Crosscutting Activities in Systems Engineering and Analysis

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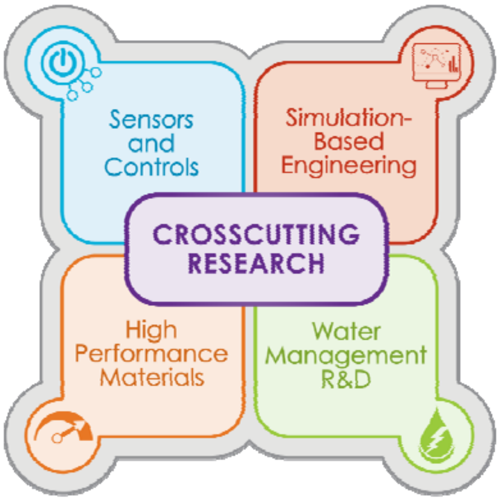
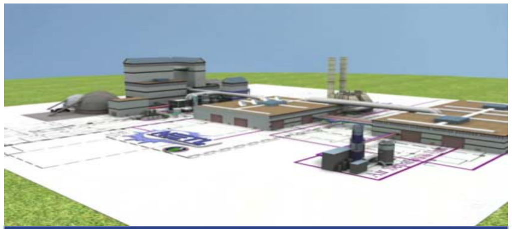
Energy Process and Analysis Team
Systems Engineering & Analysis Directorate

Outline

- **Systems Engineering & Analysis at NETL**
- **High Performance Materials**
  - Advanced Ultra-Supercritical (AUSC) Power Cycles
- **Sensors and Controls**
  - Dynamic Modeling of Advanced Power Cycles
  - Role of Sensor R&D in Mitigating the Impacts of Cycling on Coal-Fired Power Plants
  - Direct Power Extraction (DPE) Analyses
- **Simulation-Based Engineering**
  - Institute for the Design of Advanced Energy Systems (IDAES)
- **Water Management R&D**
  - Hybrid & Dry Cooling Study
  - Power Plant Effluent R&D
  - Trace Metals Analysis
  - Case Studies on Power Plant Water Use – Practices and Future Issues
  - Produced Water Desalination Metrics
  - Water-Energy Integrated Model



NATIONAL ENERGY TECHNOLOGY LABORATORY



Systems Engineering & Analysis

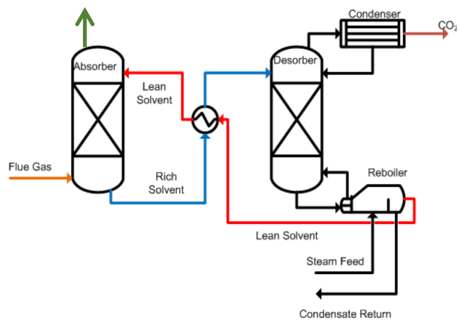
Process Systems Engineering

Energy Process Analysis

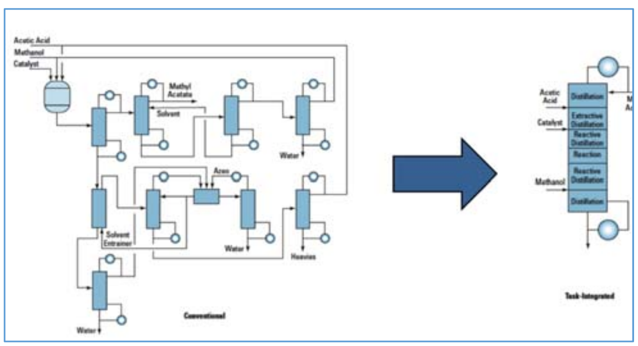
Energy Systems Analysis

Energy Market Analysis

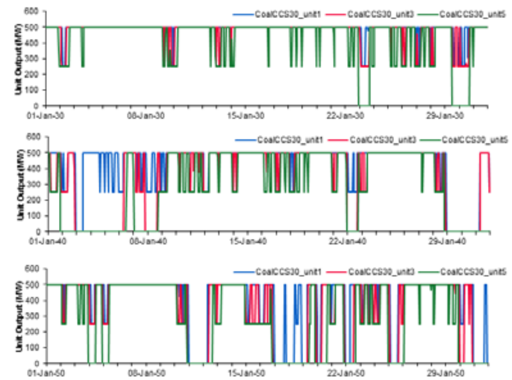
NETL Systems Engineering & Analysis



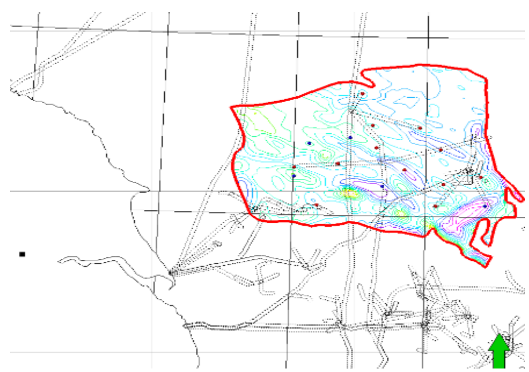
Advanced Technology Design and Cost Estimation

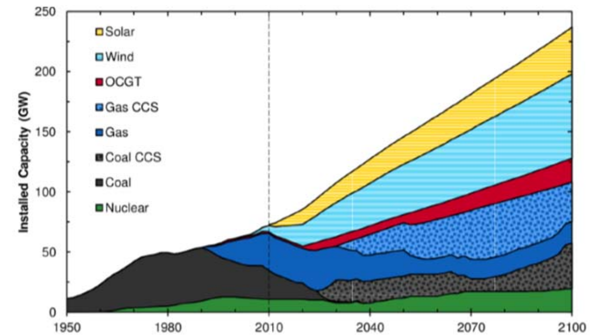


Innovative Advanced Energy Systems through Process Systems Engineering



Grid, Infrastructure, and Energy Reliability





Regional and National Energy-Economy Model

Life Cycle Analysis

High Performance Materials

Advanced Ultra-Supercritical (AUSC) Power Cycles

- **Conduct performance and economic assessments of advanced material-enabled coal-fueled power plants**
  - Advanced ultrasupercritical (AUSC) Rankine-cycle-based pulverized coal (PC) and oxy-circulating fluidized bed (CFB) plants
  - Also find application in supercritical carbon dioxide (sCO_2) oxy-CFB plants
- **Operating conditions possible due to Ni-based superalloys**
  - Up to 5,000 psi, 1,400 °F (345 bar, 760 °C)
  - Developed under the AUSC Materials Consortium
  - Inconel 740 (ASME code approved for use in boilers) and Haynes H282 alloys
- **Detailed presentation tomorrow at 3pm – Track B, Session 6**
  - Update on the Techno-Economic Viability of AUSC Systems

High Performance Materials

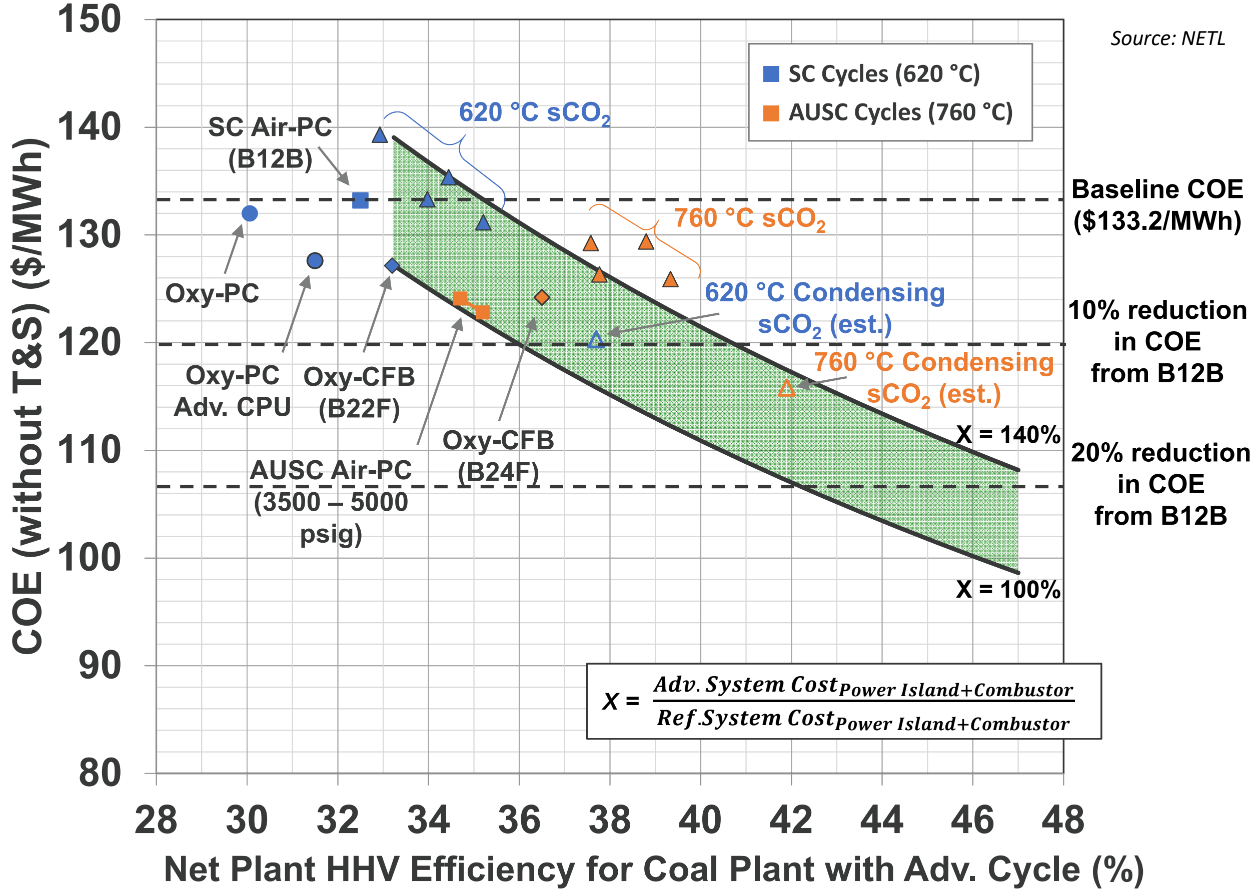
Advanced Ultra-Supercritical (AUSC) Power Cycles

- **Thermodynamic and economic analyses**
  - Analyses follow NETL Quality Guidelines for Energy Systems Studies (QGESS)
  - Cost estimates developed at same detail level as NETL's Cost and Performance Baseline for Fossil Energy Plants report series; in particular, Volume 1, Bituminous Coal and Natural Gas to Electricity (the "Bituminous Baseline")
  - Bituminous Coal (Illinois #6), generic Midwestern location, ISO ambient conditions
  - Estimated emissions of Hg, PM, NOx, and SO_2 are all at or below the applicable regulatory limits at the time of preparation for all cases
  - 550 MW net scale, 85% capacity factor
  - 2011 $
  - CCS cases include transport and storage (T&S) in a saline formation
  - Incorporated results from the literature and in consultation with developers for advanced technologies

High Performance Materials

Steam Rankine and Indirect sCO_2 cycles with CCS

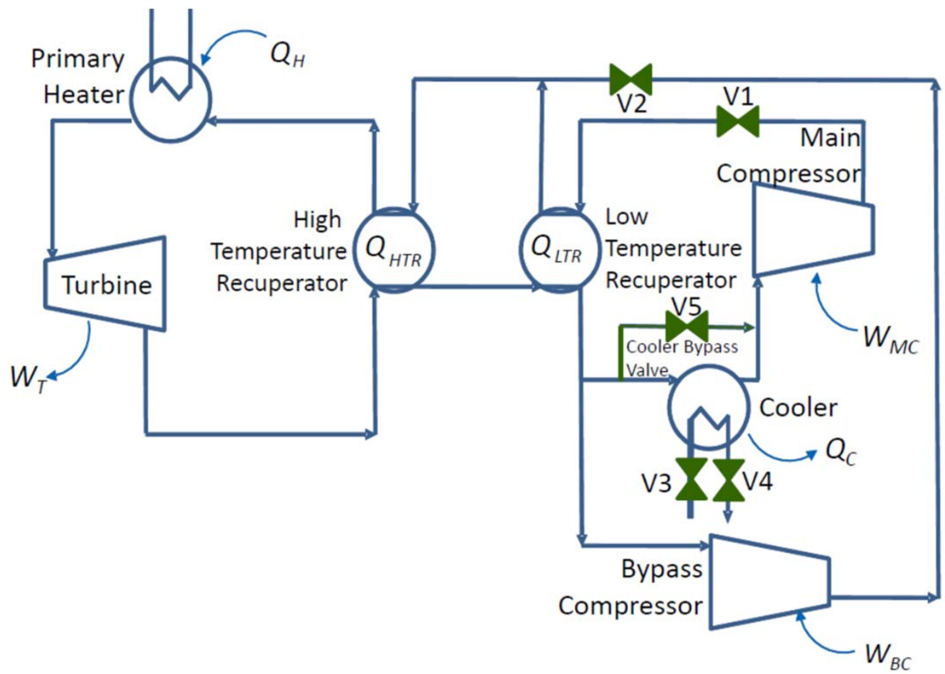
- Reference: Supercritical Oxy-combustion CFB with Auto-refrigerated CPU (Case B22F)
  - $0/tonne CO_2 revenue
  - 550 MWe
- COE reductions are relative to an air-fired, supercritical PC coal plant with CCS (Case B12B)
- Ongoing work assessing condensing CO_2 cycles



Sensors and Controls

Dynamic Modeling of Advanced Power Cycles

- **Advance the understanding of thermodynamic and environmental performance, and economics, of fossil energy power system technologies from a sensors and controls perspective, in order to guide R&D, reduce technical risks, and inform key stakeholders.**
- **DOE's Supercritical Transformational Electric Power (STEP) Program**
  - Supercritical CO_2 (sCO_2) Crosscutting Initiative (CCI) t demonstrate sCO_2 Brayton cycle technologies at scale
- **DOE announced project award to develop sCO_2 test facility (October, 2016)**
  - $80M federal contribution, 20% industry cost share, an 6-year duration
  - Managed by team led by GTI, SwRI, and GE Global Research
  - Design, build, and operate 10 MWe sCO_2 Pilot Plant Test Facility in San Antonio, TX
  - Operational in 2020



Source: NETL

Sensors and Controls

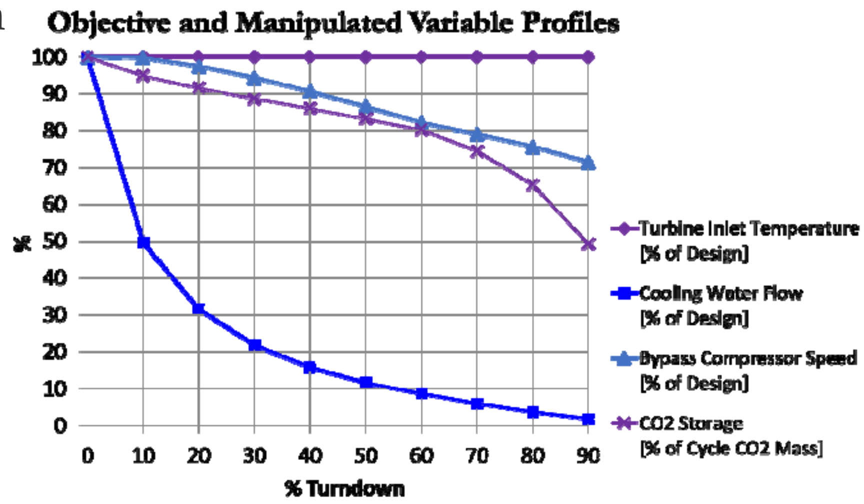
Dynamic Modeling of Advanced Power Cycles

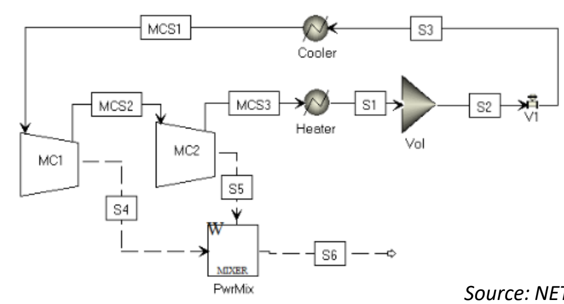
- **Operational procedures and controls R&D to reduce technical risk**
  - Startup, shutdown, load follow, plant trips, etc.
  - Cope with highly nonlinear fluid property changes, especially near the critical point
  - Cope with high degree of heat recuperation and pressure interactions
  - Maintain stable, safe operation with CO_2 working fluid in supercritical region
  - Operate commercial cycles with coupled, constant-speed turbomachinery
- **Develop control strategies for the dynamic operation of a 10MWe supercritical CO_2 recompression Brayton cycle**
  - Aspen Dynamics® and Aspen Custom Modeler® to develop dynamic system model.
  - Other software (such as Matlab/Simulink®) may be used for advanced control implementation.

Sensors and Controls

Dynamic Modeling of Advanced Power Cycles

- **Transient model of 10 MW recompression Brayton cycle built in Aspen Dynamics®**
  - Tested several heat-input reduction strategies.
  - Implementing regulatory PID controls
- **Model of multi-stage centrifugal compressor built in Aspen Custom Modeler®**
  - Studied main compressor operation near CO_2 critical point (ASME Turbo Expo paper GT2017-63090)
- **Future Work**
  - Perform system identification studies on current 10 MW system model and use to improve PID control and to propose initial advance control method.
  - Incorporate ACM multi-stage compressor model into system model
  - Develop compact heat exchanger models (design and dynamic) in ACM (Post-doc under Turbines FWP)



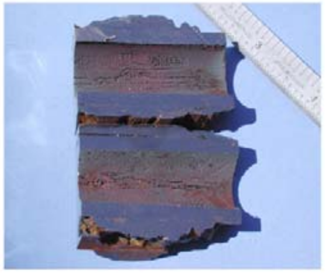


Source: NETL

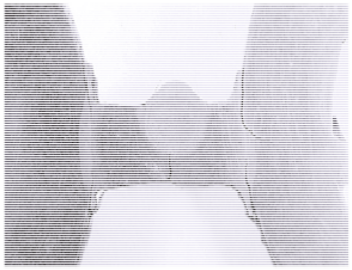
Sensors and Controls

Role of Sensor R&D in Mitigating the Impacts of Cycling on Coal-Fired Power Plants

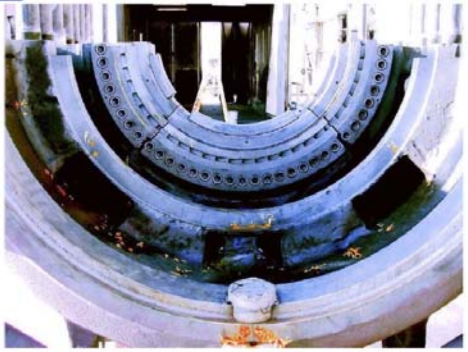
- **Effects of cycling**
  - Increases Operating and Maintenance (O&M) costs
  - Lowers efficiency, resulting in increased fuel consumption and emissions
  - Loss of generating revenue
  - Decreases remaining useful life due to accumulated damages
- **Existing coal-fired power plants built in the 1960's were designed for baseload operation (high capacity factor)**
  - Limited tolerance for cyclic operation



Waterwall web cracking



Boiler tube corrosion

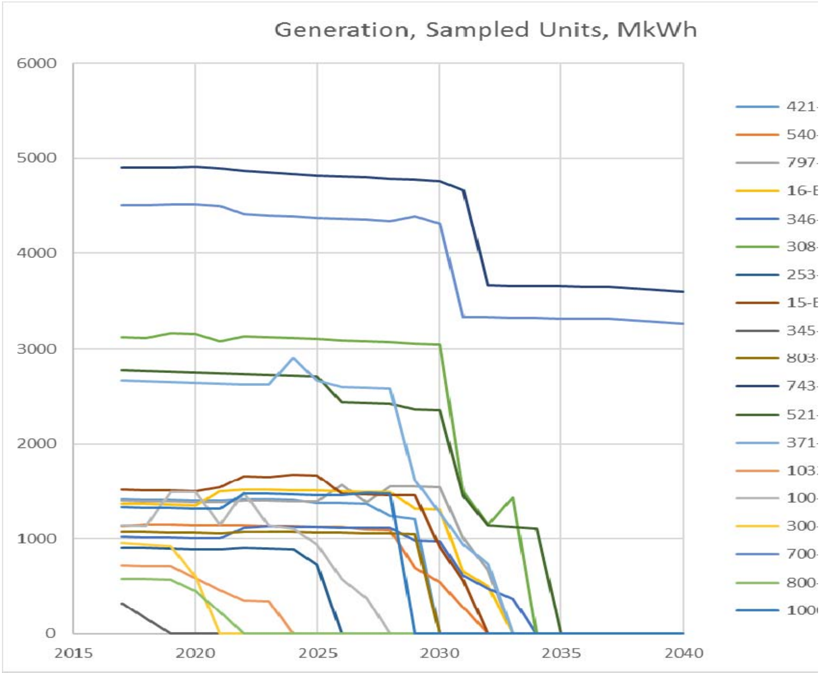


Turbine casing damage

Sensors and Controls

Role of Sensor R&D in Mitigating the Impacts of Cycling on Coal-Fired Power Plants

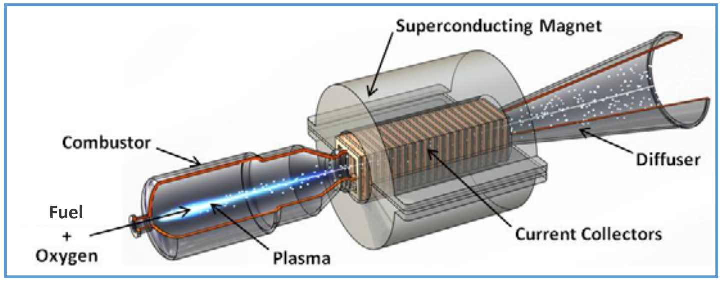
- **Most energy-market models do not account for cycling-induced degradation (heat rate and O&M impacts)**
- **ANL/NETL used ANL's EISM energy-market model to examine this issue**
  - Units accumulate damage due to cycling operation and must retire if too much occurs
  - Results indicate coal units retiring much more quickly and on a larger scale than any other models currently show
- **Ongoing work will model the impacts of R&D in sensors and controls to mitigate the damage due to different operational modes**
- **Detailed presentation tomorrow at 3pm – Track A, Session 6**
  - Scenario Simulations of Potential Cost Savings from R&D in Sensors and Controls for Coal-Fired Power Plants

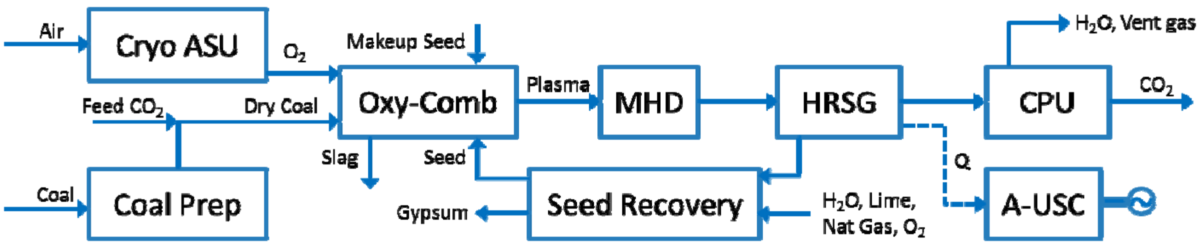


Electricity generation from selected coal units show sharp drop-offs in output due to cycling

Sensors and Controls

Direct Power Extraction (DPE) Analyses





- **Collaborated with NETL R&IC Multiphase Modeling team to develop a tool for oxy-coal MHD system design and optimization**
- **Developed the *first* pure oxygen-fired coal MHD system performance and cost analysis with CCS**
  - Performance analysis of a baseline oxy-coal DPE system with CCS provides a cost and performance data against which advanced DPE systems can be compared
  - Completed balance of plant design, capital cost estimation, and COE analysis
    - Issues include: MHD component costs, coal dryer cost, seed makeup cost, 80% capacity factor, and reduced net power output
    - Large uncertainty in DPE-specific component costs, which are scaled from legacy cost scaling algorithms

Sensors and Controls

Direct Power Extraction (DPE) Analyses

- **Ongoing/Future work**
  - DPE Scoping Study
    - Complete a screening analysis of DPE integrations with other power systems to identify promising DPE system combinations that can meet transformational efficiency and cost-of-electricity goals, while providing flexible, modular, and/or low-water power.
    - Comparative analysis against baseline study to identify best DPE configurations for more detailed studies
  - Investigate effects/dependency of electrode/channel wall temperature on baseline oxy-coal DPE system performance
  - Optimization of seed recovery process to improve cost & performance (FY17)
  - Look at alternate fuels (e.g., petcoke), supersonic channels

Simulation-Based Engineering

Institute for the Design of Advanced Energy Systems (IDAES)

- **Challenges:**
  - Determining **which technologies to pursue** and **how to optimally integrate them** while taking into account their full life cycle environmental footprint and determining their potential in the market.
  - Current computational tools and analysis approaches cannot simultaneously address such complex interactions, nor can they address a sufficient number of scenarios in the timeframes required.
- **Vison:**
  - Become the **premier resource for the identification, synthesis, optimization and analysis** of innovative advanced energy systems at scales ranging from process to system to market.
  - Support the transformation of the national energy landscape to meet DOE's three enduring strategic objectives: energy security, economic competitiveness, and environmental responsibility.
- **Integrates NETL's historic capabilities in Systems Engineering & Analysis**
- **Impact:**
  - Rapid integrated identification and assessment of novel energy technologies and their potential impact within complex systems and markets in order to prioritize and direct R&D efforts.

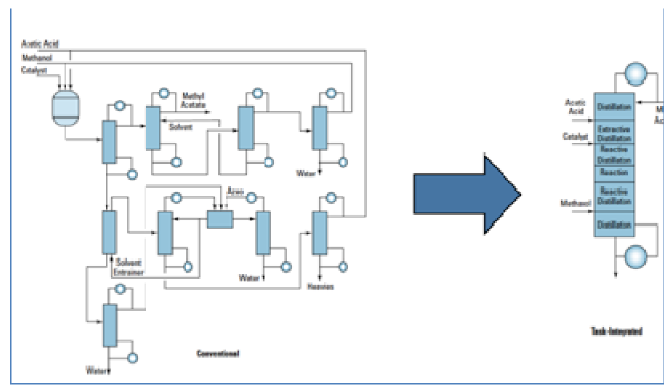
Simulation-Based Engineering

Institute for the Design of Advanced Energy Systems (IDAES)

- **Approach:** Develop and utilize multi-scale, simulation-based computational tools and models to support design, analysis, optimization, scale-up and troubleshooting.
- **Next generation modeling and optimization platform**
  - Flexible and open modeling environment
  - Complete provenance information
  - Supports advanced solvers and computer architecture
  - Intrusive uncertainty quantification
  - Process synthesis, integration, and intensification
  - Process control and dynamics
- **Apply emerging models and tools to support internal/external development**
  - Chemical looping
  - Novel advanced combustion systems concepts
  - Carbon capture (via CCSI[2])

IDAES
Institute for the Design of Advanced Energy Systems

Development Of Innovative Advanced Energy Systems Through Advanced Process Systems Engineering



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Simulation-Based Engineering

Institute for the Design of Advanced Energy Systems (IDAES) - Tools

Laboratory and/or Literature Data

Automated Fitting Algorithms for Physical Properties, Thermodynamics and Kinetics

Process Model Library

Model Customization for Specific Applications and Innovative Concepts

Detailed presentation tomorrow at 3pm – Track B, Session 6

Conceptual Design
Process Synthesis
Process Integration

Process Dynamics
Process Control
Process Optimization

Identify New Advanced Energy Concepts

Analysis of Energy Systems

Understand Data Requirements

Investigate Multiple Scenarios across Time and Length Scales

Incorporation and Assessment of Uncertainty Across Models/Scales

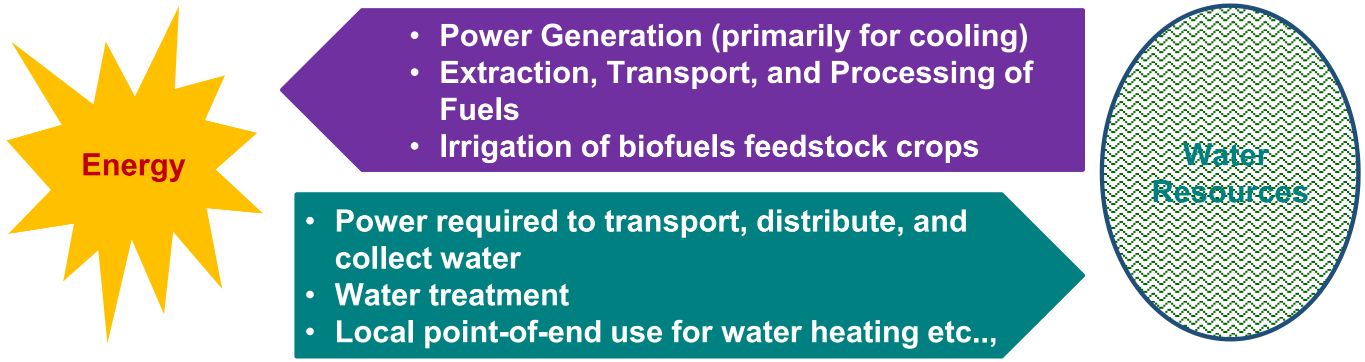
Inherently Dynamic Systems – Design & Control

Solvers and Computational Platform to Enable Solution of Large Scale Problems

Data Management to Maintain Provenance, Organize Models, Enable Links Among Scales/Tasks

Water Management R&D

- Develop tools and metrics that allow for a better understanding of power plant water utilization under potential water constrained futures.
- Inform the direction of the NETL R&D to mitigate the impact of water availability threats on both current and future fossil-fueled electric power generation capacity



Power Generation*
• Thermoelectric power generation accounts for a majority of water usage for power generation – Nearly 52% of surface fresh water withdrawals – A total of 43% of total water withdrawals • Vulnerable to physical constraints of water availability and regulations limiting access to it – Power plants in the US forced to modulate/shutdown power generation during a recent drought in 2012 – Can constrain the type and location of power plants that can be built

Water Resources
• Water scarcity, variability, and uncertainty are becoming more prominent in the US – Population growth – Climate change – Precipitation profile redistributions • Environmental impacts and regulations alter water availability profile • Strong temporal dependence • Highly localized due to water rights and other region-specific issues

Water – Energy Dependency is one dimension of the larger Water – Energy - Food Nexus

*Sources: 1. US DOE, "The Water – Energy Nexus: Challenges and Opportunities – Overview and Summary," 2014;
2. IEA, "Water for Energy Resource: Is Energy Becoming a Thirstier Resource," Excerpt from the World Energy Outlook 2012.
3. NREL, "Water Constraints in an Electric Sector Capacity Expansion Model," NREL/TP-6A20-64270 , 2015.
4. "The Energy-Water-Food Nexus", D. L. Keairns, R. C. Darton, and A. Irabien, Annu. Rev. Chem. Biomol. Eng. 2016.7:9.1-9.24

Water Management R&D

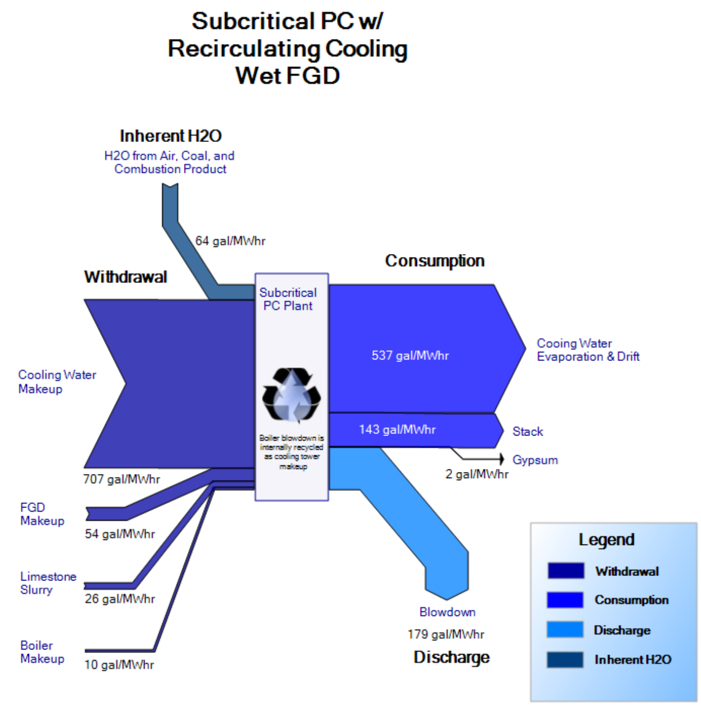
Hybrid & Dry Cooling Study

- **Assess the performance and cost impacts of state-of-the-art dry cooling technologies**
  - Update and expansion of published chapter in NETL's Cost and Performance Baseline for Fossil Energy Plants: Volume 1, Bituminous Coal and Natural Gas to Electricity, Rev. 2b (the "Bituminous Baseline")
  - Current Rev. 3 (July, 2015) used as new basis
  - Supercritical pulverized coal (SC PC) and natural gas combined cycle (NGCC) plants, with and without carbon capture
  - Expanded matrix of atmospheric conditions
  - Technology performance and cost in cooperation with Black & Veatch
- **Inform water-energy integrated model**
- **Identify R&D opportunities**

Water Management R&D

Power Plant Effluent R&D

- **Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category (ELG)**
  - Final rule issued by EPA under the Clean Water Act, effective 1/4/16
  - Sets the first federal limits on the levels of toxic metals in wastewater that can be discharged from power plants
- **Plant sources**
  - Flue gas desulfurization (FGD)
  - Fly ash
  - Bottom ash
  - Flue gas mercury control
  - Gasification of fuels such as coal and petroleum coke
- **Establish technology baselines**
  - Identify and characterize (chemical constituent) process liquid discharge streams from coal plants (conventional, advanced power, and chemical)
  - Identify water treatment technologies that can achieve required discharge limits, including zero-liquid discharge (ZLD) options
  - Develop performance and cost models to be incorporated into NETL techno-economic analyses
- **Identify R&D opportunities**
  - Mitigate performance and cost impacts



Water Management R&D

Trace Metals Analysis

- **Complementary to previously-mentioned effluent R&D**
- **Characterize trace elements in effluent streams from advanced power systems**
  - "Coal contains the periodic table" – heavy metals content in blowdown from pulverized coal combustion relatively well known
  - Conduct literature survey to characterize trace elements in process water streams from IGCC, oxycombustion, CCS, chemical looping, etc.

Water Management R&D

Case Studies on Power Plant Water Use – Practices and Future Issues

- **A collaborative effort between NETL and power plant staff**
  - Develop a report based on their water use practices and future issues and concerns regarding plant water
  - Conduct several power plants tours
    - Primary focus on coal plants
    - Secondary focus on natural gas combined cycle (NGCC) plants
- **Address water use challenges and issues holistically**
  - Measurements
  - Conditions
  - Normal and cycling operations
  - Permits
  - Disposal
  - Run off

Water Management R&D

Produced Water Desalination Metrics

- **Detailed system-level analyses will be used to develop metrics for desalination of extracted brines from carbon storage reservoirs to manage plume and pressure or produced water from oil/natural gas production**
  - Costs, performance, energy, scale, effluent conditions, final conditions
- **NETL membrane R&D may also be incorporated into this work**

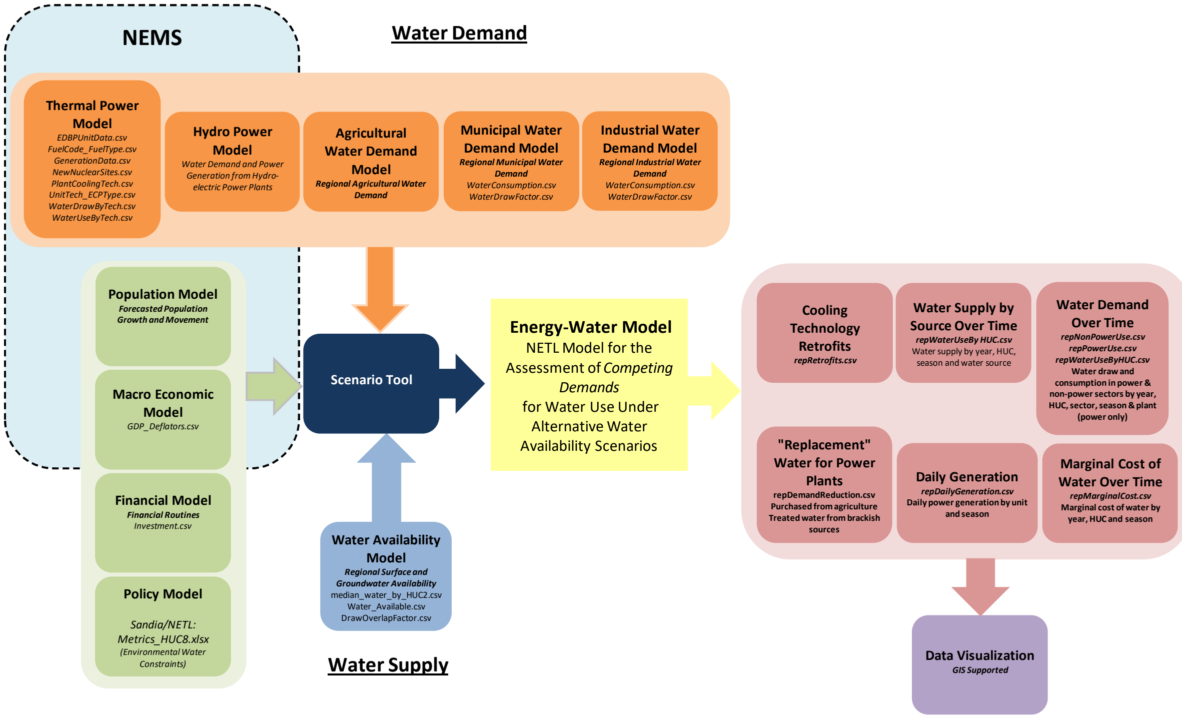
Water Management R&D

Water-Energy Integrated Model

- **Motivation**
  - Water – Energy interdependency is an important factor that has to be taken into consideration in the deployment of power generation technologies
    - Siting considerations
    - Environmental considerations
    - Technology considerations
    - Municipal, Industrial, and Agriculture considerations
  - Current energy capacity forecasting tools such as NEMS do not adequately take into account potential water constraints in deployment considerations
- **Objectives**
  - Develop tools and metrics that inform electric power generation design choices related to water availability and the cost of power plant water utilization
  - Explore electric power technology options and use results to inform R&D
  - Mitigate the impact of adverse water availability conditions on current and projected future thermoelectric electric power generation capacity

Water Management R&D

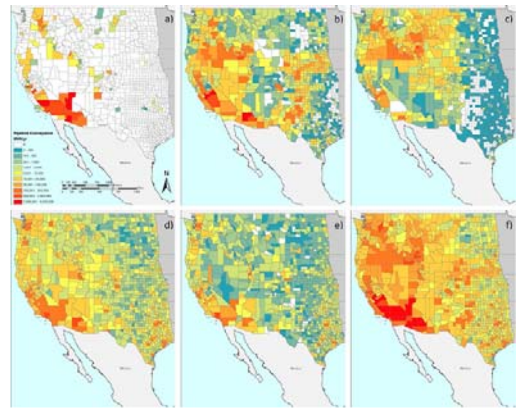
Water-Energy Integrated Model

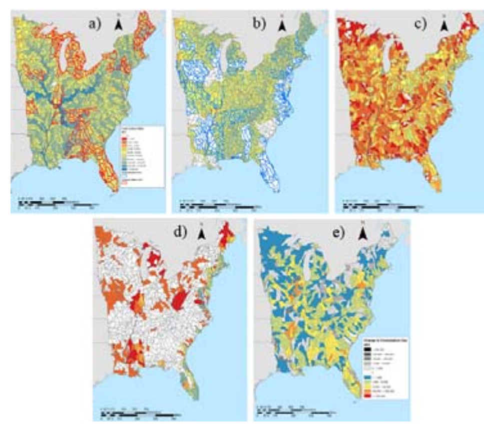


Water Management R&D

Water-Energy Integrated Model

- **Sandia Water Availability Data**
  - Original 17 Western States
  - NETL funding for 31 Eastern States
  - HUC-8 (Hydrologic Unit Code) watershed level
  - Fresh surface, fresh ground, municipal waste, brackish ground water

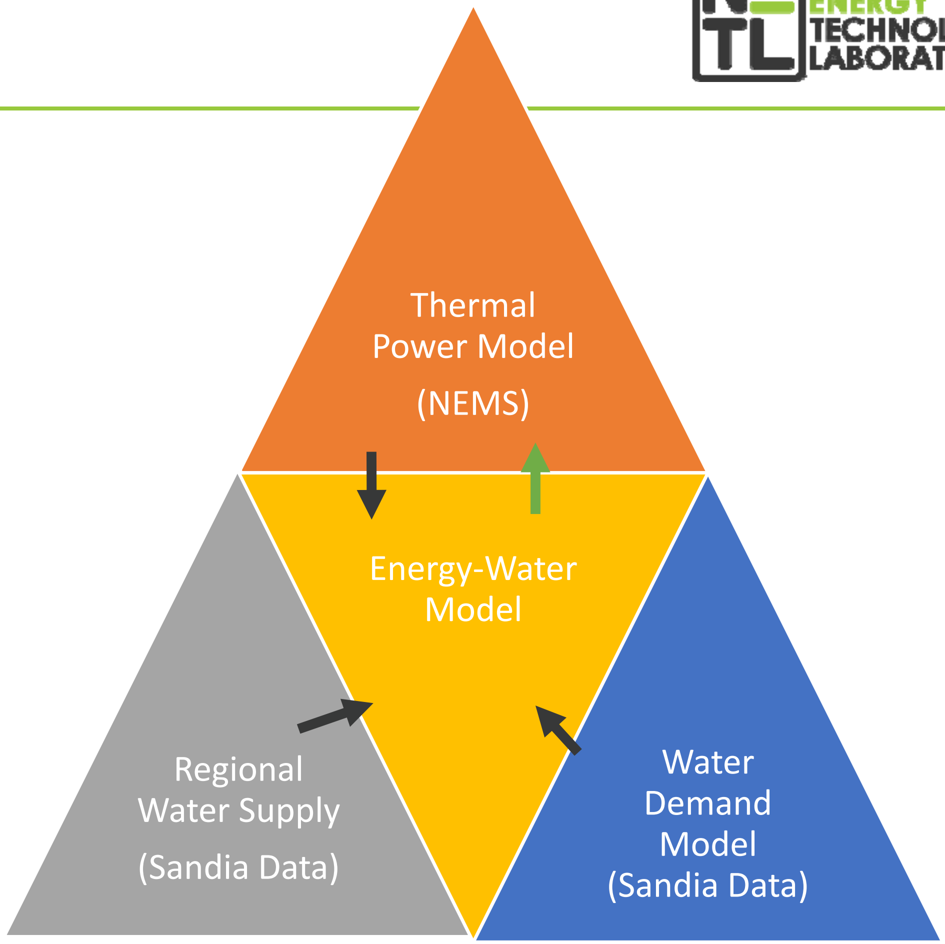




Water Management R&D

Water-Energy Integrated Model

- **Prototype Model Design and Data**
  - Time Period: 2012 to 2040
  - Regions: HUC 8 – Hydrologic Unit Code (8 digits 2,200 HUs, 700 mi^2)
  - Model Objective Function: Minimize the total cost of satisfying water demand in each HUC 8



Water Management R&D

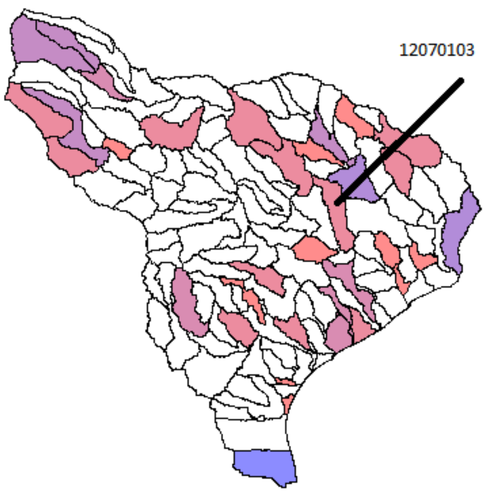
Water-Energy Integrated Model

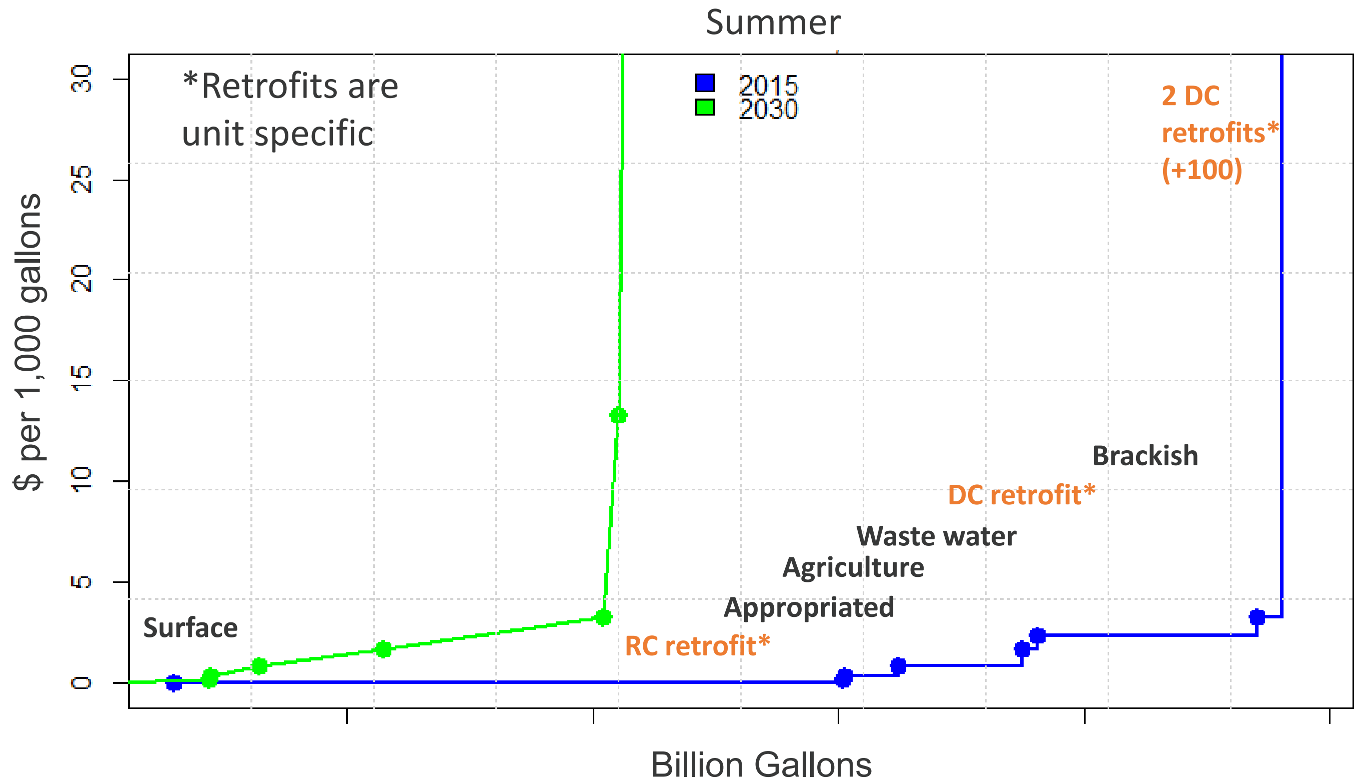
- **Model Design**
  - Multi-period seasonal planning model
  - Prototype model developed in GAMS (General Algebraic Modeling System)
    - Linear programming model
  - Optimizes to minimize the cost of satisfying the demand for water
  - Performs an economic trade-off between purchasing water at various costs from constrained water sources or spend capital to retrofit power plants with less intensive water cooling technologies
    - Appropriated water
    - Impaired water (waste or bine waters)
    - Purchase from Ag
    - Retrofit cooling system to recirculating or dry cooling

Water Management R&D

Water-Energy Integrated Model

- Marginal Cost Supply Curve for Water
  - HUC 12070103 – Navasota, Texas

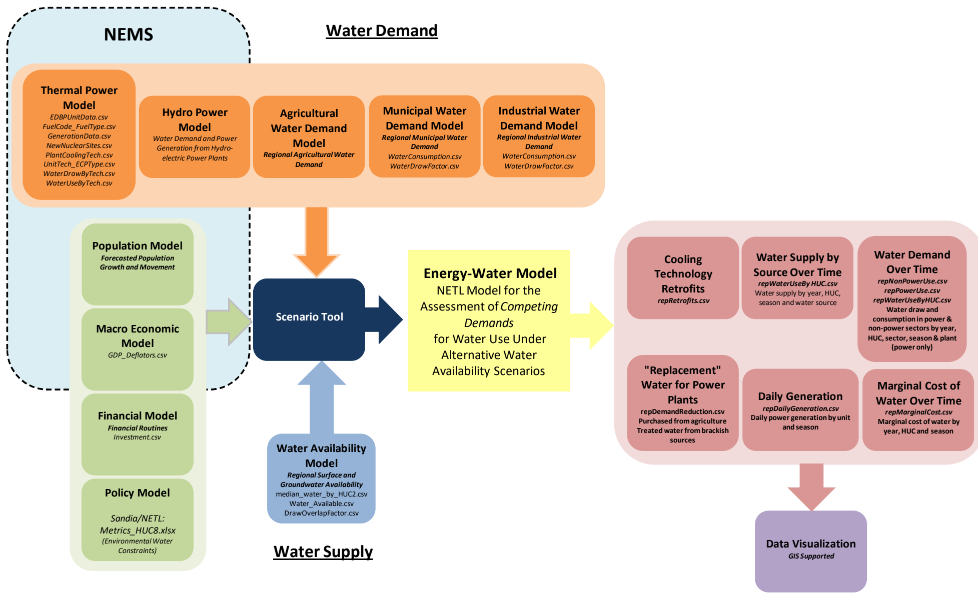




Water Management R&D

Water-Energy Integrated Model

- **Future Work**
  - Refine data
  - Update water availability and water demand projections
  - Develop and incorporate drought scenarios
  - Refine cooling system impacts on costs and performance
  - Test and perform analysis on integrated prototype model into EIA's NEMS (two-way coupled model)
    - CF, build, import, purchase water, retrofit cooling technology



Questions?

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