ID. Also near Idaho Falls is the Horse Butte Wind Farm (HBWF), which contributes nearly 60 MWe to UAMPS Members. Therefore, an initial analysis was conducted to understand the potential integration of a NuScale plant with the HBWF and to demonstrate the compatibility and synergy of these clean energy sources. This paper provides a brief description of the design and characteristics of the NuScale SMR and the HBWF, followed by results and conclusions from the integration of these two generating sources, including implications on load-following operations of the NuScale plant.

III. NUSCALE DESIGN OVERVIEW

The NuScale SMR plant is an innovative design that builds on sixty years of world-wide experience with the commercial application of pressurized water reactor (PWR) 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 plant application while allowing for standardized and simplified construction, operation and maintenance to improve safety and lower lifecycle costs.

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 pressure vessel, which is immersed in a large pool of water. Several power modules (as many as 12) are co-located in the same pool to comprise a single plant. A dedicated turbine/generator system is coupled to each module to provide a gross electrical power of 50 MWe.

A diagram of the NuScale power module is shown in Fig. 1. The reactor vessel is approximately 17.7 m (58 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. Above the core is a central hot riser tube, a helical coil steam generator surrounding the hot riser tube, and an internal pressurizer.

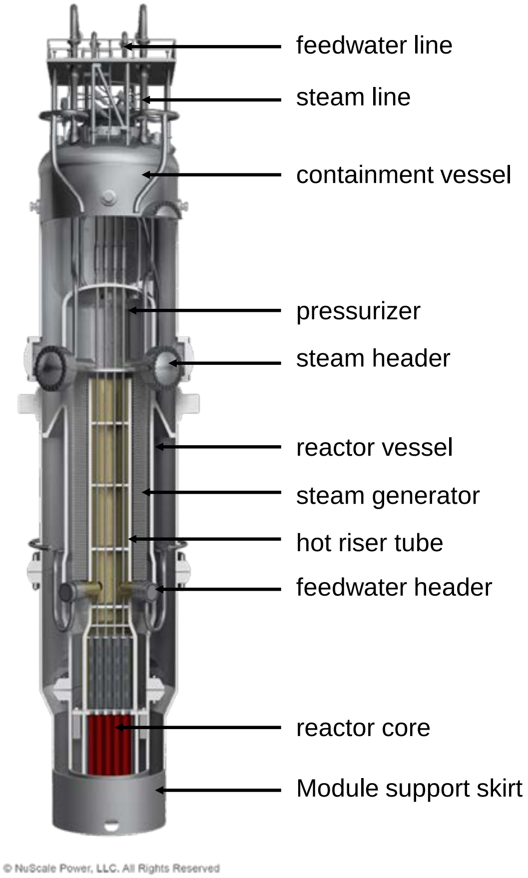

Fig. 1. Schematic of a NuScale power module.

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 annulus. On the secondary side, feedwater is pumped into the steam generator 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 vessel that is approximately 23.2 m (76 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. Multiple modules are placed in a single large pool contained within an aircraft-resistant reactor building. A cut-away view of a twelve-module reactor plant is shown in Fig. 2.

As can be seen in Fig. 2, the NuScale power modules are located below grade in a large common 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 the entire decay heat produced by up to 12 fully mature cores for greater than 30 days. After 30 days, air cooling of the 12 NuScale power modules is sufficient to avoid fuel damage. The pool also helps to reduce and delay fission product releases 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 additional challenges to fuel access.

There are several key features of the NuScale plant that collectively distinguish it from the many other SMRs being developed today.

- *Compact size.* The nuclear steam supply system, including containment, can be entirely prefabricated off site and shipped by rail, truck or barge to the site. This reduces construction time due to parallel fabrication considerations and reduces overall schedule uncertainty due to the reduced amount of on-site construction activities.
- *Natural circulation cooling.* Natural circulation operation and integral design eliminates pumps, pipes, and valves in the primary system and hence the maintenance and potential failures associated with those components, while also reducing house load.
- *Triple Crown of Safety.* The NuScale plant, with its innovative design is able to safely shut down and self-

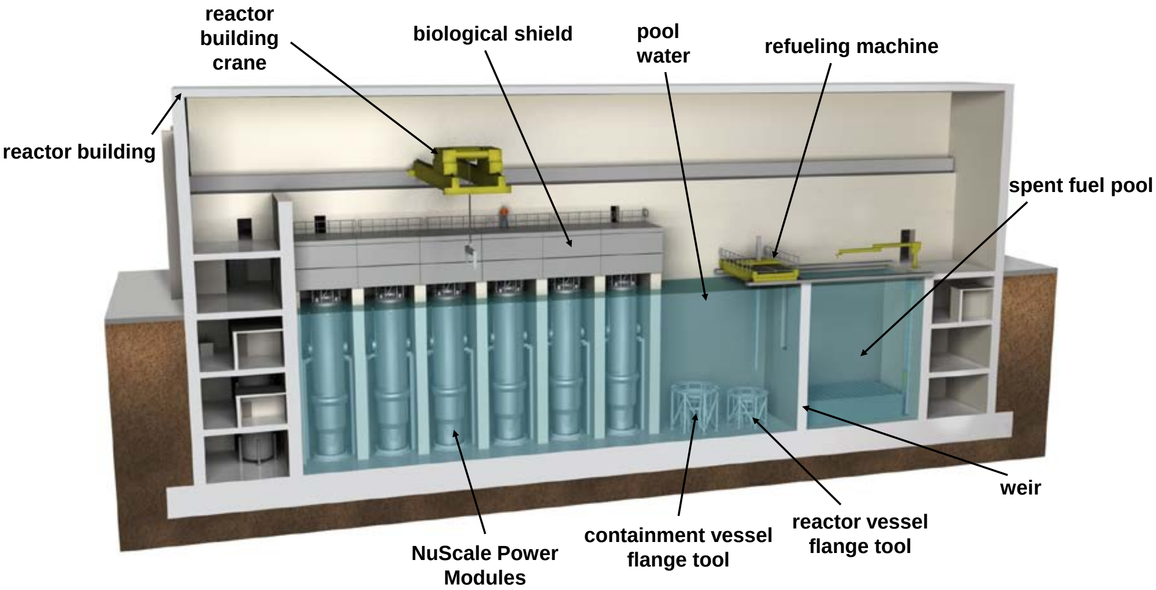

Fig. 2. Cut-away view of reactor building for 12-module NuScale plant.

- cool with no operator action, no AC or DC power, and no additional water for an unlimited period of time.
- *Dedicated power trains.* Because each power module, including the power conversion system, is independent of other modules, each module can be shut down while other modules continue to operate. This feature allows for flexible dispatching of the plant output to match grid demand or balance intermittent generation from wind turbines.

The synergy created by these unique features, especially plant simplicity and the plant-level flexibilities afforded by the multi-module configuration, all combine to position the NuScale plant for early and successful integration with renewable generating sources.

IV. UAMPS CARBON FREE POWER PROJECT

In October 2014, the Utah Associated Municipal Power Systems (UAMPS) announced the introduction of their Carbon Free Power Project (CFPP). UAMPS is a consortium of 44 utilities with service areas in eight states, including Utah, Arizona, New Mexico, Idaho, California, Nevada, Oregon and Wyoming. The consortium established their CFPP to encourage the deployment of clean baseload electrical power options in response to the expected closure of coal fired generating plants in the coming decades. As a result of their SmartEnergy analysis, UAMPS concluded that SMRs represent an important option for their future consideration and are working with NuScale Power for the deployment of the first NuScale plant within the UAMPS service area. Although site evaluations are underway, a promising location for the plant is in the vicinity of Idaho Falls, Idaho—possibly on the 890 mi^2 Idaho National Laboratory (INL) federal reservation. Energy Northwest (ENW) is expected to be the operator of the UAMPS CFPP plant in Idaho. They bring not only their experience in operating the CGS, but also their experience in load-shaping maneuvers on a large nuclear plant.

Also in the vicinity of Idaho Falls is the Horse Butte wind farm (HBWF). The 17,600 acre wind farm was commissioned in 2012 and is comprised of 32 Vestas V100 turbines, each with a capacity of 1,800 kWe, yielding a maximum generating capacity of 57.6 MWe. The turbines, operated by UAMPS, have a hub height of 80 m and a diameter of 100 m. The location of the HBWF and the INL Site relative to Idaho Falls is shown in Fig. 3.

Fig. 3. Location of Horse Butte wind farm and Idaho National Laboratory Site in Idaho.

V. INTEGRATING NUSCALE PLANT WITH HBWF

The NuScale plant incorporates unique features that enhance its ability to load follow, either due to changes in electricity demand or variable generation by renewable sources on the grid. This is accomplished through a combination of the small unit capacity of a NuScale module (50 MWe gross) and a multi-module approach to the plant design. This design strategy provides a uniquely scalable plant and gives the plant owner considerable flexibility in both the build-out of the plant and also its operation, including for load-following. The key power management options of the NuScale plant for load-following operations, designated NuFollow™, include the following:

- Taking one or more modules offline for extended periods of low grid demand or sustained wind output,
- Maneuvering reactor power for one or more modules during intermediate periods to compensate for hourly changes in demand or wind generation, or
- Bypassing the module's steam turbine directly to the condenser for rapid responses to load or wind generation variations.

Each of these methods has a different response time and implications with respect to plant performance and operation. In general, their impacts are reduced relative to large plants due to the smaller reactor systems, smaller turbine/generator systems, and system simplifications that are enabled by the smaller reactor size.

Equipment in the NuScale plant is being designed for load-following operation to further reduce impacts from power cycling. One example is that the module design and operating parameters allow reactor power changes using only control rod movement down to 40% reactor power, i.e. it does not require adjustments to the boron concentration in the primary coolant. This improves the maneuverability of the reactor while not creating additional liquid wastes associated with boron addition and dilution. The condenser is designed to accommodate full steam bypass, thus allowing rapid changes to system output while minimizing the impact to the reactor, which can continue to run at full power. Finally, the multi-module nature of the NuScale plant and the staggered refueling of individual modules result in a plant configuration in which at least one module is near beginning of life (BOL). It is generally easier to perform power maneuvers on BOL cores because of the higher reactivity in the core enables™ better xenon override. Therefore the operator has the flexibility to use near-BOL modules to perform power maneuvering functions for intermediate-term load-following while the modules with higher burnup can be used for coarse-level power adjustments.

The Electric Power Research Institute (EPRI) maintains the User Requirements Document (URD), which is a major compendium of guidelines and specifications for standardized plant designs, including specifications for desired load-following characteristics. EPRI recently updated the URD to Rev.13 specifically to envelope SMRs. The new version contains more aggressive load-following specifications to reflect the more flexible features anticipated for SMRs. The NuScale plant is able to meet all of the new Rev.13 requirements, as listed in Table 1.

To understand how well a NuScale plant can mitigate variability from a wind farm, an analysis was conducted using actual wind generation data from the Horse Butte wind farm. The HBWF presents an especially challenging case study because its total generating capacity is comparatively small (less than 60 MWe), which can result in short-term changes in generation that are significant fractions of the farm's total output. Figure 4 shows the frequency of occurrence of 5-minute changes in output from the HBWF, expressed as percent per minute and normalized to the maximum wind generation during a 7-day period. This frequency distribution is compared to similar 7-day results for wind generation across the entire BPA system, which was roughly one hundred times larger than the HBWR output. As seen in the figure, most of the ramp rates for the larger BPA system were on the order of 1% per minute. In contrast, the HBWF experienced a significant number of ramp rates up to 5% per minute. Hence in this case, the smaller HBWF requires a higher level of agility from the NuScale load-following response.

It should be noted, however, that the substantially larger total output from the BPA system results in a different challenge—one of bulk replacement power. Over the same 7-day period shown in Fig. 4, the absolute BPA wind output varied from zero to over 4.2 GWe, and the largest 5-minute change was 136 MWe. Output changes of this magnitude require a combined response of several generating assets on the grid, including nuclear, hydroelectric and fossil.

Figure 5 provides a hypothetical scenario to demonstrate the integration of a NuScale plant with the Horse Butte wind farm. Included in the graph are: (1) the US-averaged daily electricity demand profile (arbitrary normalization) showing typical morning and evening demand peaks, (2) the actual generation from the HBWF taken for a single day in November, 2014, and (3) the output from a single NuScale module that would be needed to meet the grid demand beyond what the HBWF can provide.

Table 1. Load-following characteristics included in EPRI User Requirements Document specifications.

URD Requirement	**Rev.12 Description**	**Rev.13 (SMR) Description**
3.4.1.1	24 hour load cycle: 100% → 50% → 100%	24 hour load cycle: 100% → 20% → 100%
3.4.1.1	Ramp rate of 25% per hour	Ramp rate of 40% per hour
3.4.2.1	Capable of automatic frequency response	Capable of automatic frequency response
3.4.3	Step change of 20% in 10 minutes	Step change of 20% in 10 minutes
3.4.4.1	Frequency variation tolerance	Frequency variation tolerance

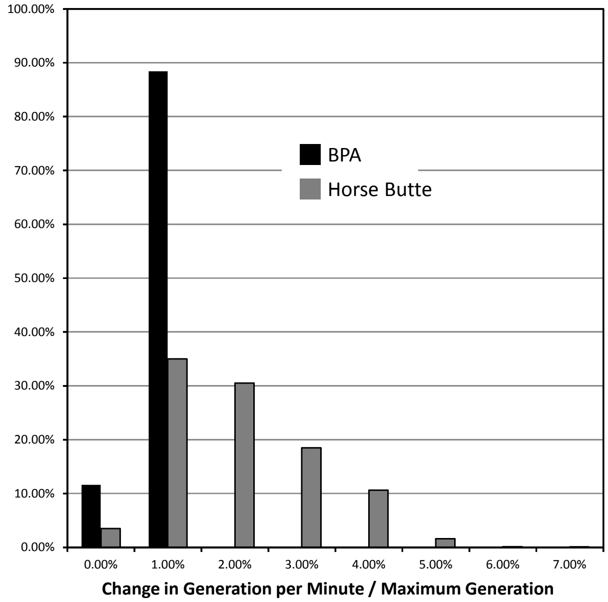

Fig. 4. Impact of wind farm size on relative generation changes.

Figure 6 provides two examples of how the NuScale module might yield the desired output. In one case, shown in the upper portion of the figure, the variation in the NuScale output is entirely a result of turbine bypass, i.e. the reactor continues to operate at full power. The amount of wasted power, which results from dumping main steam directly to the condenser, is also plotted and exactly tracks the power produced by the wind farm. Another approach that achieves the same demand-matching is to maneuver the module's reactor power for coarse-level load shaping and to use the turbine bypass equipment to provide the balance of load-following. This option is shown in the lower portion of the figure. This scenario has the benefit of reducing both the amount of wasted energy and cycling of the power conversion equipment. However, the dispatcher must have an accurate forecast of wind power and the operator must be allowed to make changes in reactor power with minimal notice. Forecast and dispatch adjustments would need to be made hourly to support these types of operations. Also, maneuvering the reactor power introduces a number of operational considerations.

From an economic perspective, it is preferable to not throttle back the nuclear plant or dump steam, but rather sell the excess electricity from the combined output of the HBWF and the gross output from the NuScale module to neighboring utilities. However, this may not be an option in some applications and locations. One method for selling such excess power is currently in the early stages of deployment, the Electricity Imbalance Market (EIM). This new market was established to help balancing authorities cope with increased penetration of non-dispatchable renewable energy. Participation in this market requires the unit to have Automatic Generation Control (AGC), among other features. Adaptation of AGC to nuclear power is not new technology; however it will require new approaches and considerations to accommodate regulatory policies.

An alternative to selling excess capacity is to use the power, either as electricity or steam, to support non-grid applications such as water desalination or chemical production. Using this "hybrid energy system" approach, the combined wind and nuclear output can be optimized to meet grid demand and yield additional valued products without requiring the nuclear plant to vary its output. Interest has been growing in recent years for the economic benefits of hybrid energy systems, especially for integration of nuclear power and renewables.[3,4]

This simple case study demonstrates that the NuScale plant can be integrated with intermittent renewable sources, even for the challenging dynamics of a smaller scale wind farm. The plant's NuFollow™ features allow for enhanced load-following capabilities and several operational flexibilities for responding to demand and generation variations.

Even with the NuFollow™ features, load following with a nuclear plant has several operational and economic impacts. Reactor operations are the least impacted when changes in electrical output are accomplished by closing or opening the bypass valve to redirect main steam flow from the turbine to the condenser. This can be done much more

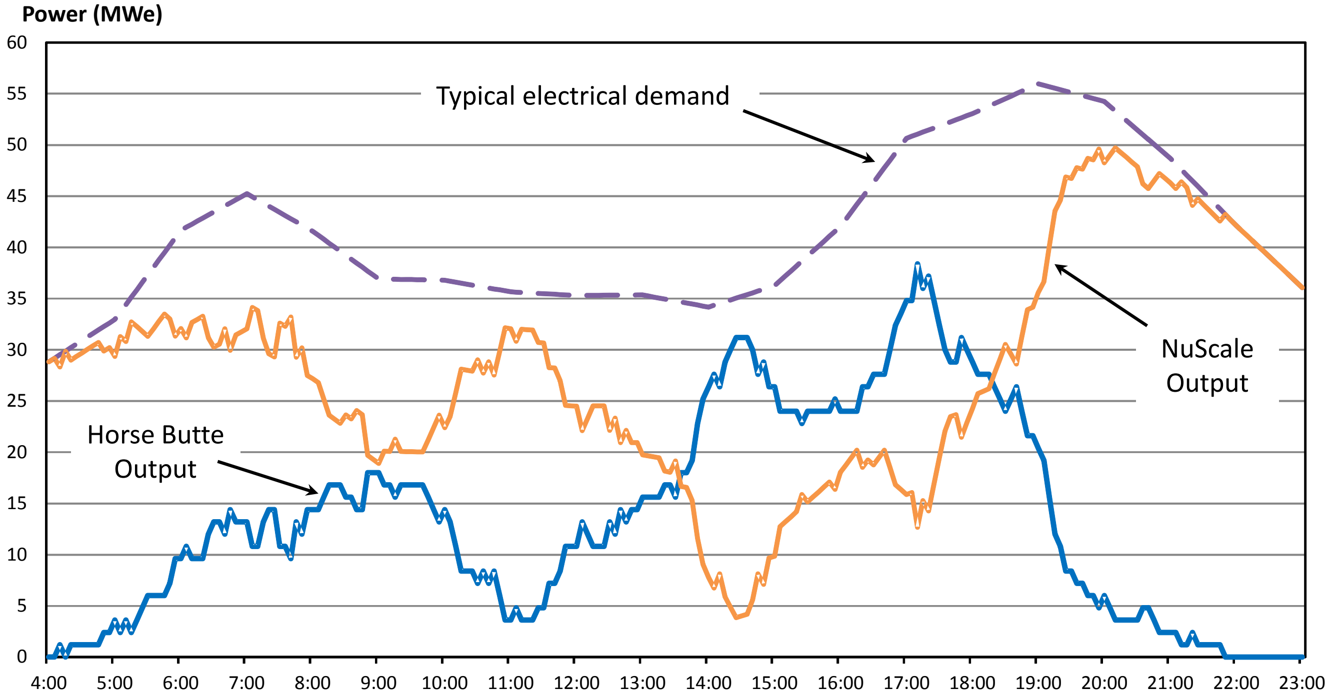

Fig. 5. Example of NuScale module load-following to compensate for generation from the Horse Butte wind farm and daily demand variation.

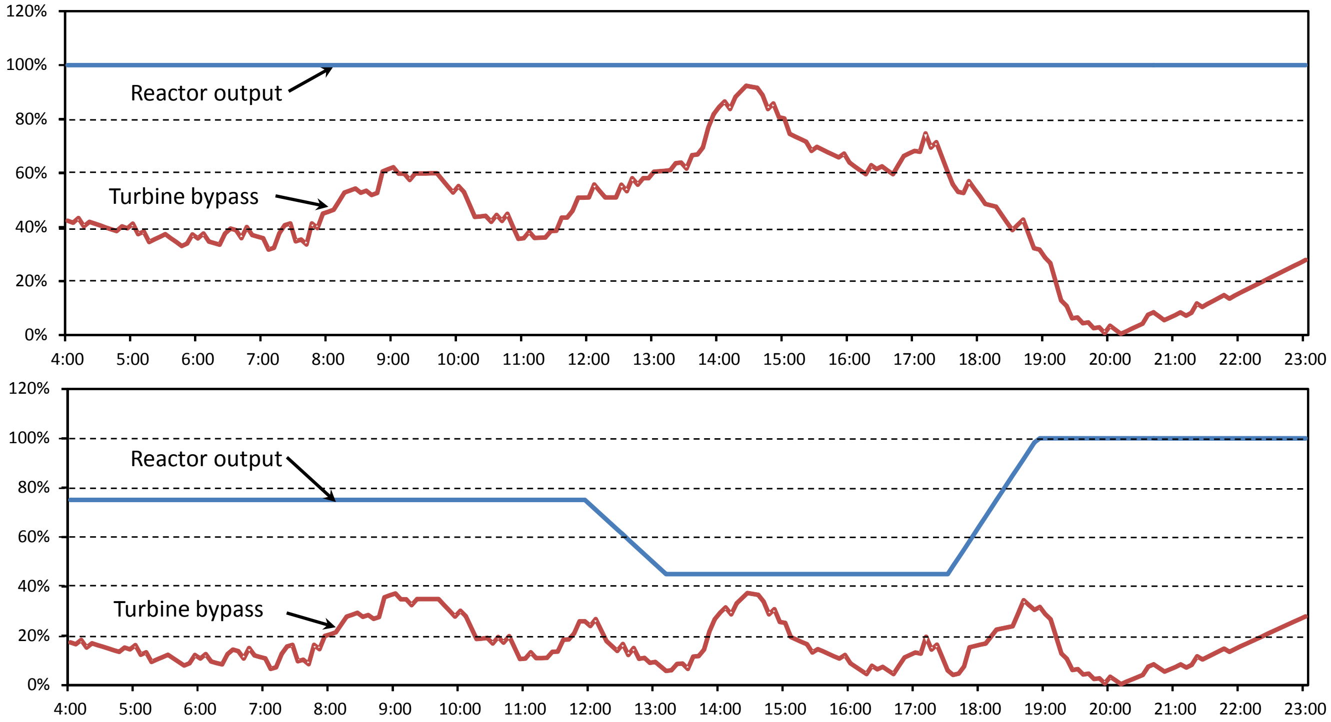

Fig. 6. Two load-following options to achieve the NuScale module output shown in Fig. 5: use only turbine bypass (upper graph), or use combination of reactor power maneuvering and turbine bypass (lower graph).

quickly than adjusting reactor power and allows for increased maneuverability of the plant's output. The drawback of this operation is that an excessive amount of energy is wasted in the form of turbine bypass flow and extended periods of high bypass flow to the condenser will tend to increase wear on the equipment, thus resulting in increased maintenance and equipment replacement.

Adjusting reactor power for partial or full load-following requires a reliable wind forecast such that reactor power can be scheduled for daily or even hourly dispatches while remaining at a power level reasonably above that required to generate the expected electrical output. Turbine output is then trimmed via the turbine bypass valves for fine-tuned matching of output to demand. This option minimizes the amount of wasted energy which in turn minimizes the excess loading of the bypass equipment, including the condenser. Additional challenges associated with reactor power maneuvering include:

- *Fuel design*: Must be optimized for resilience due to frequent thermal cycling of the fuel.
- *Capacity factor*: Routine thermal and operational cycling will likely cause components to degrade faster and may result in increased maintenance and lower module availability.
- *Reactivity control*: Although the reactor module is designed for power maneuvering using only control rods, extended periods of low power operation may require some boron adjustment.
- *Staffing*: The impact of routine power maneuvering could impact operator workload and maintenance, and hence overall staffing requirements.
- *Waste heat rejection*: A sustained operation using turbine bypass will increase the waste heat load of the plant and place additional requirements on the cooling tower capacity.
- *Refueling schedule*: Sustained operation of the module at low power may impact the schedule for refueling. This is less of an issue for a NuScale plant because of the staggered refueling strategy enabled by the multi-module design of the plant and the fact that refueling activities will be conducted by permanent, in-house staff.

Ultimately, it will be economics, policy mandates and regulatory requirements that will drive the decision regarding the extent of load-following by the nuclear plant in an integrated nuclear-renewable environment.

VI. SUMMARY

The NuScale plant incorporates several design features that enhance its responsiveness to load-following operations. The module design allows changes to reactor power down to 40% using only control rod movement (no boron adjustments) to increase power maneuverability. The condenser is designed to accommodate full steam bypass, thus allowing rapid changes to system output while minimizing the impact to the reactor system, which can be maintained at full power. For larger output adjustments, entire modules can be shut down for extended periods of low demand or high renewable generation.

A hypothetical scenario was analysed in which a single small NuScale module was used to balance the output of a relatively small wind farm to balance an isolated load. In this case study, the only generation options were wind and nuclear with sufficient nuclear power to supply all expected demand but allowing preferential use of the non-dispatchable wind power. The analysis showed that the NuScale module could adequately compensate for wind output variations using a combination of power maneuvring and turbine bypass, or turbine bypass alone. The same result applies to more realistic scenarios of larger markets with an increasingly high penetration of wind and reduced coal and gas generation as fuel prices and carbon penalties increase. In these scenarios, the addition of an efficient load-following nuclear power plant will help minimize the need for fossil-based peaking power while allowing greater penetration of renewable sources.

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