Renewable Integration and Plant Flexible Operations

*Insights from EPRI Research*

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Overview

• Understanding Flexible Operations: Drivers and Impacts

• Insights from EPRI Research on Meeting Future Demand for Flexible Operations
Overarching Issues

• Maintain grid security
• Meet demand on sub-hourly basis
• Maintain continuous environmental compliance
• Implies challenges
  – How can flexible operations be valued such that added costs of flexible operations are recovered?
  – What is the optimal generation mix and level of generation capacity reserves?
  – Answers are key to assuring future asset viability
Natural Gas Prices and Demand for Gas Unit Flexible Operations

• Low gas prices in North America
  – Accelerating shift to higher capacity factors for gas-fired assets
  – Putting coal on the margin
  – Gas competitive with nuclear

• High gas prices internationally
  – Increasing layups of gas-fired plants in Europe
  – Increasing transients in operation of gas plants

Trends in Worldwide Gas Prices

Net Generation from Fuel Sources

Source: U.S. Energy Information Administration, Form EIA-023, Power Plant Operations Report
German Power Generation (January 2012)

**Demand, Wind Generation**

- Increasing power demand
- Declining wind feed-in

**Generation Dispatch**

- Gas
- Coal
- Nuclear
- Must-run
- Wind

Anti-correlation between peak demand and wind generation → Significant cycling of gas and coal assets

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Range of Variability Is Challenging

Max for year near the 50 GW of capacity

Minimum < 5 GW

Range = 100% down to 10% of peak 30 hours
Engineering Challenges of Flexible Operation

• Drivers
  – Variable generation (i.e., wind and solar)
  – Demand response
  – Automated load management and aggregation
  – Distributed generation
  – Changing demand (i.e., load curve)
  – Changing economics (e.g., natural gas prices)
Modes of Flexible Operation: Impacts

**Asset Operational Changes**

- Faster Load Ramps
- More Startups
- More Frequent Load Changes
- More Frequent and Deeper Minimum Load Operation
- Reserve Shutdown

**Impacts on Plant Operations and Maintenance**

- Increased Fuel Costs
- Increase in Number of Thermal Cycles
- Reduced Plant Efficiency
- Maintaining Cycle Chemistry
- Increased Corrosion
- Risk of Operator Error
Engineering Challenges of Flexible Operation

• Limitations on flexible operations
  – Minimum temperature and pressure conditions
  – Emissions controls requirements
  – Design limits on thermal and mechanical stresses
Flexible Operation: Major Damage Mechanisms

• Thermal fatigue
• Creep-fatigue interaction
• Corrosion pitting
• Differential thermal expansion

[Imagery of damage mechanisms and components associated with flexible operation]

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Damage Effects Are Not Immediate
Increasing HRSG Tube Failures over Years

VGP: Vertical Gas Path
HGP: Horizontal Gas Path
Operational Impacts

• Increased heat rate
• Lower capacity factors… lower revenues
• Increased emissions levels per MWh
• Fuel contracts and inventory management
• More plant transients… increased opportunity for human error
• Maintenance costs incurred during reserve standby
• Accelerated rate of material damage
• Requires change to plant preventive maintenance strategy

Economic viability of generating asset is the major concern
Cost Impacts of Flexible Operation

• **Strategically important to plant owners:**
  – Basis for bidding, rate cases, capital budgets
  – Cost has both tangible and intangible elements

• **Cost evaluation is technically challenging:**
  – Limitations on availability and accurate use of historical data
  – Relevancy of statistical sample of plants
  – Costs typically realized years after start of cycling operation

• **Potential approach to improved cost evaluation:**
  – Pareto analysis of cost elements
  – Industry collaborative – common framework for self-assessment
  – Benchmark against some component life-consumption models
Insights on Meeting Future Demand for Flexible Operations

• Ongoing research
  – Damage effects
  – Case studies
  – Operational and maintenance strategies
  – Anticipating challenges through fleet transition studies
Insights on Meeting Future Demand for Flexible Operations

• Anticipating challenges

  – Will transitioning the generation fleet evolve such that fleet operational flexibility capabilities will be adequate to support increasing variability in generation and demand?

  – To what extent do costs and operational limitations associated with flexible operations of generation assets affect mix of technologies in the future generation fleet?
Insights on Meeting Future Demand for Flexible Operations

- Integrate generation planning and unit commitment perspectives
  - Consider long-term asset investment decisions and evolution in generation asset mix
  - Include policy and economics drivers
  - Assess flexibility needs in context of regional differences in generation fleet composition
  - Consider role of electricity trade

- Research approach
  - Intertemporal, CGE model
  - Unit commitment model
  - Calculation of flexibility metrics
  - Sensitivity studies
Integrated View of Multiple Regions

Summer Capacity in GW
(source: EPA/IPM)
Example: National Generation Mix

- Solar
- Geothermal
- Biomass
- Wind
- Hydro+
- Nuclear (New)
- Nuclear (Existing)
- Gas w/CCS
- CCS Coal
- New Gas
- Existing Gas
- New Coal
- Existing Coal Ret
- Existing Coal
- Baseline

TWh

2010 2015 2020 2025 2030 2035 2040 2045 2050
Example: Texas Region Capacity Mix
Unit Commitment (UC) Model

- Electrical power system simulation of optimal dispatch of generating units on a grid
- Large-scale mixed-integer optimization problem
- Examples of inputs
  - Ramp rates
  - Minimum turndown limits
  - Startup costs
Example: TX Region, 2030, Peak Week

2030 Ref Scenario, Texas

- Wind
- Solar
- Gas Turbines
- Gas w/ CCS
- NGCC
- Coal w/ CCS
- CCS Retrofit
- Coal
- Hydro
- Biomass
- Geothermal
- Nuclear
- Energy for Load
Example: TX Region, 2030, Selected Month

NGCC dispatch with ramp rate, turndown constraints

NGCC dispatch with no constraints
Example: TX Region, 2030, Selected Week

NGCC unit count and generation with ramp rate, turndown constraints

NGCC unit count and generation with no constraints
Example: TX Region, 2015 and 2030

Ramp Duration Curve comparing variable generation, net load (2015)

Ramp Duration Curve comparing variable generation, net load (2030)
Characterize and Measure Flexibility

• Examine start/stop, ramping, low-load operations behavior under wide range of conditions with different generation technology mixes

• Define, calculate key metrics, e.g.:
  – Distribution of capacity vs. startup times
  – Ramp rates, durations, and statistics
  – Insufficiency of capacity capable of providing necessary flexibility capabilities:
    • Duration of time periods with “flexibility deficit”
    • Magnitude of deficit in capacity terms
Other Emerging Insights

- Will over-reliance on imports/inter-regional trade create new generation planning challenges?
- To what extent do new “mission profiles” (e.g., prolonged low turndown operations, different patterns of output) imply:
  - Needs for new power plant staff capabilities and training?
  - Needs for new organizational and O&M procedural approaches?
- Need to focus technology R&D on specific capabilities, e.g.:
  - More rapid 1–3 hour ramping capability
  - More resilience of flexibly operating units through improved design, monitoring & diagnostics, and maintenance (e.g., HRSG drain design and maintenance)
  - Establish capabilities to achieve lower levels of power output for longer periods of time (i.e., low turndown)
Together…Shaping the Future of Electricity
Flexible Operation: Major Damage Mechanisms

- Thermal fatigue
  - Affects boiler-turbine circuit
  - Temperature mismatch between steam and metal surfaces
  - High amplitude stress cycles result
  - Rapid cooling caused by liquid quenching; surface tensile stresses

Thermal stress process
- **Tensile stress** (hot metal)
- **Compressive stress** (cold fluid)

Images:
- Tube-to-header crack in HRSG
- Ligament cracking in boiler header
Flexible Operation: Major Damage Mechanisms

• Creep-Fatigue Interaction
  – Creep damage found in units operating near design life
  – Cycling these older units can increase fatigue damage
  – Interaction of these mechanisms is synergistic, greatly reducing cycling operational life
  – Remaining life estimation is area of significant study
Flexible Operation: Major Damage Mechanisms

- Corrosion pitting
  - Associated with unit layup
  - Unprotected metal surfaces exposed to oxygen, water, and oxygen
  - Resulting pitting can initiate corrosion-fatigue cracking
  - New research looking at feedwater treatments that protect surfaces during shutdown
Flexible Operation: Major Damage Mechanisms

• Differential Thermal Expansion
  – Affects components in boiler, turbine, generator
  – Accelerated wear of generator winding insulation due to load swings
  – Generator wedge fretting
  – Risk of axial rubs in steam turbines due to relatively rapid expansion during fast starts

Cycling accelerates wear of stator windings

Generator rotor after frequent cycling
Flexible Operation: Major Damage Mechanisms

• Flow-Accelerated Corrosion (FAC)
  – Mechanism influenced by material and local steam conditions
  – Cycling and reduced minimum load operation exposes new areas to risk
  – FAC prevention is a significant safety issue

Changing steam conditions cause FAC in heaters, extractions, drains
Flexible Combined-Cycle Plant
An Integrated Approach to Improve Flexibility Capabilities

- Reduce NOx/CO emissions at low load
- Install inlet dampers
- Isolation/venting of fuel headers

- Accommodation of winding thermal growth

- Automated startups
- Improved operator displays and alarm management

- Improved drains and attemperator sprays
- New alloys – thinner walled headers
- Improved tube-to-header connection
- Stack damper
- Steam bypass

- Improved drains
- Improved casing design to reduce distortion
- Improved thermal insulation
Future Plant Considerations

• Design basis must reflect emerging role of coal and gas as load-balancing assets

• Potential conflict between flexibility and thermal efficiency

• Materials improvements can reduce thermal stress

• New makeup water and air removal schemes

• Management of water quenching (improved drains and attemperator sprays)

• System-approach to combined cycle plant design

• Provide operators the tools to improve situational awareness

Industry initiative on intrinsically flexible plants is needed
Improving Asset Flexibility: Systematic Approach

- Equipment Impacts
- Operational Impacts
- Cost Impact

- Improved Flexible Operation of Existing Assets
- Improved Flexible Operation of Future Plants

Improve operational flexibility of current and future assets
PRISM 2.0: Improved Regional Model

U.S. Regional Energy, GHG, and Economy (US-REGEN) Model

- **General Equilibrium Economy Model**
  - Aggregate Economic Representation
  - Energy Markets for Oil, Natural Gas, Coal, and Bioenergy
  - Foreign Exchange
  - Land use (Ag and Forest)

- **Energy Demand (Electric & Non-Electric)**
  - Energy Efficiency across Commercial, Industrial, and Residential Sectors
  - Transportation: Detailed model of vehicle technologies and intermodal choices

- **Electric Sector Module**
  - CO₂ Mitigation Technologies
  - Environmental Controls: Air, Water, Land
  - Transmission
Design Choices

Framework

Static/Dynamic Recursive ↔ Intertemporal Optimization
Partial Equilibrium ↔ General Equilibrium
National Aggregate ↔ Regional disaggregation

Electric Model

Levelized cost / process model ↔ Investment and Dispatch
Large unit classes ↔ Individual units
Peak-baseload ↔ Hourly (or less)
Simple dispatch ↔ Unit commitment
Pipeline transmission ↔ Detailed power flow

Macro Model

Aggregate sectors ↔ Industrial detail
Fuel as sectoral input ↔ End-use service structure
US-REGEN Reference Case

• Baseline reference: EIA Annual Energy Outlook (AEO)
  – Projected level of energy demand (AEO 2011)
  – Reference energy prices (AEO 2013)

• Electric sector policies
  – Renewables
    • Existing state RPS requirements
    • Production tax credit through 2020
  – Environmental
    • Environmental controls required on existing coal units (MATS, cooling water, coal ash)
    • CAA Sec 111(b): No coal units without CCS
US-REGEN Reference Case
Technology Assumptions

• Nuclear
  – New nuclear allowed
  – 80% of existing nuclear extended to 60 years
  – 6 GW constructed before 2020; maximum build rate = 7 GW/decade thereafter

• Renewable Energy
  – Cost reductions over time

• Coal
  – Existing unit lifetime = 70 years
  – CCS (50% or 90%) retrofit available as of 2025
  – CCS (50% or 90%) available for new units as of 2030

• Transmission
  – Historical growth rates
Example Reference Case
UC Output – TX Region, 2015 and 2030

Ramp Duration Curve (2015)

Ramp Duration Curve (2030)
Inflexion Tool – Example Output
Distribution of resource capacity vs. start up time
Inflexion Tool – Example Output
3-Hour Ramp Magnitude
Inflexion Tool – Example Output
Period of Flexibility Deficit Metric