INL/MIS-22-70434-Revision-0

Research Highlight - Dispatch Optimization, System Design and Cost Benefit Analysis of a Nuclear Reactor with Molten Salt Thermal Storage

May 2024

Changing the World's Energy Future

Gabriel Jose Soto Gonzalez, Ben Lindley, Ty Neises, Cory Stansbury, Michael J. Wagner

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-22-70434-Revision-0

Research Highlight - Dispatch Optimization, System Design and Cost Benefit Analysis of a Nuclear Reactor with Molten Salt Thermal Storage

Gabriel Jose Soto Gonzalez, Ben Lindley, Ty Neises, Cory Stansbury, Michael J. Wagner

May 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-NE0008988

Dispatch Optimization, System Design and Cost Benefit Analysis of a Nuclear Reactor with Molten Salt Thermal Storage

Published in MDPI- Energies https://doi.org/10.3390/en15103599

Gabriel J. Soto, Ben Lindley, Ty Neises, Cory Stansbury, Michael J. Wagner

Nuclear power plants and variable renewable energy (VRE) systems will play a vital role in ensuring a robust energy grid that meets clean energy standards in the next decades. As energy markets become more saturated with VRE, market conditions become more volatile due to fluctuating availability of resources. For example, energy demand tends to peak out-of-phase with the availability of solar energy; demand peaks during early morning and late afternoon hours when solar resources are at their minimum. This offset widens the range of wholesale energy prices throughout the day. Prices in VRE-saturated markets like the California Independent System Operator market (CAISO) decrease and even reach negative values in the middle of the day when demand is low and supply is high. They, however, increase rapidly when demand spikes in the evening as residential load comes online and the previously abundant solar power wanes. These high pricing periods are particularly lucrative for nuclear power plants (NPP) which have historically served as a reliable option for baseload power supply. While NPPs have the ability to ramp production to load follow demand trends, they have a large ratio of capital costs to variable operating costs and so are incentivized to operate at full power whenever possible including in the middle of the day when prices are unfavorable.

One technology that would help NPPs operate more flexibly while increasing economic performance in volatile energy markets is thermal energy storage (TES). TES allows the NPP to maintain constant thermal output but allows the ability to reduce electrical power output by storing excess energy (e.g., during low or negative pricing periods). With an over-sized turbine, generator, and supporting subsystems, the NPP can then sell its design point electrical output plus any stored energy in the TES subsystem during high pricing periods. This added capacity would incur higher capital costs while pushing the power conversion cycle to perform at lower efficiencies during charging periods; however, these costs can be offset against enhanced revenue from an optimized energy dispatch strategy.

We develop a model to investigate the techno-economic performance of a NPP coupled with TES. Our model uses the Westinghouse lead-cooled fast reactor (LFR) as a baseline for the nuclear plant for its many safety and performance advantages, including but not limited to better fuel utilization, ability to operate at higher temperatures, and lower waste production. The TES in our model is a two-tank molten salt system with 60% $NaNO_3$, 40% KNO_3 solar salt as the thermal fluid which is used in concentrating solar power plants and is of increasing interest for nuclear reactors. We also assume a steam Rankine cycle design for the power conversion cycle. The TES molten salt loop is integrated between the working fluid (e.g., the steam in the power cycle before entering the turbine) and the primary heat transfer fluid (another steam loop, itself having a lead-to-steam heat exchanger with the LFR). Alternative configurations exist which might reduce efficiency penalties from the added heat exchanger loops, but this configuration is also actively pursued in the industry and allows the ability to draw more generalizable conclusions. The nominal output of the LFR base design is 950 MWt or approximately 465 MWe. The outlet coolant temperature of the LFR is taken to be 570 C; though higher temperatures are possible, this design point matches the highest operating temperatures (around 560 C) of the molten salt thermal fluid.

Operations of the LFR-TES plant are carried through under market conditions representative of regions with large quantities of VRE. We assume the power plant is a price taker, which simplifies the complex bidding process in these dynamic markets. Instead we use a time series of tariff rates, or price multipliers, to capture the variance in clearing prices within the purported energy market. We use a synthetic tariff rate time series from SAM with generic midday peaks for testing and a normalized price curve from CAISO data to simulate volatile pricing schedules. We also use weather records hosted in SAM meant to represent a 'typical' year in Phoenix, AZ as a case study for our plant simulations.

The techno-economic performance of this LFR-TES configuration is evaluated using engineering models with varying levels of fidelity. A mixed-integer linear programming (MILP) model is used to generate optimal operating schedules for energy dispatch, including charging and discharging schedules for the TES. These optimal schedules maximize profit over a given time horizon and are used as targets for the thermodynamics engineering model in the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). SAM solvers and modules, including a new module created to simulate a simple nuclear reactor, are used to calculate steady-state thermodynamic and energy balance at each simulation step. Off-design performance—when additional TES power is added to the nominal LFR output—is calculated using tabulated data provided to SAM from more detailed thermodynamic calculations within the Engineering Equation Solver (EES).

Within the optimization cadence for the full system simulation, we first solve an MILP for a 48-hour time horizon, then truncate and use only the first half of that solution for the SAM engineering model calculations. A new MILP is then solved using the end-conditions of the previous SAM solution for another 48-hour horizon and the process is repeated for a full year. The rolling time horizon strategy prevents biasing towards over-using stored energy by the end of the day, helping to anticipate any expected spikes in energy pricing the next morning. Perfect forecasting is assumed for the 48 hour time horizon.

We conducted 1 year simulations for the LFR-TES plant under Phoenix, AZ weather conditions and both a generic midday peak price schedules as well as normalized CAISO price schedules. As mentioned previously, the baseline LFR design outputs about 465 MWe from the nominal turbine and generator design. The LFR-TES requires an oversized turbine to handle added thermal input from storage. A parameter sweep over the two design variables—the oversized capacity of the turbine (larger than 465 MWe) and the amount of thermal energy storage (measured in hours of equivalent full-load power cycle output)—is then conducted for each simulation year in the given market. Our metric for economic performance is the power purchase agreement (PPA) price calculated by SAM after a year of operation; the PPA price is the minimum price of energy at which the plant should sell its energy to the grid to guarantee an internal rate of return in a given time period (e.g., 11% return in 20 years). Lower PPA prices are better as they make the plant more competitive while still guaranteeing a return on investment.

We find that under the generic midday peak price schedule, the optimal design point is the baseline LFR design with no TES. Additional revenue from selling stored energy during high price periods does not offset the extra costs of the oversized turbine or TES system. When that same price schedule is made to simulate more volatile markets (price peaks are amplified, troughs are deepened, but the time series is still normalized to 1 so as to not artificially inflate the revenue) the optimal design point shifts in the Turbine-TES parameter space. More turbine capacity and additional TES reduces the PPA price below that of the baseline design. When the same price peaks and troughs are amplified by a factor of 2, the optimal design point is that of a 700 MWe turbine with 5 hours of TES and improves the PPA price by 4.88%. Under the normalized CAISO pricing schedule, the optimal design increases to 750 MWe for the power cycle and 5 hours of TES with a 10% improvement on PPA price.

Sensitivity studies were also conducted on another potentially important design parameter, the TES cost per kWh. We find that varying the TES cost from the nominal simulations in the parameter sweep ($29.8 kWh) does not alter the optimal design point for any of the market scenarios, only the final PPA price and associated costs. We also calculated sensitivity of the optimal design point to reduced efficiency from the additional heat exchanger loops in the LFR-TES configuration which was not captured in the engineering model. Even with an additional 5% performance penalty, PPA improvements in the CAISO market simulations are still 5.57%. Our research has ultimately shown that despite additional costs incurred, it is still economically advantageous to both add thermal storage capabilities and correspondingly oversize the turbine electric output for plants performing in volatile energy markets saturated by variable renewable energy.