The Cost of Regulatory Uncertainty in Air Emissions for a Coal-fired Power Plant

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Introduction

- Regulations on air emissions from coal-fired power plants will change
- Multiple types of uncertainty
  - Pollutants
  - timing
  - stringency
  - regulatory instruments
- Plant owners and operators must still make investment decisions

Motivation

A strategy that is optimal under one regulatory scenario will be very expensive under others

Therefore

Regulatory uncertainty can be expensive

Reducing or eliminating these uncertainties can have economic savings for the industry

How much?

Outline

- Other models
- Description of Method Proposed
  - Multiperiod Decision Model
  - Stochastic Optimization Model
- Illustration of the method through one example
- Policy Implications and Future Work

Other Approaches

- General equilibrium models of the U.S. economy
  - NEMS (Energy Information Administration - EIA)
  - AMIGA (Argonne National Lab)

- Bottom-up models
  - IPM (EPA)
  - T. Johnson (CMU)

All assume perfect foresight and forecast electric power sector decisions for a given set of environmental regulations.

Proposed Model

- Based on decision maker operating one coal-fired power unit
- Models sequential decisions
- Accounts for the uncertainty in future regulations
- Uncertainties evolve with time
- Decisions incorporate past investments and updated uncertainty
- Can be used to determine the inherent costs of different types of regulatory uncertainty

Proposed Model

- Considers a wide range of compliance options
  - Add-on control technologies or plant replacement
  - Allowances trading
    - Cap and Trade → Allowances bought and sold
    - If no regulations :
      Allocated allowances = 100% of plant emissions

Multi-period Decision Model (MPDM)

Year 1

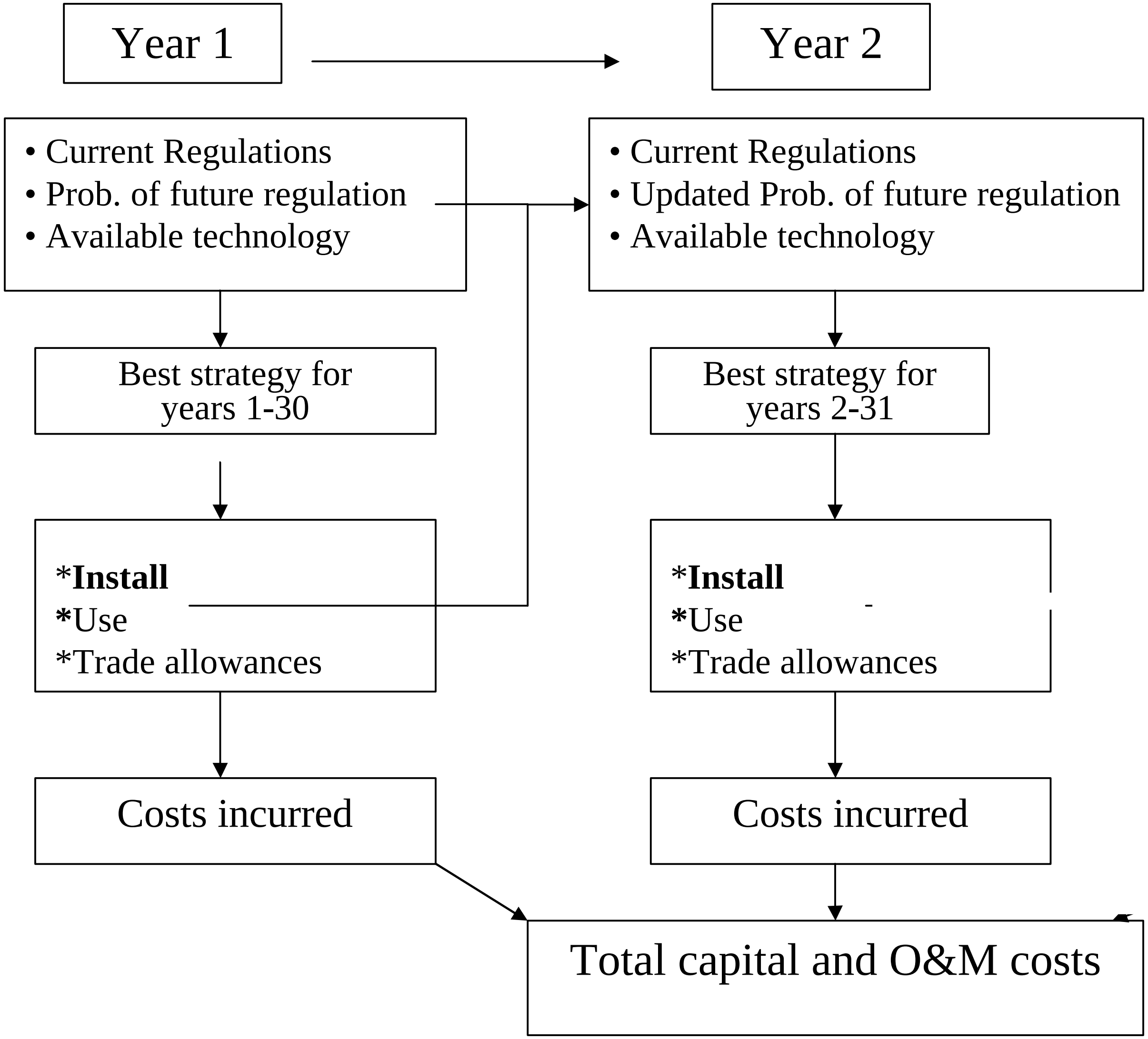
- Current Regulations
- Prob. of future regulation
- Available technology

Best strategy for
years 1-30

*__Install__
__*__Use
*Trade allowances

Costs incurred

Multi-period Decision Model (MPDM)



Year 1

Year 2

- Current Regulations
- Prob. of future regulation
- Available technology

- Current Regulations
- Updated Prob. of future regulation
- Available technology

Best strategy for years 1-30

Best strategy for years 2-31

*Install
*Use
*Trade allowances

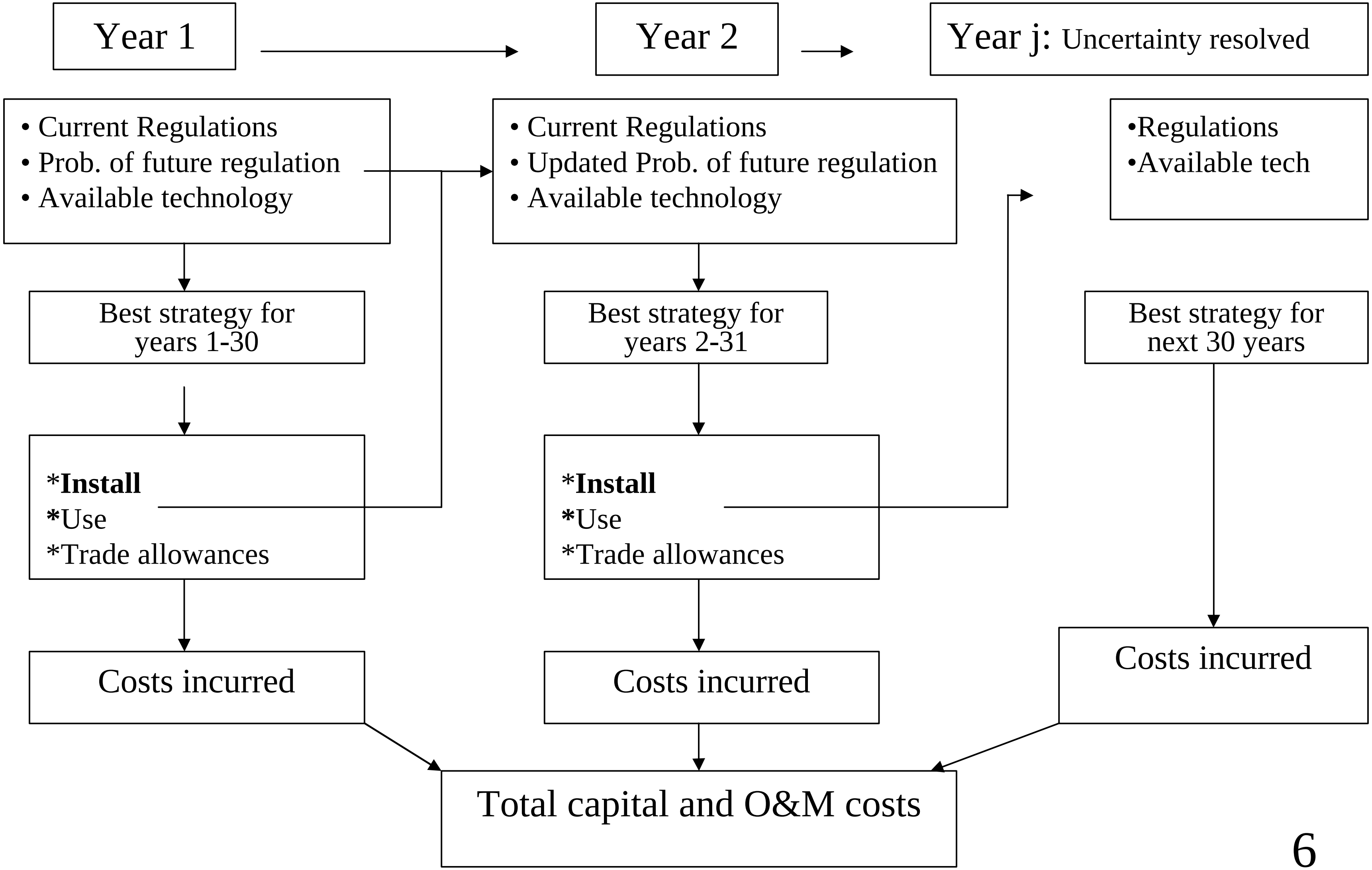
*Install
*Use
*Trade allowances

Costs incurred

Costs incurred

Total capital and O&M costs

Multi-period Decision Model (MPDM)



Year 1

Year 2

Year j: Uncertainty resolved

- Current Regulations
- Prob. of future regulation
- Available technology

- Current Regulations
- Updated Prob. of future regulation
- Available technology

•Regulations
•Available tech

Best strategy for years 1-30

Best strategy for years 2-31

Best strategy for next 30 years

*Install
*Use
*Trade allowances

*Install
*Use
*Trade allowances

Costs incurred

Costs incurred

Costs incurred

Total capital and O&M costs

Scenarios

- Are used to represent uncertainty
- “Bundle” of assumptions on future regulations and allowances market behavior for every year of the planning horizon
  - Policy Instrument
  - Emission Rates
  - The number of allocated allowances
  - Allowances prices

Example Scenario

Parameter	Pollutant	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012-2032
Policy Instrument	SO_2	Cap and Trade (Can buy and sell allowances)									
	NO_x					Cap and Trade (Can buy and sell allowances)					
	Hg							Cap and Trade (Can buy and sell allowances)			
	CO_2										
Maximum Emissions Rate Allowed	SO_2	Maximum emissions rate allowed > Current plant emissions rate									
	NO_x	Maximum emissions rate allowed > Current plant emissions rate									
	Hg	Maximum emissions rate allowed > Current plant emissions rate									
	CO_2	Maximum emissions rate allowed > Current plant emissions rate									
Allowance Prices	SO_2	$142	$149	$157	$166	$182	$245	$162	$173	$184	$196 - $331
	NO_x	-	-	-	-	$2,477	$2,558	$2,490	$2,497	$2,404	$2,510 - $2,648
	Hg	-	-	-	-	-	-	$207,198	$200,340	$193,710	$187,299 - $95,546
	CO_2	-	-	-	-	-	-	-	-	-	-
Allowances Allocated	SO_2	35% of current emissions				13% of current emissions					
	NO_x	100% of current emissions				40% of current emissions					
	Hg	100% of current emissions						40% of current emissions			
	CO_2	100% of current emissions									

Multiple Scenarios Are Possible

- Every scenario is assigned a probability
- Probabilities are subjective for each decision maker
- Probabilities evolve over time as new information about which scenarios are still possible is acquired
- All scenario uncertainty is eventually resolved
- Construction time is longer than allowed compliance time

Stochastic Optimization Model (SOM)

Finds the optimal investment, operating, and allowance trading strategy that

Minimizes the expected NPV of the cost to produce electricity over the planning horizon

$$E(NPV) = \Sigma E(NPV|Scenario)Prob(Scenario)$$

Subject to regulatory and operating constraints

SOM Inputs

- **Plant Characteristics**
  - Emissions
  - O&M
  - Controls already installed
    - Cost and Performance

- **Alternative Control Technologies**
  - Costs and performance of control technologies (IECM)

- **Scenarios**
  - Policy Instrument
  - Allowances allocated
  - Emissions rates allowed
  - Allowances Prices

- **Probabilities of each scenario**

SOM Decision Variables

- **Installation Variables**
  - Whether to install a particular technology
    - Binary variable. For every period, for every control
- **Operation Variables**
  - Whether to use an available technology
    - Binary variable. For every control, for every period, for every scenario
  - Number of allowances to buy and sell
    - Continuous variable. For every pollutant, for every period, for every scenario

Base Case

- **Power Plant:**
  - 500 MW, (85% capacity)
  - ESP, Low NO_x Burner
  - Allowances allocated annually cover 35% of plant's SO_2 current emissions. In compliance with NO_x requirements

Scenarios:	**(Abbreviation)**
– Business As Usual.	BAU
– In 2007: More stringent SO_2, NO_x. In 2009: Hg	2P+1
– In 2007: More stringent SO_2, NO_x, and Hg	3P
– In 2007: More stringent SO_2, NO_x and Hg. In 2009 CO_2	3P+1
– In 2011: More stringent SO_2, NO_x, Hg and CO_2.	4P

- **Control Technologies:**
  - Add-on controls and Plant Retirement

- **Lead time:**
  - Time between the announcement of the program and the compliance date = 1 year
  - Time for constructing any of the control technologies considered = 2 years

Scenarios

Scenario Name		BAU
Probability		0.05
Number of phases		1
Year of implementation		2003
SO_2	Reduction in allowances allocated	-
	Max Emissions Rate (lb/mbtu)	
	Policy Instrument	Trade
	Price	\$142 - \$331
NO_x	Reduction in allowances allocated	-
	Max Emissions Rate (lb/mbtu)	
	Policy Instrument	
	Price	-
Hg	Reduction in allowances allocated	-
	Max Emissions Rate (lb/mbtu)	-
	Policy Instrument	-
	Price	-
CO_2	Reduction in allowances allocated	-
	Max Emissions Rate (lb/kWh)	-
	Policy Instrument	-
	Price	-

Scenarios

Scenario Name		BAU	3P+1	
Probability		0.05	0.2	
Number of phases		1	2	
Year of implementation		2003	2007	2009
SO_2	Reduction in allowances allocated	-	63%	63%
	Max Emissions Rate (lb/mbtu)			
	Policy Instrument	Trade	Trade	Trade
	Price	$142 - $331	$143	$134 - $6
NO_x	Reduction in allowances allocated	-	60%	60%
	Max Emissions Rate (lb/mbtu)			
	Policy Instrument		Trade	Trade
	Price	-	$2,477	$2,490-$118
Hg	Reduction in allowances allocated	-	60%	60%
	Max Emissions Rate (lb/mbtu)	-		
	Policy Instrument	-	Trade	Trade
	Price	-	$221,624	$207,198
CO_2	Reduction in allowances allocated	-	-	60%
	Max Emissions Rate (lb/kWh)	-		
	Policy Instrument	-	-	Trade
	Price	-	-	$25 - $140

Control Technologies

- **Add-on Control Technologies**
  - SO_2: Wet Flue Gas Desulfurization (WFGD)
  - NO_x: Hot Side Selective Catalytic Reduction (SCR)
  - Hg: Carbon Injection
  - CO_2: Carbon Capture and Sequestration (CCS) Amine System
- **New Plant**
  - New Coal Fired Power Plant with all the environmental controls
  - Integrated Coal Gasification Combined Cycle Plant (IGCC) + SCR
  - IGCC + SCR + CCS via Selexol Process
  - Natural Gas Combined Cycle Power Plant (NGCC) + Dry SCR
  - NGCC + SCR + CCS

Evolution of Scenario Probabilities

If BAU	Year							
	2003	2004	2005	2006	2007	2008	2009	2010
Probabilities of scenario BAU	0.05	0.05	0.05	0.33	0.33	0.33	0.33	1
Probabilities of scenario 2P+1	0.15	0.15	0.15	-	-	-	-	-
Probabilities of scenario 3P	0.20	0.20	0.20	-	-	-	-	-
Probabilities of scenario 3P+1	0.5	0.5	0.5	-	-	-	-	-
Probabilities of scenario 4P	0.1	0.1	0.1	0.66	0.66	0.66	0.66	-

Evolution of Scenario Probabilities

If BAU	Year							
	2003	2004	2005	2006	2007	2008	2009	2010
Probabilities of scenario BAU	0.05	0.05	0.05	0.33	0.33	0.33	0.33	1
Probabilities of scenario 2P+1	0.15	0.15	0.15	-	-	-	-	-
Probabilities of scenario 3P	0.20	0.20	0.20	-	-	-	-	-
Probabilities of scenario 3P+1	0.5	0.5	0.5	-	-	-	-	-
Probabilities of scenario 4P	0.1	0.1	0.1	0.66	0.66	0.66	0.66	-

If 3P+1	Year							
	2003	2004	2005	2006	2007	2008	2009	2010
Probabilities of scenario BAU	0.05	0.05	0.05	-	-	-	-	-
Probabilities of scenario 2P+1	0.15	0.15	0.15	-	-	-	-	-
Probabilities of scenario 3P	0.20	0.20	0.20	0.29	0.29	-	-	-
Probabilities of scenario 3P+1	0.5	0.5	0.5	0.71	0.71	1	1	1
Probabilities of scenario 4P	0.1	0.1	0.1	-	-	-	-	-

MPDM Runs

Determine optimal strategy given

- No uncertainty: Only one scenario is possible
  - $\mathbf{d}^*(\boldsymbol{s})$ = optimal strategy when scenario s is known to occur by decision maker in first period
- Uncertainty: Multiple scenarios are possible
  - a_s = Initial subjective probability of scenario s
  - $\mathbf{d}^*(a,\boldsymbol{s})$ = optimal strategy when scenario s happens but the decision maker does not know this and has to make decisions based on a set of probabilities α

$d^*(s)$: Optimal deterministic strategies

Run	$d^*(BAU)$		$d^*(3P+1)$	
	Scenario 1 (BAU)		**Scenario 4 (3P+1a)**	
	Install	**Operate**	**Install**	**Operate**
2003	-	Coal	-	Coal
2004	-	Coal	-	Coal
2005	-	Coal	NGCC/SCR	Coal
2006	-	Coal	-	Coal
2007	-	Coal	-	NGCC/SCR
2008	-	Coal	-	NGCC/SCR
2009	-	Coal	-	NGCC/SCR
2010	-	Coal	-	NGCC/SCR
2011	-	Coal	-	NGCC/SCR
2012	-	Coal	-	NGCC/SCR
2013	-	Coal	-	NGCC/SCR
2014	-	Coal	-	NGCC/SCR
2015	-	Coal	Coal/FGD/CCS	NGCC/SCR
2016	-	Coal	-	NGCC/SCR
2017	-	Coal	-	Coal/FGD/CCS
2018	-	Coal	-	Coal/FGD/CCS
2019	-	Coal	-	Coal/FGD/CCS
2020	-	Coal	-	Coal/FGD/CCS
...	...	...	...	...
2032	-	Coal	-	Coal/FGD/CCS

NPV($d^*(s)$)

Model Run	$d^*(BAU)$	$d^*(3P+1)$
NPV(Capital)	-	313
NPV(O&M)	567	833
NPV(SO2 Allowances)	89	17
NPV(NOx Allowances)	-	-23
NPV(Hg Allowances)	-	-101
NPV(CO2 Allowances)	-	-307
Total NPV (2000 M$)	656	732

$d^*(a,s)$: Optimal strategies under uncertainty

Run	$d^*(a,BAU)$		$d^*(a,3P+1)$	
	Scenario 1 (BAU)		**Scenario 4 (3P+1a)**	
	Installation	**Operation**	**Installation**	**Operation**
2003	-	Coal	-	Coal
2004	-	Coal	-	Coal
2005	NGCC/SCR	Coal	NGCC/SCR	Coal
2006	-	Coal	-	Coal
2007	-	Coal	-	NGCC / SCR
2008	-	Coal	-	
2009	-	Coal	-	
2010	-	Coal	-	
2011	-	Coal	-	
2012	-	Coal	-	
2013	-	Coal	-	
2014	-	Coal	-	
2015	-	Coal	FGD/CCS-Coal	
2016	-	Coal	-	
2017	-	Coal	-	Coal/FGD/CCS
2018	-	Coal	-	
2019	-	Coal	-	
2020	-	Coal	-	
2021	-	Coal	-	
2022-2032	-	Coal	-	

NPV(d^*(a,*s*))

Model Run	$d^*(a,BAU)$	$d^*(a,3P+1)$
NPV(Capital)	212	313
NPV(O&M)	567	833
NPV(SO2 Allowances)	89	17
NPV(NOx Allowances)	-	-23
NPV(Hg Allowances)	-	-101
NPV(CO2 Allowances)	-	-307
Total NPV (2000 M$)	868	732

Expected value of perfect information

$$EVPI(a) = \sum_{s \text{ in } scenarios} a_s \left(NPV\left(d^*(a,s)\right) - NPV\left(d^*(s)\right) \right)$$

Scenario *S*	1 BAU	2 2P+1	3 3P	4 3P+1	5 4P
$NPV[d^*(a,s)]-NPV[d^*(s)]$	212	79	30	0	130
Initial probabilities	0.05	0.15	0.20	0.5	0.10
EVPI (in year 2000 $M)	41				

Sensitivity Cases

- Changes in the initial probabilities
- Introduction of scenarios with more stringent CO_2 cap
- Changes in fuel price

Policy Implications

- Cost of uncertainty can be significant
  - EVPI for base case analysis $40 million
  - $16 Billion if 400 similar generating units

- Uncertainty costs can be small if the solution set is small
  - If there is a narrow set of possible regulations and solutions are obvious

- Changes in scenarios can have major impact on the optimal strategies.

Future Work

Expand analysis changing assumptions about:

- **Plant characteristics:** location, life span, efficiency, costs/feasibility of new technologies
- **Regulations:** Allowing banking, more scenarios, different policy instruments
- **Market:** Uncertainty on allowance prices
- **Decision process:** Different decision rule, (consider the option to wait), dispatching decisions, different criteria to update probabilities

d*(*s*): Optimal deterministic strategies

Run	*$d^*(1)$*		*$d^*(2)$*		*$d^*(3)$*		*$d^*(4)$*		*$d^*(5)$*	
	Scenario 1 (BAU)		**Scenario 2 (2P+1)**		**Scenario 3 (3P)**		**Scenario 4 (3P+1a)**		**Scenario 5 (4P)**	
	Install	**Operate**	**Install**	**Operate**	**Install**	**Operate**	**Install**	**Operate**	**Install**	**Operate**
2003	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2004	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2005	-	Coal	SCR	Coal	SCR/CI	Coal	NGCC/SCR	Coal	-	Coal
2006	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2007	-	Coal	CI	SCR	-	SCR/CI	-	NGCC/SCR	-	Coal
2008	-	Coal	-	SCR	-	SCR/CI	-	NGCC/SCR	-	Coal
2009	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	FGD/SCR/CCS	Coal
2010	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	FGD/SCR/CCS	Coal
2011	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	-	FGD/SCR/CCS
2012	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	-	FGD/SCR/CCS
2013	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	-	FGD/SCR/CCS
2014	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	-	FGD/SCR/CCS
2015	-	Coal	-	SCR/CI	-	SCR/CI	Coal/FGD/CCS	NGCC/SCR	-	FGD/SCR/CCS
2016	-	Coal	-	SCR/CI	-	SCR/CI	-	NGCC/SCR	-	FGD/SCR/CCS
2017	-	Coal	-	SCR/CI	-	SCR/CI	-	Coal/FGD/CCS	-	FGD/SCR/CCS
2018	-	Coal	-	SCR/CI	-	SCR/CI	-	Coal/FGD/CCS	-	FGD/SCR/CCS
2019	-	Coal	-	SCR/CI	-	SCR/CI	-	Coal/FGD/CCS	-	FGD/SCR/CCS
2020	-	Coal	-	SCR/CI	-	SCR/CI	-	Coal/FGD/CCS	-	FGD/SCR/CCS
...	...	...	...	...	...	...	...	...	...	FGD/SCR/CCS
2032	-	Coal	-	SCR/CI	-	SCR/CI	-	Coal/FGD/CCS	-	FGD/SCR/CCS

$d^*(a,s)$: Optimal strategies under uncertainty

Run	$d^*(a,1)$		$d^*(a,2)$		$d^*(a,3)$		$d^*(a,4)$		$d^*(a,5)$	
	Scenario 1 (BAU)		**Scenario 2 (2P+1)**		**Scenario 3 (3P)**		**Scenario 4 (3P+1a)**		**Scenario (4P)**	
	Installation	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**
2003	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2004	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2005	NGCC/SCR	Coal	NGCC/SCR	Coal	NGCC/SCR	Coal	NGCC/SCR	Coal	NGCC/SCR	Coal
2006	-	Coal	-	Coal	-	Coal	-	Coal	-	Coal
2007	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	Coal
2008	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	Coal
2009	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	Coal
2010	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	Coal
2011	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2012	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2013	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2014	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2015	-	Coal	-	NGCC/SCR	-	NGCC/SCR	FGD/CCS-Coal	NGCC/SCR	-	NGCC/SCR
2016	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR	FGD/CCS-Coal	NGCC/SCR
2017	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	NGCC/SCR
2018	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2019	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2020	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2021	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2022	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2023	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2024	-	Coal	SCR/CI-Coal	NGCC/SCR	SCR/CI-Coal	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2025	-	Coal	-	NGCC/SCR	-	NGCC/SCR	-	Coal/FGD/CCS	-	Coal/FGD/CCS
2026	-	Coal	-	Coal/SCR/CI	-	Coal/SCR/CI	-	Coal/FGD/CCS	-	Coal/FGD/CCS
...	...	...	...	...	...	...	...	...	...	...
2032	-	Coal	-	Coal/SCR/CI	-	Coal/SCR/CI	-	Coal/FGD/CCS	-	Coal/FGD/CCS

Deterministic strategy for scenario 3P+1 with stringent CO2 cap

Run	$d^*(6)$	
	Scenario 6 (3P+1b)	
	Installation	**Operation**
2003	-	Coal
2004	-	Coal
2005	CI	Coal
2006	-	Coal
2007	New Coal Plant+ALL	CI
2008	-	CI
2009	-	New Coal + ALL
2010	-	New Coal + ALL
2024	-	New Coal + ALL
2025	-	New Coal + ALL
…	…	…
2032	-	New Coal + ALL

$d^*(l, s)$: Optimal strategies under uncertainty

Run	$d^*(l,2)$		$d^*(l,3)$		$d^*(l,6)$	
	Scenario 2 (2P+1)		**Scenario 3 (3P)**		**Scenario 6 (3P+1b)**	
	Installation	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**
2003	-	Coal	-	Coal	-	Coal
2004	-	Coal	-	Coal	-	Coal
2005	SCR/CI	Coal	SCR/CI	Coal	SCR/CI	Coal
2006	-	Coal	-	Coal	-	Coal
2007	-	Coal/SCR	-	Coal/SCR/CI	FGD/CCS	SCR/CI
2008	-	Coal/SCR	-	Coal/SCR/CI	-	SCR/CI
2009	-	Coal/SCR/CI	-	Coal/SCR/CI	-	SCR/CI/FGD/CCS
…	-	…	-	…	…	…
2032	-	Coal/SCR/CI	-	Coal/SCR/CI	-	SCR/CI/FGD/CCS

$d^*(s)$: Optimal deterministic strategies
Sensitivity Case – Fuel Prices

	$d^*(7)$		$d^*(8)$		$d^*(9)$	
	Scenario 7 (2P+1c)		**Scenario 8 (3Pc)**		**Scenario 9 (3P+1c)**	
	Installation	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**
2003	-	Coal	-	Coal	-	Coal
2004	-	Coal	-	Coal	-	Coal
2005	-	Coal	NGCC/SCR	Coal	NGCC/SCR	Coal
2006	-	Coal	-	Coal	-	Coal
2007	NGCC/SCR	Coal	-	NGCC/SCR	-	NGCC/SCR
2008	-	Coal	-	NGCC/SCR	-	NGCC/SCR
2009	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2010	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2011	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2012	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2013	-	NGCC/SCR	-	NGCC/SCR	CCS	NGCC/SCR
2014	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2015	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS
2016	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS
...	...	...	...	...	...	...
2032	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS

$d^*(l, s)$: Optimal strategies under uncertainty

Model Run	$d^*(w,7)$		$d^*(w,8)$		$d^*(w,9)$	
	Scenario 7 (2P+1c)		**Scenario 8 (3Pc)**		**Scenario 9 (3P+1c)**	
	Installation	**Operation**	**Installation**	**Operation**	**Installation**	**Operation**
2003	-	Coal	-	Coal	-	Coal
2004	-	Coal	-	Coal	-	Coal
2005	NGCC/SCR	Coal	NGCC/SCR	Coal	NGCC/SCR	Coal
2006	-	Coal	-	Coal	-	Coal
2007	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2008	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2009	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2010	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2011	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2012	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2013	-	NGCC/SCR	-	NGCC/SCR	CCS	NGCC/SCR
2014	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR
2015	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS
2025	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS
...	-	...	...	...	...	...
2032	-	NGCC/SCR	-	NGCC/SCR	-	NGCC/SCR/CCS

Lead Time Assumption

When a regulation is announced there is not enough time to take actions to reduce emissions without incurring in substantially higher costs

Costs are due to;

-High allowance prices the first years of the regulation

-Fines

-Expensive installation costs (high demand of control technologies)

-Extended outages – not coordinated.

Policy Instruments

- No cost allowance allocated with cap and trade (CAT)
- Allowance auction with cap and trade (ACAT)
- Maximum achievable control technology standards (MACT)
- Dynamic Generation Performance Standard (GPS) Recalculated every year based on plant output MW-hr

CAT System
Such as that used in the CAAA90 SO_2

Advantage: compliance is achieved at the lowest minimum cost. Given a well functioning market those with the lowest cost emission reduction opportunities would sell unused allowances they received to others whose reduction opportunities were more costly

Concerns:

-Existing units are granted allowances perpetually

-New Units must acquire the allowances they need

-No reward for efficiency if allocation based on historical amount of fuel consumed.

Emissions from coal plants in U.S. (Tons)

SO_2	8,950,000
NO_x	5,000,000
Hg	50
CO_2	1.2E+09

CAAA90

- Required operators of electric power plants to reduce emissions of SO_2 and NO_x
- Phase II of SO_2 program begun on January 1, 2000
- More stringent NO_x emissions reductions are required under various Federal and State laws (From 1997 to 2004 summer season cap)
- Additional reductions may be required because:
  - Reduce regional haze and improve visibility
  - Reduce ground-level ozone
  - Reduce fine particulates PM (2.5 microns diameter)

Hg

- Emissions affected by:
  - Hg content in coal
  - Chlorine content
  - Boiler temperature
  - Firing type – Plant configuration
  - Flue gas temperature
- Switch to low Hg coal
- Most promising emission control is Activated Carbon Injection
  - Has been proven in municipal waste combustors
  - Mercury is adsorbed onto the sorbent and is then removed along with the fly ash in the fabric filter or electrostatic precipitator ESP.
  - Wet scrubbers remove oxidized mercury but not elemental (Converting elemental Hg to an oxidized state helps)
- Substantial uncertainty on performance and costs of emissions control. Data comes from smaller scale tests
- Marginal cost of injecting activated carbon to remove Hg increases as the quantity to be removed grows. Costs can be reduced by recycling the carbon
- Some date suggests that SCR system with a Wet FGD system can eliminate the need to inject activated carbon.

Hg exposure

- Hg is carried by winds and deposited in land and water
- Once enters water biological processes transform it in methylmercury a highly toxic form that bioacumulates in fish
- People are exposed to Hg primarily through eating fish
- The developing fetus is the most sensitive to mercury effects that include damage to nervous system development (delayed onset on walking and talking..)
- Hg can cause tremors, inability to walk, convulsions and death. Damage to senses and brain

Models

- “top-down” models:
  - Treat power plants as aggregates of representative facilities
  - Less technological detail
  - Incorporate interactions and economic impacts
- “bottom-up” models:
  - Plant-level models

NOx

- Formation of ozone
- Acid deposition
- Eutophication of water bodies
- Inhalable fine particulates
- Visibility degradation

Multipollutant Regulations

- Emission caps in the four pollutants → complex interactions among the compliance strategies and the resulting allowance prices and electricity prices
- Example: A hg cap raises the cost of operating coal plants. If less coal plants are operated, then less CO2 is emitted and the CO2 allowances are lower. This reduces costs of power suppliers and lowers electricity prices. But, increasing natural gas use could increase gas prices and increase electricity prices. If there is a RPS, then probably gas prices would not rise so much.

Allowance prices

- CO2 cap lead to a much lower allowance prices for NOx, SO2 and Hg because the reduction in coal use lessens the need for emissions controls
- Hg cap leads to lower SO2 allowance prices because Scrubbers remove up to 70% of Hg

Natural Gas Plants

- Natural gas: 85% Methane + ethane, propane, butane and inerts (nitrogen, carbon dioxide, helium)
- Emissions: NOx, CO (carbon monoxide), CO2, Methane (CH4) and PM(low)
- To control NOx: FGR, Low NOx burners, SNCR and SCR(Injects NH3 in the presence of a catalyst)
- Less carbon intensive than coal, but its production and cleaning result in CO2 releases

CO_2 controls

- Conservation
- Removal of CO_2 enhancing terrestrial uptake in biomass
- Renewables (Wind, Solar,)
- CCS
  - Technical uncertainties
  - Political and legal uncertainties

CCS

Capture:

-Separation of the gas via the use of solvents such as monoethanolamine. MEA.

*Energy penalty as high as 25%

*Exhaust stream contains impurities

-Combustion in pure oxygen

*High Energy requirement

*Flame temperature higher than the tolerated by existing generating equipment

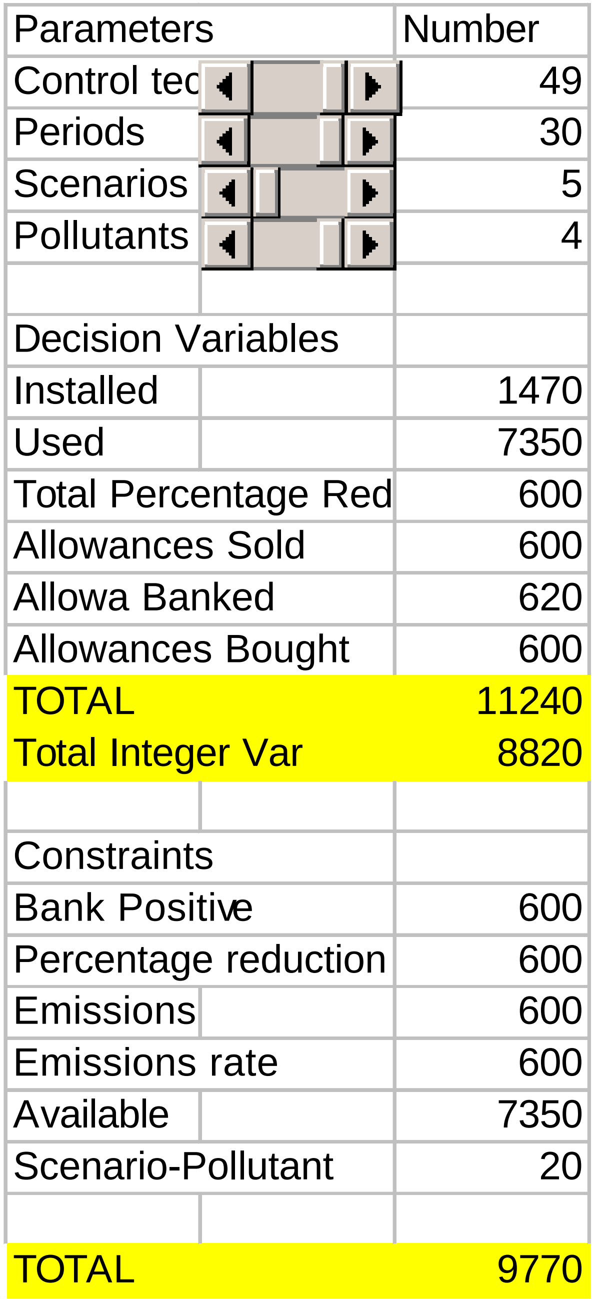
-Pre-combustions decarbonization. Steam reforming to produce syngas (Hydrogen and CO)

Sequestration

– Underground injection is not new (fluids like waste water. And gases for oil recovery)

– Sequestration in ocean waters, as dry ice or in pools. Terrestrial seq in geological formations: saline aquifers, depleted oil and gas reservoirs, sub-seabed reservoirs

– Uncertainty. Costs? How large are the potential reservoirs for CO2 sequestration?



Parameters	Number
Control tec	49
Periods	30
Scenarios	5
Pollutants	4
Decision Variables	
Installed	1470
Used	7350
Total Percentage Red	600
Allowances Sold	600
Allowa Banked	620
Allowances Bought	600
TOTAL	11240
Total Integer Var	8820
Constraints	
Bank Positive	600
Percentage reduction	600
Emissions	600
Emissions rate	600
Available	7350
Scenario-Pollutant	20
TOTAL	9770

Minimize

$$\sum_{c}\sum_{t}(1+r)^{-t} I_{c,t} CC_{c,t} + \sum_{s} p_{s} \sum_{t}(1+r)^{-t}\left[\sum_{c} U_{s,c,t} OM_{c,t} + \sum_{p} AP_{s,p,t}(AB_{s,p,t} - AS_{s,p,t})\right]$$

$$AA_{s,p,t} + AB_{s,p,t} - AS_{s,p,t} - \sum_{c} U_{s,c,t}\left(1 - EPR_{c,p,t}\right) IE_{p} \geq 0 \;\forall\; s,p,t$$

$$IER_{p} \sum_{c} U_{s,c,t}\left(1 - EPR_{c,t}\right) \leq MER_{s,p,t} \;\forall\; s,p,t$$

$$U_{s,c,1} \leq AC_{c} \;\forall\; s,c$$

$$U_{s,c,2} \leq AC1_{c} + AC2_{c} \;\forall\; s,c$$

$$U_{s,c,t} \leq AC1_{c} + AC2_{c} + AC3_{c} + I_{c,t-2} \;\forall\; s,c \;\forall\; t \geq 3$$

$$\sum_{c} U_{s,c,t} = 1 \;\forall\; s$$

$$If \quad T_{s,p,t} = 0 \Rightarrow AB_{s,p,t} = 0 \;\forall\; s,p,t$$

$$If \quad T_{s,p,t} = 0 \Rightarrow AS_{s,p,t} = 0 \;\forall\; s,p,t$$

$$AB_{s,p,t} \geq 0$$

$$AS_{s,p,t} \geq 0$$

$$U_{s,c,t} \in \{0,1\}$$

$$I_{c,t} \in \{0,1\}$$