ELECTRIC POWER RESEARCH INSTITUTE

Renewable Integration and Plant Flexible Operations

Insights from EPRI Research

Revis James — Director

John Bistline — Project Manager

May 14, 2014

Overview

- Understanding Flexible Operations: Drivers and Impacts

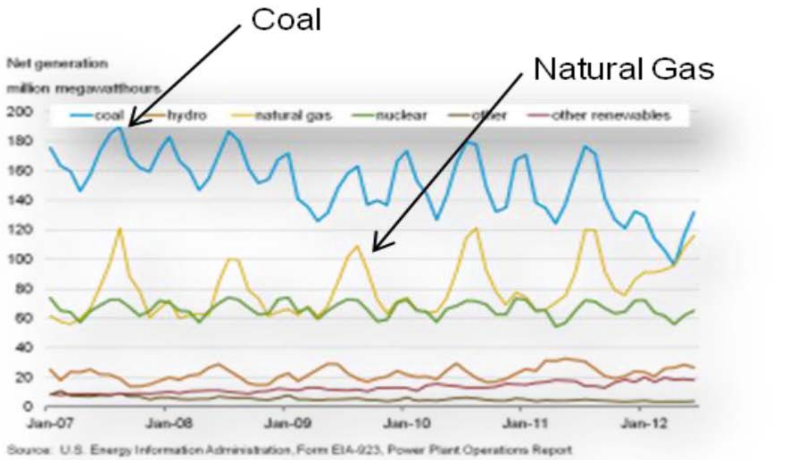
- Insights from EPRI Research on Meeting Future Demand for Flexible Operations

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

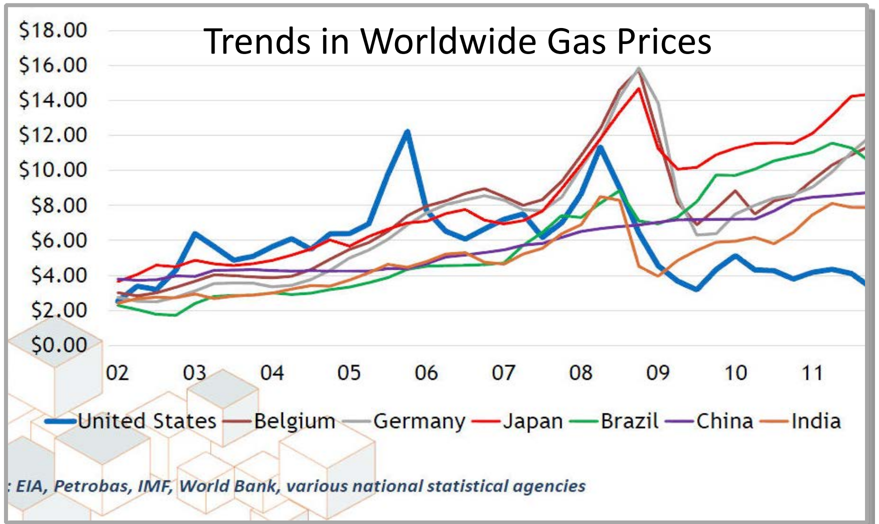
Natural Gas Prices and Demand for Gas Unit Flexible Operations

- 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

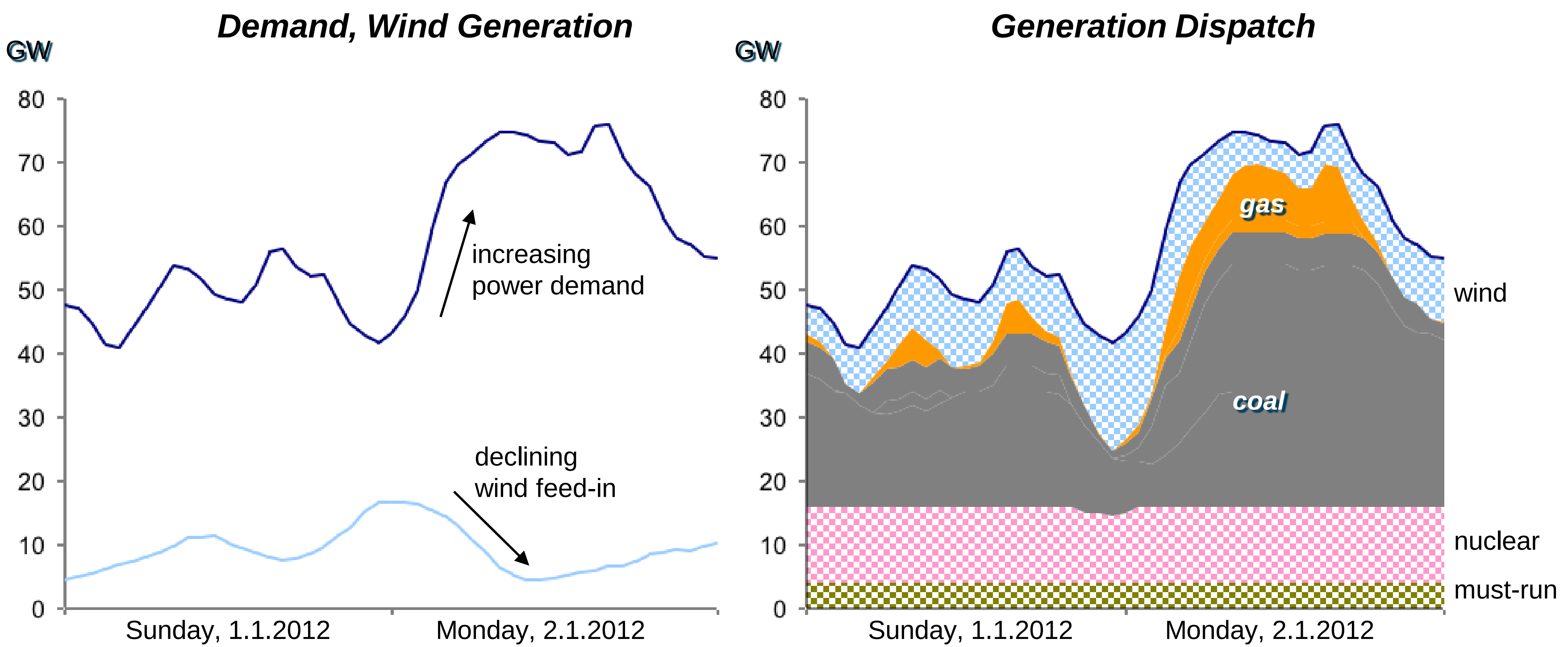


Net Generation from Fuel Sources

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



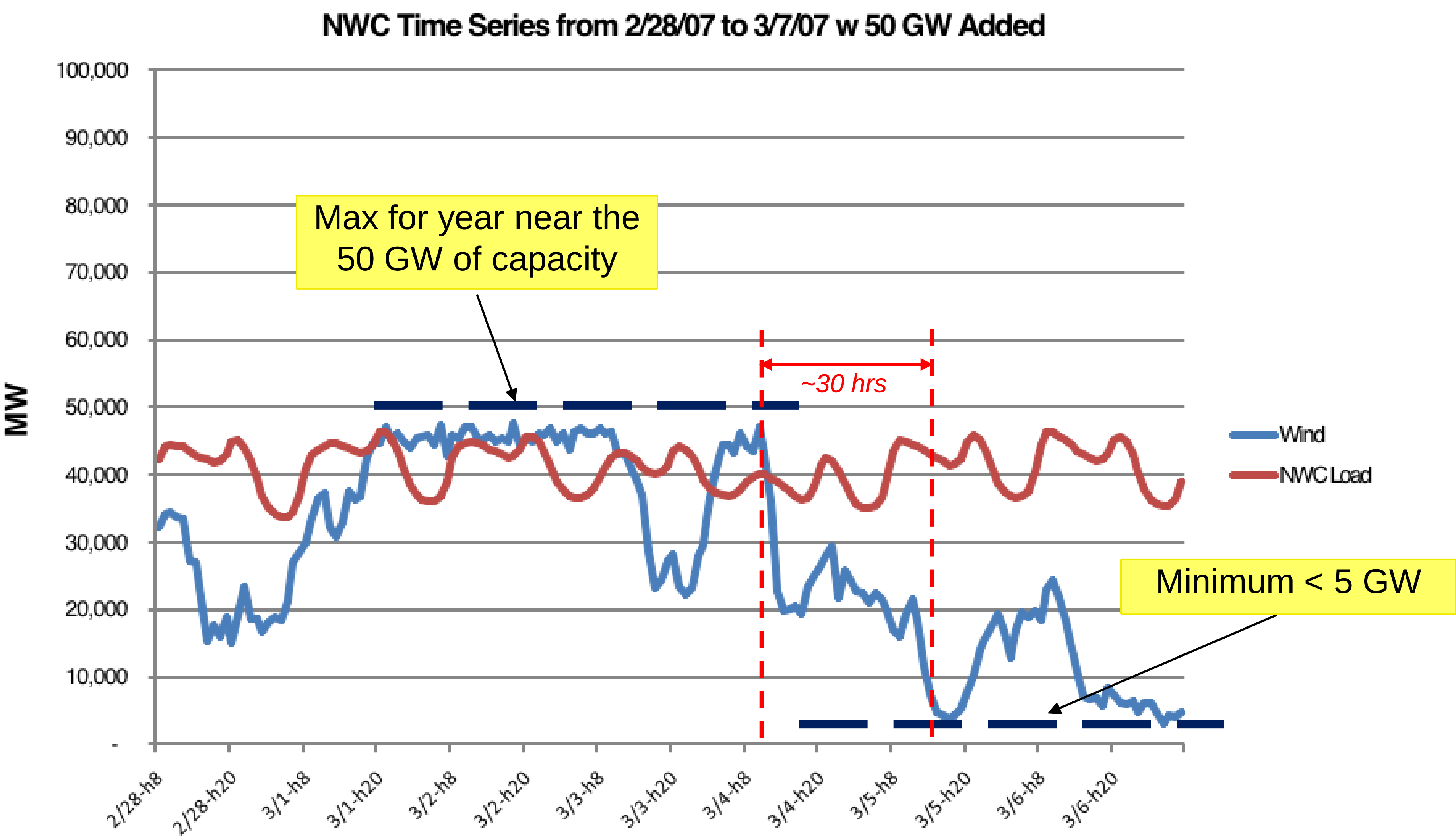
German Power Generation (January 2012)



Used with permission from RWE

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

Range of Variability Is Challenging



Range = 100% down to 10% of peak 30 hours

EPRI ELECTRIC POWER RESEARCH INSTITUTE

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 → **Impacts on Plant Operations and Maintenance**

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

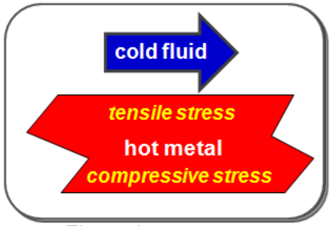
- Increased Fuel Costs
- Increase in Number of Thermal Cycles
- Reduced Plant Efficiency
- Maintaining Cycle Chemistry
- Increased Corrosion
- Risk of Operator Error

Engineering Challenges of Flexible Operation

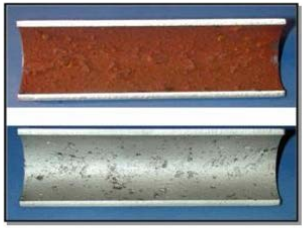
- Limitations on flexible operations
  - Minimum temperature and pressure conditions
  - Emissions controls requirements
  - Design limits on thermal and mechanical stresses

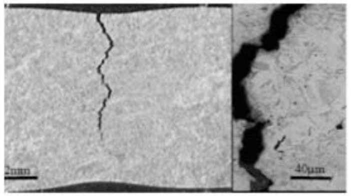
Flexible Operation: Major Damage Mechanisms

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

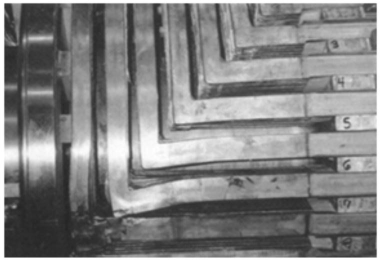


Thermal stress process


Corrosion in boiler tubes

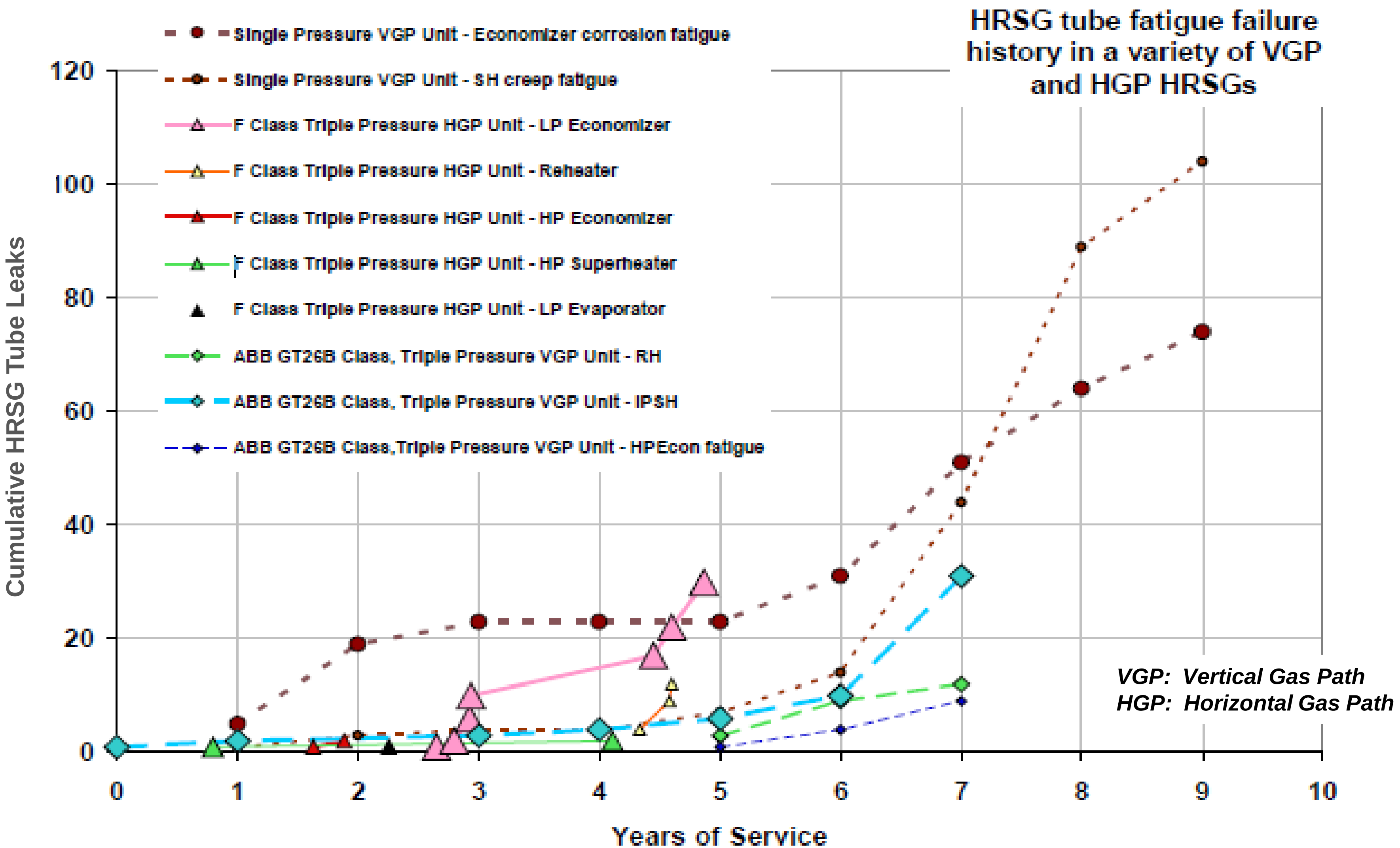

Creep-Fatigue Interaction


Ligament cracking in boiler header


Generator rotor after frequent cycling

ELECTRIC POWER RESEARCH INSTITUTE

Damage Effects Are Not Immediate
Increasing HRSG Tube Failures over Years



ELECTRIC POWER RESEARCH INSTITUTE

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?

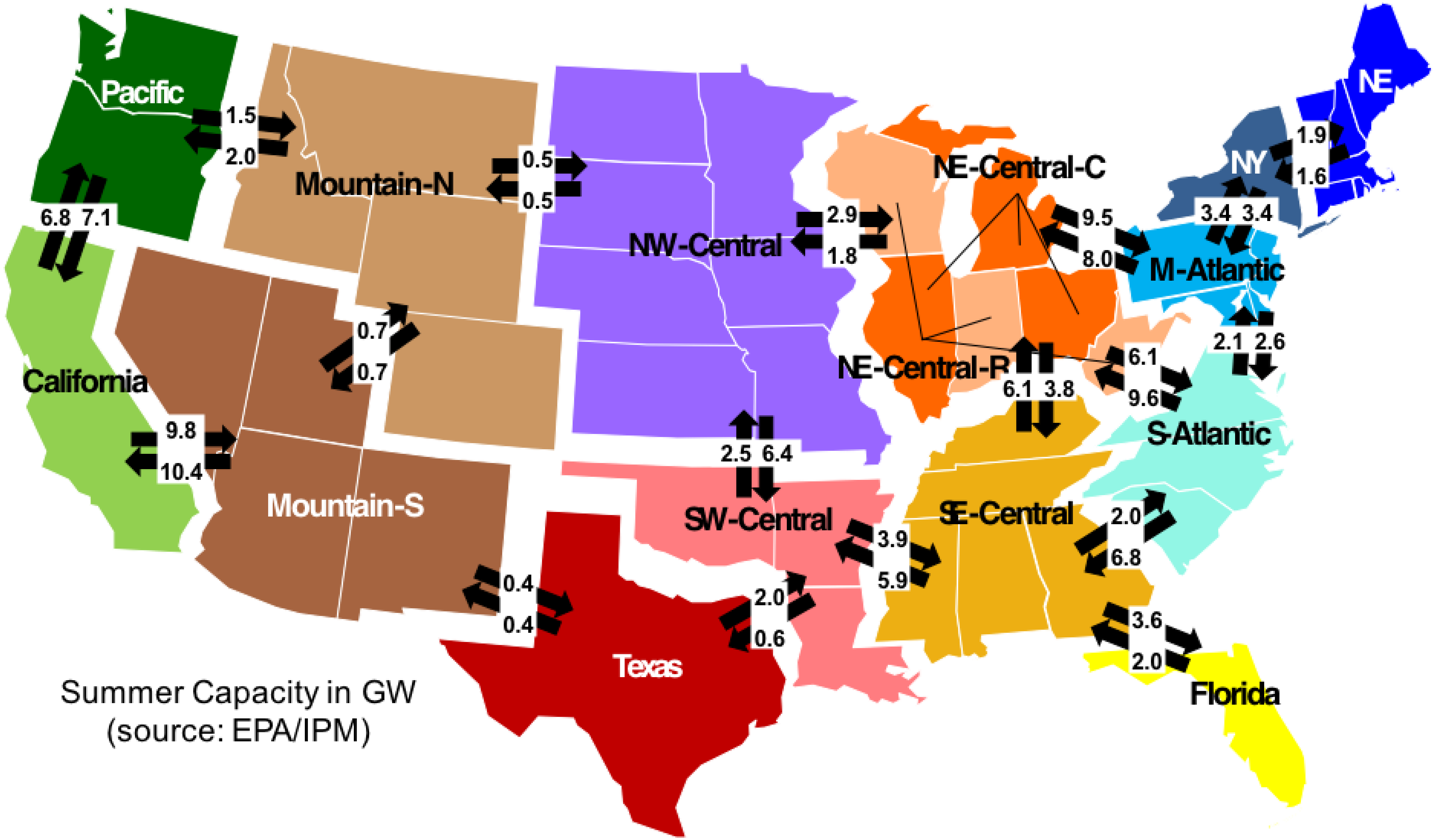
EPRI ELECTRIC POWER RESEARCH INSTITUTE

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

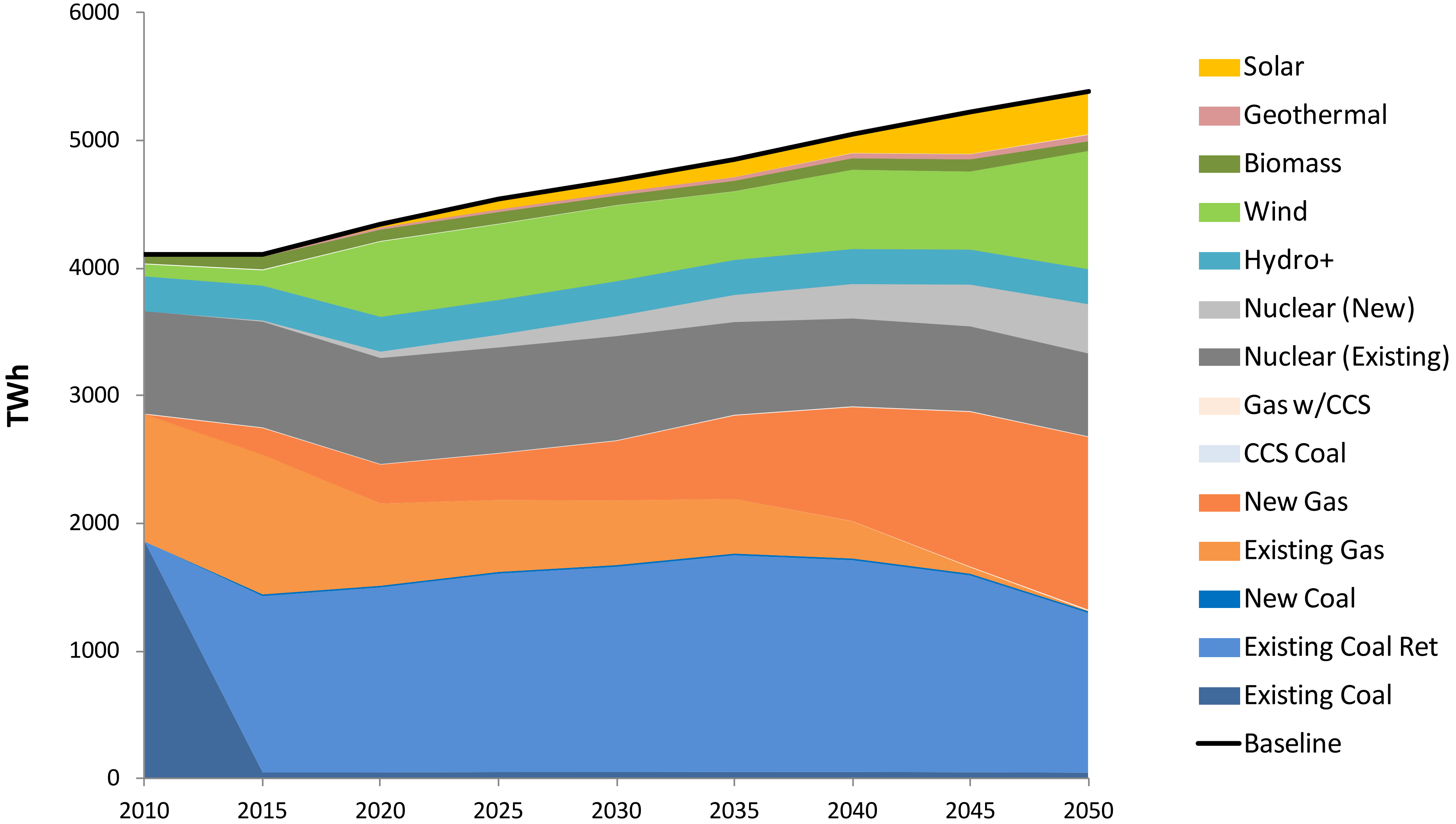
Integrated View of Multiple Regions



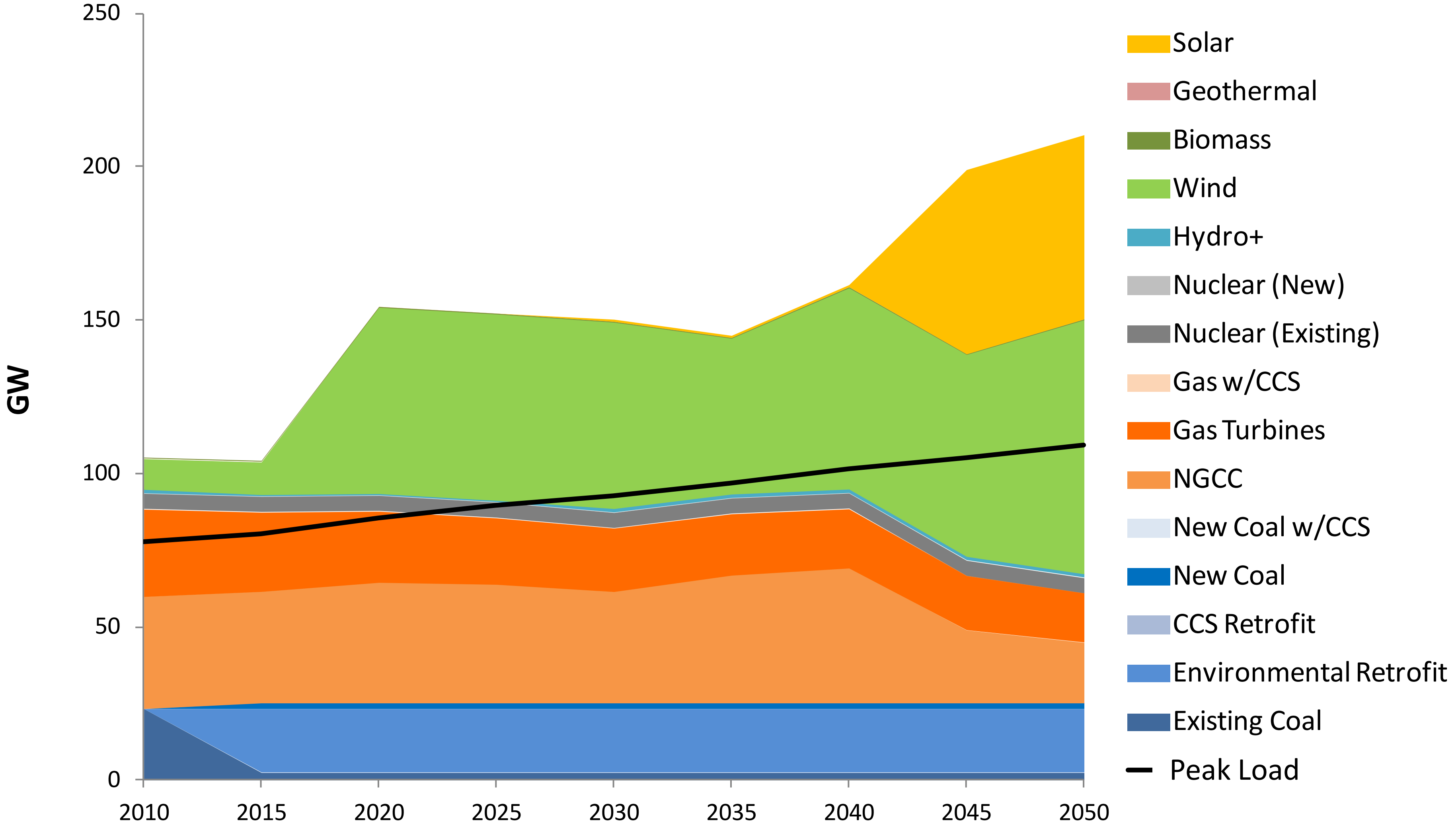
Summer Capacity in GW
(source: EPA/IPM)

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Example: National Generation Mix



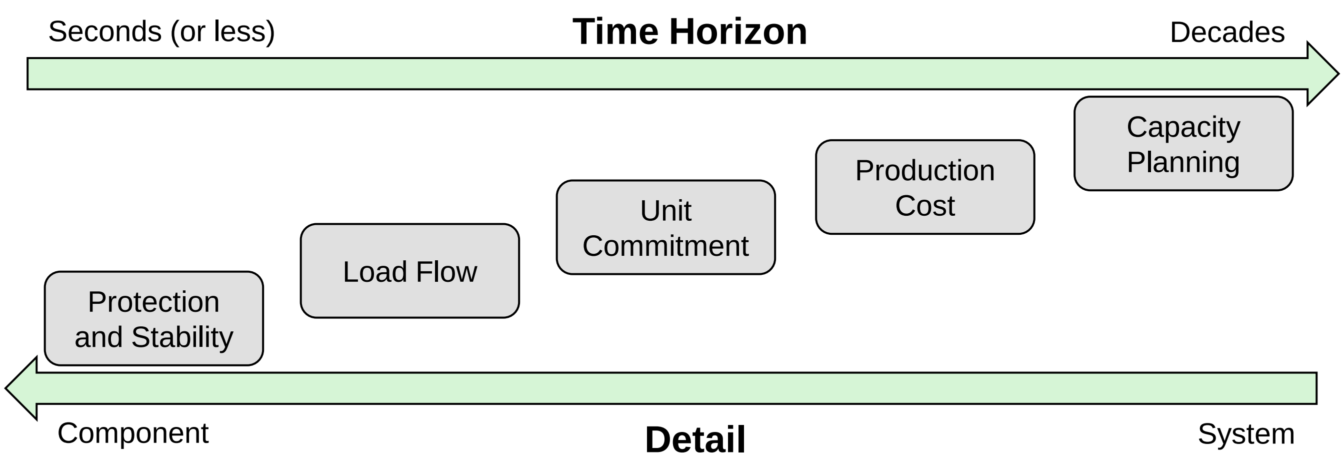
Example: Texas Region Capacity Mix



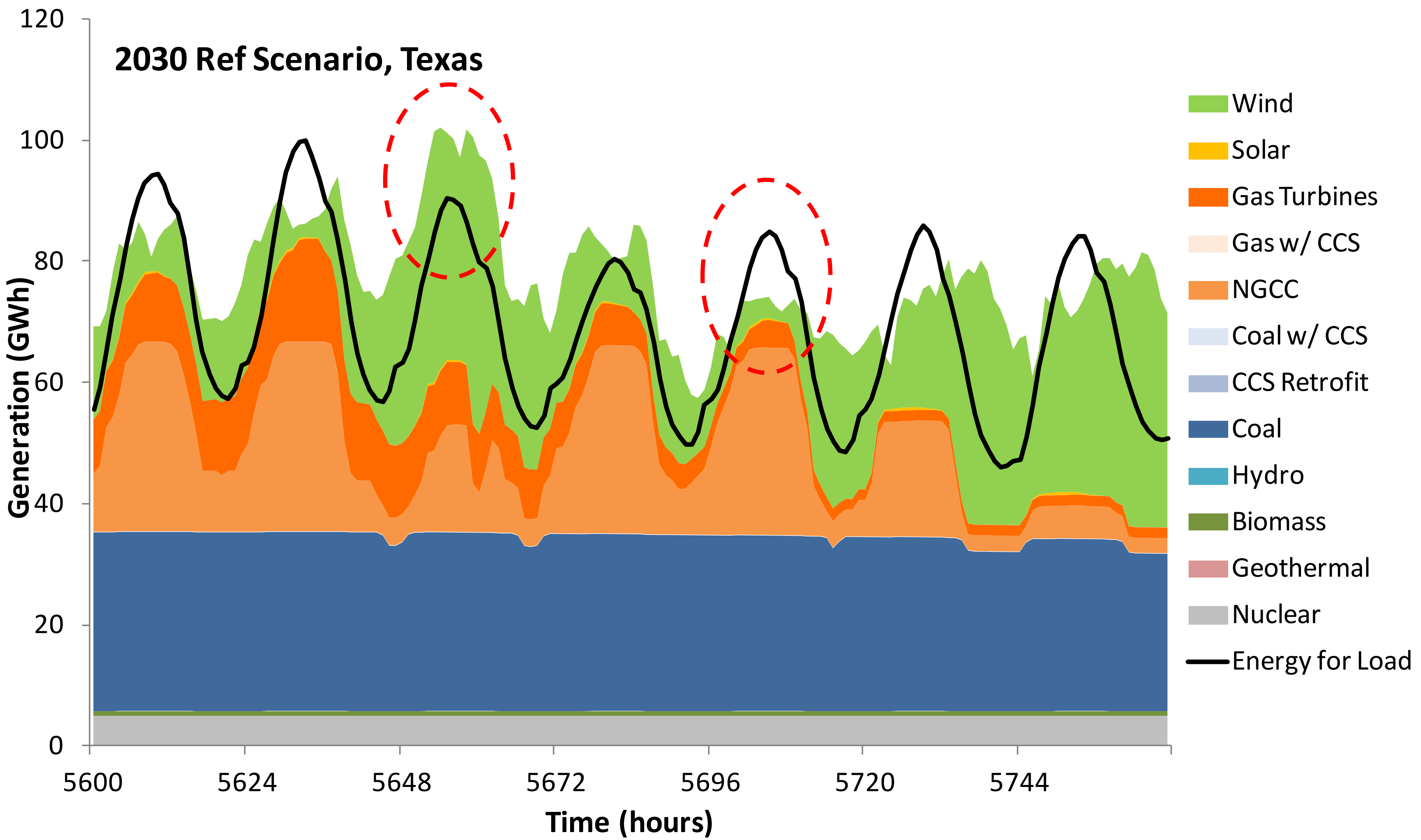
ELECTRIC POWER RESEARCH INSTITUTE

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



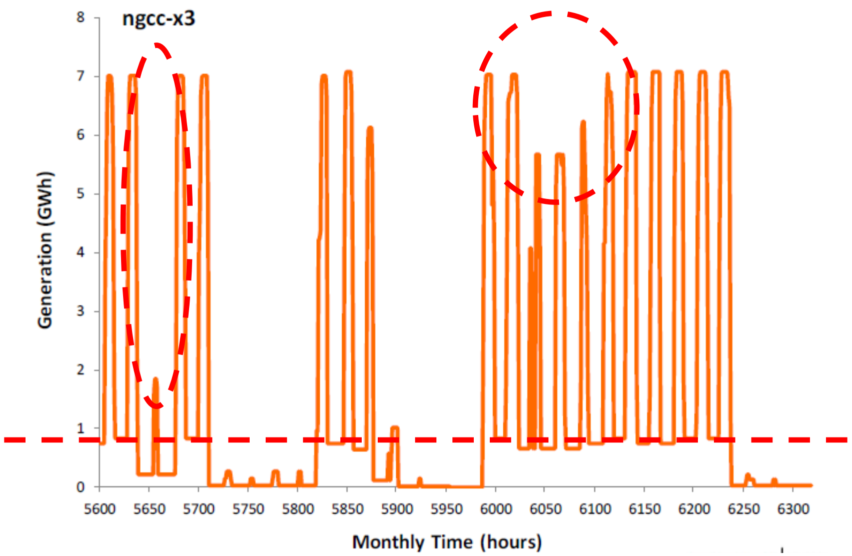
Example: TX Region, 2030, Peak Week



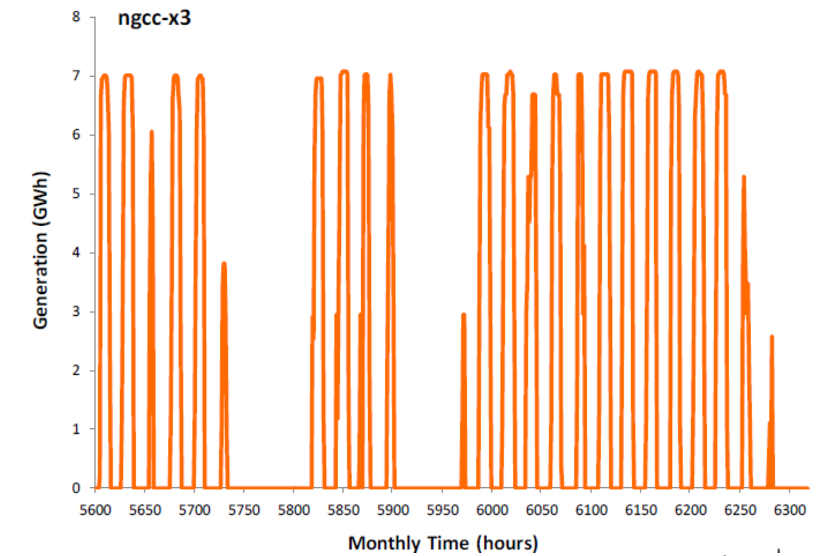
ELECTRIC POWER RESEARCH INSTITUTE

Example: TX Region, 2030, Selected Month

NGCC dispatch with ramp rate, turndown constraints



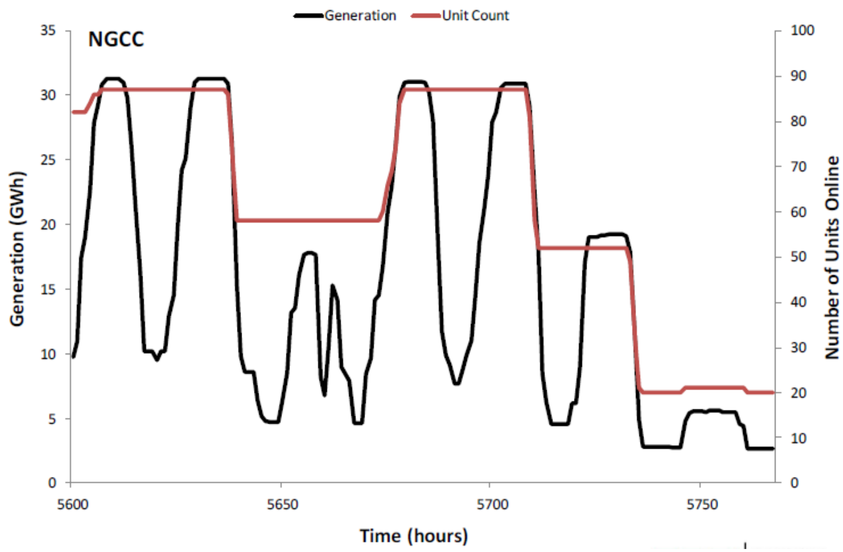
NGCC dispatch with no constraints



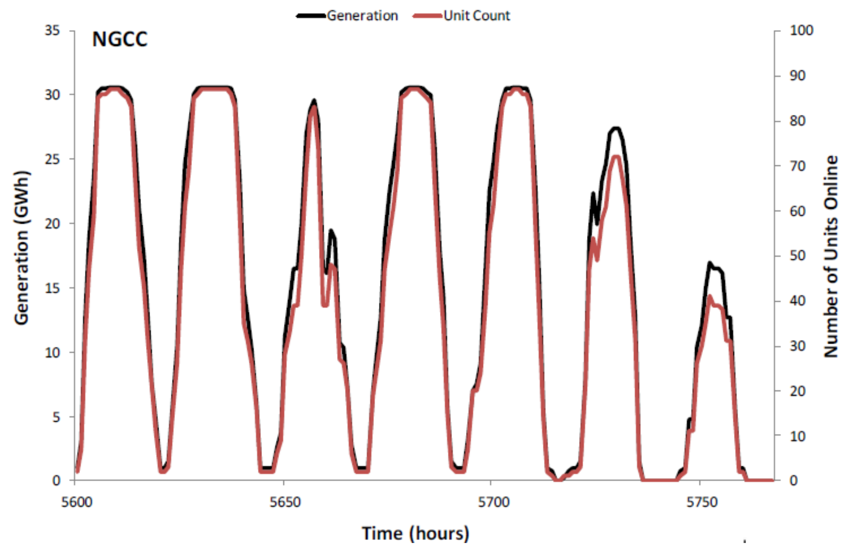
EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Example: TX Region, 2030, Selected Week

NGCC unit count and generation with ramp rate, turndown constraints



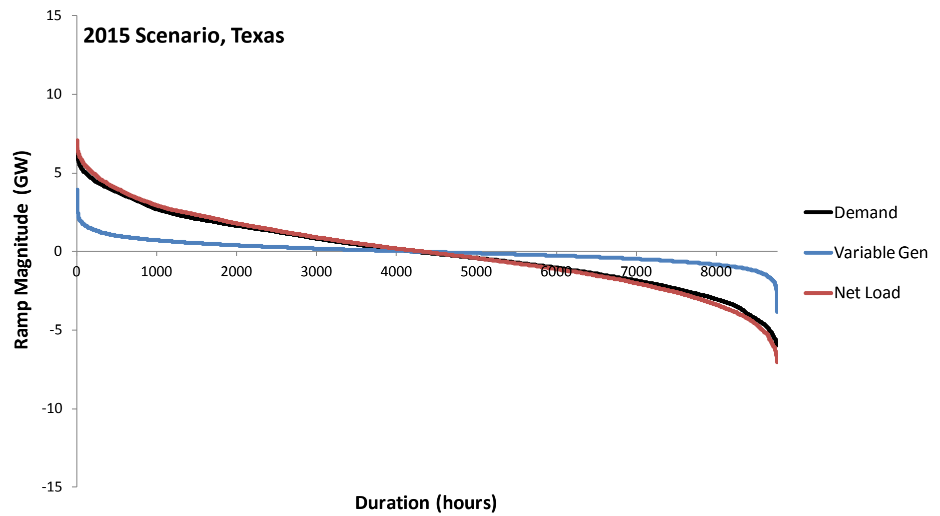
NGCC unit count and generation with no constraints



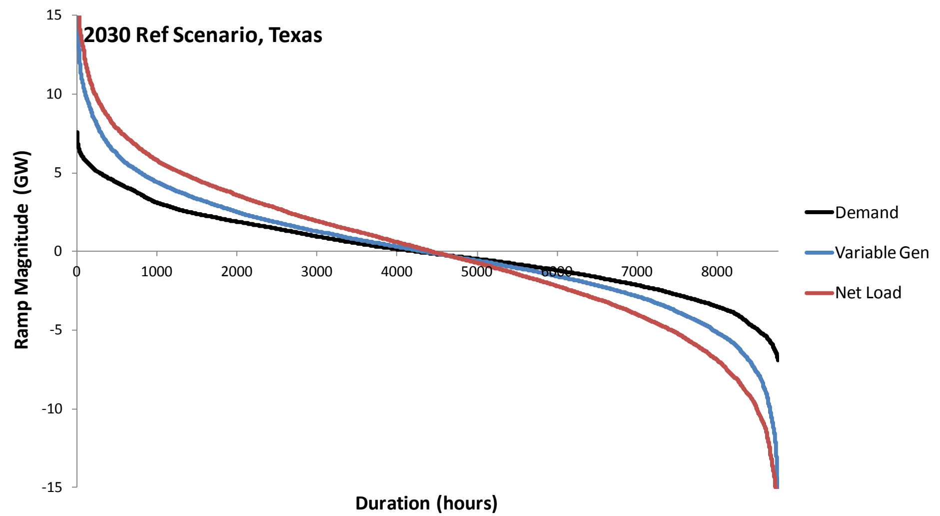
ELECTRIC POWER RESEARCH INSTITUTE

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

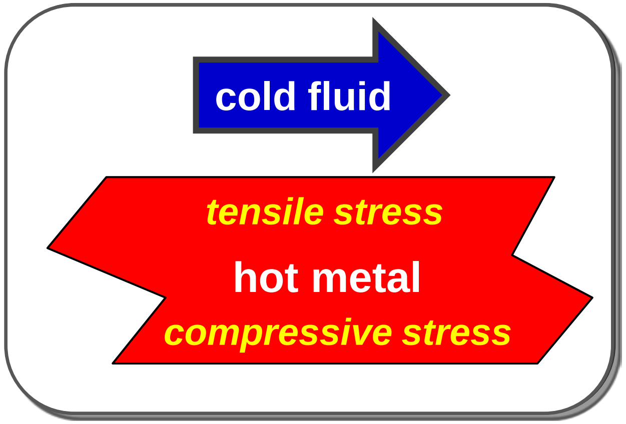
Other Emerging Insights

- 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

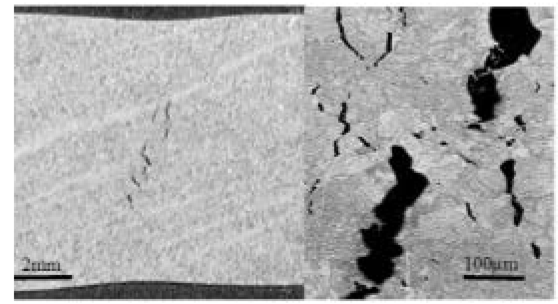
Tube-to-header crack in HRSG

Ligament cracking in boiler header

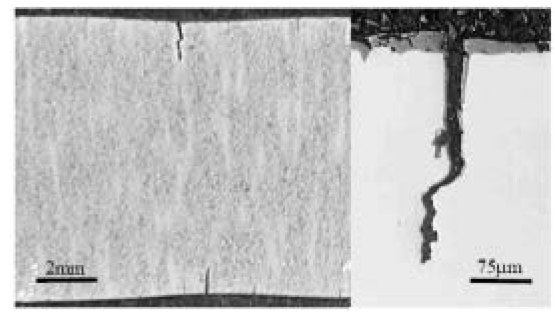
28

Flexible Operation: Major Damage Mechanisms

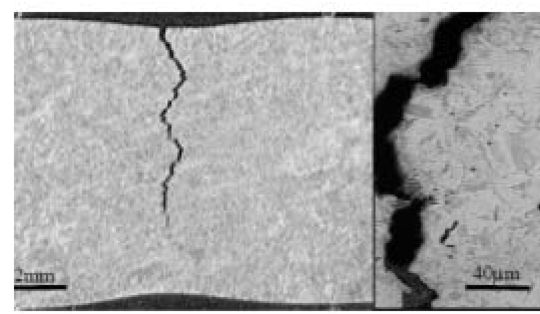
- Creep-Fatigue Interaction
  - Creep damage found in units operating near design life
  - Cycling these older units can increase fatigue damage
  - Interaction of these mechanisms is synergistic, greatly reducing cycling operational life
  - Remaining life estimation is area of significant study



Creep



Fatigue

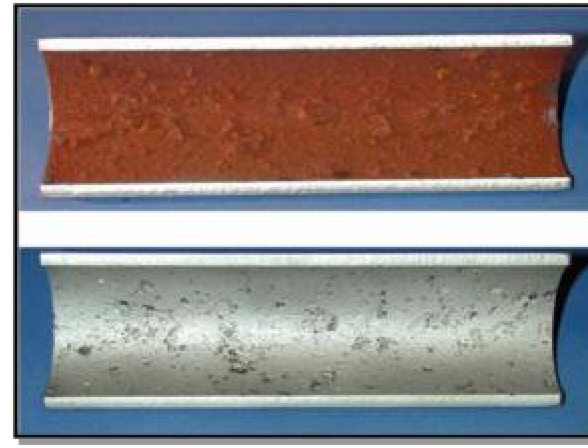


Creep-Fatigue Interaction

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

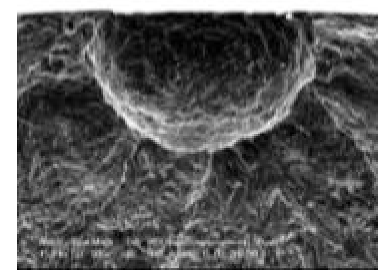
Flexible Operation: Major Damage Mechanisms

- 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



Corrosion in boiler tubes

Pitting on steam turbine rotor

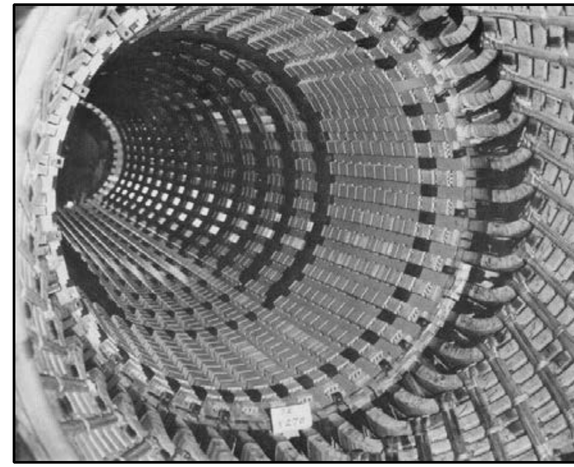


Pit morphology

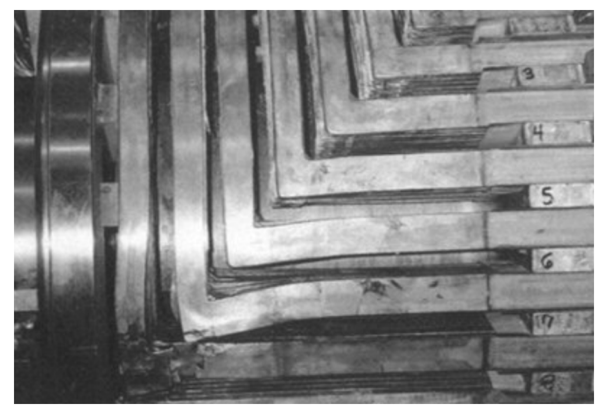
30

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

ELECTRIC POWER RESEARCH INSTITUTE

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

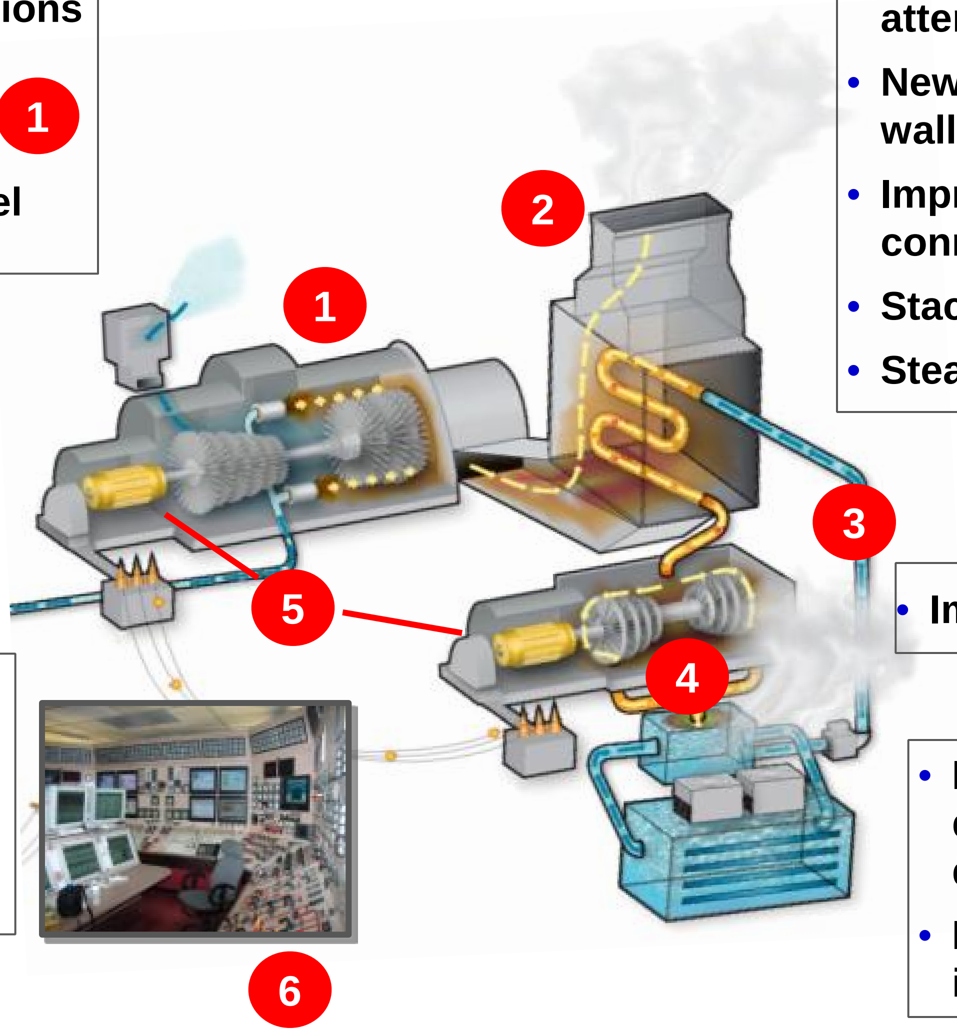
1

- Accommodation of winding thermal growth

5

- Automated startups
- Improved operator displays and alarm management

6



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

2

- Improved drains

3

- Improved casing design to reduce distortion
- Improved thermal insulation

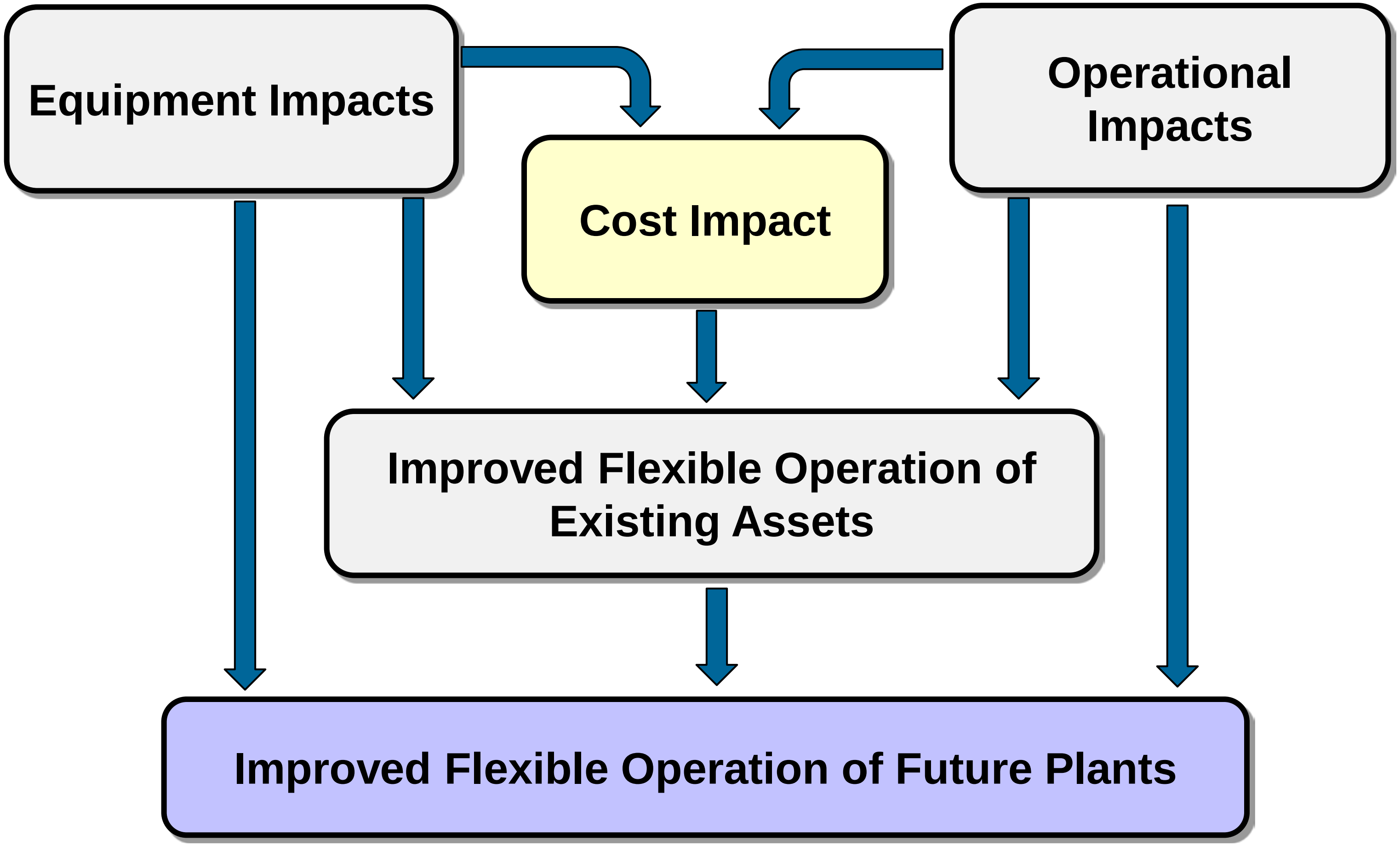
4

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

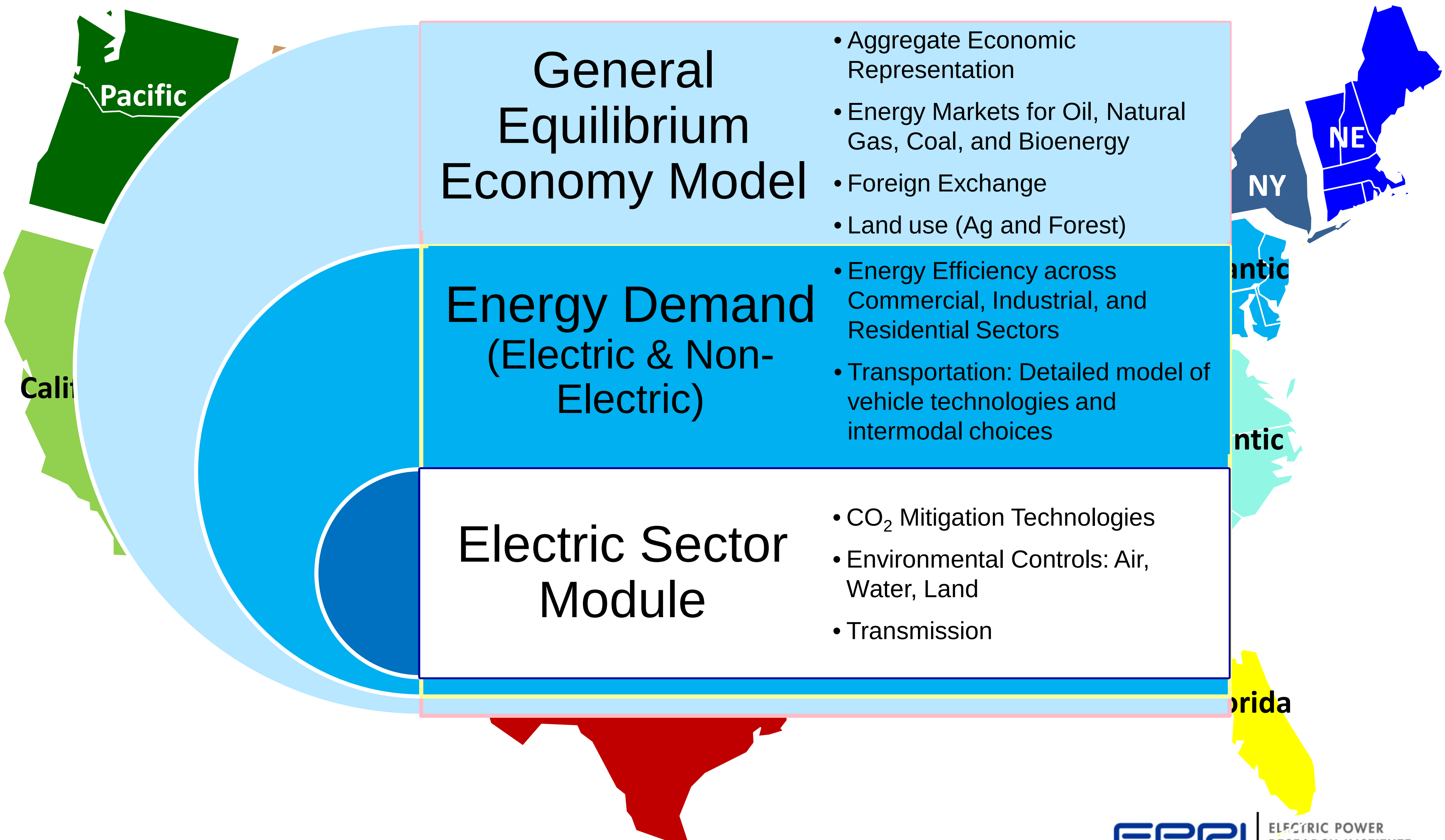
Improving Asset Flexibility: Systematic Approach



Improve operational flexibility of current and future assets

PRISM 2.0: Improved Regional Model

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



EPRI | ELECTRIC POWER RESEARCH INSTITUTE

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

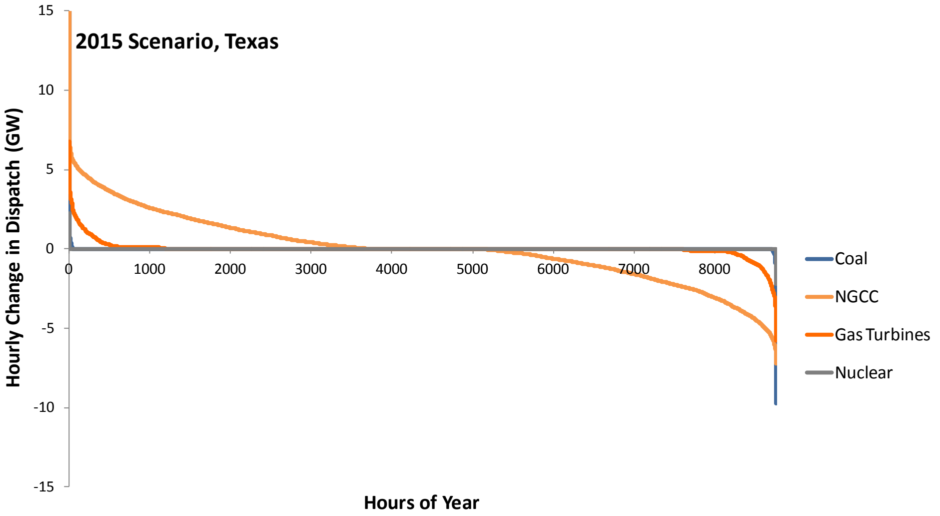
- Baseline reference: EIA Annual Energy Outlook (AEO)
  - Projected level of energy demand (AEO 2011)
  - Reference energy prices (AEO 2013)
- Electric sector policies
  - Renewables
    - Existing state RPS requirements
    - Production tax credit through 2020
  - Environmental
    - Environmental controls 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

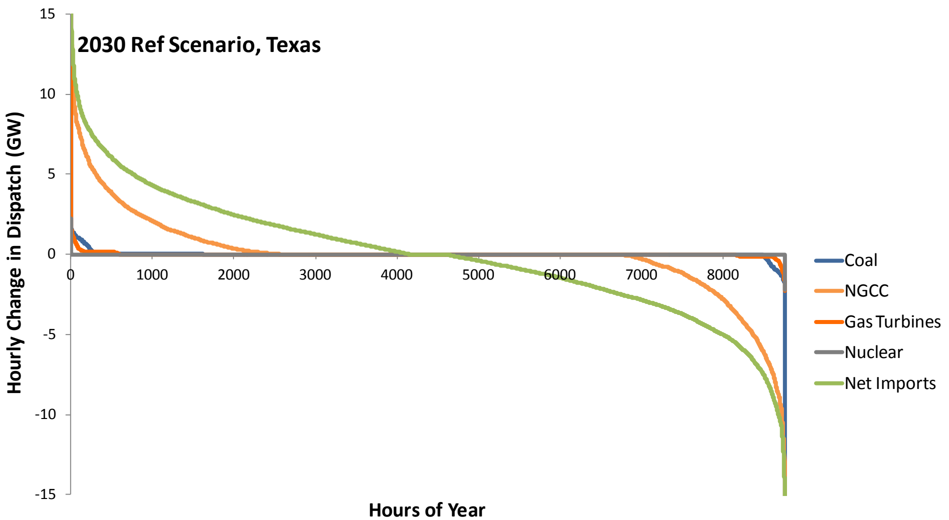
- Nuclear
  - New nuclear allowed
  - 80% of existing nuclear extended to 60 years
  - 6 GW constructed before 2020; maximum build rate = 7 GW/decade thereafter
- Renewable Energy
  - Cost reductions over time
- Coal
  - Existing unit lifetime = 70 years
  - CCS (50% or 90%) retrofit available as of 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)

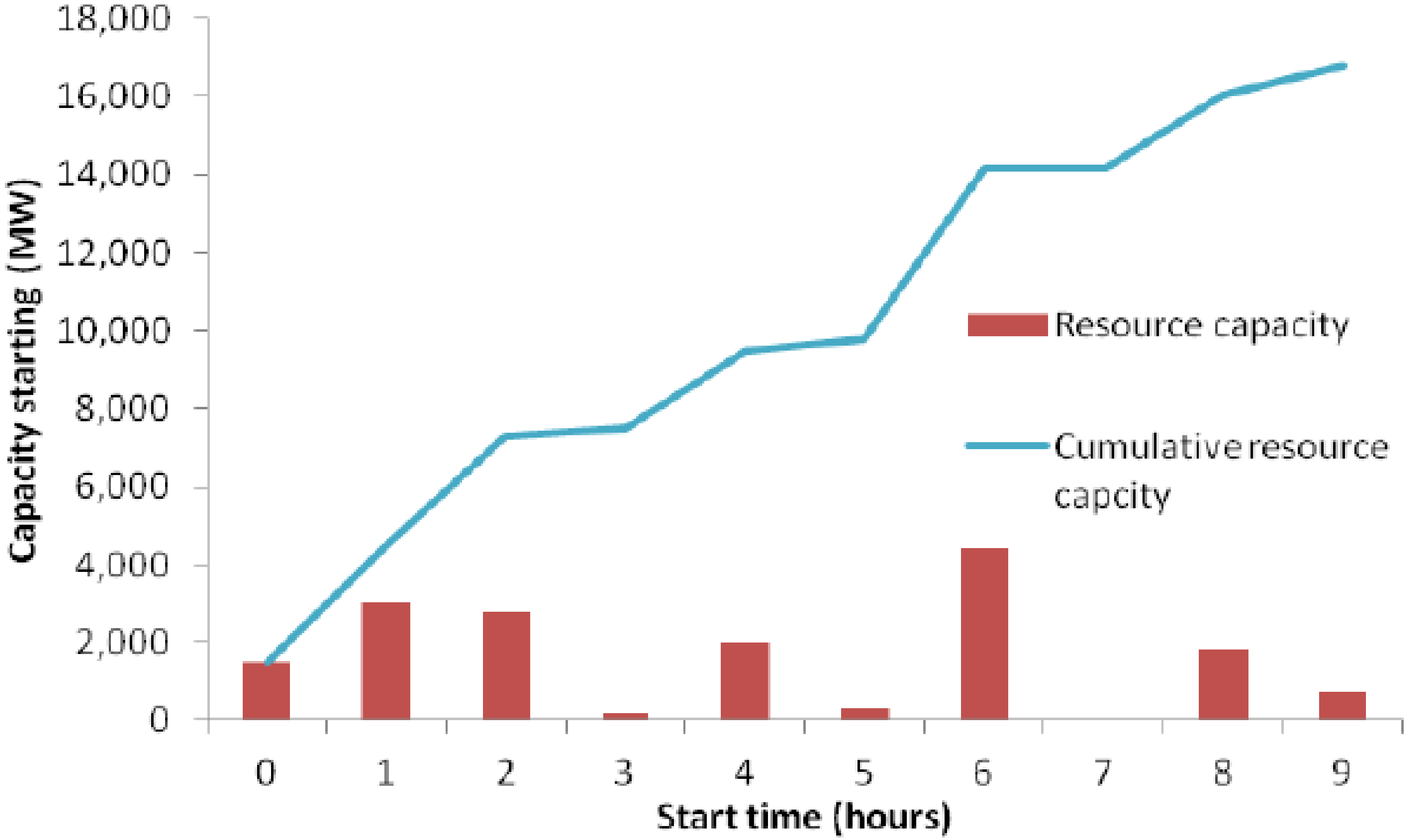


Ramp Duration Curve (2030)

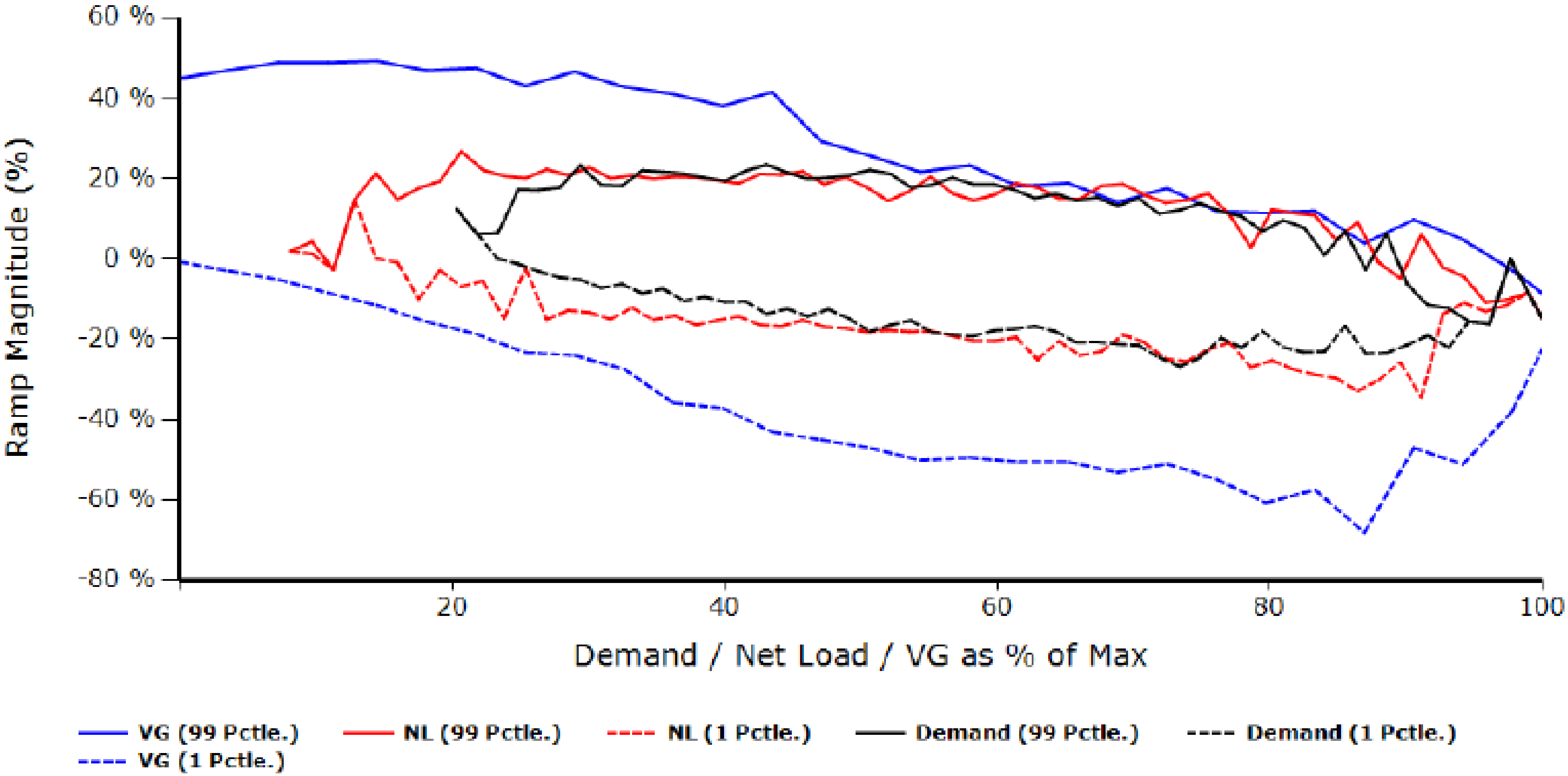


ELECTRIC POWER RESEARCH INSTITUTE

Inflexion Tool – Example Output
Distribution of resource capacity vs. start up time



Inflexion Tool – Example Output
3-Hour Ramp Magnitude



EPRI ELECTRIC POWER RESEARCH INSTITUTE

Inflexion Tool – Example Output
Period of Flexibility Deficit Metric