New operational paradigms—nuclear energy flexibility

Nuclear flexibility can be key to enabling deployment of other clean energy generators.

- Operational flexibility
- Product flexibility
- Deployment flexibility

Flexible Nuclear Energy for Clean Energy Systems, September 2020
https://www.nice-future.org/flexible-nuclear-energy-clean-energy-systems
Cross-sectoral energy solutions for a resilient net-zero future

Future Energy System: Transforming the Paradigm
Integrated systems leverage contributions from all low emission energy generation options to support decarbonization of electricity, industry, and transportation

Goals
- Maximize energy utilization and generator profitability
- Minimize environmental impacts
- Maintain affordability, grid reliability and resilience

- Nuclear energy from large light-water reactors to microreactors
- New chemical processes
- Biofuel
- Clean water
- Hydrogen for vehicles and industry
- Hydrogen for industry
- Other generation including variable renewables and municipal waste
- Electricity
- Industry

IES
Integrated Energy Systems

IDAHO NATIONAL LABORATORY
DETAIL – Dynamic Energy Transport and Integration Laboratory

- Vehicles
  - Wireless Charging
- Power Plant Operations
  - Human Systems Simulation Lab (out of picture)
- Hydrogen
  - High Temperature Electrolysis
- Power Emulation
  - Digital, Real-Time Grid Simulation
- Power Systems
  - Distributed Energy & Microgrid
- Energy Storage
  - Battery Testing (out of picture)
- Vehicles
  - Fast Charging
- Vehicles
  - Thermal Energy Distribution System
    - Includes Thermal Energy Storage
  - MAGNET
    - Microreactor Agile Nonnuclear Experimental Testbed
- Vehicles
  - Distributed Energy & Microgrid
- Vehicles
  - Power Plant Operations
  - Power Systems
IES Optimization at INL

- HERON
  - https://github.com/idaholab/HERON
  - RAVEN plugin
    - https://github.com/idaholab/RAVEN
  - Optimize capacity/component sizing
    - Dispatch optimization

- ORCA
  - Optimization of Real-time Capacity Allocation
  - Under development
  - Real-time economic optimization
HERON

• Bringing FORCE together for Technoeconomic Analyses

RAVEN
• Stochastic Analysis
• Synthetic Histories

TEAL
• Economic Metrics
• Cash Flows

FARM
• Process Analysis
• AI Training, Control

HYBRID
• Process Models
• API Framework

HERON
• Stochastic Technoeconomic Analysis
• Component Sizing Optimization
• Dispatch Optimization
Macro Technoeconomic Analysis

• Holistic Energy Resource Optimization Network

• Solve:
  − Optimal size for IES systems (generators, storage, industrial processes)

• Such that:
  − Respect technical limitations
  − Evaluate continuous-time responses
  − Optimize component dispatch
  − Maximize expected profitability
    • Requires uncertainty quantification
  − Weight expected profit by risk
    • Value at Risk, risk assessment
Risk-Informed Optimization

• Stochasticity
  – Consider more than one projected future
  – Statistically consider hundreds or thousands

• Optimize system size for expected benefit
  – Expected NPV
  – Value at Risk
Synthetic Histories

- Synthetic Histories allow exploring many possible futures
- Train on historical or projected data
  - Capture short, long-term deterministic effects
  - Characterize residual uncertainty
- Sample new histories
  - Each independent, identically-distributed
  - Same characteristics as training, new behavior
  - Clustering, correlation, multiyear evolution
HERON Two-Loop Optimization

Statistical Economic Metrics

Component Sizing

Repeat for Many Histories

New System

solar demand wind markets
“Outer” Optimization Components and Markets

- Nuclear Power Plant
  - Core (Steam Generator)
  - Turbine (Steam to Electricity)
- Hydrogen Generator
- Hydrogen Storage
- Battery Storage
- Thermal Energy Storage
- Electricity Market
  - Real Time, Day Ahead
- Hydrogen Market
- See https://github.com/idaholab/FORCE for examples

Optimize
- Size
- Dispatch
“Inner” Optimization – Dispatch

- Continuous Time
- Flexible Economic Drivers
- Multiple Commodities
- Arbitrary Policies
- Signal Response
- Storage Flex

Optimize Size

Optimize Dispatch, Commitment
30-year projection
ORCA – IES Real-Time Economic Optimization

- IES optimization occurs at multiple time scales
  - "Real-Time" = days, hours, minutes, etc.
- Operation optimization of IES
  - Integration of IES with digital twin
    - RTO sits between M&S and operations
  - How do we operate optimally?
    - Maximize profits
    - Production scheduling
    - Arbitrage
- Why RTO?
  - $$$

Fig. 1. Typical control hierarchy in process control.
Krishnamoorthy et al. 2018
Deregulated Electricity Market RTO

Day Ahead Market
Hourly bids submitted day before

Real Time Market
Bids submitted before next period

Current IES State
Price Forecast
IES Digital Twin

IES Digital Twin
• Inputs
• Outputs
• Constraints

Optimization
LP/MIP/NLP/Rule Based

Optimization
RHO/MPC/Rule Based

Day Ahead LMP from PJM Pricing Node 1.

Real Time LMP from PJM Pricing Node 1.

• ISO determines clearing price and generators

Current Focus
ORCA – Dispatch Optimization

• Economic Model Predictive Control/Receding Horizon Optimization
  - Forecast LMP forward in time (i.e., 12 hours)
  - Use model to predict IES performance
  - Optimize dispatch for maximum revenue
  - Use dispatch for next time step only
    • Implement as setpoints/control actions
  - , repeat
IES Mathematical Model Example

• NPP + Electrical Storage
  • NPP supplies constant capacity
  • Electrical storage for arbitrage

• \( S \): state of charge at time (MWh)
• \( e \): round trip efficiency (0,1)
• \( P_{\text{charge}} \): charging at time (MW)
• \( P_{\text{discharge}} \): discharging at time (MW)
• \( t \): time step (minutes)
• \( LMP \): LMP at time ($/MW)
• \( C_{\text{NPP}} \): NPP capacity (MW)

• Objective function: maximize revenue
ORCA Example

- 05-31-2022 to 06-07-2022
- PJM Pricing Node 1 (5-minute real time market)
- Perfect knowledge LMP forecast

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
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<tbody>
<tr>
<td>5 minutes</td>
<td>0.8</td>
<td>1 Week</td>
</tr>
<tr>
<td>50 MW</td>
<td>20 MWh</td>
<td>Revenue</td>
</tr>
<tr>
<td>0 MWh</td>
<td>20 MW</td>
<td>Increase</td>
</tr>
<tr>
<td>20 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **1 Week Revenue**
  - IES: $8,511,996.26
  - NPP only: $8,265,764.33
- **Revenue Increase**: $246,231.93
Many types of models/ROMs:

- **Black box** – no information: only inputs $\rightarrow$ outputs
- **Grey box** – some information: inputs $\rightarrow$ outputs, derivatives (Jacobians, Hessians, etc.)
- **White box** – all information: inputs $\rightarrow$ outputs, functional form, derivatives

**ORCA – Digital Twin for Physical System Control**

**Workflow in Digital Twin Framework**

- **Modelica/DYMOLA Model**
  - Physics-based system model
- **RAVEN Environment**
  - ML algorithms applied to ROM
- **PyNumero Framework**
  - A high-level python framework for nonlinear optimization algorithms
  - Reduce time required to prototype new nonlinear programming algorithms

**Physical Systems**

- **Supervisory Control**
  - Steam Generator
  - Steam Storage
  - Steam Turbine
  - Hydrogen generator
  - Hydrogen Storage
  - Electrical Storage
  - Electricity Grid

**System State Update**

- **Optimal Inputs**
- **Optimal Dispatch**
- **Reduced Order Model (ROM)**

**Run 1**

**Run 2**

**Run N**

**PyNumero**

**RAVEN Environment**

**Modelica/DYMOLA Model**

**PyNumero Framework**

**Workflow in Digital Twin Framework**

**Physical Systems**

**Supervisory Control**

**System State Update**

- Black box – no information: only inputs $\rightarrow$ outputs
- Grey box – some information: inputs $\rightarrow$ outputs, derivatives (Jacobians, Hessians, etc.)
ORCA – Current Work

• Build Python package to perform dispatch optimization
  − Provide tools for use in building workflows, not THE workflow
  − Given a model, perform optimization

• EMPC-based dispatch optimization
  − Current mathematical model:
    − Automatically generate Pyomo expressions for model, constraints, objective function

• Prepare for virtual demonstration of real-time economic optimization
  − Virtual model in Modelica/Dymola to emulate physical IES
  − Deep Lynx data warehouse to communicate between virtual model and optimization
  − Digital twin development for ORCA to use in economic dispatch
ORCA – Future Work

• Demonstrate real-time economic optimization on physical IES
  - DETAIL IES at INL
  - Deep Lynx data warehouse to communicate between IES and optimization
  - Digital twin development for ORCA to use in economic dispatch

• Open source ORCA

• Expand ORCA package
  - Additional optimization methods beyond EMPC
  - Integrate with other tools at INL or open-source community
Summary

• IES can make nuclear more flexible, economical
• Optimization of IES at INL
  - HERON
    • Optimal sizing for IES components
  - ORCA
    • Real-time economic dispatch optimization

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