System Dynamics & Sustainable Energy

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Presented by:

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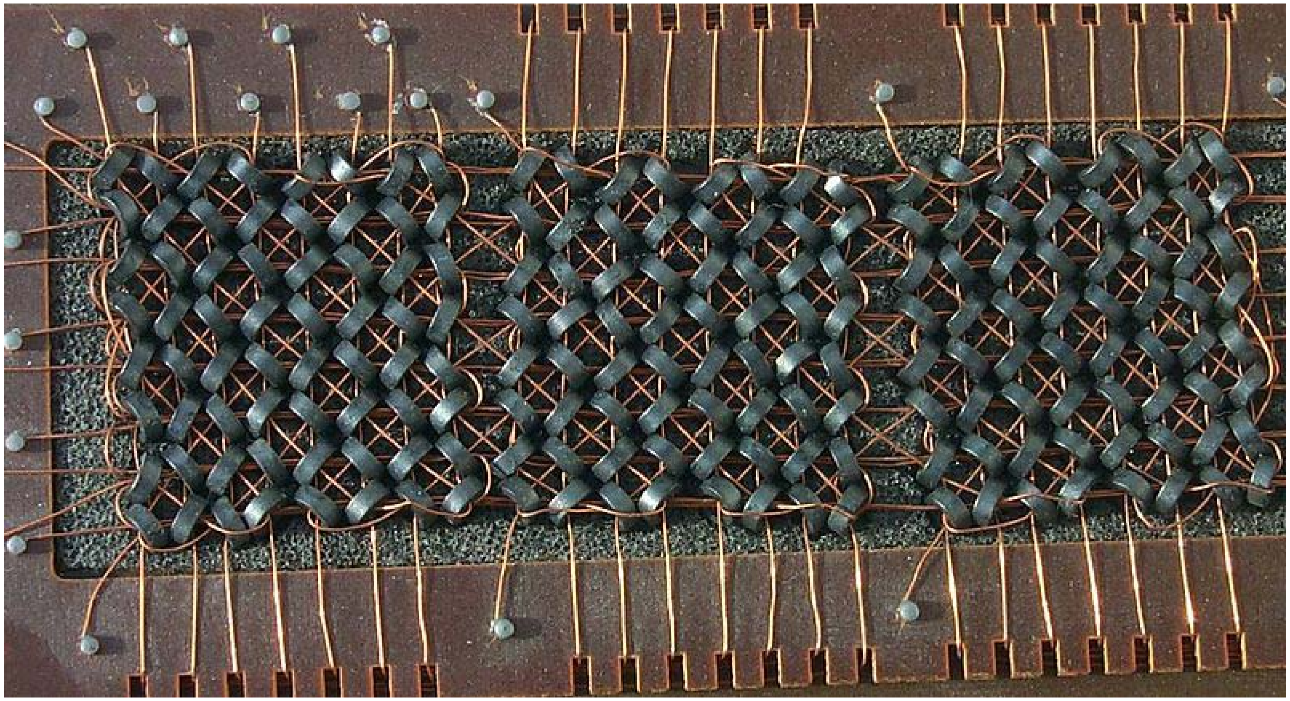
System Dynamics and Sustainable Energy: Outline

- Introduction to System Dynamics
  - Prof. Jay Forrester
  - System Dynamics in History
- Fundamentals of System Dynamics
  - SD Basics
  - Fundamental SD Models
- SD Models and Energy
  - World Dynamics
  - Electric Utilities
- SD models and Renewables
  - Some Previous Models
  - Simple Diffusion Model Example

- Jay Forrester and the Whirlwind Project
  - 1946-1956: Semi Automatic Ground Environment (SAGE) program and systems engineering
  - coincident-current random-access magnetic computer memory
  - 1956: Becomes Professor at MIT's Sloan School of Management



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- The Early Days of System Dynamics (1956-1969)
  - Consulting with General Electric factory workforce management
  - Digital Equipment Corporation Board Member from 1957: issues of fast growth and collapse with high-technology firms
  - Industrial Dynamics Published in 1961
- Urban Dynamics (1969)
  - In conjunction with Mayor John Collins of Boston (group model building)
  - National attention with many critics
- Limits to Growth and World Dynamics (1971)
  - In conjunction with the Club of Rome
  - International attention with many critics

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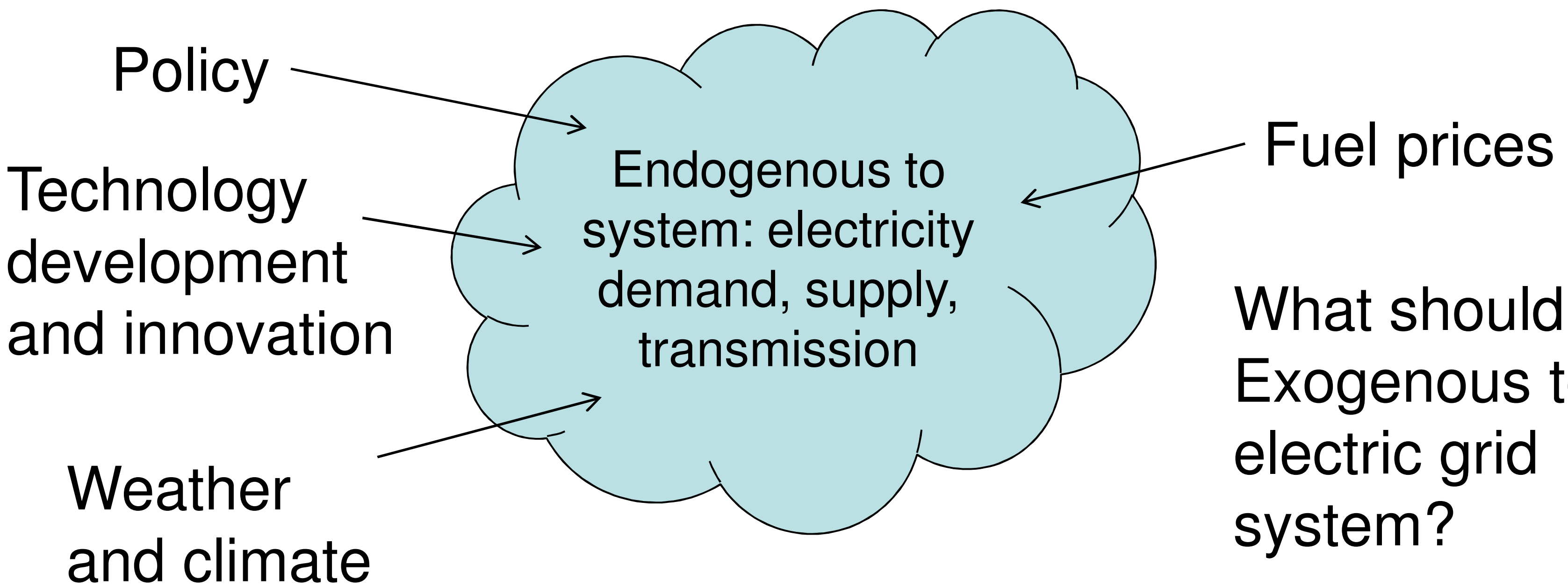
- Basics of System Dynamics Modeling
  - A system of Differential Equations solved using numerical techniques at a sequence of time-steps with complex feedback relationships between system variables
- Key Components are:
  - Simulation model (not optimization model)
    - Breaks down assumptions related to optimization (rationality of decision-makers, monetized / utilitarian value maximization)
    - Often involves economic, technical AND social phenomena

- Key Components are:
  - Goal-seeking behavior that drives model decision-making
    - Technical systems behave according to physical characteristics
    - Economic and social systems can behave according to different decision-making frameworks
      - Rational utility maximization
      - Boundedly rational decision-making (with potential delays, lack of information, etc)
      - Heuristics

Fundamentals of System Dynamics

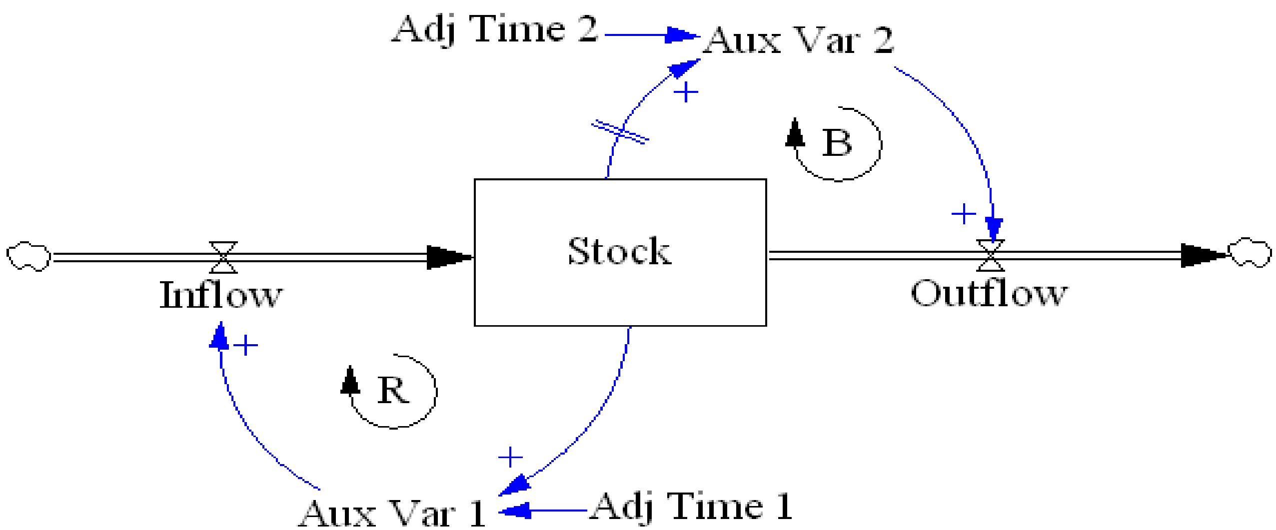
- Key Components are:
  - Closed System Boundary:
    - Must capture variables relevant to system behavior and structure
    - Can be as quite broad (always a challenge with this type of model)
    - Flexibility in deciding what is endogenous (inside system boundary) and what is exogenous (outside system boundary)



What should be Exogenous to electric grid system?

Fundamentals of System Dynamics

- Key Components are:
  - Variable separation into stocks (accumulation over time) and flows (auxiliary variables)
  - Feedback and delays: relationships between variables are non-linear and involve both physical and informational delay processes
    - Negative Feedback Loops (Balancing)
    - Positive Feedback Loops (Reinforcing)



- Some Fundamental SD Models
  - System Archetypes from Peter Senge, author of The 5th Discipline: Systems Thinking: http://www.systems-thinking.org

Reinforcing Loop

Fixes that Fail

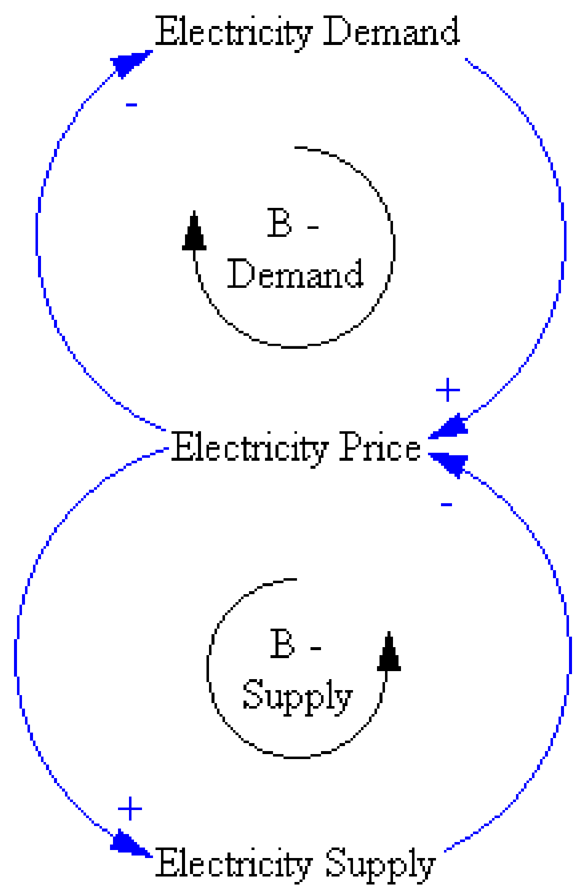
Diagrams removed due to copyright restrictions.
Please see Bellinger, Gene. "Archetypes: Interaction Structures of the Universe." Mental Model Musings, 2004.

Balancing Loop

Drifting Goals

Limits to Success

- Basic system dynamic model of the electricity sector
  - Causal-loop diagram (high level representation of the key variables of interest and their causal relationships)
  - What are the key basic variables of interest?
  - What are the direction of relationships?
  - Are the directly or inversely related?
  - Are there any delays in the system?
  - Intermediate variables of interest?



- A more complex SD Model Archetypes:
  - Diffusion and Innovation (the Bass diffusion model)
  - Who are the potential adopters of a given product (think consumer products such as iphones)?
  - What influences them to adopt a product?

Diagram removed due to copyright restrictions.Please see any system dynamics diagram of diffusion innovation, such as http://commons.wikimedia.org/wiki/File:Adoption_SFD.gif.

Above: Sterman (2000) Business Dynamics

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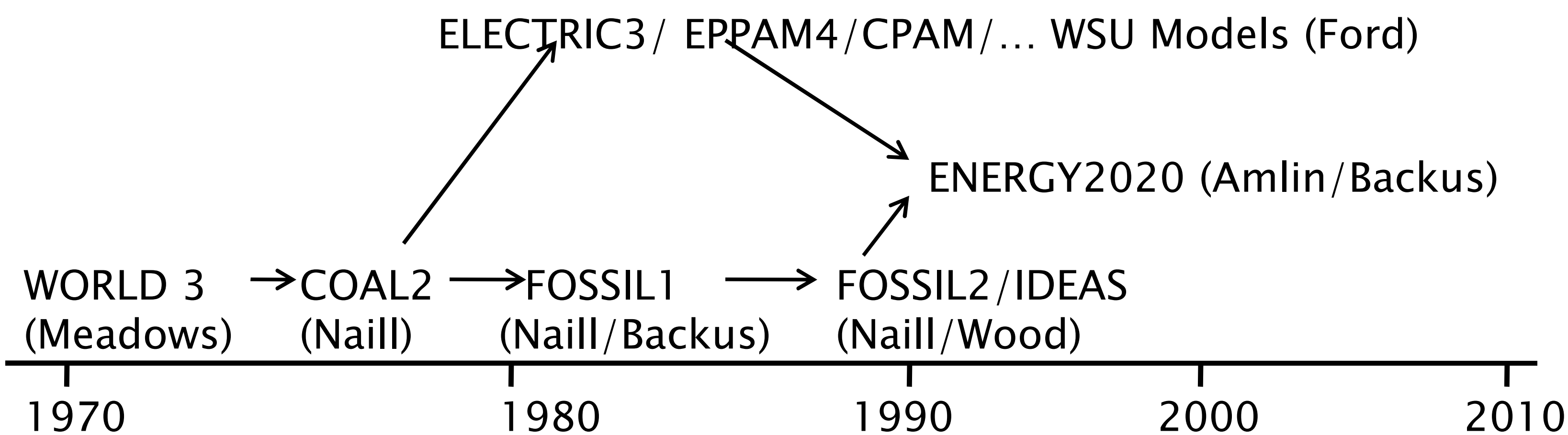
SD Models and Energy

- Series of System Dynamic Models in Energy
  - Early 1970s: development of FOSSIL1/FOSSIL2 displaces use of "Project Independence Evaluation System" PIES
  - 1978 ~ 1995, FOSSIL2/IDEAS (Integrated Dynamic Energy Analysis Simulation) used widely for energy policy evaluation
  - Mid-1990s, Energy Information Administration introduces National Energy Modeling System to replace FOSSIL2 model
  - Energy2020 developed to integrate FOSSIL2 with utility-specific EPPAM SD Model



SD Models and Energy

- Energy2020 Basic Model Structure
  - Sectors: energy-supply, energy-demand, pollution-accounting
  - Scenario testing with thousands of policy levers
  - Includes both fossil-fuel and renewable energy sources
  - Includes industry, electricity, transportation and other energy uses
  - Detailed historical data used to calibrate model

Diagrams removed due to copyright restrictions.
Please see Fig. 1.1, 3.6 in "Modeling of Greenhouse Gas Reduction Measures to Support the Implementation of the California Global Warming Solutions Act (AB32): ENERGY 2020 Model Inputs and Assumptions." Systematic Solutions, Inc., February 1, 2010.

Review of Some Models on Wind and Diffusion

- Electric sector model for capacity expansion
  - Looks at shifting electricity demand profile and generation asset mix over time
  - Includes different time-scales of interest (hours, days, months and years)
  - Includes endogenous demand elasticity, technology learning and economies of scale

Image removed due to copyright restrictions.
Please see Fig. 15.8 in Vogstad, Klaus-Ole. "A System Dynamics Analysis of the Nordic Electricity Market: The Transition from Fossil Fuelled Toward a Renewable Supply within a Liberalised Electricity Market." Doctoral thesis, Norwegian University of Science and Technology, December 2004.

Review of Some Models on Wind and Diffusion

- Few System Dynamics Models focused on Diffusion and Incorporation of Renewables into Electricity Sector
- Combine capacity expansion framework with diffusion framework for new technology (i.e. Dyner 2006)
  - Adds influence of different exogenous policy mechanisms
  - Some attempt at estimating R&D spending influence on costs
  - Scope trade-off: detailed model of specific technology versus large interactions across system variables

Image removed due to copyright restrictions.
Please see Fig. 3 in Dyner, Isaac, and Monica Marcela Zuluaga. "SD for Addressing the Diffusion of Wind Power in Latin America: The Colombian Case." 24th International Conference of the System Dynamics Society, July 23-27, 2006.

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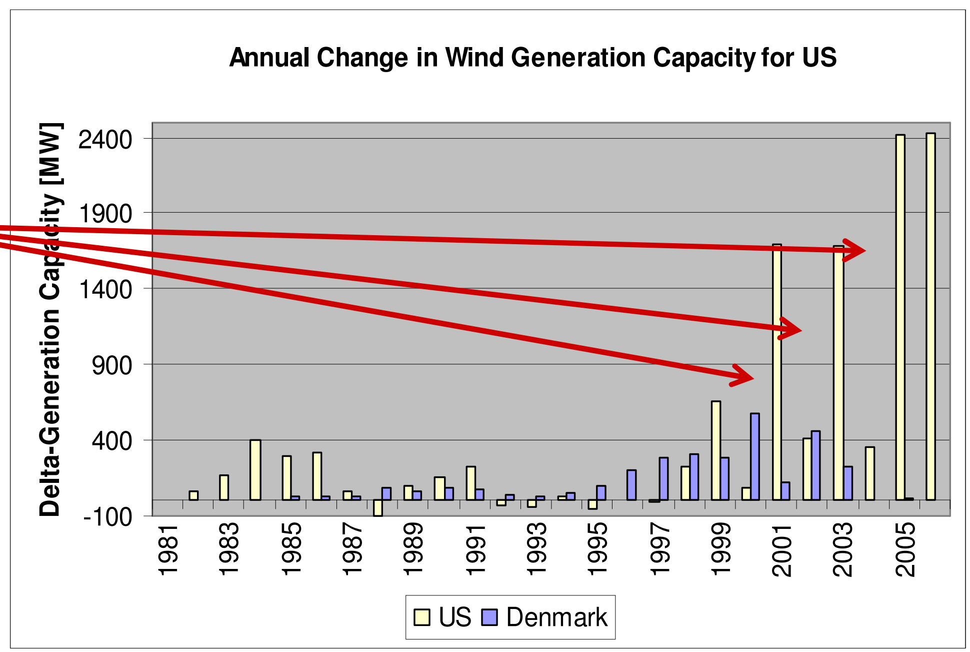
SD Models and Renewables

- Why diffusion framework?
  - Adoption of new technologies: wind energy, solar power, distributed generation, electric vehicles, storage
- What caveats?
  - Complex interaction with larger technical system
- Potential solutions?
  - Combine with optimization based models such as economic-based capacity expansion models (two interconnected models)
  - Bring technical complexities into a diffusion model for the technology (try to capture system interaction within system dynamics space)

Revisiting wind energy

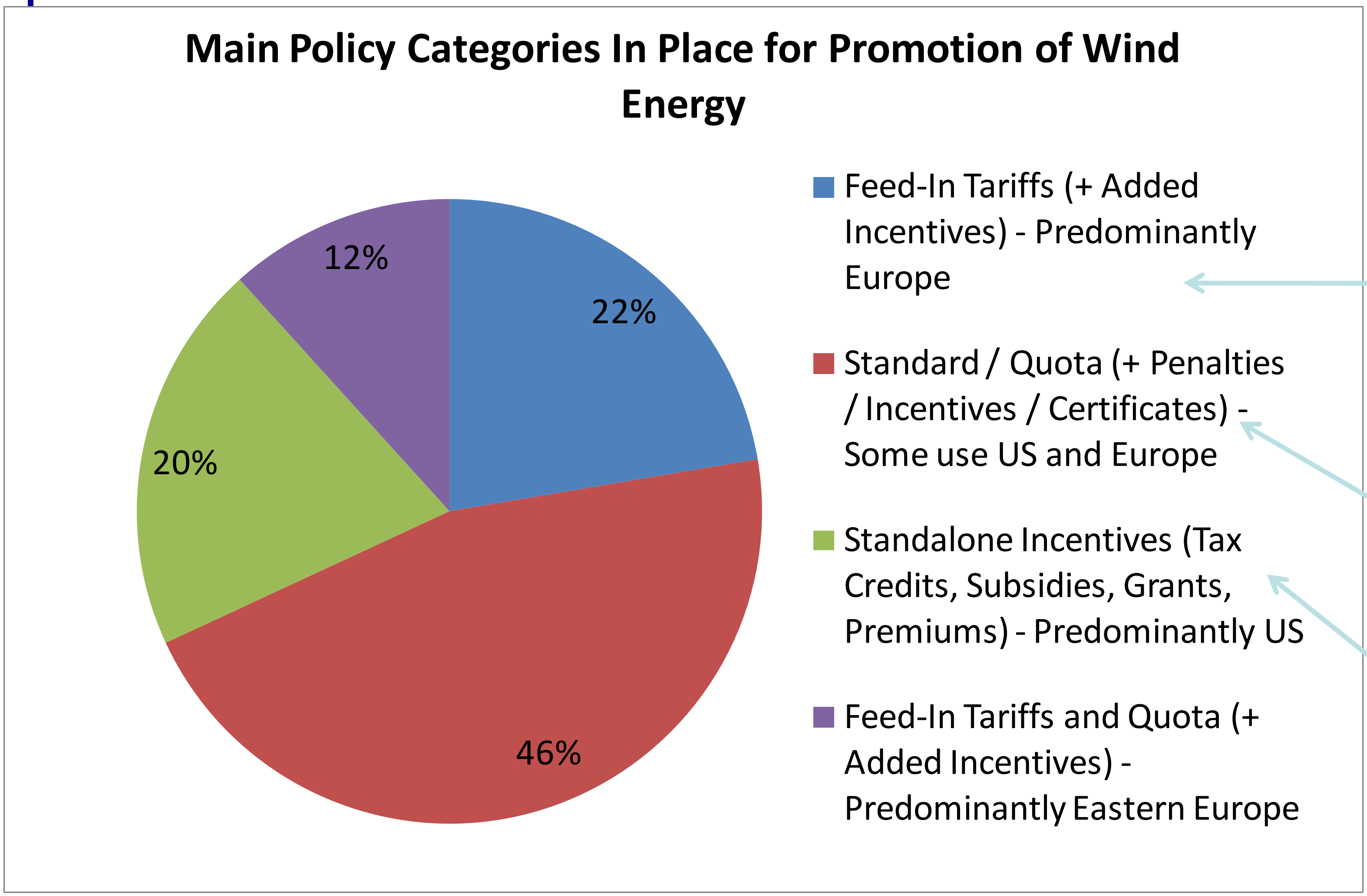
- Historically inconsistent US federal policy for wind energy
  - Periodic expiration of Production Tax Credit (PTC) in 1999, 2001, and 2003 cause collapse in industry growth
  - Financial crisis in 2009 diminish viability of PTC causing shift of emphasis by AWEA towards national renewable electricity standard (RES)

PTC Expirations



[1]Wiser, R and Bolinger, M. (2008). *Annual Report on US Wind Power: Installation, Cost, and Performance Trends*. US Department of Energy – Energy Efficiency and Renewable Energy [USDOE – EERE].

Revisiting wind energy: policy support for wind

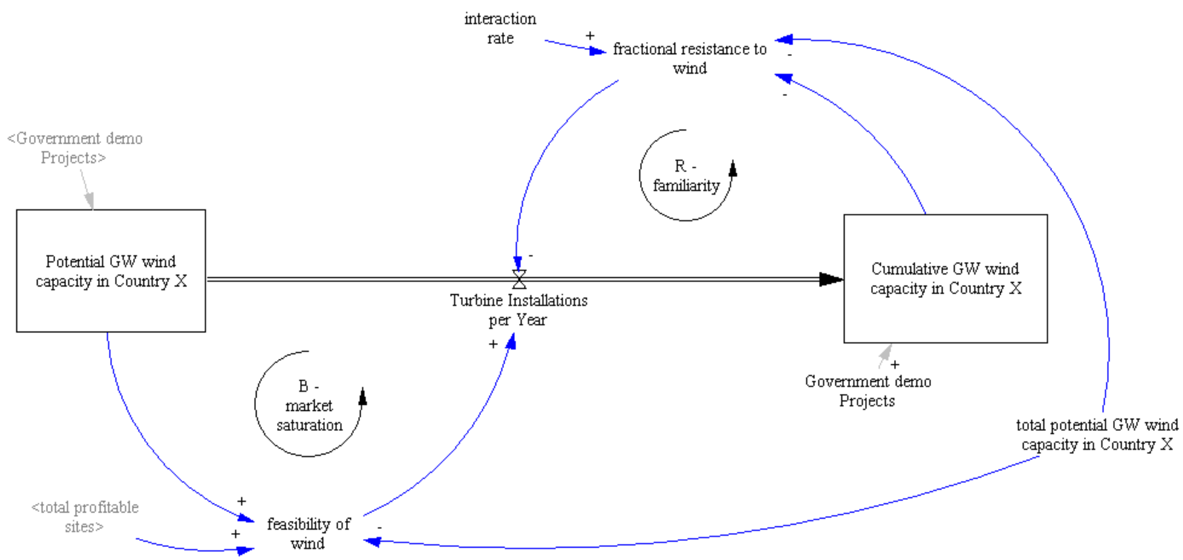


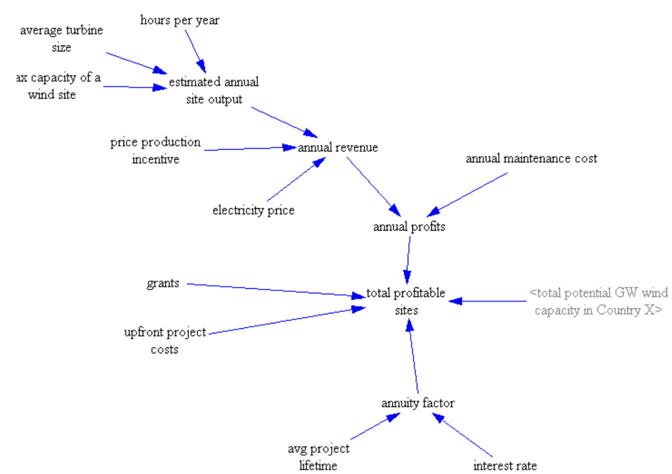
Cases
Germany, Spain, Portugal, Denmark
Colorado, Illinois
California, Idaho

Data sources: IEA 1997, GWEC 2008, DSIRE 2009, AWEA 2009.

Simple Diffusion Model for Wind Energy

- Basic Model Design:
  - Bass diffusion model using word of mouth and direct advertising substituted:
    - primary reinforcing loop (increased familiarity with wind technology)
    - primary balancing loop (depletion of high wind resource sites profitable for development)
  - Policy, electricity price, costs and demand treated as exogenous

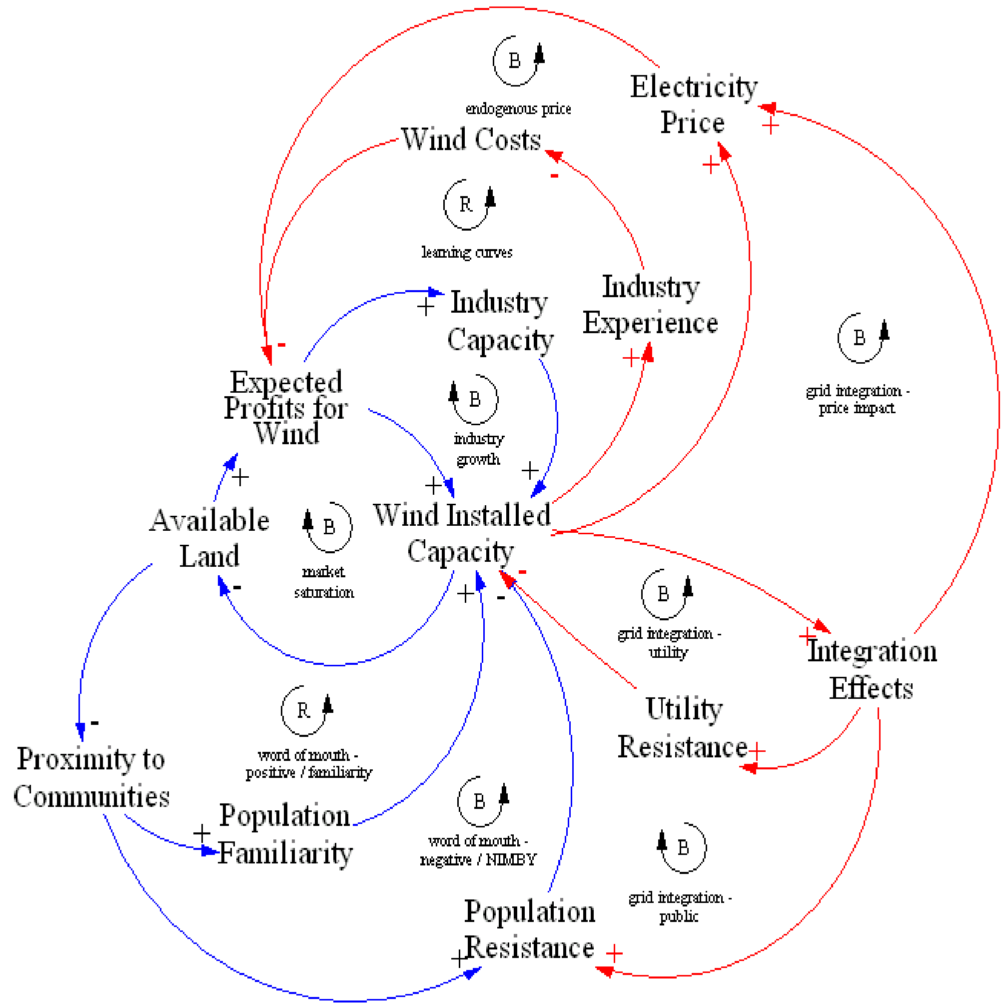




(Demo of simple wind diffusion model)

Wind Energy Diffusion Model Development

- Endogenous Factors:
  - Learning curve and technology improvement
  - Both utility and community acceptance
  - Electricity prices
  - System costs
  - System integration
  - Land-use
  - Industry capacity
- Sub-model development for each area



Thanks!

Q&A

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Introduction to Sustainable Energy
Fall 2010