Flexibility in Engineering Design

with examples from electric power systems

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with support from Prof. Mort Webster, Engineering Systems, MIT

Reference to text

"Flexibility in Engineering Design"
MIT Press, 2011

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Theme of Presentation

A Change in Paradigm of Design

- Back to ‘common sense’ approach
- Increasingly used in industry

Essence of Paradigm:

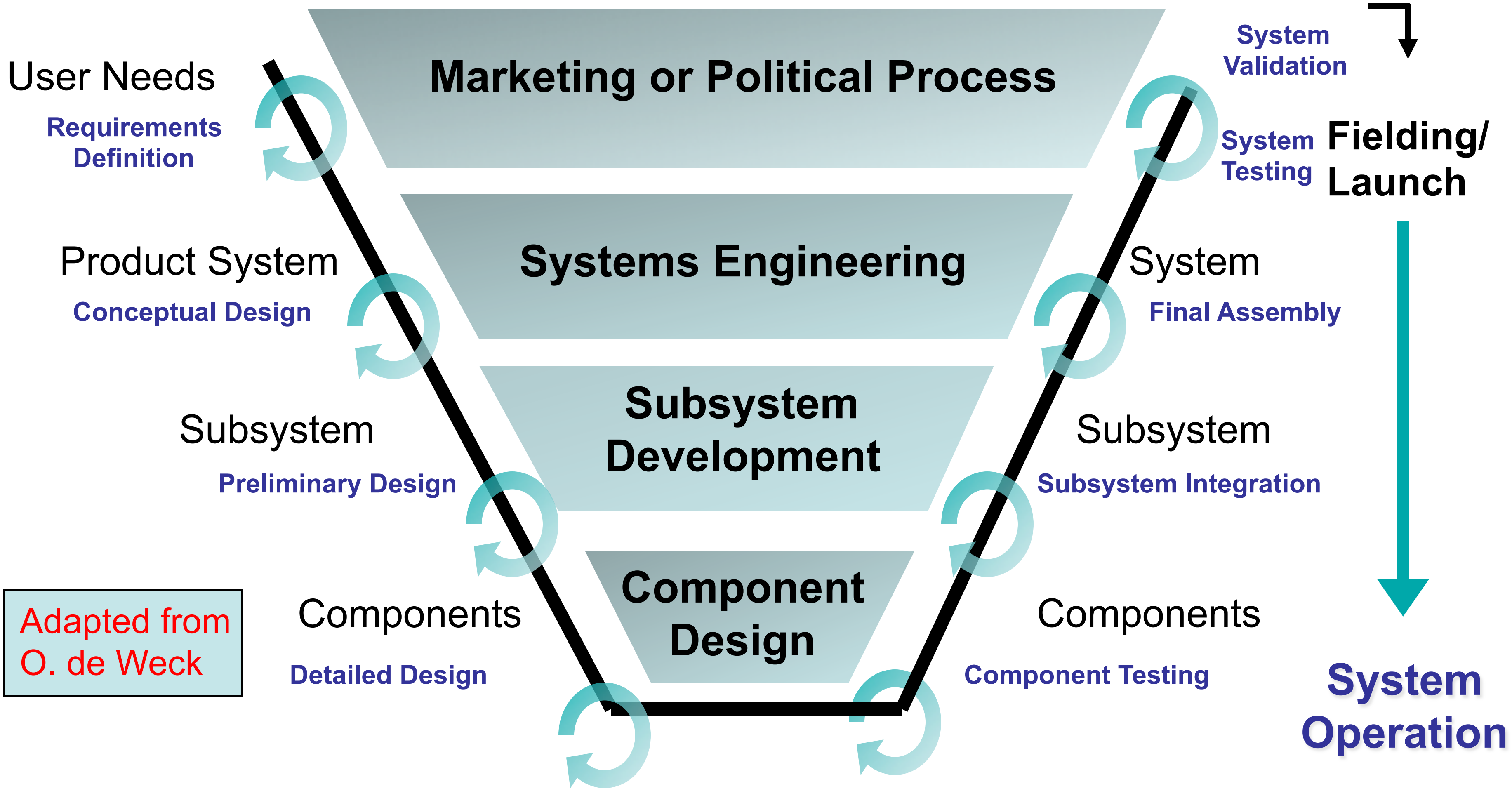
- As we cannot predict future, we must design for adaptability, so as to
- Take advantage of upside opportunities
- Avoid downside problems

Outline of Presentation

1. Discussion of Standard Procedure for design of Engineering Systems
2. Flaw of Averages
3. Concept of Alternative Paradigm
4. Analytic Procedure
5. Example Applications
6. Wrap-up and Questions

Standard Procedure for Design of Engineering Systems

Traditional Systems Paradigm



User Needs
Requirements Definition

Product System
Conceptual Design

Subsystem
Preliminary Design

Components
Detailed Design

Marketing or Political Process

Systems Engineering

Subsystem Development

Component Design

System Validation

System Testing

Fielding/ Launch

System
Final Assembly

Subsystem
Subsystem Integration

Components
Component Testing

System Operation

Adapted from O. de Weck

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Implicit Assumptions of TSE

- Customers, public know what the needs are
- These requirements are time-invariant
- The system or product can be designed as one coherent whole and is built and deployed in one step
- Only one system or product designed at a time
- The system will operate in a stable environment as far as regulations, technologies, demographics and usage patterns are concerned

Assumptions of TSE – not Realistic!

- Customers know the needs? New ones emerge!
- The requirements are fixed ?
  These change with needs and new regs, etc, etc.
- The system can be designed as a coherent whole and built and deployed in one step? Often not
- Only one system being designed? Families likely
- The system will operate in a stable environment as far as regulations, technologies, demographics and usage patterns are concerned? We wish…

Traditional (Systems) Engineering

- Has been very successful, delivering highly complex systems of all sorts
- However, it can now do better…
- If we step outside its “box” of assumptions
- … which are unrealistic!

The Reality Is

- Our systems are in the middle of uncertainties

- Economic Financial conditions … Boom and Bust
- Technological change … fracking, wind, nuclear…
- Regulatory… New Rules: Environmental, economic…
- Shape of Industry… deregulation, merchant suppliers …
- Political… will there be a carbon tax? …
- Other … 3-mile island, Sandy, climate change? …

Bottom Line: Outcomes only known probabilistically

The Flaw of Averages

Further Crucial Reality: Flaw of Averages

- Design to "most likely", "average" or "requirement" scenario is **BAD – gives wrong results**
- benefits of better scenarios "never" equal losses of poorer scenarios (a few theoretical exceptions)

Example:

  Design plant to most likely capacity

  20% Higher sales => lost sales -- can't deliver demand

  20% Lower sales => losses

Systems are non-linear, need to examine range

- We need to analyze scenarios

Flaw of Averages

- Named by Sam Savage (“Flaw of Averages, Wiley, New York, 2009)

It is a pun. It integrates two concepts:

- A mistake => a “flaw”
- The concept of the “law of averages”, that that things balance out “on average”

- Flaw consists of assuming that design or evaluation based on “average” or “most likely” conditions give correct answers

Mathematics of Flaw

- Jensen's law:
- $E[\, f(x)\,] \le f[\, E(x)]$ if $f(x)$ is convex function

- Notation: $E(x)$ = arithmetic average, or "expectation" of x
- In words:

  $E[\, f(x)]$ = average of possible outcomes of $f(x)$

  $f[\, E(x)]$ = outcome calculated using average x

Example

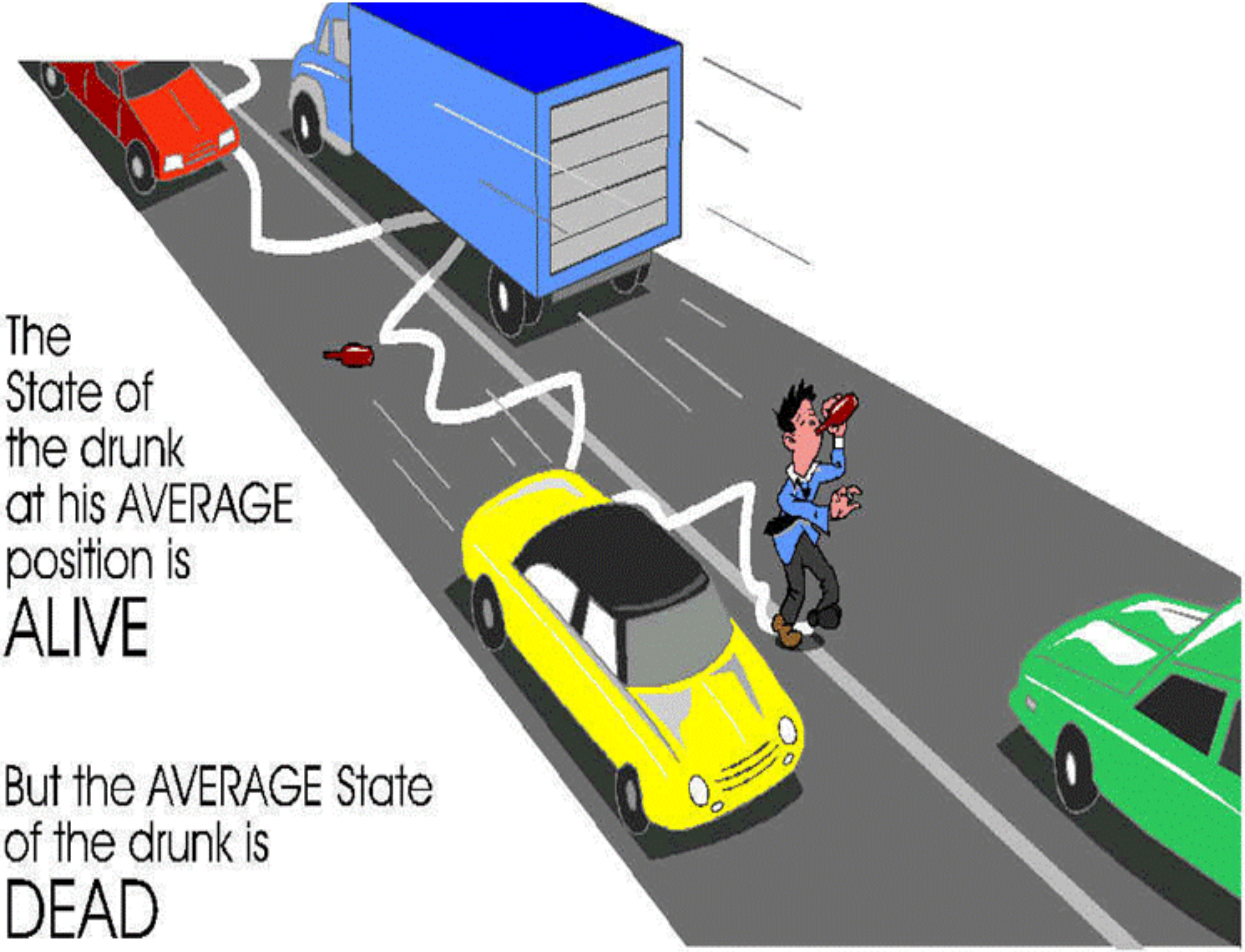
Given: $f(x) = \sqrt{x} + 2$

And: $x = 1, 4,$ or 7 with equal probability

- $E(x) = (1 + 4 + 7) / 3 = 4$
- $f[E(x)] = \sqrt{4} + 2 = 4$
- $f(x) = 3$, 4, or $[\sqrt{7} + 2] \sim 4.65$
  with equal probability
- $E[f(x)] = (3 + 4 + 4.65) / 3 \sim 3.88 \leq 4 = f[E(x)]$

In Words

- Average of all the possible outcomes associated with uncertain parameters,
- generally does not equal
- the value obtained from using the average value of the parameters



The
State of
the drunk
at his AVERAGE
position is
ALIVE

But the AVERAGE State
of the drunk is
DEAD

Practical Consequences

Because Engineering Systems not linear:

- Unless you work with distribution, you get wrong answer
- design from a realistic description differs – often greatly – from design you derive from average or any single assumption of "requirements"
- This is because gains when things do well, do not balance losses when things do not (sometimes they're more, sometimes less)

Concept of Alternative Paradigm

New, Flexible Approach to Design

- Recognizes Uncertainty
- Analyses Possible Outcomes of Designs
- Chooses Flexible Designs to
  - Reduce, eliminate downside risks (in general, less ambitious initial projects – less to lose)
  - Maximize Upside opportunities (that can expand or change function, when, if, and how seems desirable given future circumstances)

20 to 30 % Increases in Expected Value Routine!

The Concept

- Flexible design recognizes future uncertainty. The economy, technology, regulations all change.
- Flexible design creates systems easily adaptable to actual futures. It differs from the traditional approach, which defines a future and creates a design for that situation – which has little chance of occurring!
- Traditional design often leaves us with infrastructure poorly suited to actual conditions, and thus inefficient..

Great increase in Expected Value

- systems with flexibility to adapt to new conditions can greatly increase expected value.
- With flexibility we can
  - avoid future downside risks (by building smaller with confidence that can expand as needed)
  - profit from new opportunities by appropriate actions
- Reduce initial capital expenditure (CAPEX).
  - Lower initial CAPEX because less complex at start
  - Lower Present Values, because costs deferred many years (and maybe even avoided)

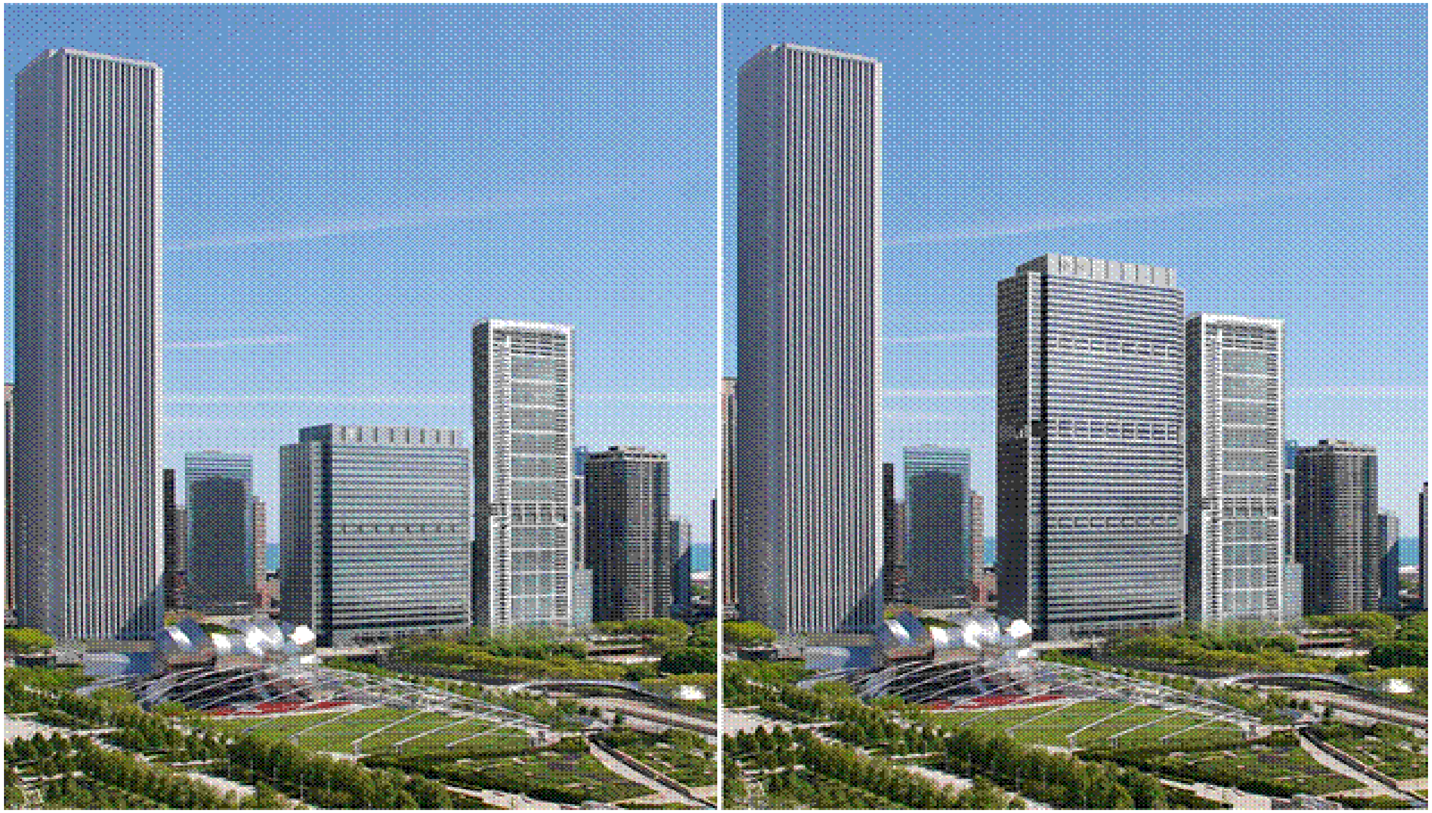
Higher returns, lower cost = A Great Formula

HCSC Building in Chicago

- In 2007-2009, 3000 people were coming to work in the 30-story HCSC building in Chicago,
- … and a 27-story addition was being built right on top of them!

- The structure was designed in 1990s with extra steel, utilities, elevator shafts, etc to permit doubling of height.
- This flexibility was exploited a decade later

Here' s the Picture



Vertical Expansion of Health Care Service Corporation Building, Chicago. Phase 1 (left) and Phase 2 (right) in center of image.

Source: Goettsch Partners, 2008 and Pearson and Wittels, 2008.

The Paradox

- 30-story building with capacity to expand
  - costs more than one without expansion capacity
  - Yet saves money!
- Why is this?
- The fair comparison is between
  - 30-story expandable building and
  - what HCSC would build otherwise to meet its long-term needs – such as a 40-story building
- Flexible design saves money 2 ways:
  - Lower initial Capital Expenditures (CAPEX)
  - Deferral, possible avoidance, of expansion costs

Analytic Procedure

Main Elements of Procedure

1. Recognition of Uncertainty … and its characterization
2. Simulation of Performance for Range of Scenarios
3. Evaluation… necessarily multi-dimensional, one number not enough to describe a distribution

Recognition of Uncertainty

- Best estimates of established trends and procedures – what is the record? Error rate? Standard deviation?
- Judgment about important, possible but unprecedented scenarios. For example, new environmental regulations, technological change, mergers of competitors, etc.

Analysis of Scenarios: Process

- Develop screening models
  - Simplified, “mid-fidelity” models of system that run quickly (minutes, not hours or a day)
- Simulate system performance under range of scenarios
  - Sample distribution hundreds or more times
- Identify “plausible sweet spots” for detailed analysis .

Evaluation

- Analysis results are distributions
  - This is as it should be; if future is a distribution, results must be also
- Evaluation must be multi-dimensional
  - Because several numbers needed to characterize distributions
- Useful metrics
  - Average expectation
  - Extremes such as P_5 , P_{95}
  - Others: Initial Capex (capital expenditure)

Example Analyses
for
Electric Power Systems

1. Renewables in Texas
2. Technological Innovation

1. Renewables in Texas

Issue: Standard planning process is deterministic and simplistic: Capacity planned based on estimates – operations not analyzed

Analysis: Combine both capacity planning and operational constraints, along with uncertainty

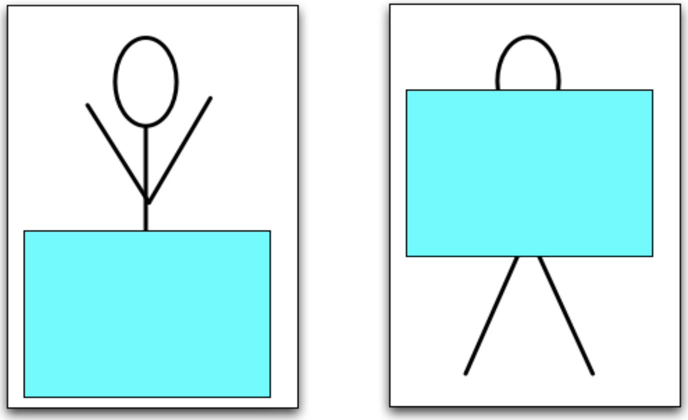
Results:

a. Demonstration that simple process misestimates consequences

b. More flexible, more advantageous design

Long-Term Generation Planning with Operations Constraints

- **Today:** Simple analysis does not tie actual operations into long-term plan
- The “Short Blanket” Problem
- Our analysis (the blanket) does fully cover us



Investment Decisions

Operations Constraints

Based on Dr. Bryan Palmintier

Long-Term Generation Planning with Operations Constraints

- **Challenge: Short time scale embedded in long-term planning – problem too big**
- **We get wrong/bad answers – case of RPS** Renewable Portfolio Standard (e.g.. 20%)

Goal	Result with Simple Design
Estimate carbon price	Off by factor of 2
Design for 45Mt CO2 cap	Infeasible Can't do RPS + Cap

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Long-Term Generation Planning with Operations Constraints

- **Root cause of wrong answers**
  - **Planning model neglects variability of loads, has no “plan b” to deal with them**
- **Desire: Operational Flexibility**
  - **Issue: Renewables –production changes rapidly BUT Low CO2 technologies (e.g., Nuke) can’t ramp quickly**
  - **Need: Unit Commitment** (UC) capability, up to a week ahead

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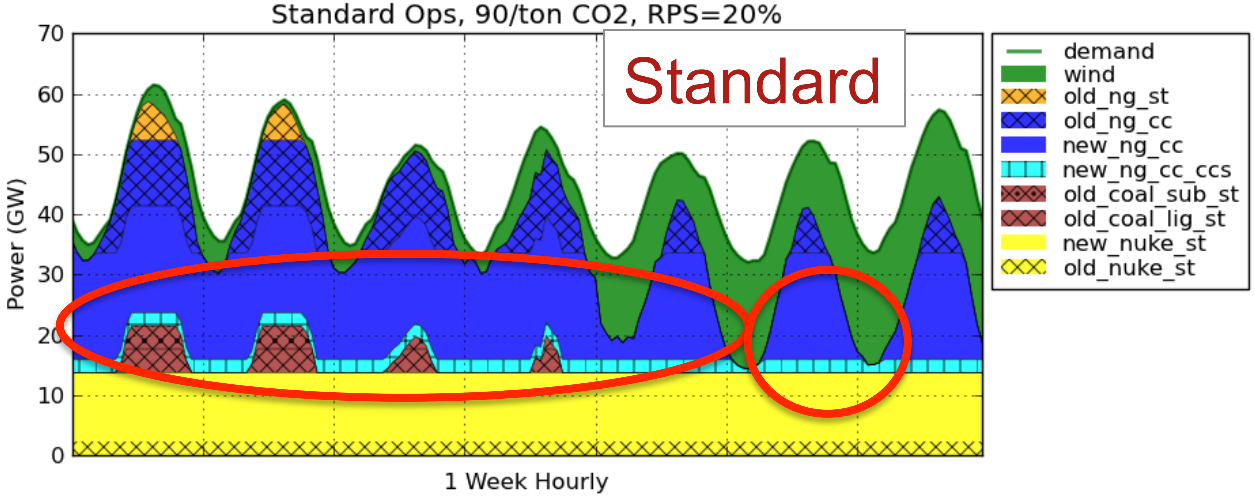
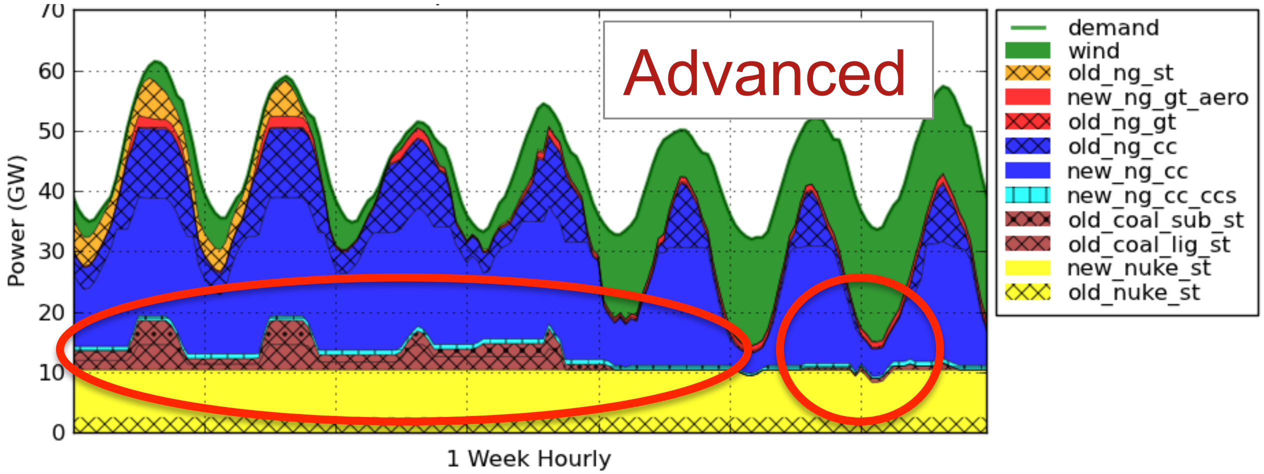
What is Driving the Results?



Standard Model implies that old coal plants (left) and combined cycle gas are used (right0– and turned on/off over few hours



Bottom Model is what would actually happen realistically – to account for start-up and ramping constraints

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2. Technological Innovation

Issue: Standard planning process is deterministic and simplistic: It does not account for R&D uncertainty– example of Flaw of Averages

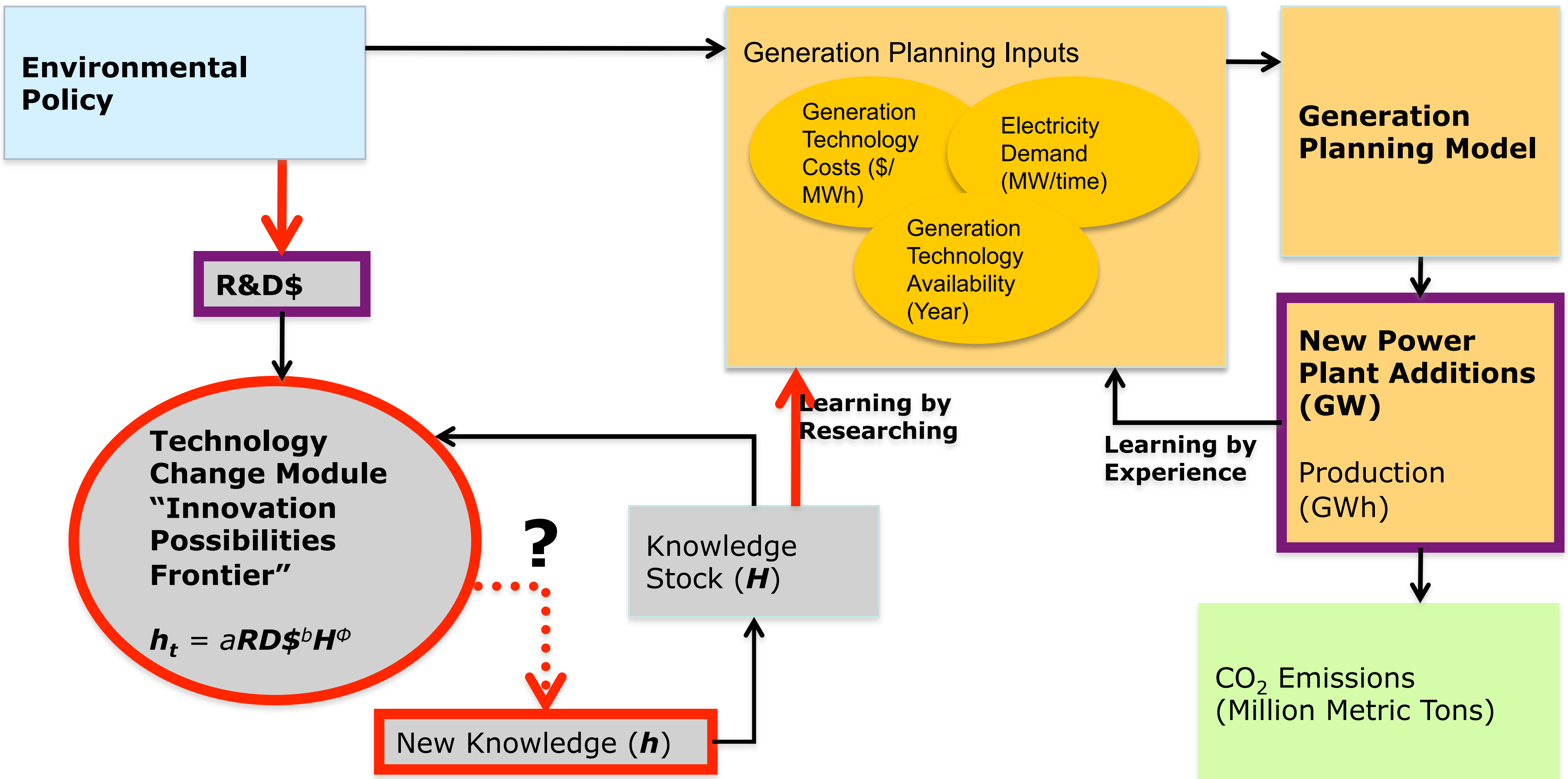
Analysis: Combine: capacity planning + economic model of R&D + stochastic R&D results

Results:

a. Demonstration that simple process misestimates consequences

b. Amount of incremental R&D depends on technology’s role in system (nuclear vs wind)

Modeling Framework



Environmental Policy

R&D$

Technology Change Module "Innovation Possibilities Frontier"

$h_t = aRD\$^b H^{\Phi}$

?

New Knowledge (***h***)

Knowledge Stock (***H***)

Learning by Researching

Generation Planning Inputs

Generation Technology Costs ($/MWh)

Electricity Demand (MW/time)

Generation Technology Availability (Year)

Generation Planning Model

New Power Plant Additions (GW)

Production (GWh)

Learning by Experience

CO_2 Emissions (Million Metric Tons)

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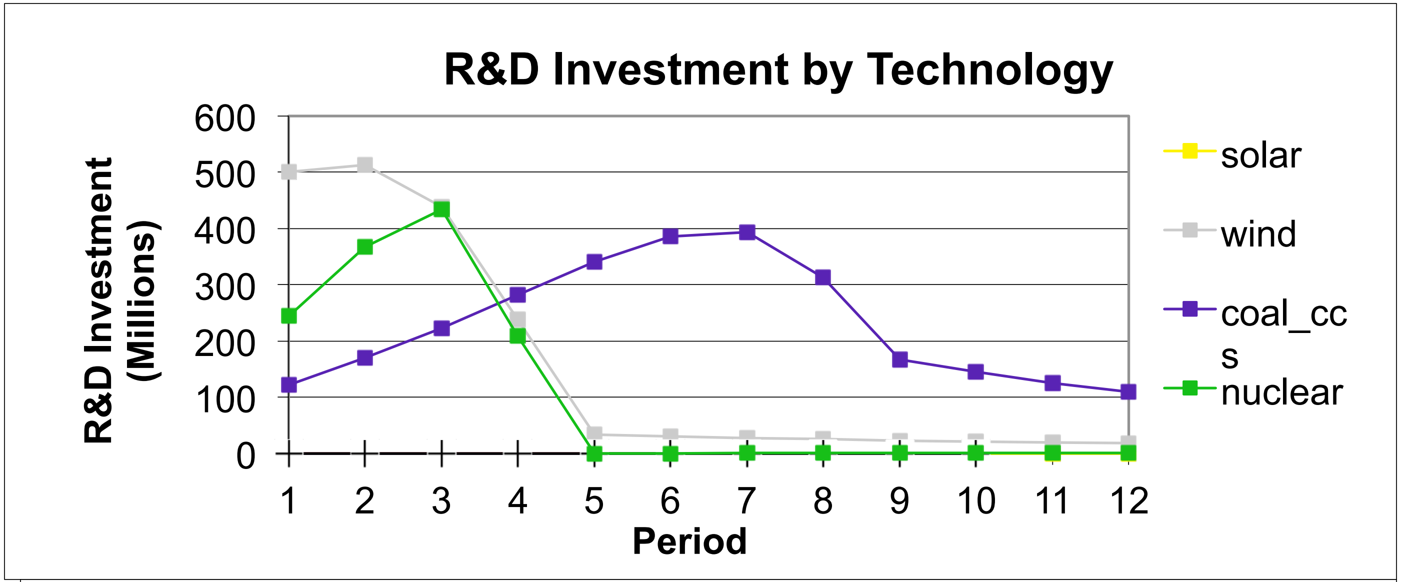
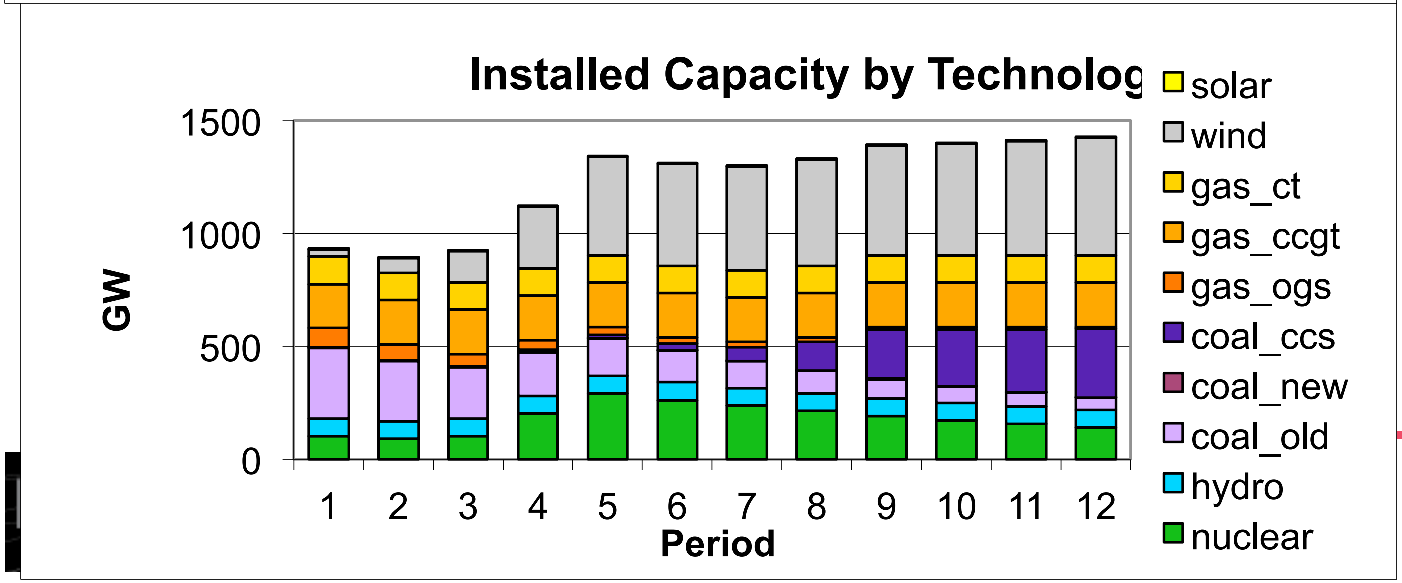
Deterministic Results : Reference Case

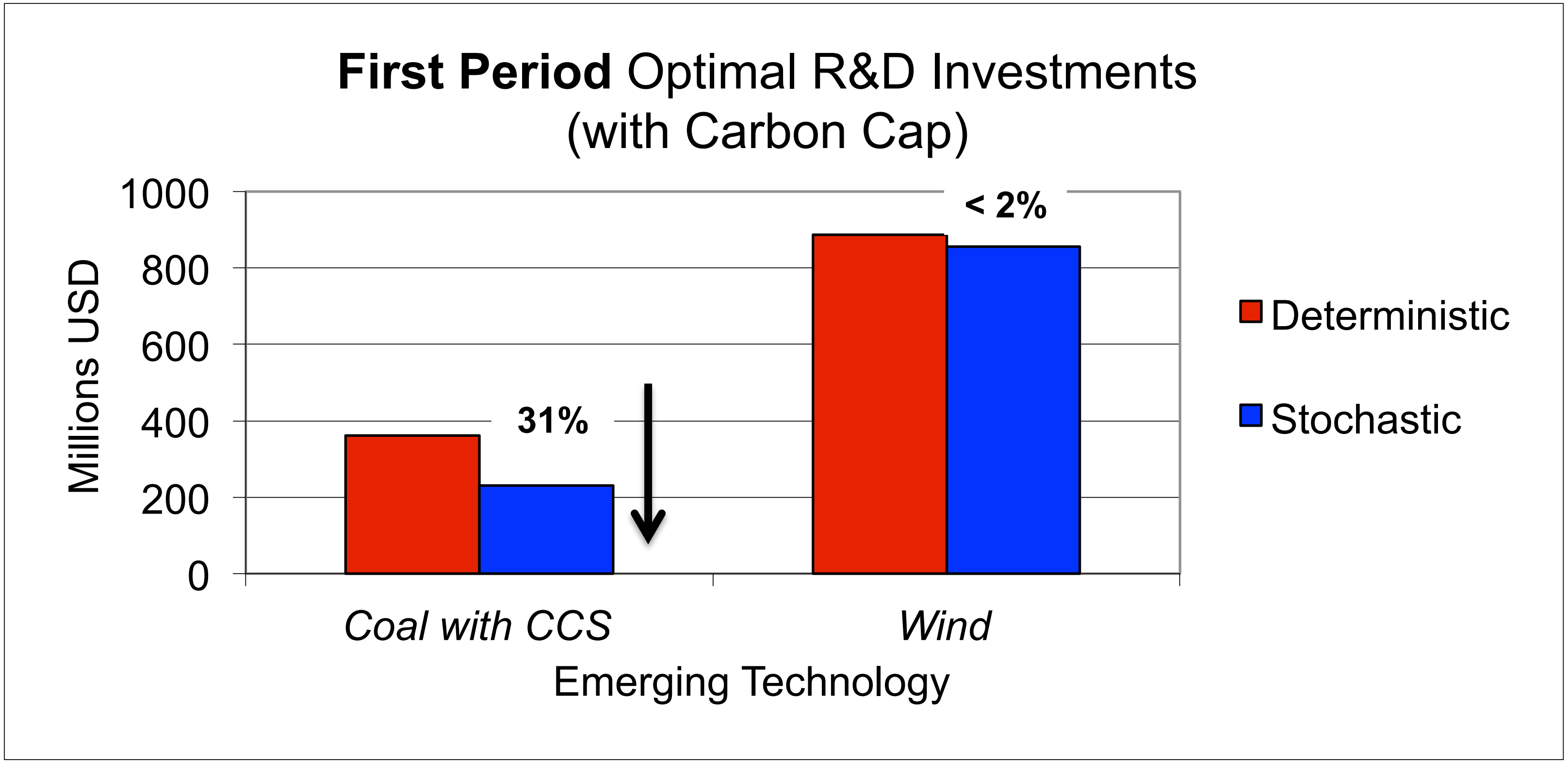




Assume there is a carbon cap

Spend on wind research early, to make it cheaper and start using it soon. Compared to coal with C capture – too expensive now

Stochastic Results : CARBON CAP



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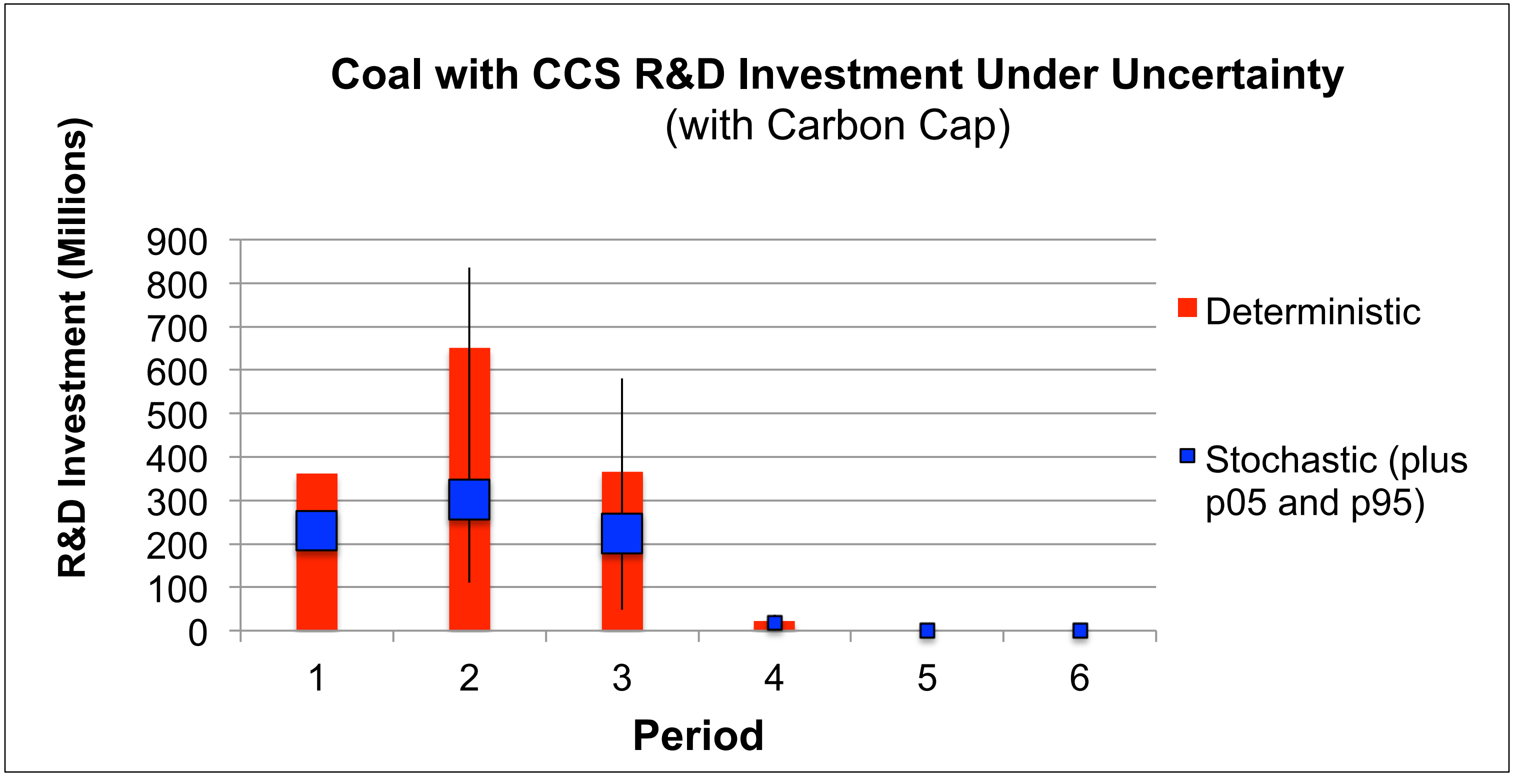
Stochastic Results : CARBON CAP



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Summary

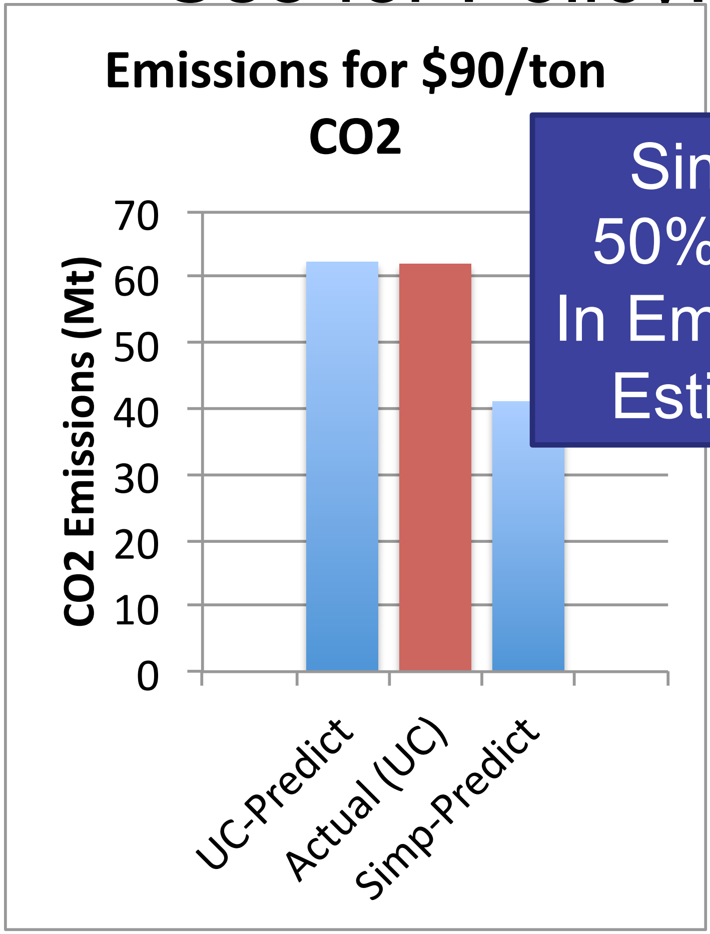
- Flexible design can greatly increase expected value from projects
- New paradigm -- Not traditional approach
- Requires research on how best to analyze and implement flexible design in practice

Thanks for your attention!

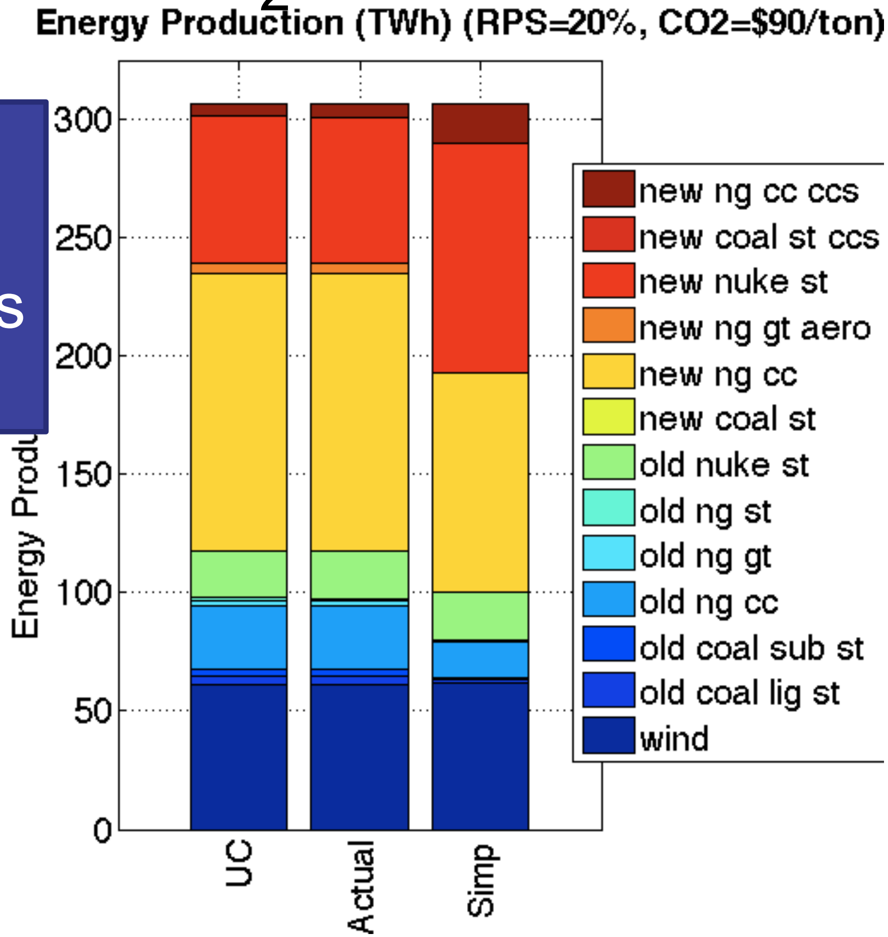
Questions and Comments?

Long-Term Generation Planning with Operations Constraints

- Use for Policy: Project CO_2 Emissions


Emissions for $90/ton CO2

Simple:
50% Error
In Emissions
Estimate


Energy Production (TWh) (RPS=20%, CO2=$90/ton)

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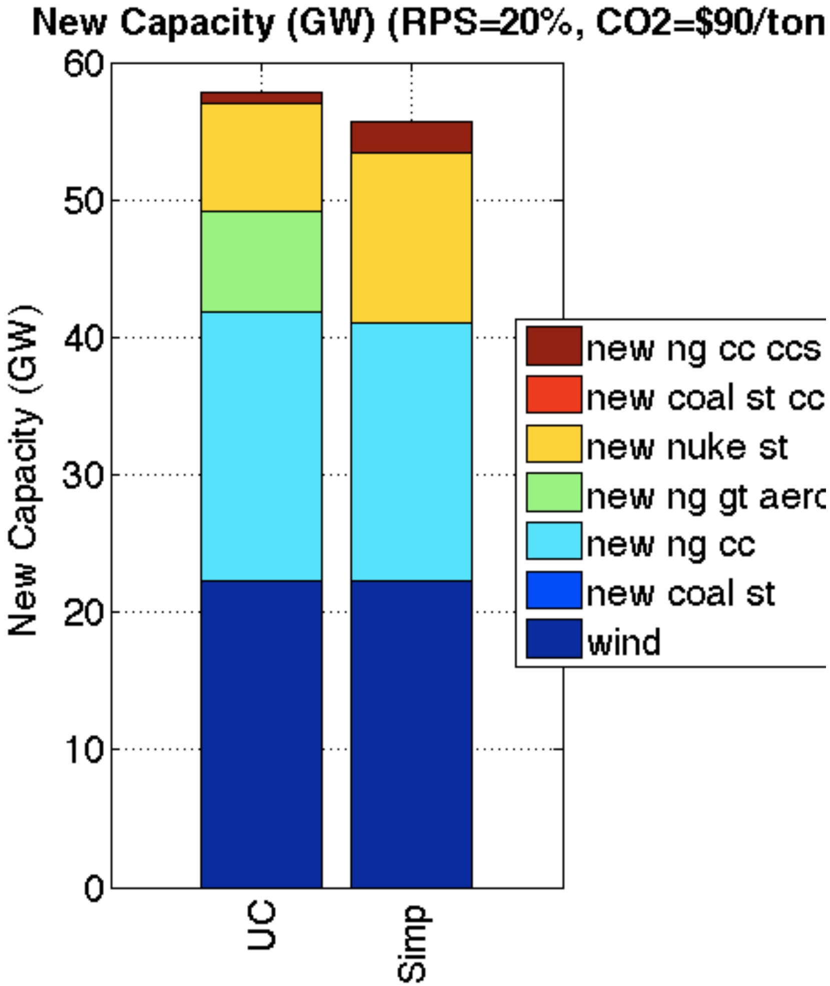
Long-Term Generation Planning with Operations Constraints

- Scenario assumed:
  - – 20% RPS
  - – $90/ton CO2
- Different Capacities
- UC: More Flexible NG-CT to balance Nukes



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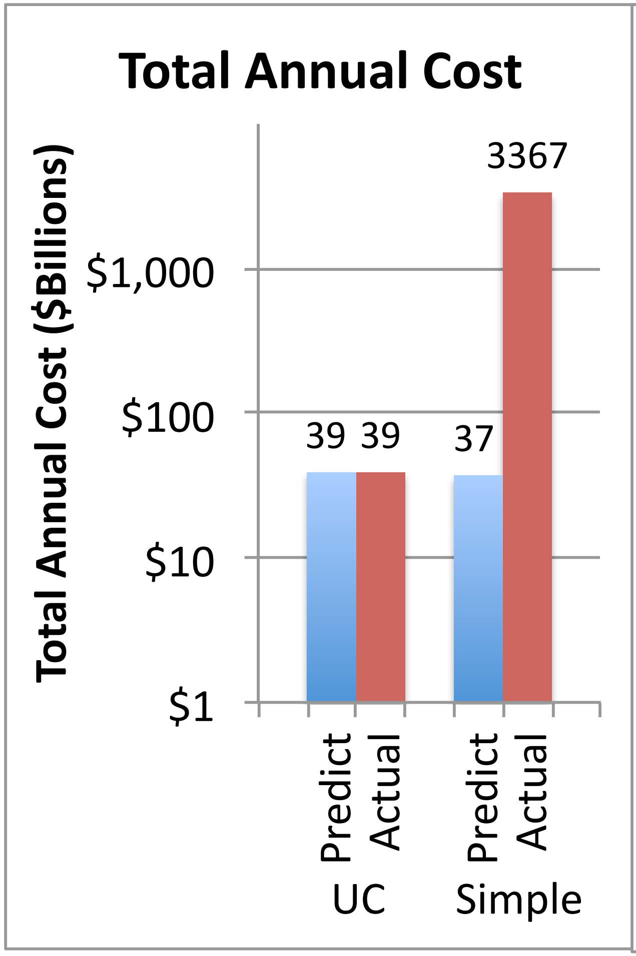
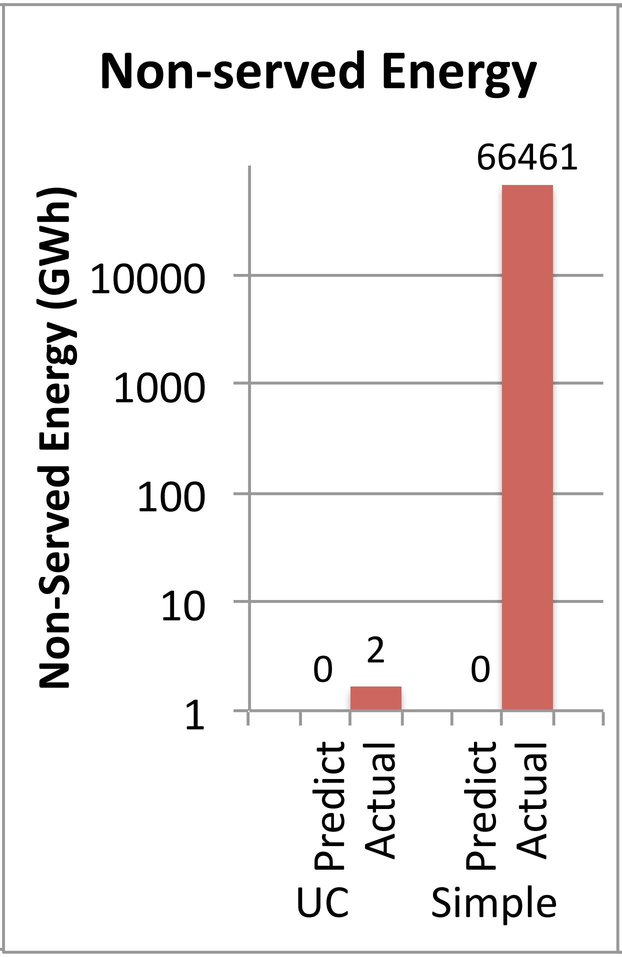
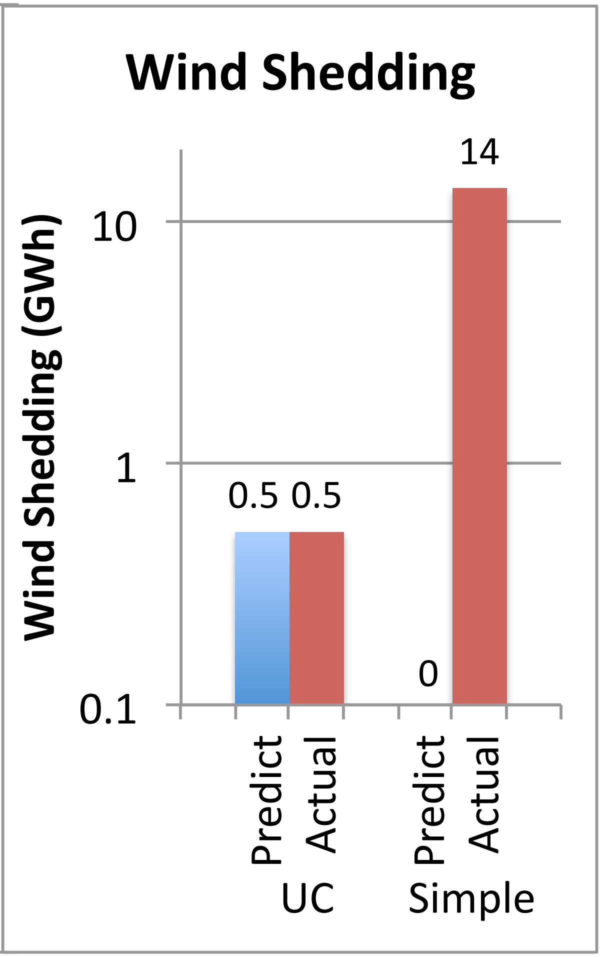
Long-Term Generation Planning with Operations Constraints


Total Annual Cost


Non-served Energy


Wind Shedding

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Deterministic Model

Structural Details

- Centralized, social planning model
- 50-year planning horizon, 5-year time steps
- Representative technologies and demand: U.S. system
- Objective

$$\min \sum_{t=1}^{t=5} NPV = \min \sum_{t=1}^{t=5} \delta_t (FixedCosts_t + VarCosts_t + RD\$_t)$$

- Decision Variables (per period)
  - **(1) R&D $ (by Technology)**
  - **(2) New Power Plants (by Technology)**
  - (3) Generation Operation
  - (4) Carbon Cap (per Period)
- Constraints
  - **(1) Cumulative carbon cap**
  - **(2) Cumulative R&D funding spending account**
  - (3) All traditional generation expansion constraints (e.g., demand balance, reliability, non-cycling nuclear technology, etc.

Generation Technologies

Old Conventional Coal
New Advanced Coal
*Coal with CCS**
Old Steam Gas
Gas Combined Cycle
Gas Combustion Turbines
Hydro
*Nuclear**
*Wind**
*Solar**

**Learning Technologies*

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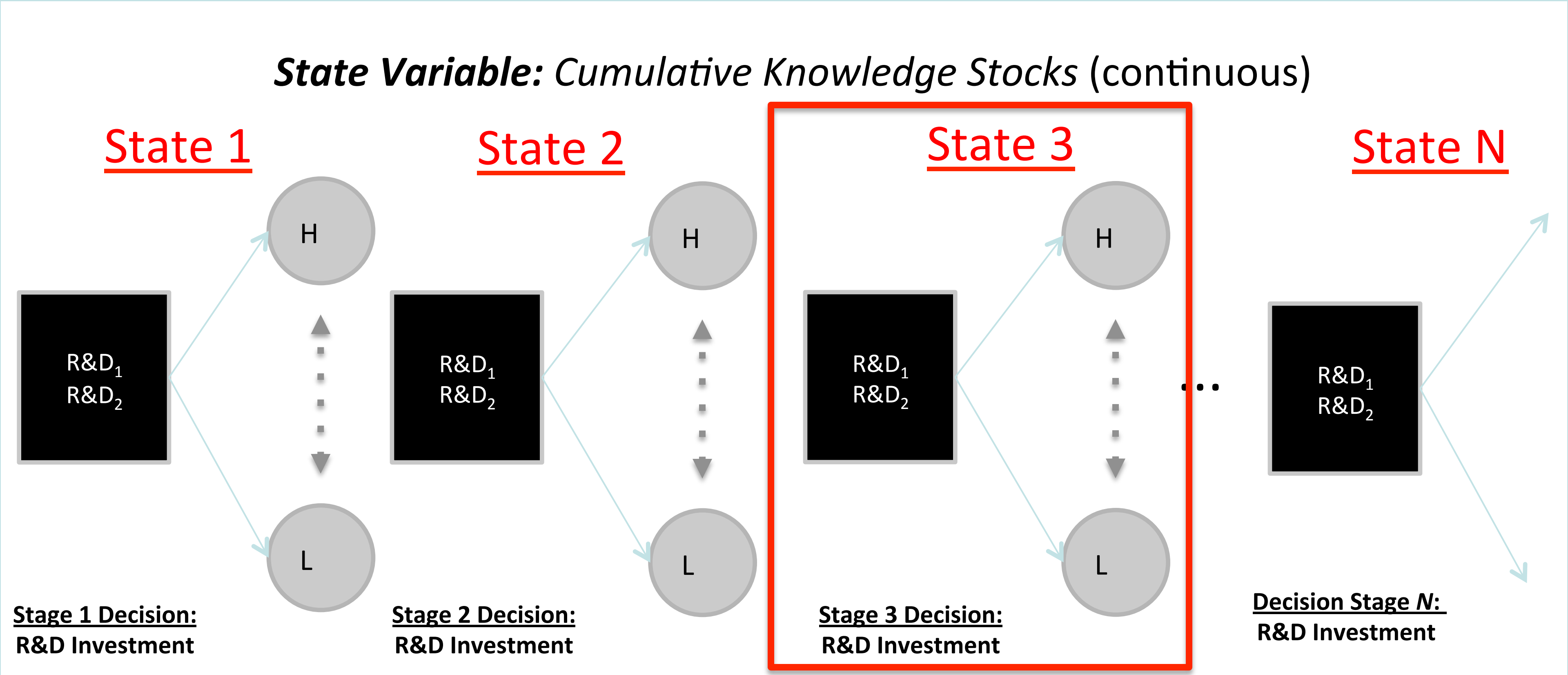
Stochastic Modeling Framework

***Decisions* R&D$_i$** *: R&D investments* (continuous)

Uncertainty: *R&D investment efficiencies* (continuous)



State Variable: *Cumulative Knowledge Stocks* (continuous)

State 1

State 2

State 3

State N

Stage 1 Decision:
R&D Investment

Stage 2 Decision:
R&D Investment

Stage 3 Decision:
R&D Investment

Decision Stage *N*:
R&D Investment

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Deterministic Results : Reference Case