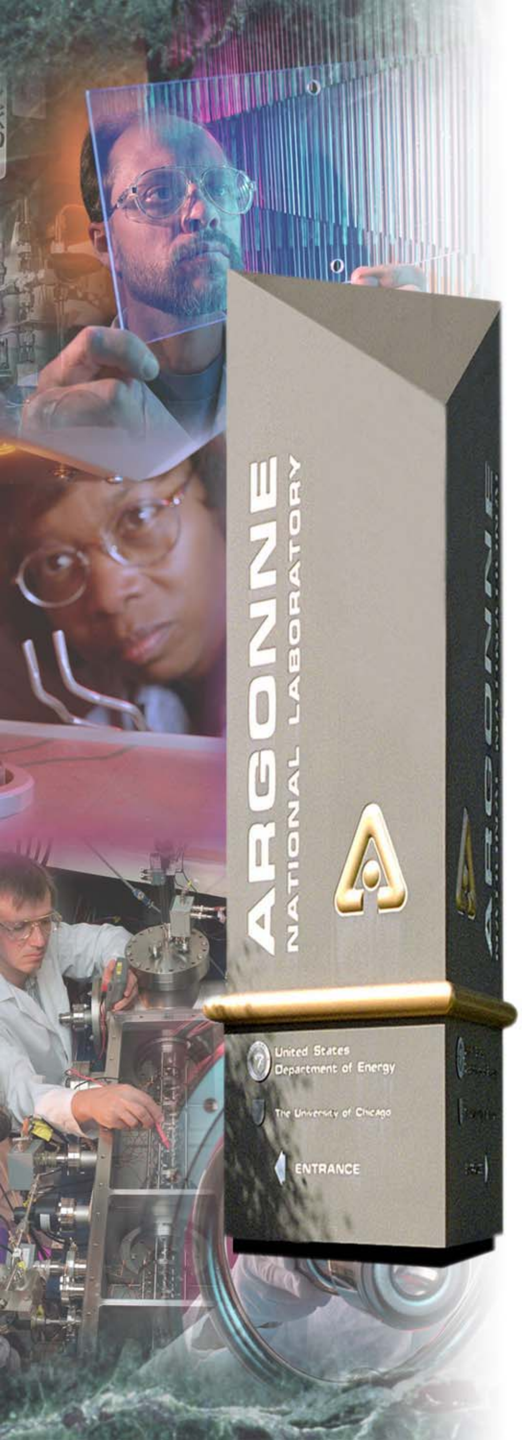


Predictions of Nuclear Energy Market Share in the U.S. Electricty Market

The 25th USAEE/IAEE North American
September 21, 2005

A. Yacout, G. Conzelmann,
V. Koritarov, L. Van Den Durpel

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline

- **Motivations for Analysis**
- **Energy Systems Modeling**
  - Plant level models (LCOE)
  - Market Models
- **ENPEP (BALANCE) Market Model**
- **US Electricity Market Model**
- **Future Work**
- **New Directions**

Motivations for Analysis

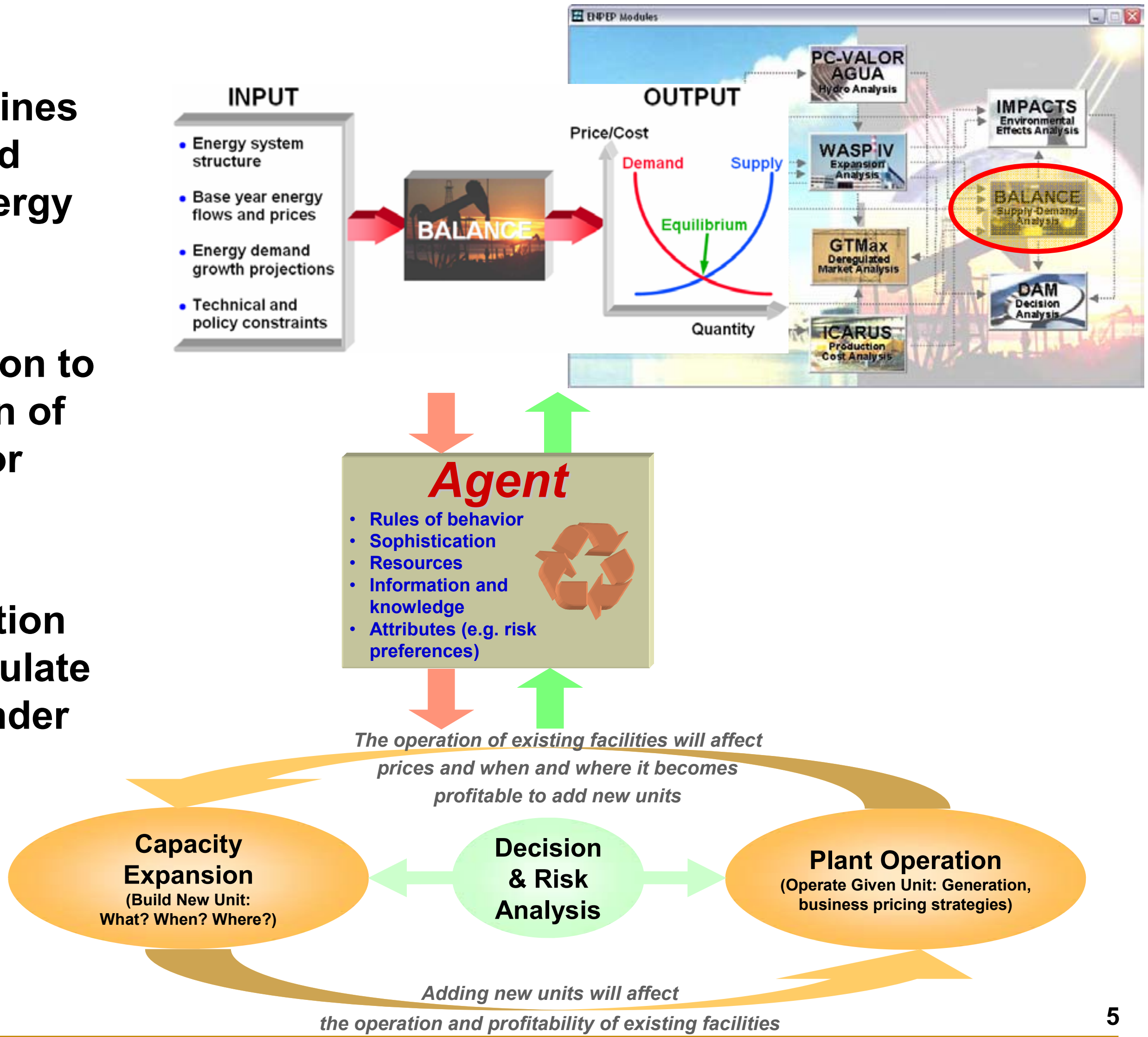
- **Resurgence of interest in nuclear energy is taking place in the US driven by**
  - National energy security concerns
  - Potential future carbon constraints
- **Ultimate success of nuclear resurgence contingent on successfully addressing the economic aspects of competition in a marketplace of fossil alternatives**
- **Purpose of this analysis**
  - Collaboration of energy sector modelers at ANL
  - Create a nuclear energy sector planning capability
  - Inform the national energy policy debate and decision-making process

Energy Systems Models

- **Plant-Level Models**
  - Estimate levelized-cost-of-electricity (LCOE)
  - LCOE = Capital Cost + O&M Cost + Fuel Cost
  - Existing models
    - *UC, GenSim (Sandia), MIT, Scully*
- **Market Level Models**
  - NEMS (EIA)
  - EPRI (using NEMS)
  - MARKAL
  - BALANCE code which is part of ENPEP (ANL-DIS)

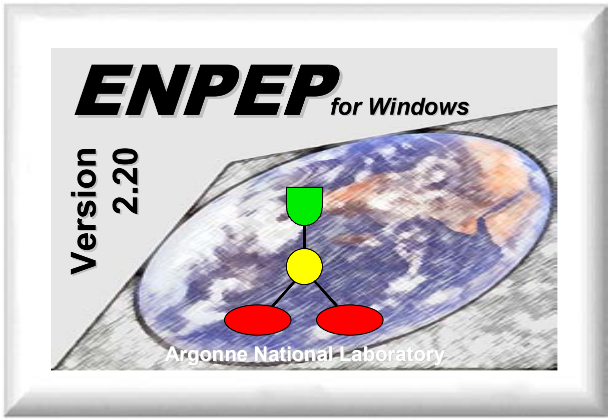
Market Simulation is Conducted Using Argonne's ENPEP-BALANCE Model as Well as New Agent-Based Approach

- **ENPEP-BALANCE determines the equilibrium supply and demand balance of an energy system**
- **ENPEP uses a logit function to project market penetration of competing technologies or commodities**
- **New Agent-Based Simulation approach attempts to simulate market entry decisions under uncertainty**
  - More representative of newly restructured electricity markets



The Nuclear System Models and ENPEP Models can be Run Together in a (Manually-) Linked Mode

Detailed Cost and
Performance by
Technology



System Dynamics Codes (DANESS/DYMOND) Of Symbiotic Nuclear Parks

Market Share by Nuclear
Technology

Projections of Future Nuclear Market Shares

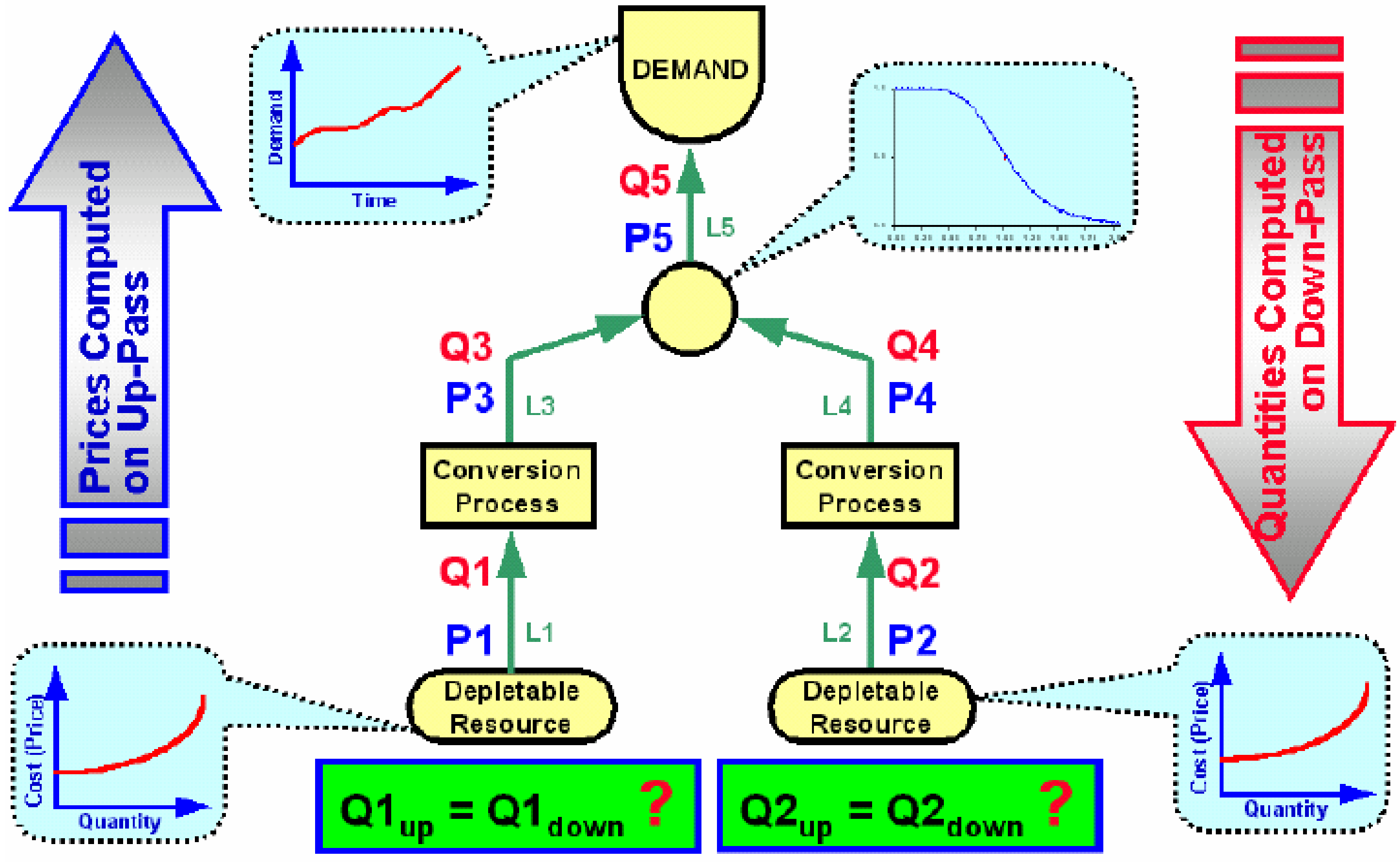
Detailed Analysis of Nuclear Costs and Fuel Chain Issues

BALANCE Model

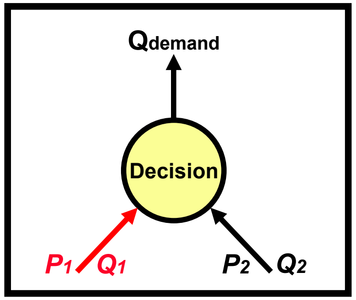
- **Non-linear market share equilibrium approach to determine the energy supply and demand balance.**
  - Each iteration solve for xi,

$$f_i\ (x_1, ..., x_n) = 0 \text{ for } i = 1, \ldots n$$

Balance Model

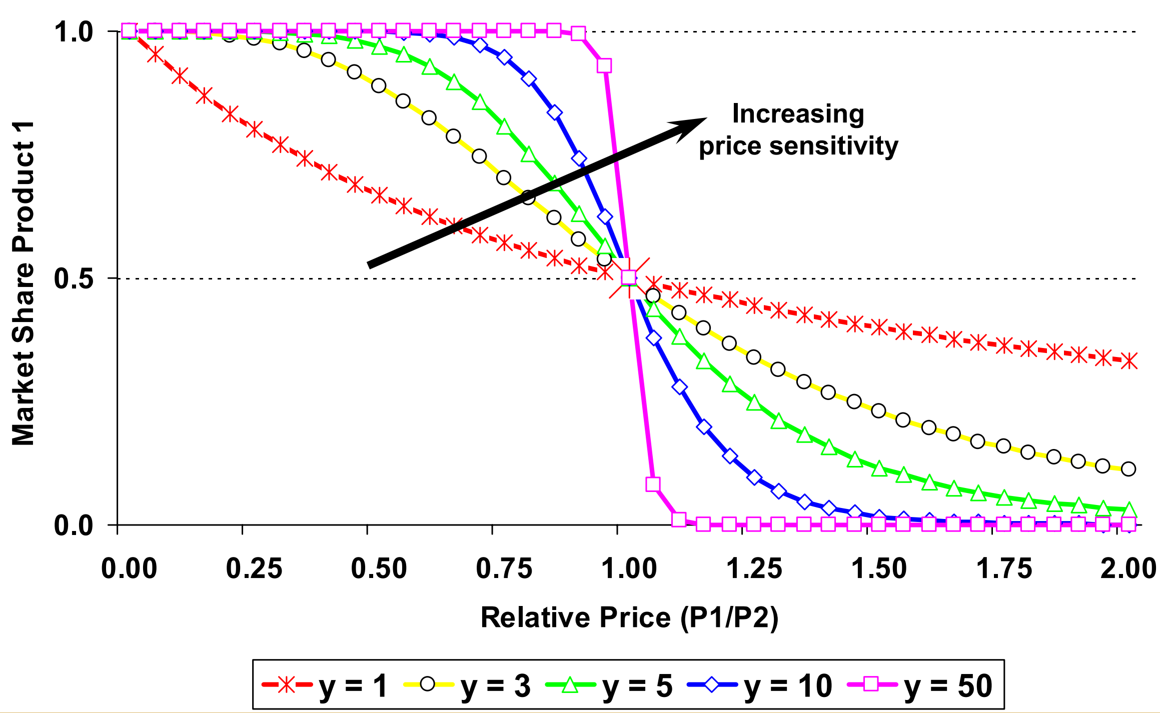


ENPEP Computes the Future Market Penetration of New Technologies Using a Logit Market Share Model

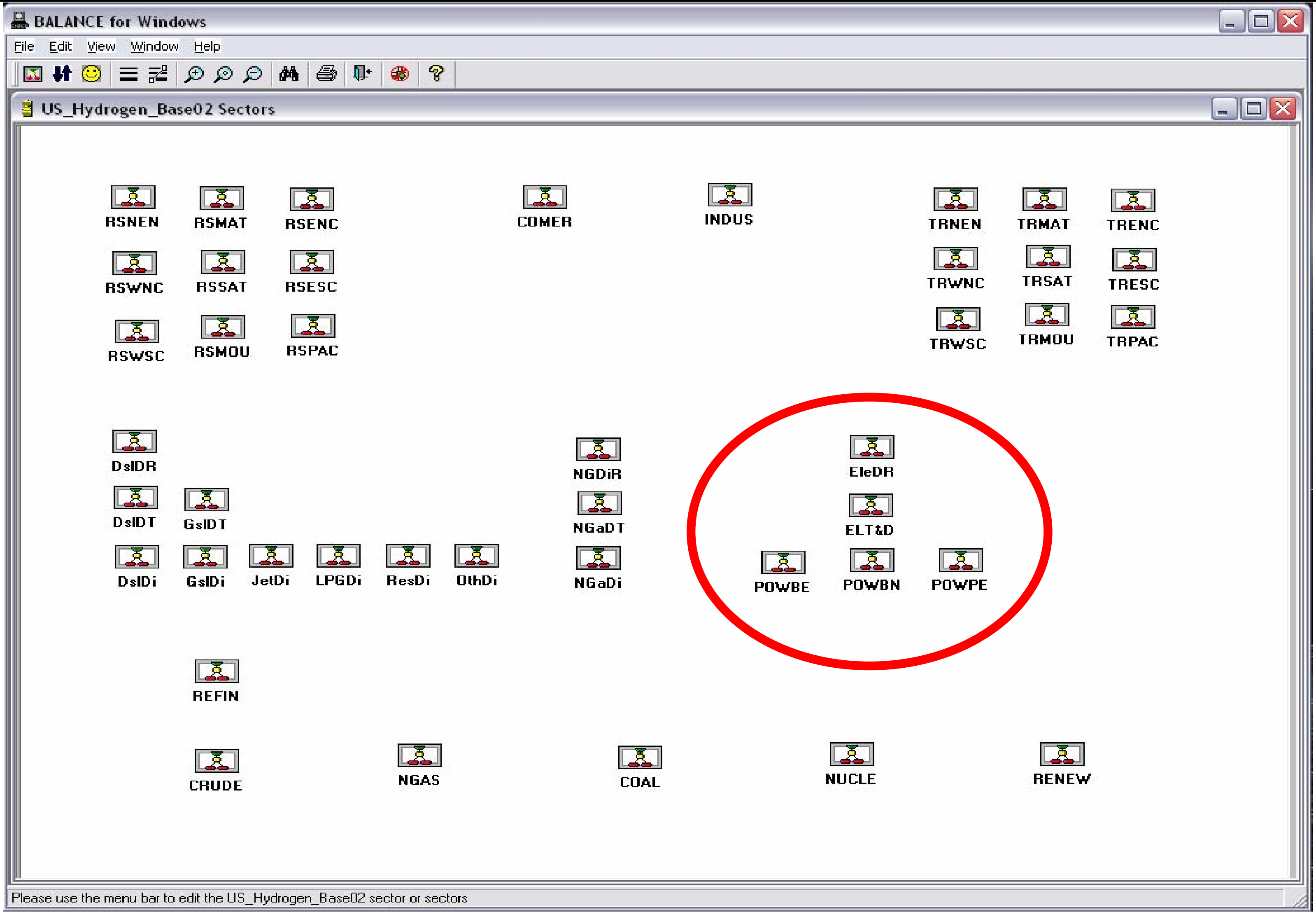


$$MS_1 = \frac{Q_1}{Q_1 + Q_2} = \frac{\left[\frac{1}{P_1 \times PM_1}\right]^{\gamma}}{\left[\frac{1}{P_1 \times PM_1}\right]^{\gamma} + \left[\frac{1}{P_2 \times PM_2}\right]^{\gamma}}$$

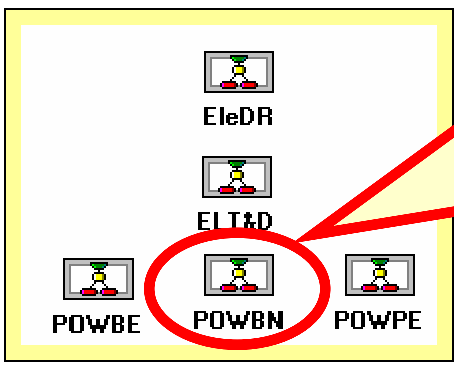
- γ price sensitivity for this decision process
- MS: market share
- P: price
- PM: premium multiplier
- Q: quantity



ENPEP Evaluates the Power Sector Development in the Context of the Entire Energy Economy



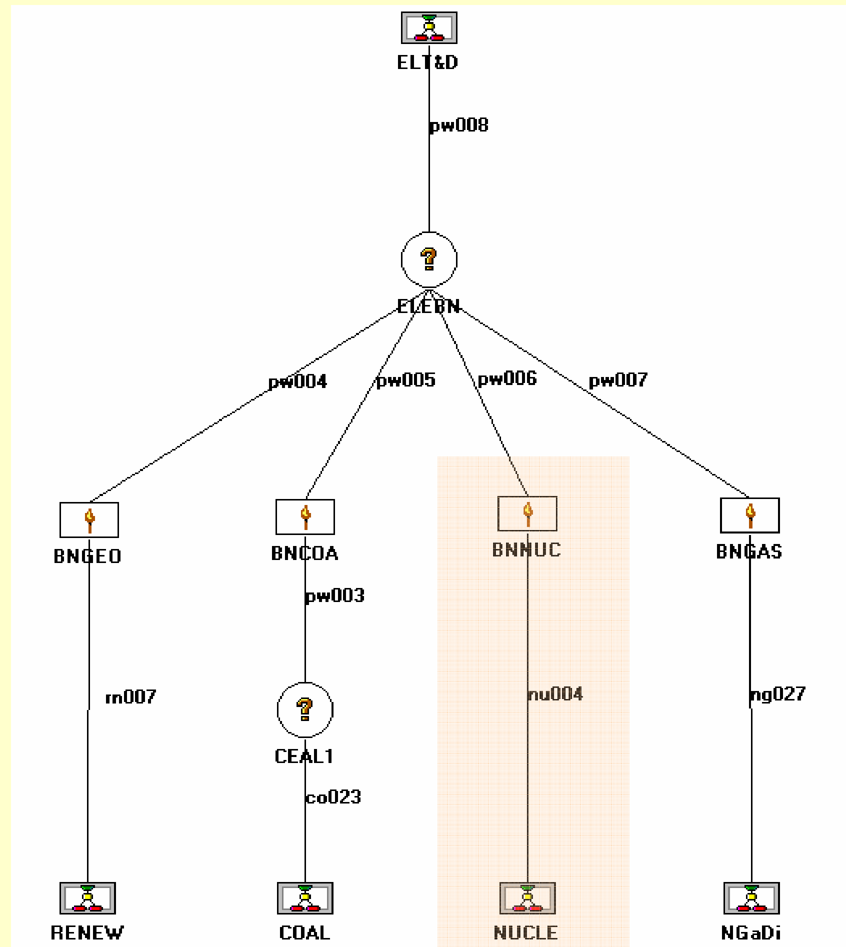
In ENPEP, New Nuclear Competes with Other Technologies for Base Load Generation



Base Load Generation

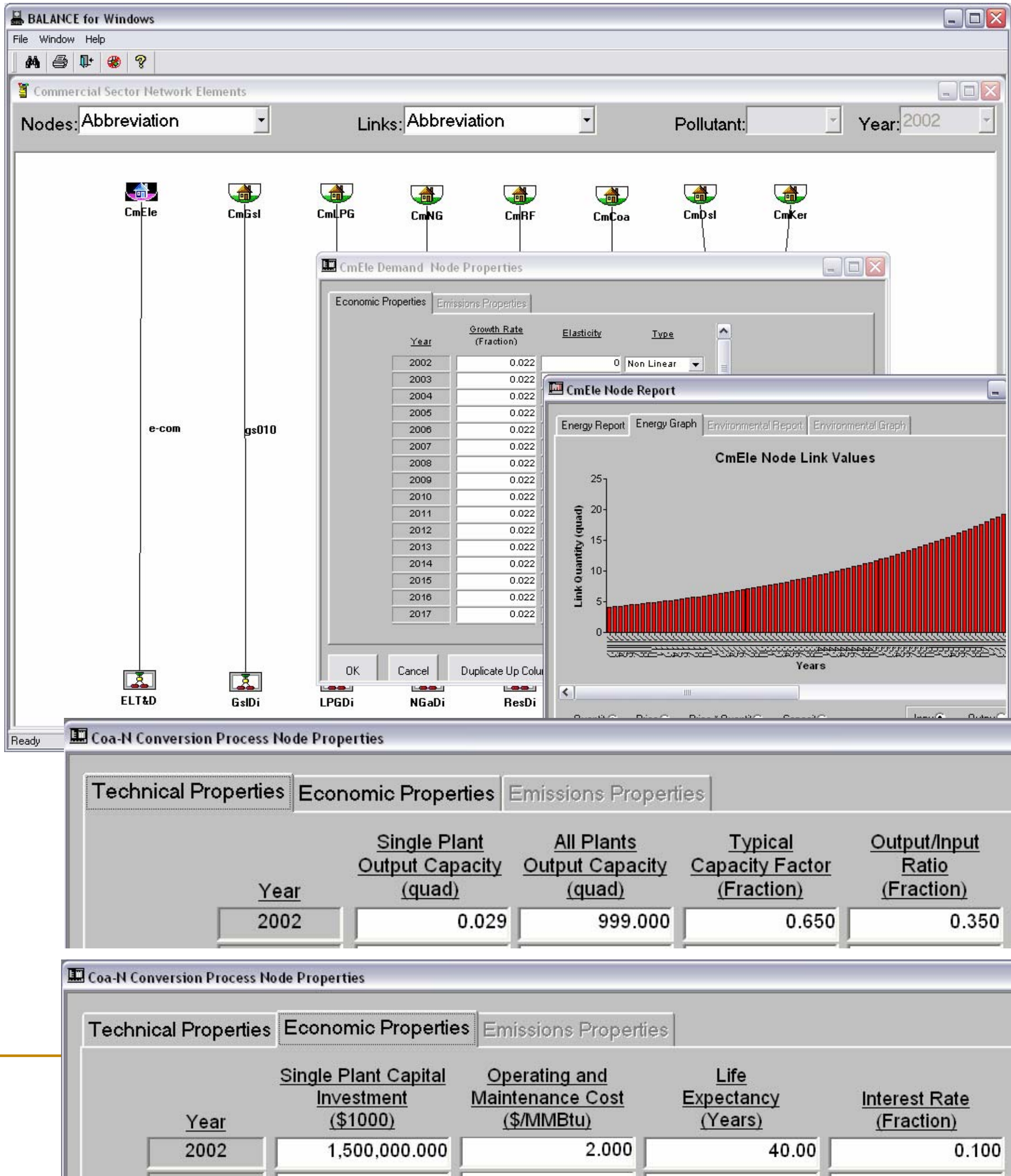
Peak Load Generation

New Base Load Generation

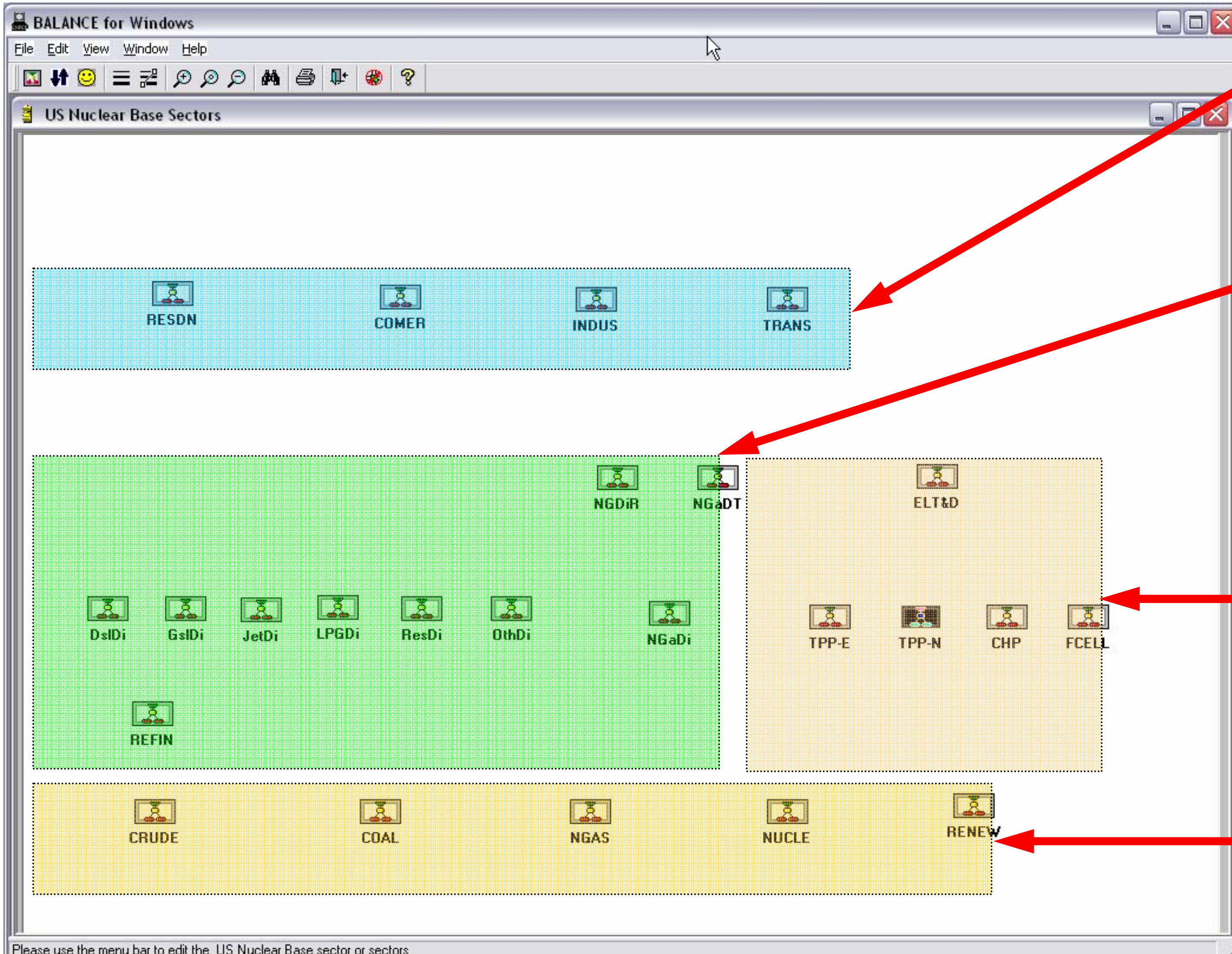


Some of the Basic Model Inputs Include the Following

- **Base year supply and demand (2002)**
- **Fuel/resource price projections**
- **Demand growth projections**
- **Retirement schedule of existing units**
- **Technology parameters**
  - Technical
  - Economic
  - Environmental
- **Data sources include**
  - EIA AEO2004
  - Other EIA reports (Petroleum Supply Annual, Natural Gas Annual, Reserves, etc.)
  - University of Chicago study



Overall Model Configuration Includes the Power Sector as well as All Major U.S. Supply and Demand Sectors



Demand Sectors

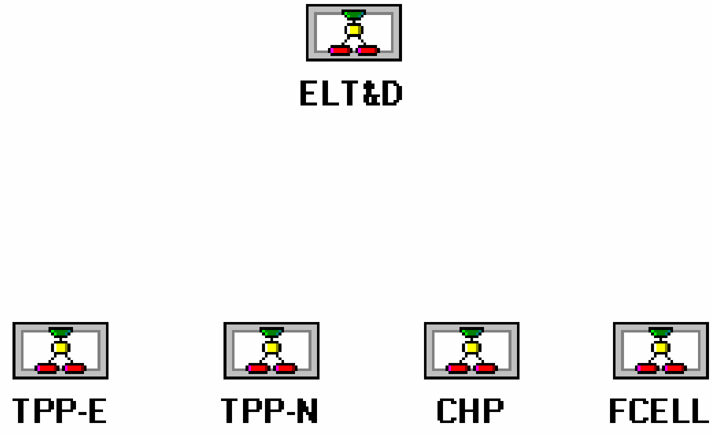
Conversion & Distribution Sectors

Power Sector

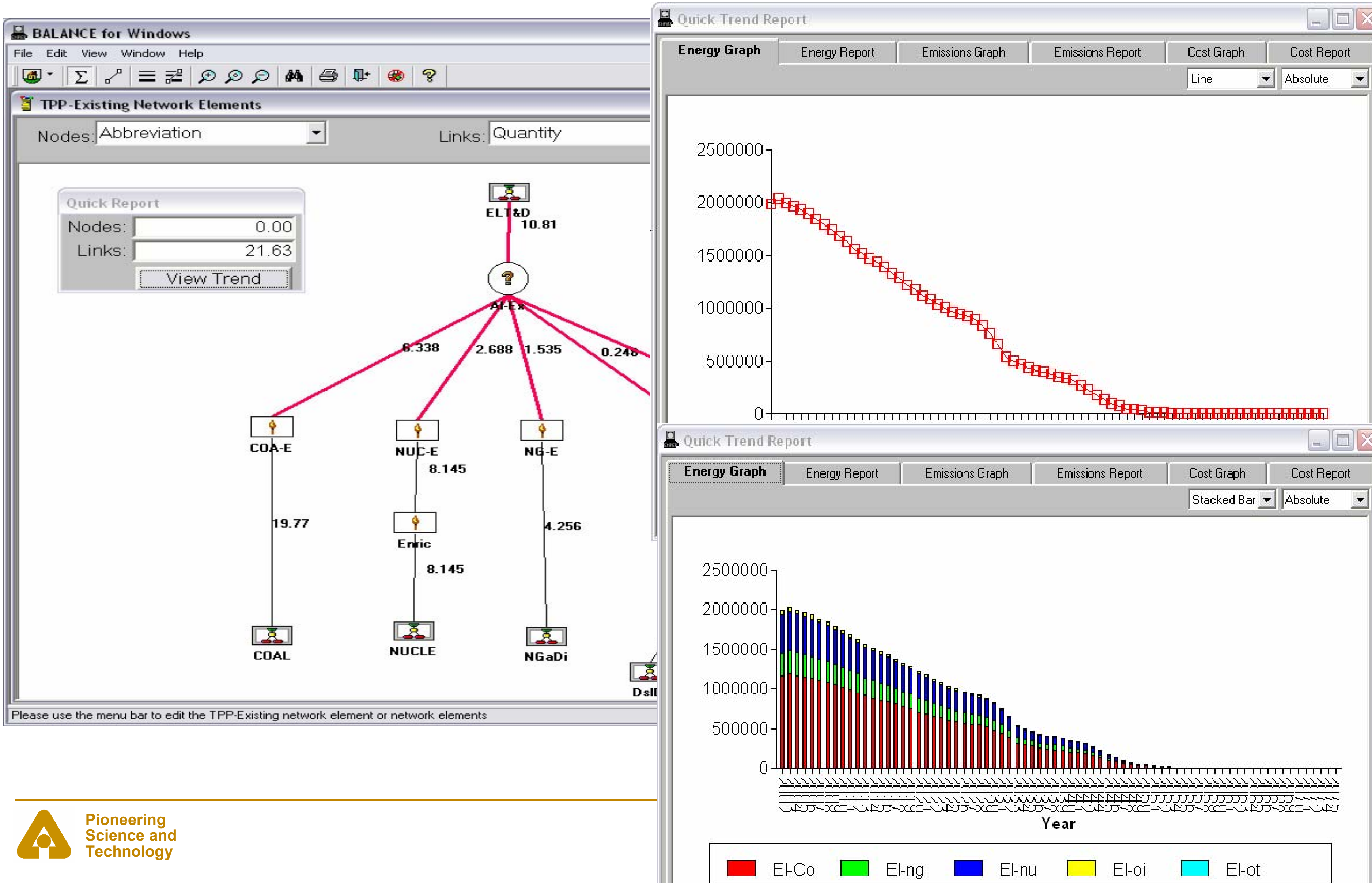
Supply Sectors

The Power Sector is Broken Down into Several Sub-Sectors

- **ELT&D: Electricity transmission and distribution**
- **TPP-E: Thermal power system as it exists in 2002**
- **TPP-N: New thermal power units including various expansion options/technologies**
- **CHP: Electricity generation from combined heat and power technologies**
- **FCELL: Fuel cells for stationary power generation**

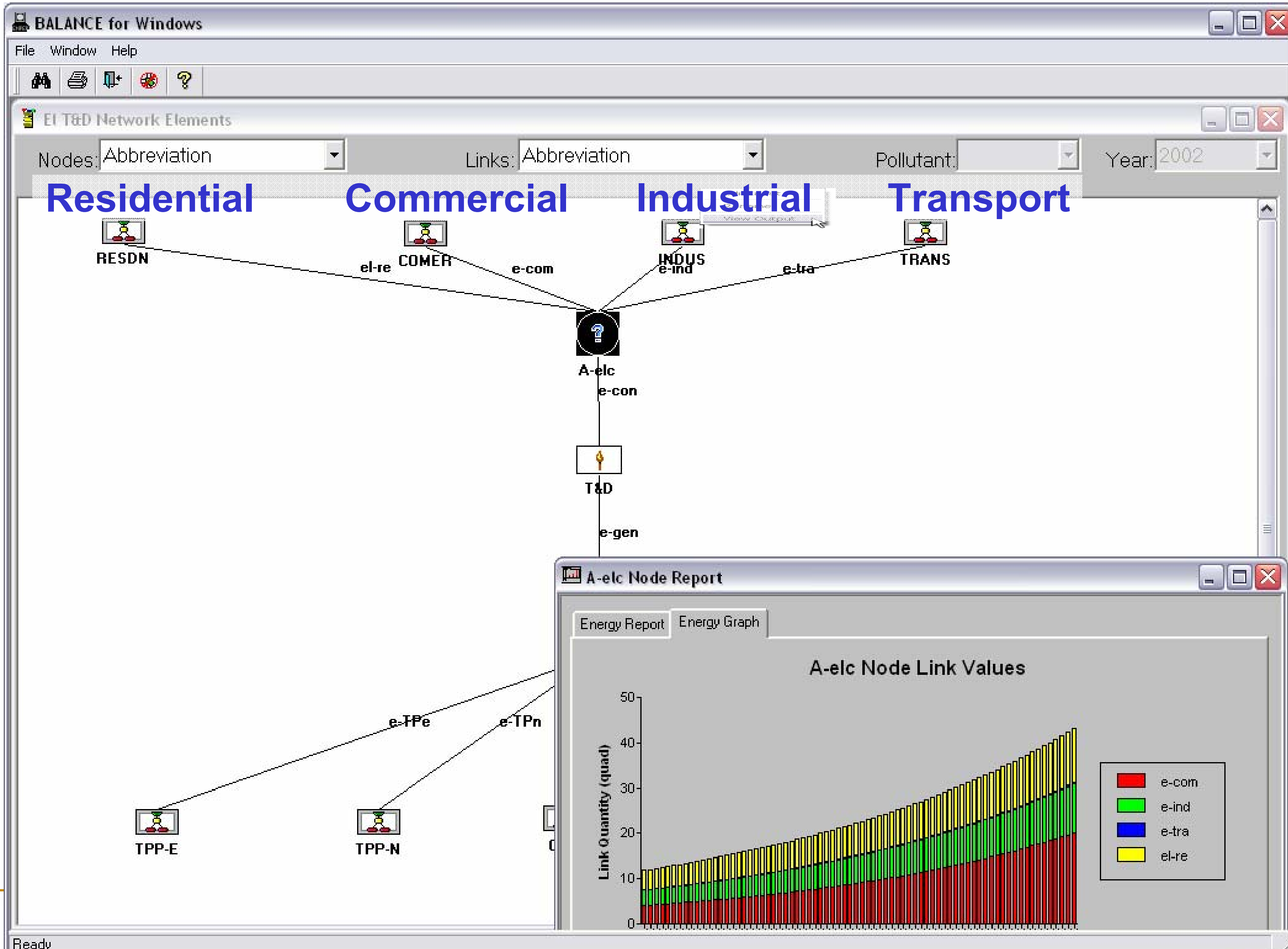


Generation from Existing System Declines as Units Retire (Zero by 2055)

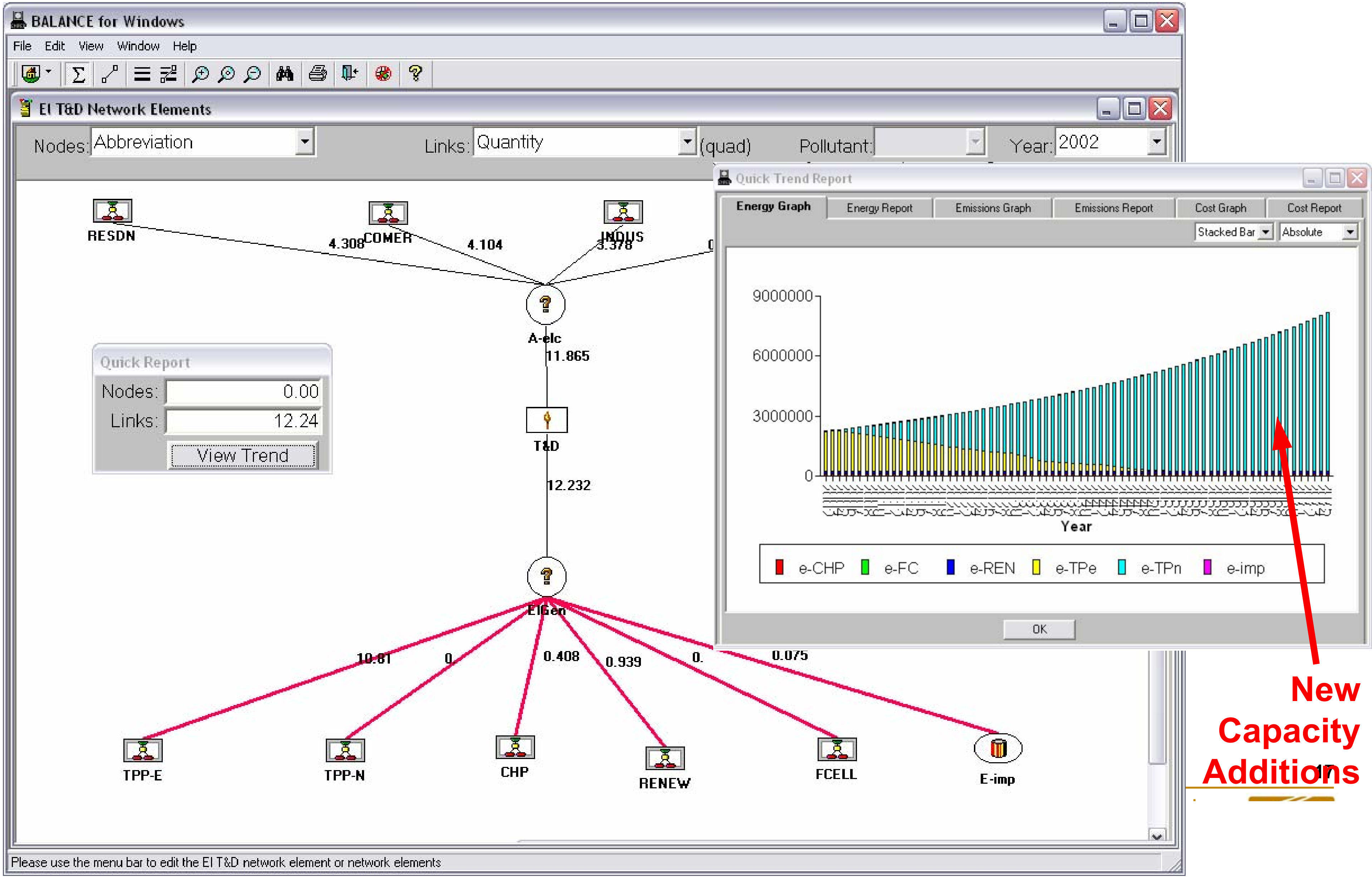


Pioneering Science and Technology

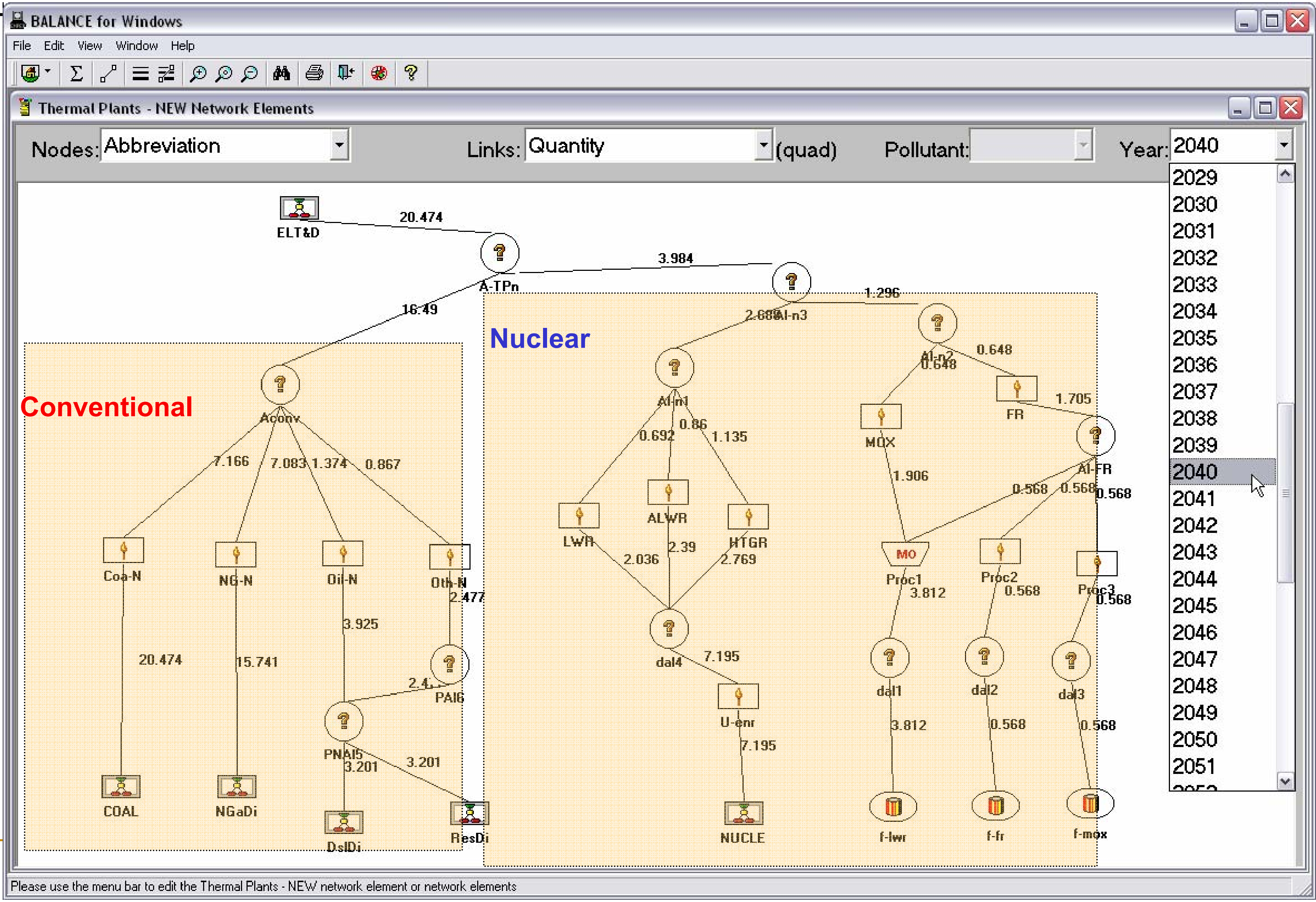
While Demand for Electricity is Projected to Grow (from 1.4%/yr for Residential to 2.2%/yr for Commercial Uses)



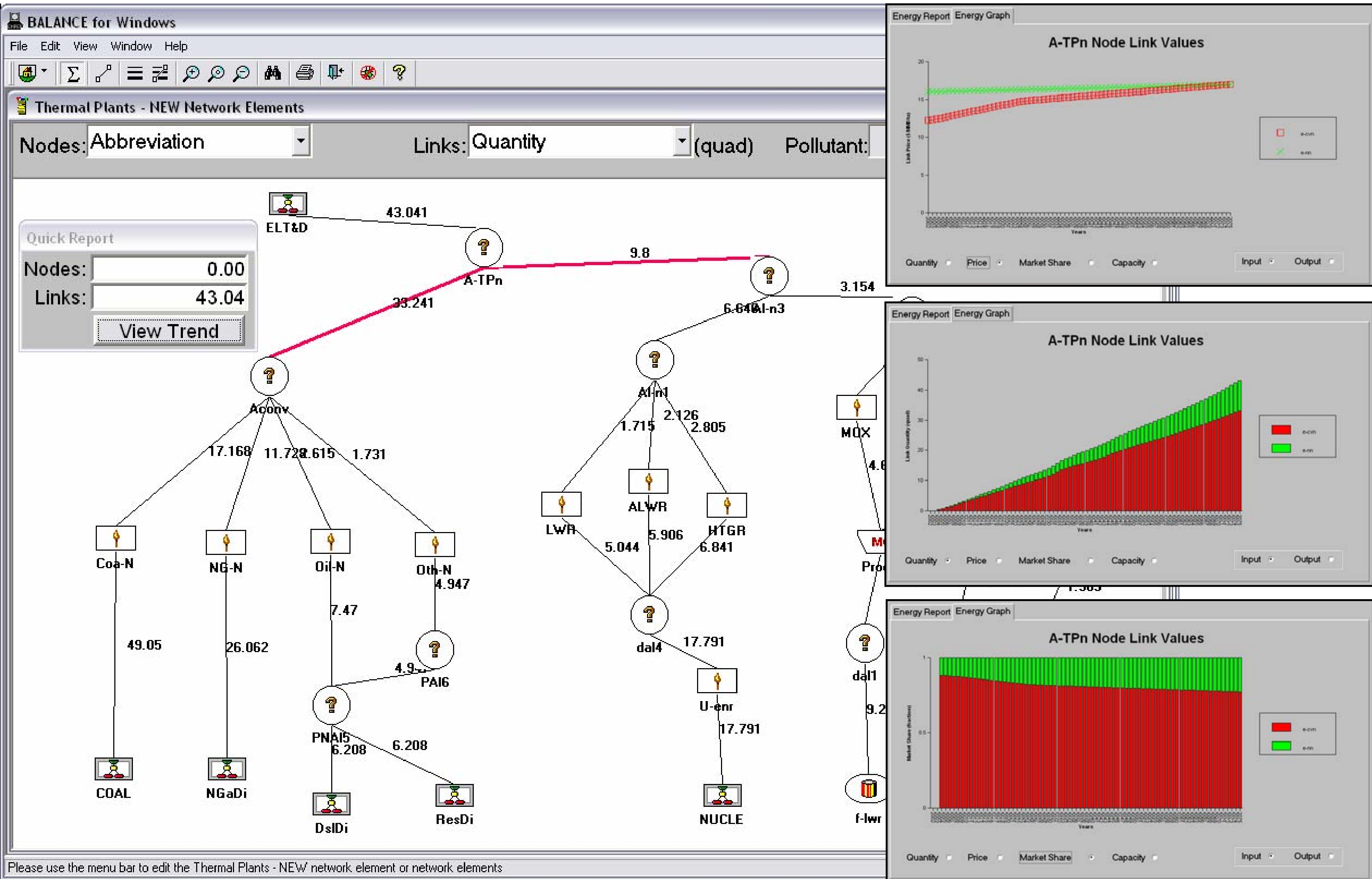
Leading to a Need to Build New Capacity: 335 GW (2025) and 1,260 GW (2075) - 2002 Total Installed Capacity is 895 GW



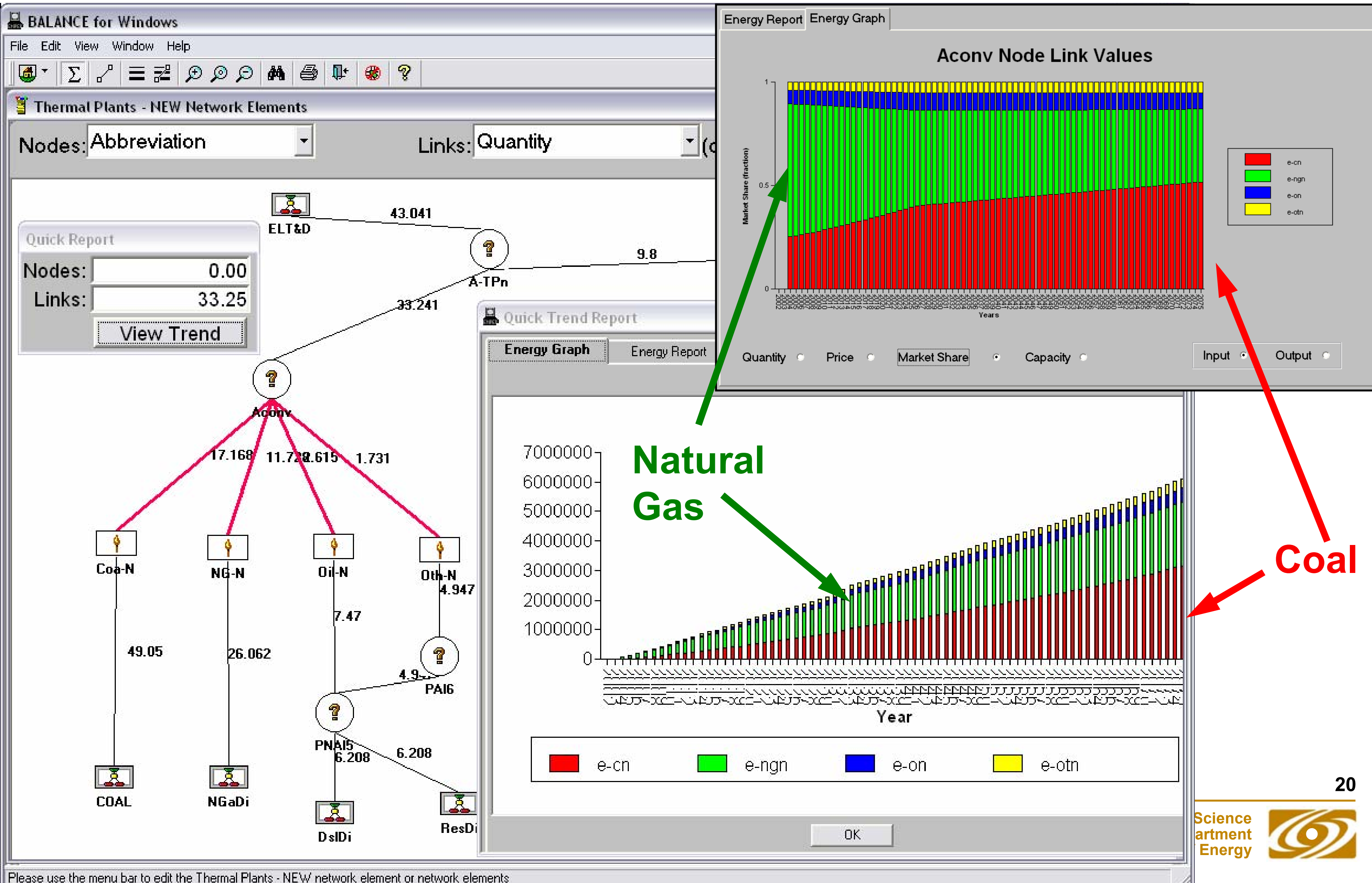
System Expansion is Decomposed into Various Technologies/Reactor Types that Compete Based on Generation Cost Using a Nested Approach



Generation Costs Increase Faster for Conventional Technologies than for Nuclear; Nuclear Captures about 23% of the New Generation Market or about 364 GW by 2075

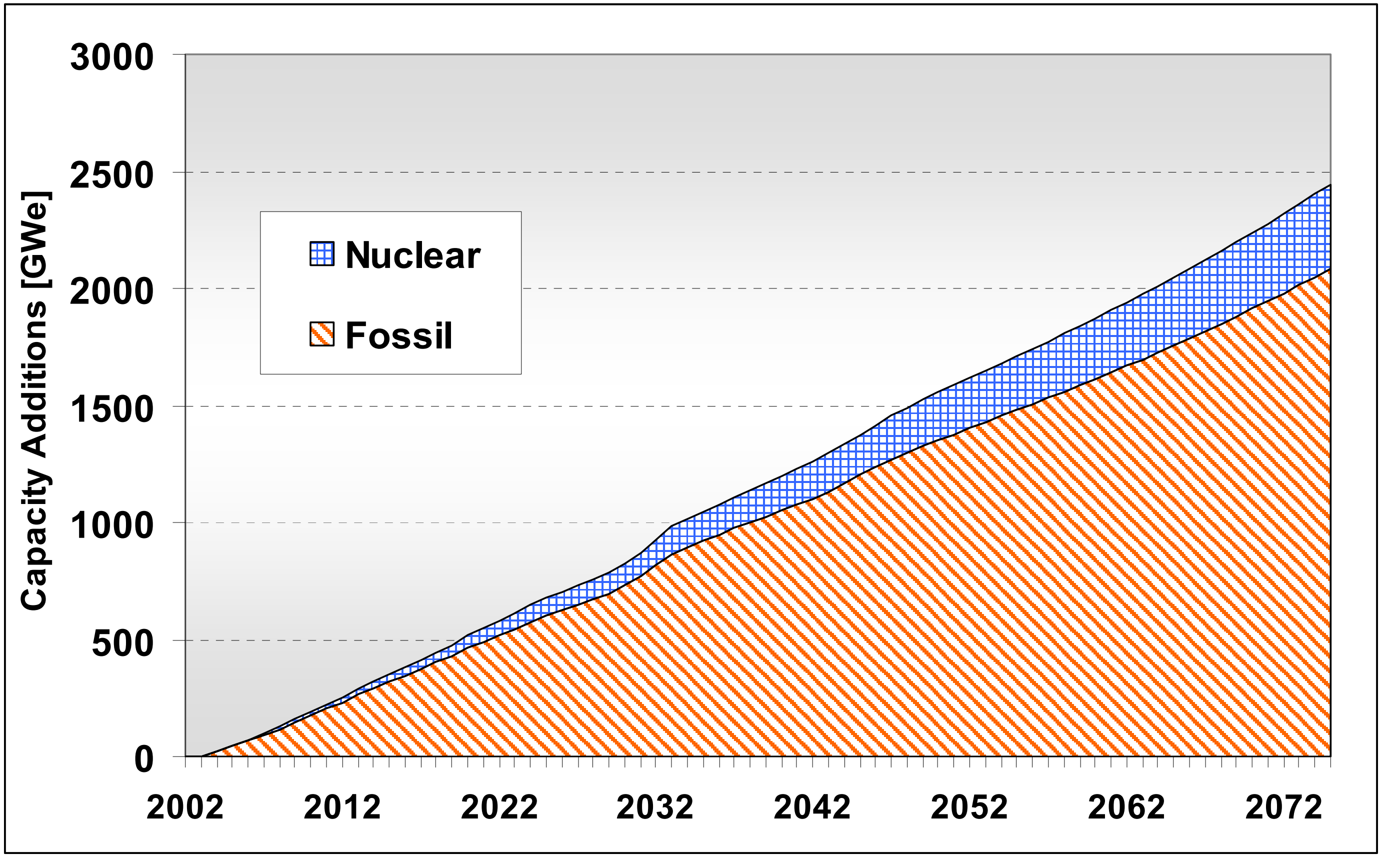


While Initially, Conventional Expansion is Mostly Gas-Based, Eventually Coal Additions Dominate

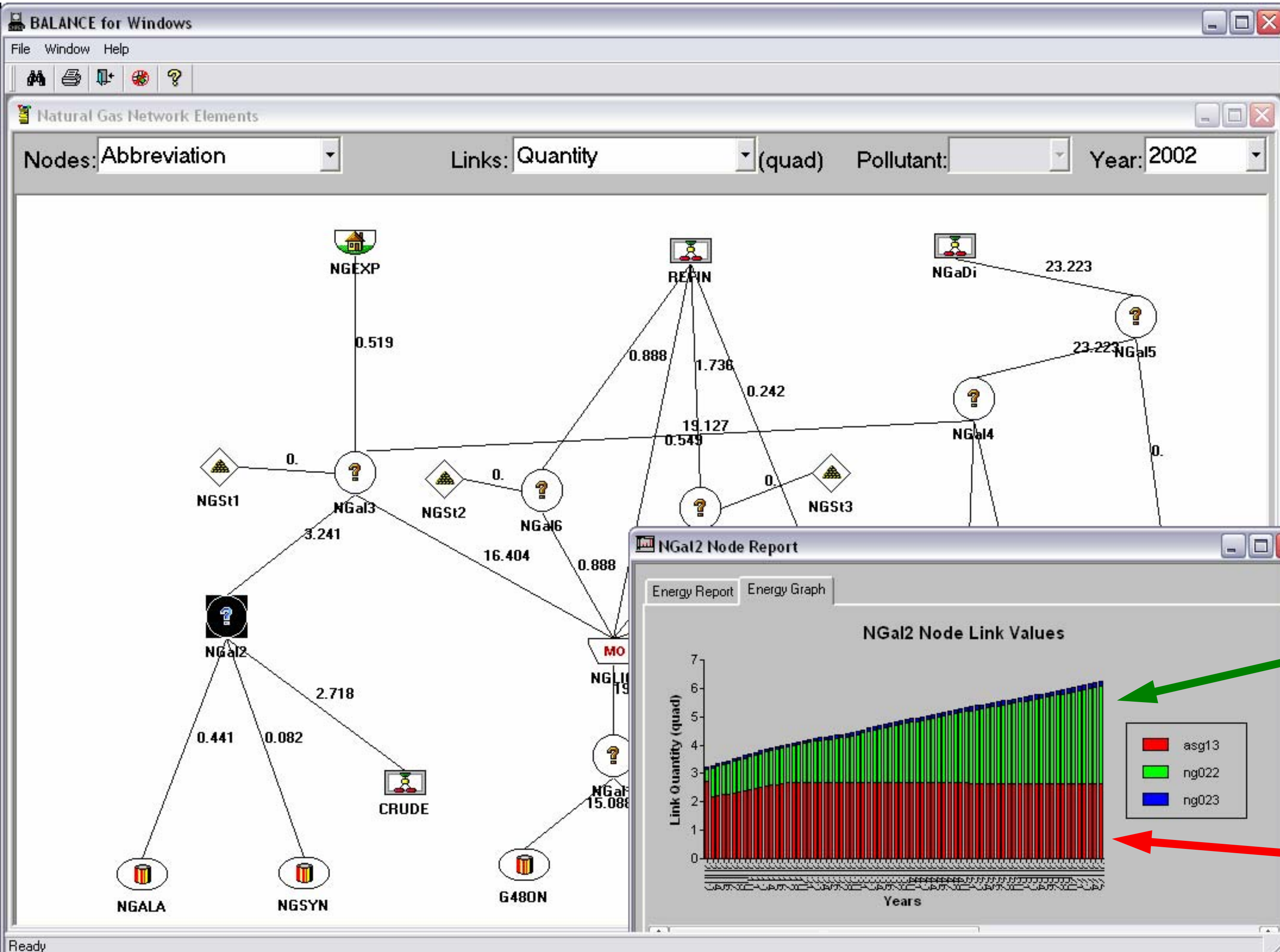


Science
artment
Energy

Nuclear Market Share



The Model Also Looks at Supply Side Issues As Well (e.g., Natural Gas Supply Sector)



Required Additional Alaska Production

Limits on Associated Gas Production

Future Work

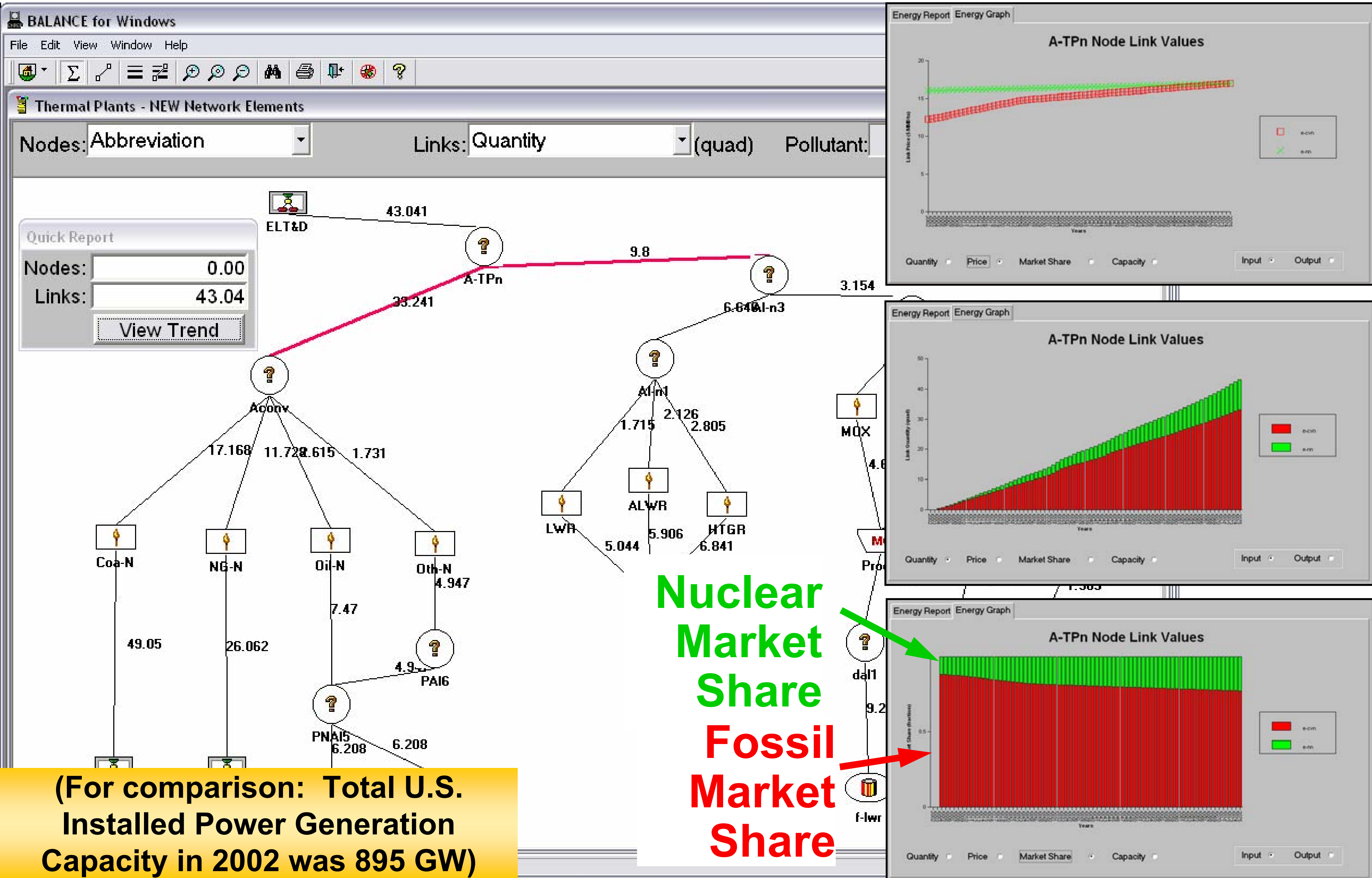
Run the model for various alternative scenarios

- Fuel price variations (high oil and gas price)
- Government incentives (U Of C Study)
- Environmental constraints (carbon tax)
- Potential for cogeneration (water, hydrogen)
- Step out in time using BALANCE to determine nuclear deployments
  - *Use DANESS/DYMOND to assess waste, resource, emissions outcomes over ~50-70 year planning horizon*

New Directions

- **Using complex adaptive systems theories and agent-based modeling techniques**
  - Better treatment of
    - *Volatility and risk*
    - *Decentralized decision making under uncertainty*
    - *Multiple objectives (not just cost minimization)*
- **Investigate Application of Operations Research Based Decision-Making in Utility Boardroom**
  - Real Option Theory replaces NPV in BALANCE

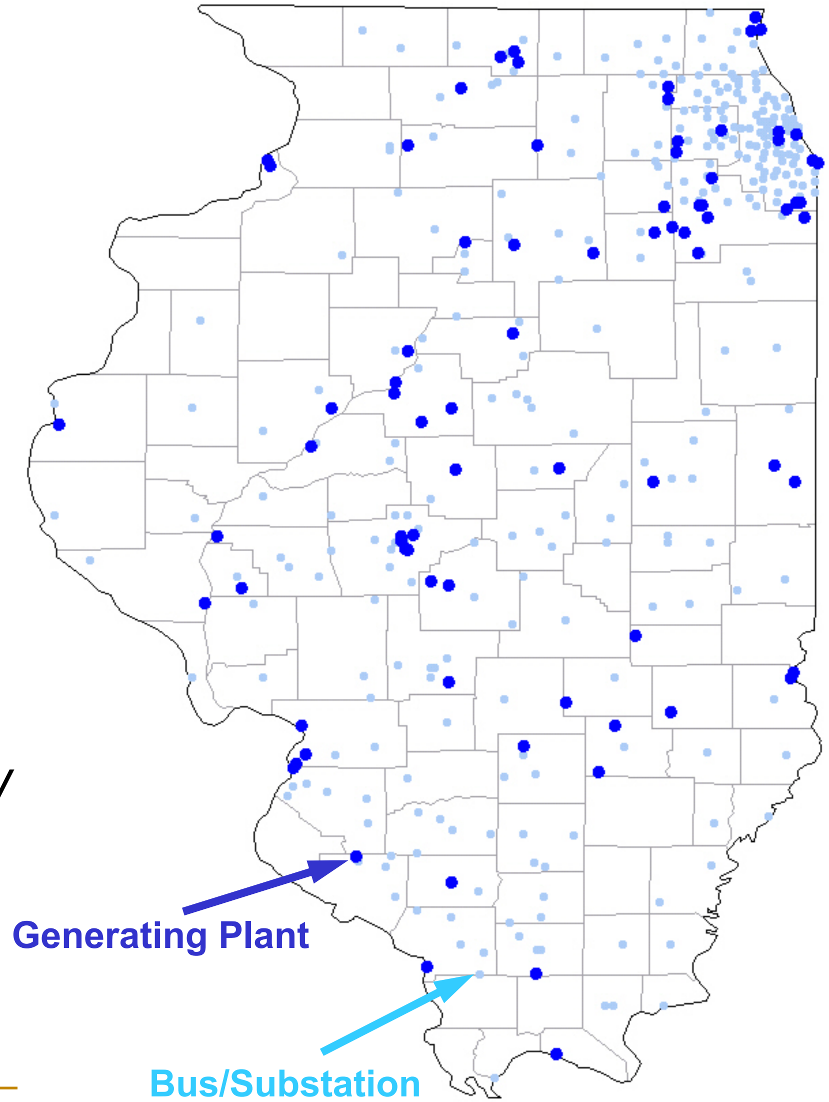
ENPEP-BALANCE Shows Need to Build New Capacity:
335 GW in 2025 and 1,260 GW in 2075 (All of U.S.)
Nuclear Captures about 23% of the New Generation Market or about 364 GW by 2075



(For comparison: Total U.S. Installed Power Generation Capacity in 2002 was 895 GW)

Current Efforts Concentrate on Modeling Nuclear Investment Decisions under Uncertainty

- **Using complex adaptive systems theories and agent-based modeling techniques**
- **Current testing of the methodology is underway using the State of Illinois power system**
  - 2000 buses/substations
  - 227 existing generation units in 79 plants/locations
  - 5 candidate technology types
    - *1 coal technology (500 MW)*
    - *2 natural gas technologies (75 MW and 250 MW)*
    - *2 nuclear technologies (110 MW HTGR and 1090 MW advanced pressurized)*
  - Forecast for 2007-2026
  - Demand growth 2%/yr from 33,225 MW (2007) to 48,403 MW (2025)

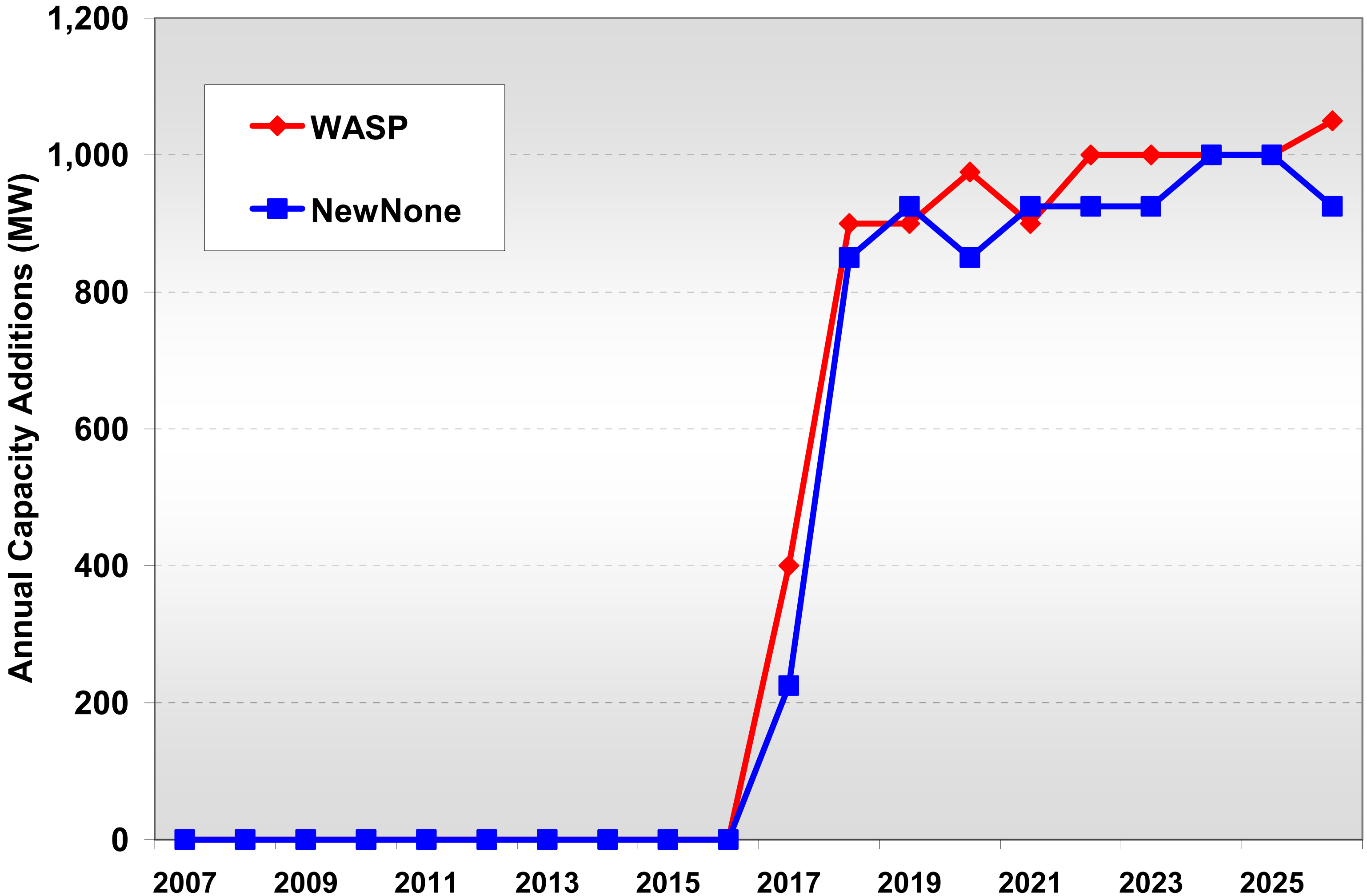


The New Capacity Expansion Approach Emulates Autonomous Decision Making Under Uncertainty

- **Software representation of individual players simulates *decentralized decision* making**
  - Agents are diverse and have unique behaviors
- **Construction decisions, announcements & schedules are based on *rational behavior***
  - Achieve corporate objectives
- **A multi-attribute utility function determines the best course of action for each *independent* market player**
  - Utility functions are the same for all players
- **Once started, project construction schedules are fluid; that is, market players *adapt* to market conditions ***
  - Accelerate
  - Delay
  - Abandon
  - Restart
- **Projects schedules are periodically reevaluated ***
  - Quarterly, semi-annual, or annual basis

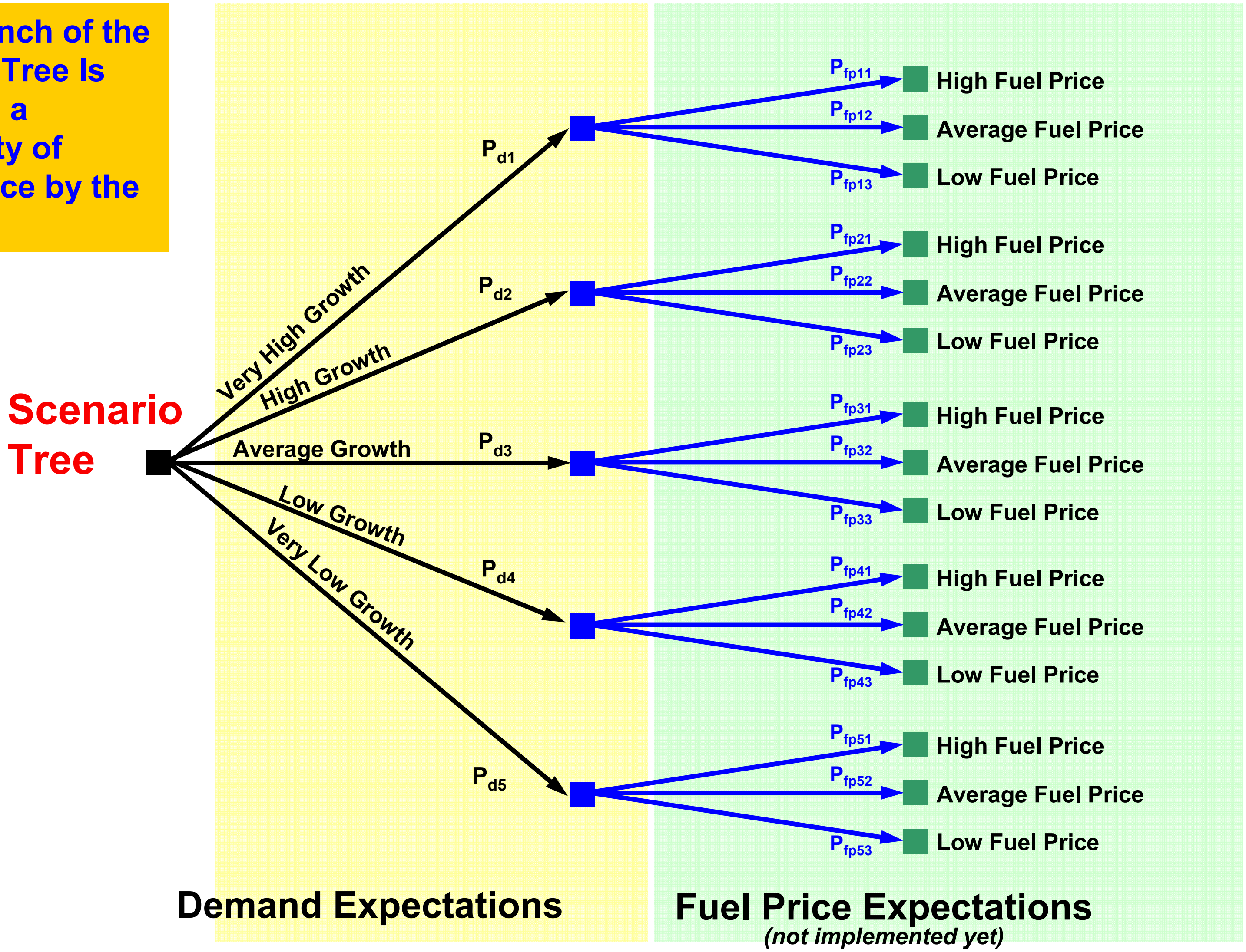
* Currently not implemented

Calibration to Standard Investment Model Assuming No Uncertainty and Centralized Planning (One Decision-Maker): Illinois Results Show Good Agreement

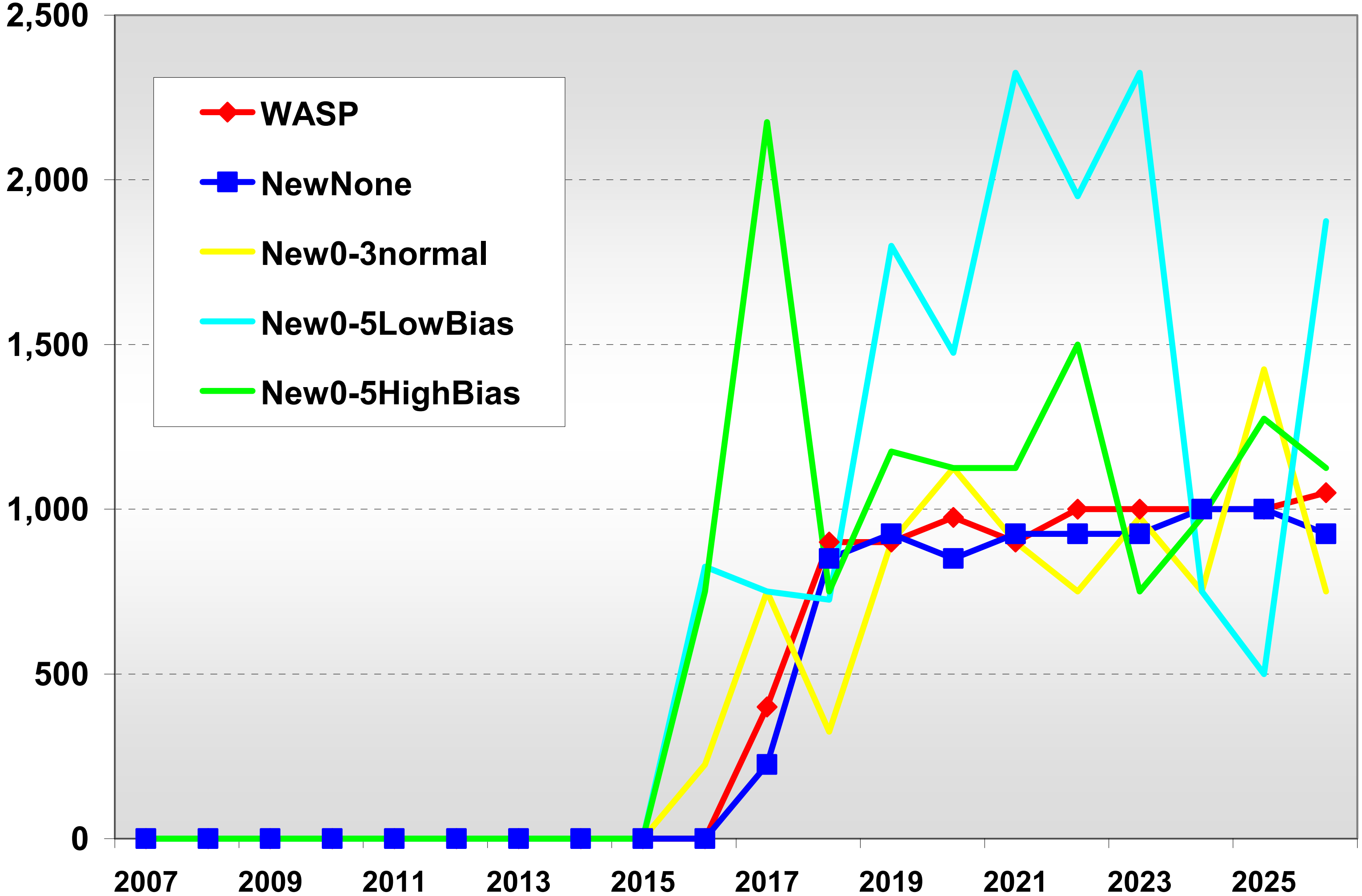


Current Model Runs Include Uncertainties Such that Agents Evaluate Technologies Under Several Possible Outcomes

Each Branch of the Scenario Tree Is Assigned a Probability of Occurrence by the Agent

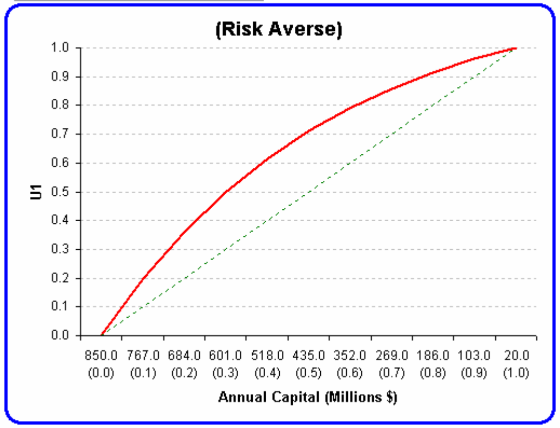


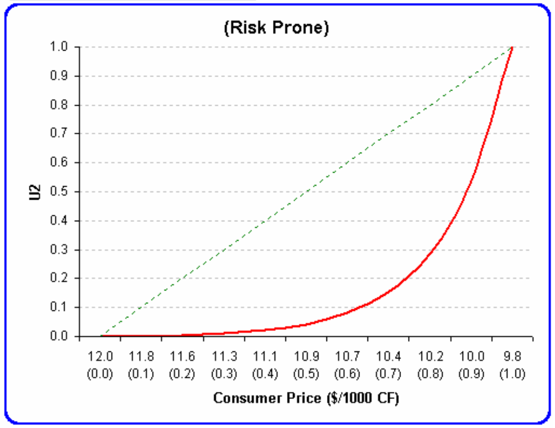
Results under Uncertainty are Distinctly Different, Depending on the Outlook of the Company

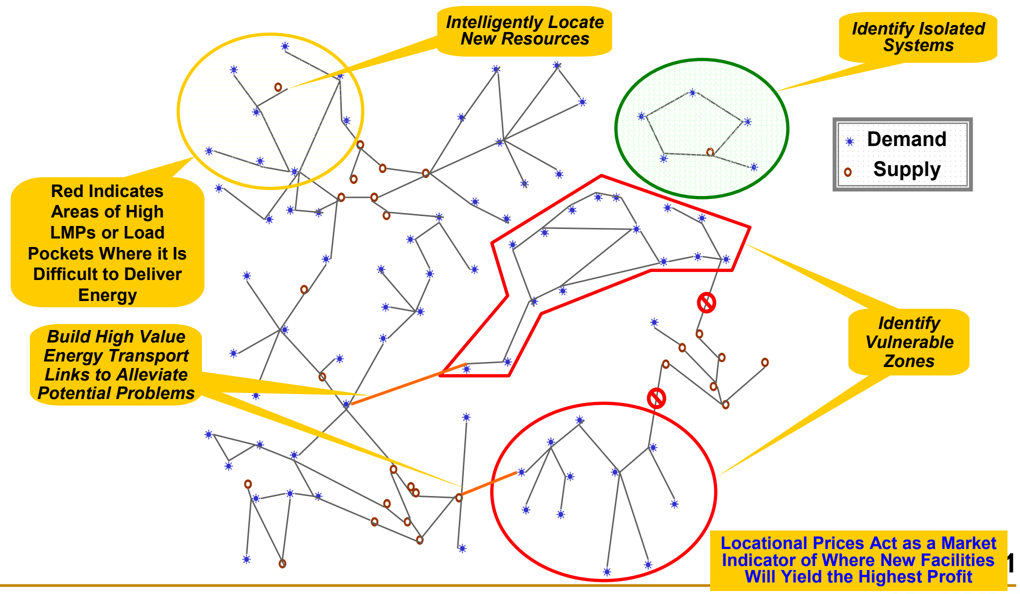


Remaining Steps in Current Fiscal Year

- **Conduct simulations with more than one company**
  - Multiple companies competing against each other
  - Different company characteristics (e.g. risk preference)
- **Develop a siting routine**
  - Identifies most profitable locations to add power generation to the grid

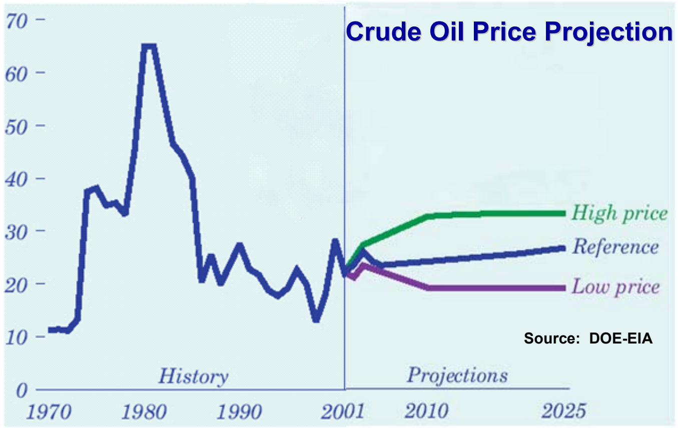




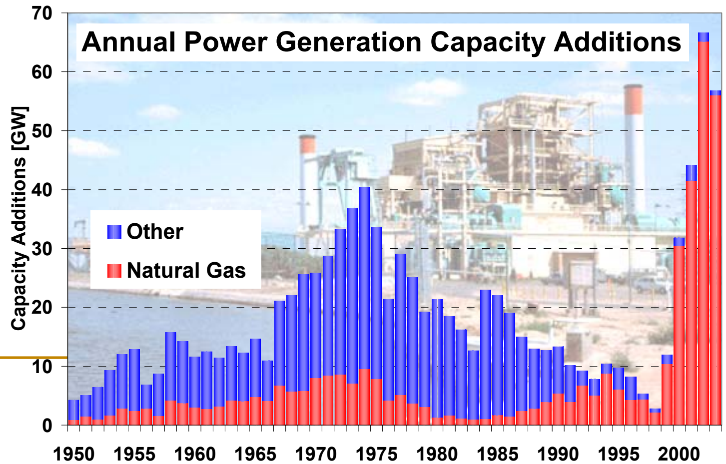


Recent Events Illustrate the Limitations of Current Energy Modeling Tools

- **Existing simulation and optimization tools are limited in accounting for volatility and uncertainty prevalent in today's energy markets**
  - Single decision-maker
  - Perfect foresight
  - Rational decision-making
  - Energy markets in equilibrium



- **Straight-line projections ignore dynamics, uncertainties, potential for sudden shocks and disruptions, market imperfections, and emerging strategies by market participants**
  - California power restructuring
  - Recent crude oil/gasoline price volatility
  - Rush to natural gas for power generation and recent collapse
  - Recent blackouts

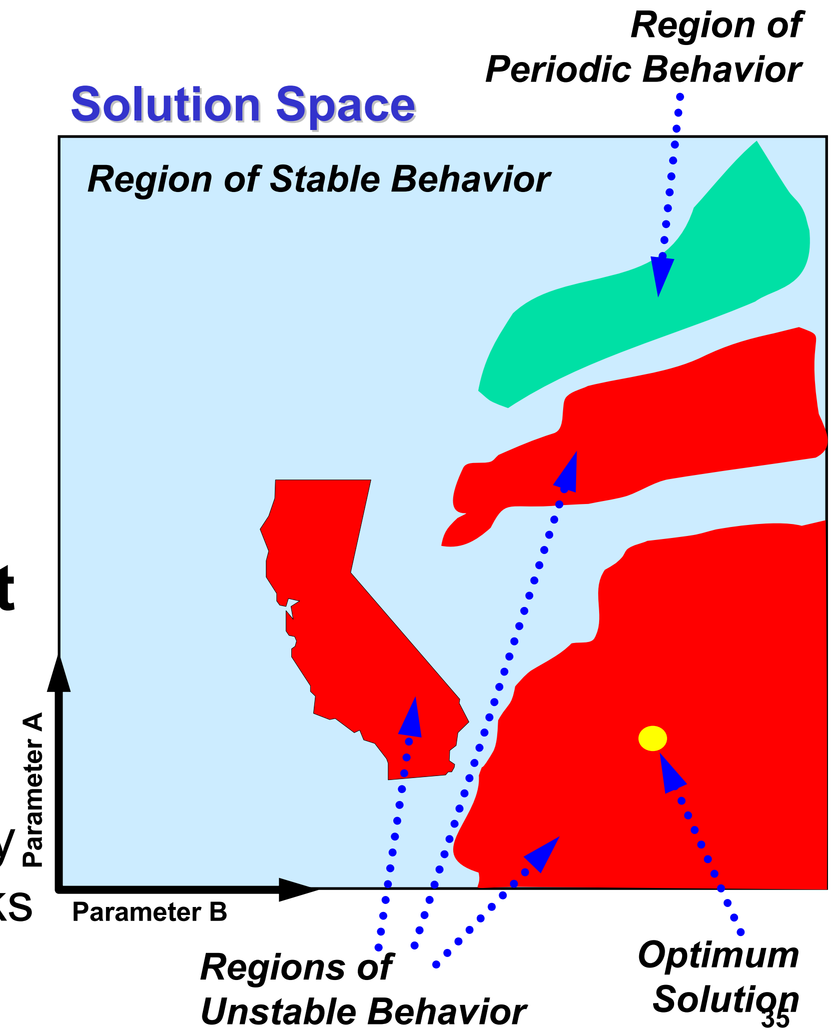


Current Modeling Attempts Do not Adequately Capture Underlying Complexities

- **System behavior evolves as a result of complex interactions between multiple interest groups/stakeholders**
- **Interest groups/stakeholders have different objectives, strategies, business profiles, and risk preferences**
- **Each interest group/stakeholder maximizes own objectives**
- **Objectives are often conflicting**
- **Decisions are based on imperfect information (private and public) and must be made in an uncertain environment**
- **Stakeholders learn and adapt to real or perceived changes in behavior of others or operating environment**

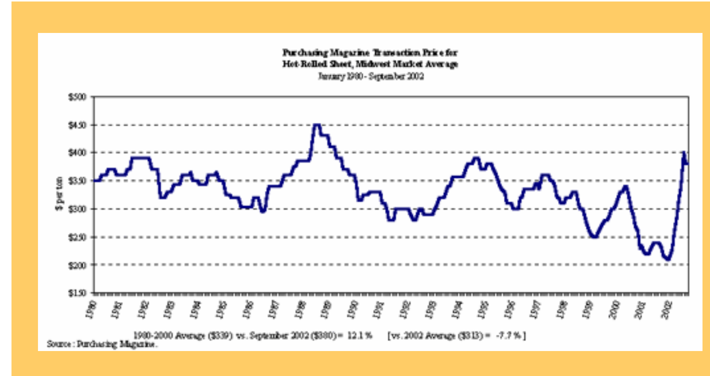
Solution Space and Test Robustness of Solutions

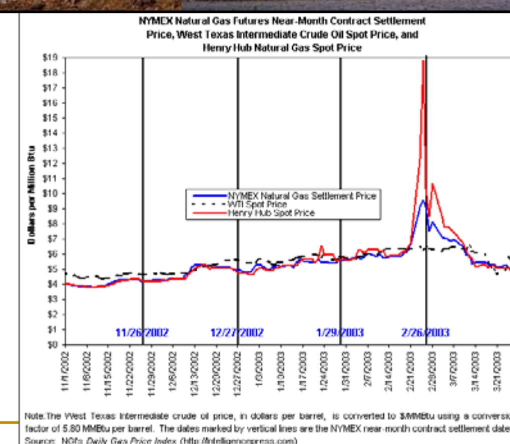
- **Better insights and understanding of complex behavior of large systems**
- **Explicit representation of uncertainty, system dynamics, emergent behavior**
- **"Optimum" or "least-cost" solution a useful benchmark, but only one data point in the solution space**
  - Sudden, sometimes small, shifts in key parameters may expose downside risks
  - May offer little flexibility to adapt decision mid-course to unexpected market developments (real options



The New Model Addresses Several Key Strategic Energy Issues

- **Energy system expansion under uncertainty**
  - How will system capacity evolve
  - Role of uncertainty and volatility
  - Are there boom and bust cycles and what can dampen them
  - Energy supply security (medium/long-term)
  - Risks of oil, gas, power supply shortages
- **Physical infrastructure vulnerability and robustnes**
  - What are key vulnerable system components
  - What are physical impacts of interruptions
    - *How much demand will be cut?*
    - *Where will demand be cut?*
  - What can be done to improve physical system robustness/reliability
- **Economic vulnerabilities and robustness**
  - What are the price impacts of component outages
  - What are the consumer impacts (temporal and spatial extent of price spikes)
  - What are the economic losses of component outages





Decision-Making Process for System Expansion

- **Software representation of individual players simulates decentralized decision making**
  - Agents are diverse and have unique behaviors
- **Construction decisions, announcements & schedules are based on rational company-level behavior**
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- **A multi-attribute utility function determines the best course of action for each independent market player**
  - Utility functions are the same for all players
- **Once started, project construction schedules are fluid; that is, market players adapt to market conditions (*not implemented yet*)**
  - Accelerate
  - Delay
  - Abandon
  - Restart
- **Project schedules are periodically re-evaluated (*not**