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INTRODUCTION

Nuclear power plants (NPPs) in the US have mostly operated as baseload plants, in which the units operate at a full rated power, providing a high-capacity factor. This method of operation is preferred for large NPPs due to the low marginal costs of operating nuclear power plants relative to other energy sources, excluding renewables. Additionally, it is more efficient and cost effective for large NPP to baseload as it requires the operators to perform fewer changes in the power plant conditions, allows efficient utilization of fuel with pre-determined fuel cycles, and involves fewer complications with monitoring and maintenance of equipment affected by non-baseload operation. However, it is not always in the best interest of the electricity grids for the NPPs to provide baseload operation. [1]

With the major changes in current electricity grids of high integration of renewables and lack of energy storage, large NPP are struggling to be profitable with baseload profile. This is generally due to the high supply of electricity during peak hours of the variable renewable energy (VRE) resources, such as solar, and the dependency of renewables on location and climate conditions. For a successful integration of VRE with nuclear energy, and to decarbonize the power systems, it is essential for NPP to operate flexibly, which is currently achieved by fast-ramping natural gas power plants. Countries with high nuclear share are also obligated to load-follow; this is the case in France, in which over 70% of the electricity is generated by NPPs. [1,2]

Flexible operation refers to power maneuvers below the rated thermal power. One form of flexible operation is load-following, which refers to power changes to match expected electrical demand. Generally, NPP operators are informed of load following in advance, providing sufficient time to plan. Although it is not possible to predict the exact electrical demand in the grid, it is possible to follow the daily, weekly, and seasonal trends in electrical demand. Load-following could also be applied for unplanned events. An outage in another power plant could also require a NPP operator to ramp up power production to compensate, while failure in an electrical equipment would require the NPP operator to ramp down.

Power plant with capabilities of rapid ramp up and down of electricity production also have an opportunity to participate in ancillary services for an additional revenue stream. Ancillary services are products of the electricity market. In addition to selling electricity to the wholesale market, electricity generating units can provide regulation up, regulation down, and spinning reserves. Frequency regulation (regulation up and regulation down) are services used to continuously maintain the grid's frequency. Units providing frequency regulation provide the reserved capacity within seconds to tens of seconds to stabilize the grid. Spinning reserves are running generating units that can ramp up within minutes of receiving dispatch [3-4]. The prices for upward reserves services (regulation up and spinning reserves) are usually higher during high energy demand hours. The downward services (regulation down) are more valuable during low demand periods, such as midnight and early morning hours [4]. Although it is not possible to determine the electricity price or the ancillary services prices in advance, it is possible to follow the electricity demand forecast and previous daily trends in prices. This provides opportunity for NPP operators to prepare when bidding into different electricity markets.

Despite the lack of load-following experience with large nuclear power plant in the United States, other than Columbia nuclear power plant, France, Germany, and Ontario, Canada have developed experience in load following [1-2,5]. Multiple studied were performed on load following with small modular reactors (SMR) [6,7]; however, limited studies have explored how load following is contributed across multi units at a site. In this research, NuScale modules are used as the case study. NuScale is an integrated pressurized water reactor with thermal power of 250 MW_{th}. On a single site, up to 12 modules of NuScale can be installed, providing electric power up to 924 MW_e. NuScale became the first SMR to be granted Standard Design Approval in 2020 [8]. Although smaller reactors might result in higher operational costs due to staffing, they can be utilized more efficiently for load-following. Having multiple units can provide higher flexibility in changing power levels and supplying the grid with electricity all year long. Additionally, load-following might perturbate the ordered sequence of refueling (every 24 months for NuScale). To maintain the 2 year refueling cycles, the loading patterns will need to be adjusted in a year-to-year basis, resulting in additional unnecessary costs. Another solution is to find the optimal outage schedule. This will also shift the focus of the planned outage to a more optimized predictive outages and maintenance.

Objective

The main objective of this research is to develop operational strategy for multi-unit SMRs. This includes finding the optimal dispatch and outage schedule for refueling the NuScale reactors in a market. The market participated in is the California Independent System Operator (CAISO). The model will be set to optimize revenue for the site by participating in different ancillary services.

OPTIMIZATION MODELS

The dispatch problem is modeled as a mixed-integer linear optimization problem, which involves using integer variables (e.g., binary variables) and continuous variables to model the dispatch. The main language used is Pyomo, a python-based optimization package. Gurobi was selected as the solver engine due to its ability in solving mixed-integer linear problems.

Due to the different timescales of the optimization---seconds to minutes for ancillary services, and months for outage scheduling--the model was divided into two optimization problems: a Short Timescale Problem (STP) and Long Timescale Problem (LTP).

Short Timescale Problem

To simplify the optimization, the STP was modelled for a single unit. The main purpose of the STP is to capture the unit response to the ancillary services market. The three main ancillary products considered are the spinning reserves, regulation upward, and regulation downward. The NuScale unit can participate in the spinning reserves using both movement of control rods and turbine bypass. The maximum capacity that a unit can reserve for spinning reserve is limited by the maximum thermal load change during the 10-minute response period. As for frequency regulation markets, the rapid response in load following is achieved by bypassing the turbine or utilizing the Automatic Generation Control (AGC) [9]. Similar to spinning reserve, the bidding capacity for the frequency regulation is limited by the maximum electric power change within the response time, 30 seconds.

The objective function of the STP is maximizing profit from operating. Revenue sources include the whole electricity market, spinning reserves market, and frequency regulation market while the costs incurred are due to operation and maintenance costs and fuel costs. The optimization solves for the optimal time-indexed thermal power, electric power sold to wholesale market, spinning reserve capacity, and regulation up and down reserve capacity. Variables solved in the STP are summarized in Table I.

Real time locational marginal prices (LMP) of 5-minute intervals for year 2021 were obtained from CAISO Open Access Same-time Information System (OASIS) using node IDAHOFAL_LNODET1, which corresponds to the node in Idaho Falls, where the first power plant in expected to be built on the Idaho National Laboratory Site. Additionally, 15-minute interval ancillary services clearing prices for 2021 were obtained from CAISO OASIS. In addition to the prices, parameters used in the optimization included NuScale parameters (maximum thermal power, thermal efficiency, ramp rates, minimum thermal power, and operation and fuel costs). Table II summarizes key parameters and the timescale of the STP.

Long Timescale Problem

The LTP main focus is to use STP results to find the power contribution among the multiple units at the site and finding the optimal outage schedule for the units. The objective function is similar to the STP objective; however, it takes into account multiple units and fuel costs are incurred at the start of refueling outage. The prices of the electricity and ancillary services were obtained from the daily weighted average of the prices calculated in STP, taking into consideration the capacity provided to each market. Most of the model variables are similar to the STP model; the LTP optimization solves for contribution of each unit to achieve the average electric power supply of the site. The average electric power of the site is equivalent to the average capacity of a unit from the STP scaled to the number of modules on site. Additional constraints are included in the LTP to model the outage. These include minimum threshold of burnup for allowable refueling, the limitation of one unit refueling at a time, and a minimum of 10 days for an outage.

Assumptions made in the LTP model include the start of each unit with different burnup and the use of the rolling horizon approach to model multiple year. The starting conditions assumes the units were refueled 6 months apart with unit 1 having the lowest burnup. The rolling horizon approach solves for an optimization of the entire time horizon (2 years); however, conditions at the middle of the first time-horizon (1 year) are used to start the next time horizon. Fig 1 shows a diagram of the rolling horizon planning. This approach is essential to avoid allowing the optimization to delay each outage to the next time-horizon.

TABLE I. Key decision variables used in STP and LTP.

Indexed Variables	STP	LTP	Units
Thermal power	$\dot{q}_t$	$\dot{q}_{n,t}$	MW_{th}
Spinning reserve capacity	$\dot{q}_t^S$	$\dot{q}_{n,t}^S$	MW_{th}
Electric power	$\dot{w}_t^E$	$\dot{w}_{n,t}^E$	MW_e
Reg up reserved capacity	$\dot{w}_t^D$	$\dot{w}_{n,t}^U$	MW_e
Reg down reserved capacity	$\dot{w}_t^D$	$\dot{w}_{n,t}^D$	MW_e
Unit burnup	-	$Bu_{n,t}$	$MW_{th}h$

TABLE II. Optimization models input parameters. [8,10]

Parameter	Value	Units
Rated thermal power	250	MW_{th}
Efficiency	0.308	-
Control rod ramp rate	40	%/hour
Turbine ramp rate	10	%/min
STP: timestep time horizon	15 1	min day
LTP: timestep time horizon	1 2	day year
Number of NuScale modules	4	-
Refueling outage duration	10	day

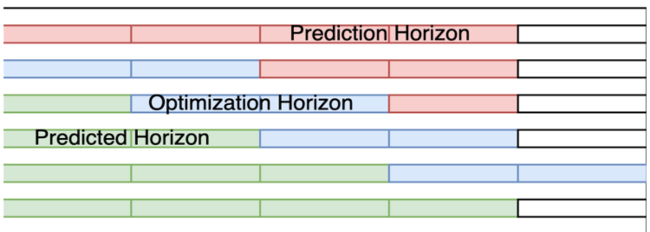

Fig. 1. Rolling horizon method using in LTP optimization. To solve for 4 years horizon, four two-year optimization horizons are required.

RESULTS

Short Timescale Dispatch

STP optimizations were completed for an entire day in 15-minute interval. The results show an optimal dispatch that involves participating in all three types of ancillary services. Load-following the unit through participation in ancillary services resulted in 8% increased profits compared to base-load operation. Results of the 2021 average daily capacity contributed to ancillary services as shown in Fig 2. As expected, the unit participates in upward reserves (spinning reserves and regulation up) during increased electricity demand: pre-commuting to work (6 am) and post-work hours (6 pm). The start of electric devices in households leads to sudden increase in load and demand; thus, prices of upward reserves increase. On the other hand, during late night and early morning hours, the demand on the grid is low and the remaining electricity supplier operates as a baseload. Therefore, downward prices are higher. Although perfect knowledge of the prices was assumed in the optimization, it is possible following the trend in Fig. 2 provides an opportunity to increase revenue by exploiting peak periods.

Long Timescale Dispatch

By using four optimization horizons of two years, the optimal outage schedule was found in Fig 3. The daily fluctuation in electric power is usually devoted to few units while other units operate on base-load profile. For example, during spring of the first year, two units are dedicated in providing ancillary services (units 2 and 3), while unit 4 only load-follows when the two other units reach the minimum operatable power (40% of rated thermal power). Unit 1 provides base-load operation most of the time. However, in the second year (part of the second optimization), the optimization appoints unit 1 for load-following to avoid concurrence of two units (units 1 and 2) due for a refueling outage.

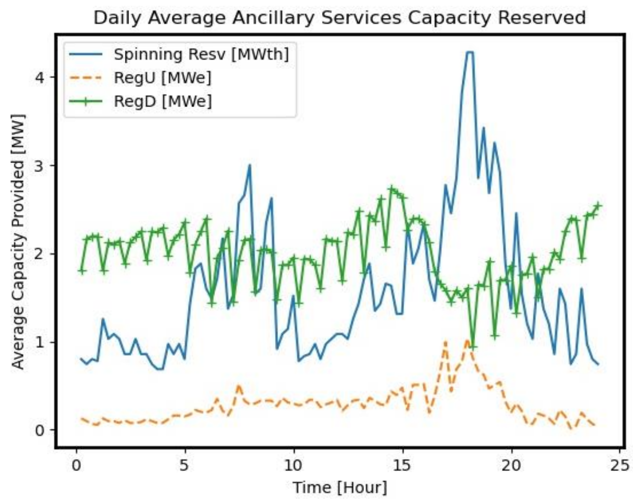

Fig. 2. Average reserved capacity of different ancillary services (spinning reserves and frequency regulations).

CONCLUSION

With the increase of integration of variable renewable into the grid, grid resilience can be compromised without flexible electricity suppliers. Flexible operation of NPP can expand the scope of integration of new nuclear power plants in regions with high share of renewables. It also provides opportunity to increase profits through participation in ancillary services. Results from STP optimization shows that average commitment to regulation down during late night and early morning hours can increase revenues. Participating in upward reserves during pre-work commuting hours and early evening hours can also generate additional revenues due to high ramp up of electricity demand. Having multiple units at a single site can also help operate flexibly. It is possible to combine base-load operation with flexible operation to extend component remaining useful life in some units and find optimal outage schedule for the units.

FUTURE WORK

The optimization conducted was limited to four units and four years of operation. It is also important to analysis the long-term outage scheduling effect on refueling outage drift

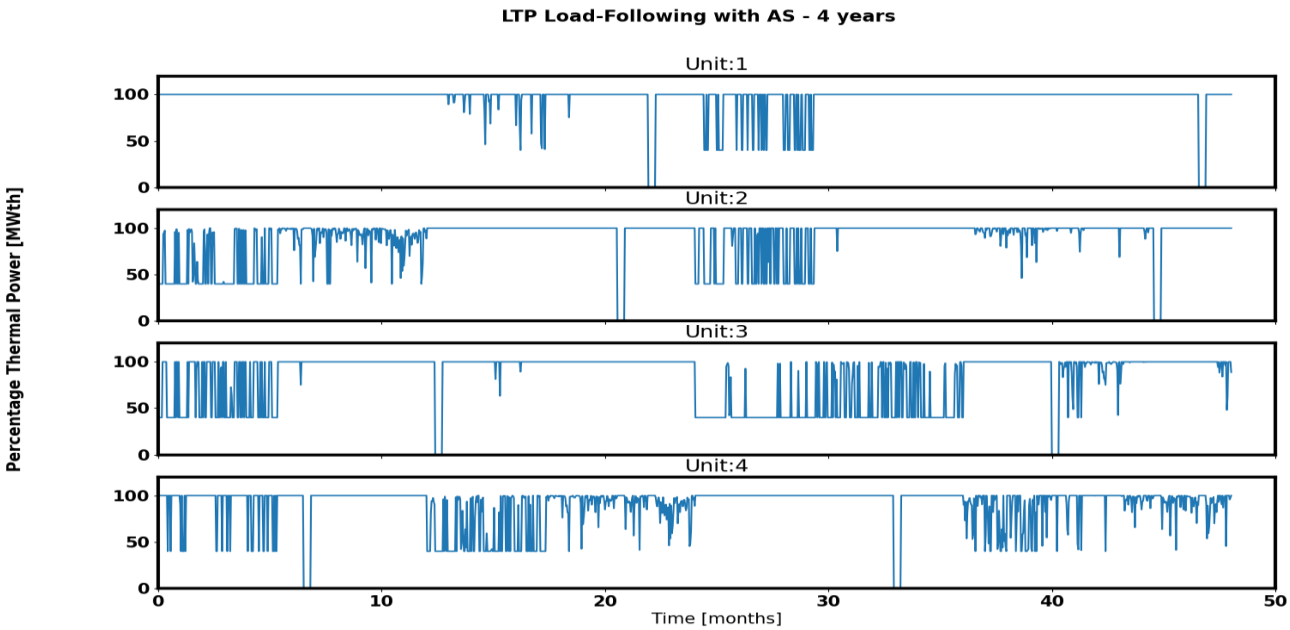

Fig. 3. LTP optimal dispatch for a four NuScale module site.

relative to base-load operating profile. A longer optimization problem is needed to study the effect on outage drift and the effect on maintenance planning. In addition, this optimization only considered revenue from the electricity markets and costs incurred due to normal operation and maintenance and refueling. A more detailed economic analysis will be completed after studying the effects of load-following on power plant equipment and the expected increase in maintenance and monitoring costs. Additionally, maintenance scheduling will be optimized to reduce the overall outage duration and frequency.

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