R&D Investment Strategy for Low-Carbon Energy Technologies

Haewon McJeon and Leon Clarke

Aug. 1, 2012

Snowmass

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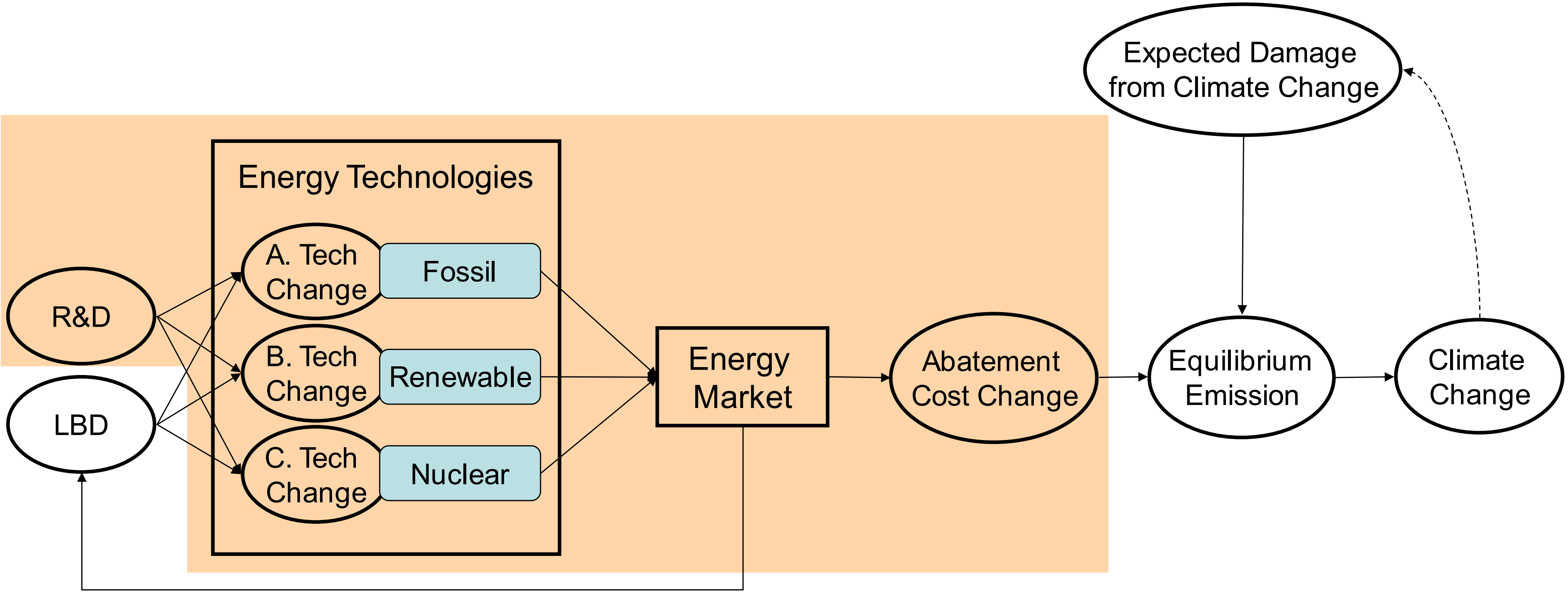
Agenda

- Introduction and Background
- Data
  - Probabilities of Success
  - Stabilization Costs
- Simple model: Single-Period Allocation
- Stochastic Dynamic Programming Model
- Synthesis and Discussion

Technological Change and Climate Change



Question:
What is the best way to develop energy technology to minimize the cost of climate change mitigation?

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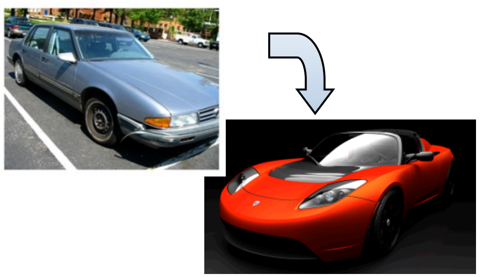
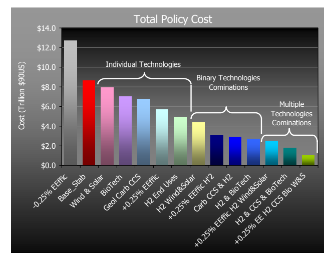
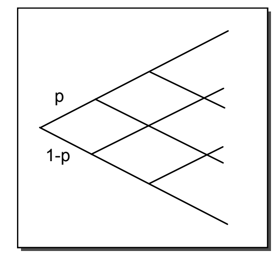
The Normative R&D Strategy Challenge

Issues and Tools

How can we better inform R&D strategy:
(1) how much effort is appropriate?
(2) how should it be allocated?







ISSUES	Potential for Advance, R&D Impact on Advance	Value of Technology	R&D Allocation Under Uncertainty
TOOLS	Technology Assessments Historical Analysis	Integrated Assessment Models	Portfolio Models, Decision Analysis

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Probabilities of Success
E. Baker, H. Chon, and J. Keisler. 2006-Present.

Climatic Change (2009) 96:379–408
DOI 10.1007/s10584-009-9634-y

Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy

Erin Baker · Haewon Chon · Jeffrey Keisler

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy

Erin Baker [a,*], Haewon Chon [b], Jeffrey Keisler [c]

[a] 220 Elab, University of Massachusetts, Amherst, MA 01003, United States
[b] Joint Global Change Research Institute, University of Maryland, 8400 Baltimore Avenue, Suite 201, College Park, MD 20740, United States
[c] College of Management, University of Massachusetts, Boston, MA 02125, United States

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Technological Forecasting & Social Change

Battery technology for electric and hybrid vehicles: Expert views about prospects for advancement

Erin Baker [a,*], Haewon Chon [b], Jeffrey Keisler [c]

[a] 220 Elab, University of Massachusetts, Amherst, MA 01003, USA
[b] Joint Global Change Research Institute, 5825 University Research Court, Suite 3500 College Park, MD 20740, USA
[c] College of Management, University of Massachusetts, Boston, MA 02125, USA

Climatic Change (2009) 96:379–408
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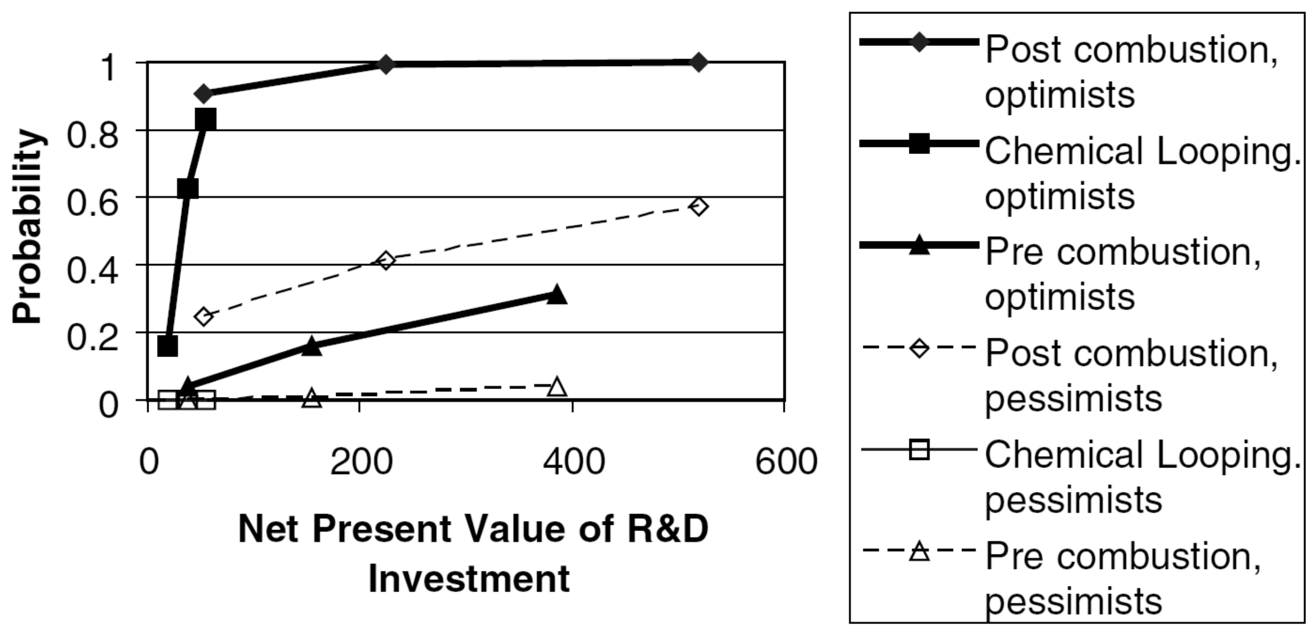
Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy

Erin Baker · Haewon Chon · Jeffrey Keisler

	Parasitic Energy Loss (%)	Non Energy Cost (2005$/tC)	Capture Rate (%)
Post-Combustion	23	30	90
Pre-Combustion	10	24	90
Chemical Looping	3	11	90
SCWO	3	10	100



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Technology	Definition of success	Cost (2005¢/kWh)	NPV of Investment	Prob. Of Success
1a. Organic	15%, 30 year, $50/m^2	5.0	120	13%
1b. Organic	31%, 15 year, $50/m^2	3.0	860	4%
2a. Inorganic	15%, 30 year, $50/m^2	5.0	40	17%
2b. Inorganic	15%, 30 year, $50/m^2	5.0	80	43%
3. CIGS	15%, 30 year, $50/m^2	5.0	80	2%
4. 3rd Gen	37%, 30 year, $100/m^2	2.9	401	2%

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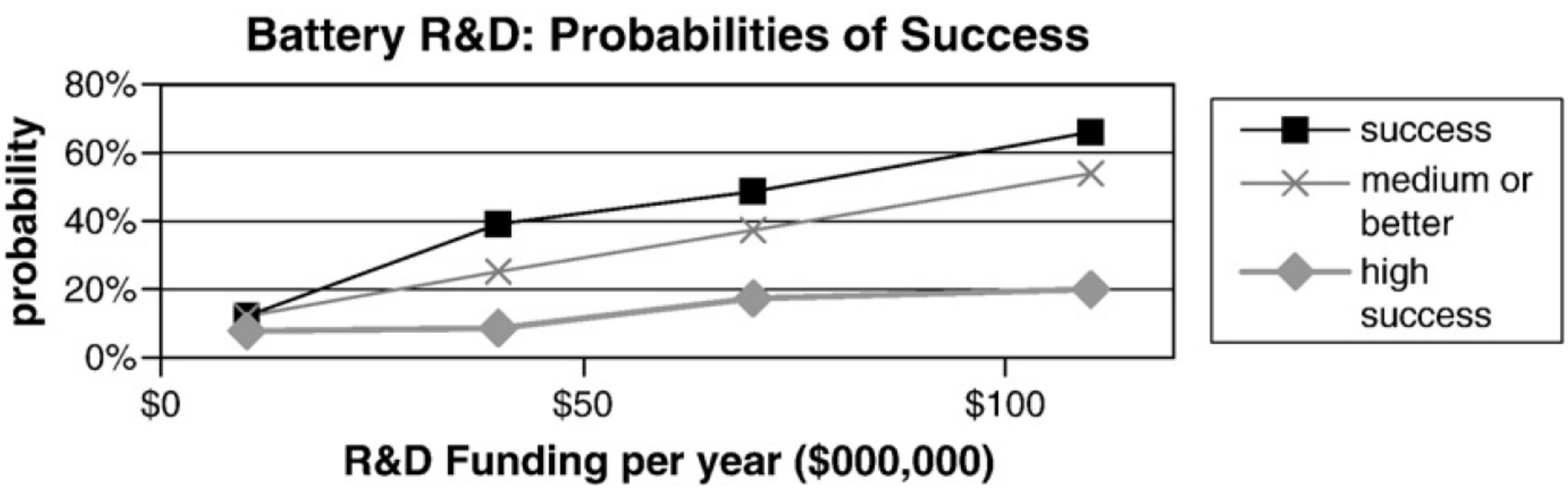
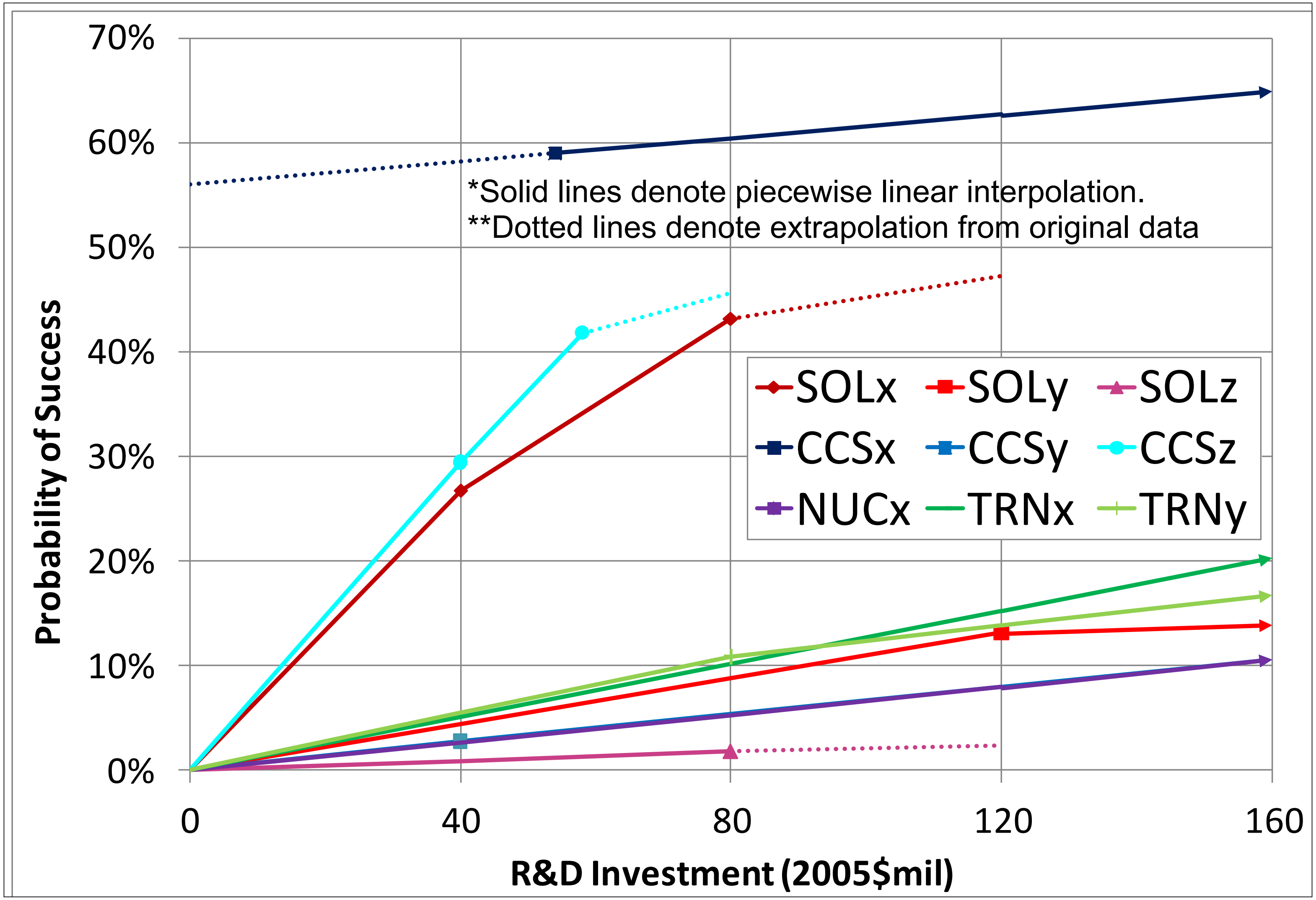
	Li-ion high endpoint	Li-ion low endpoint	Li Metal high endpoint	Li Metal low endpoint
Specific energy	200 Wh/kg	150 Wh/kg	600 Wh/kg	200 Wh/kg
Power density	600 W/L	460 W/L	600 W/L	460 W/L
Lifetime	10 years	8 years	10 years	8 years
Recharge rate	3 h	6 h	3 h	6 h
Capital cost	$125/kWh	$200/kWh	$90/kWh	$135/kWh



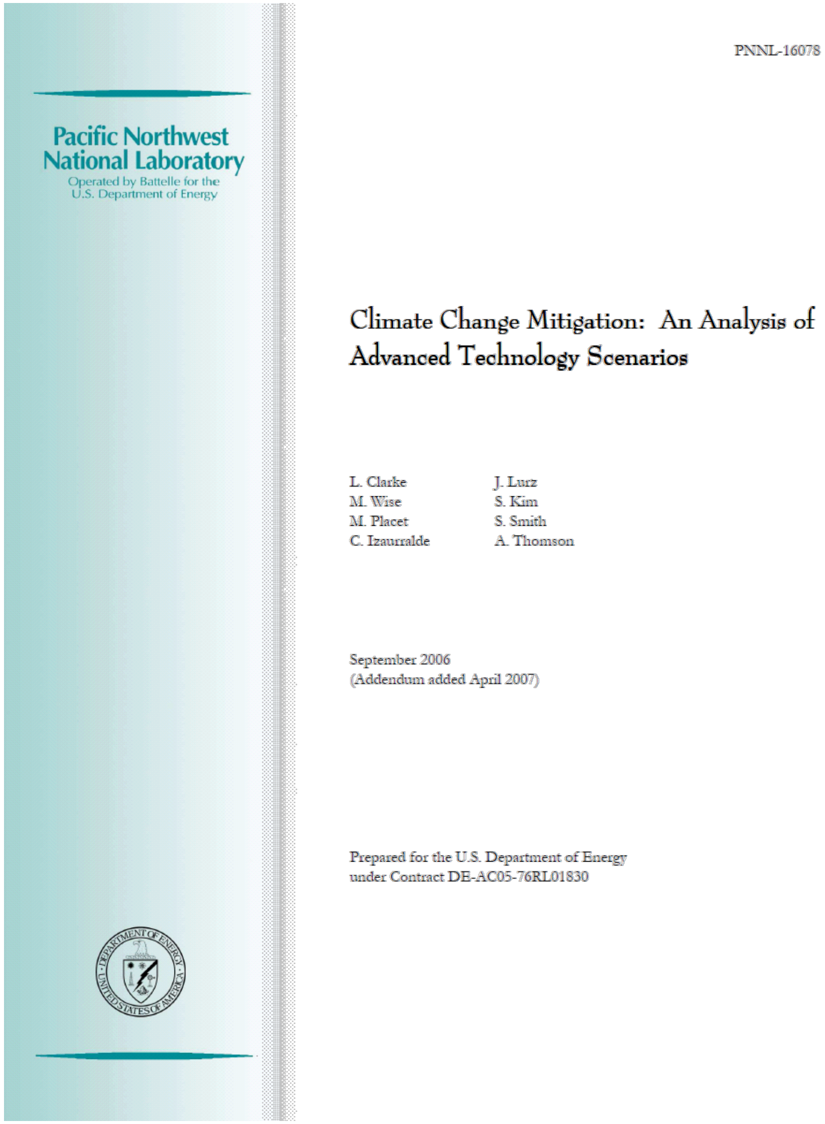
Probabilities of Technology Success

E. Baker, H. Chon, and J. Keisler, Research Series on Combining Economic Analysis with Expert Elicitations to Inform Climate Policy, 2006-Present.



The Costs of Climate Stabilization

Climate Change Technology Program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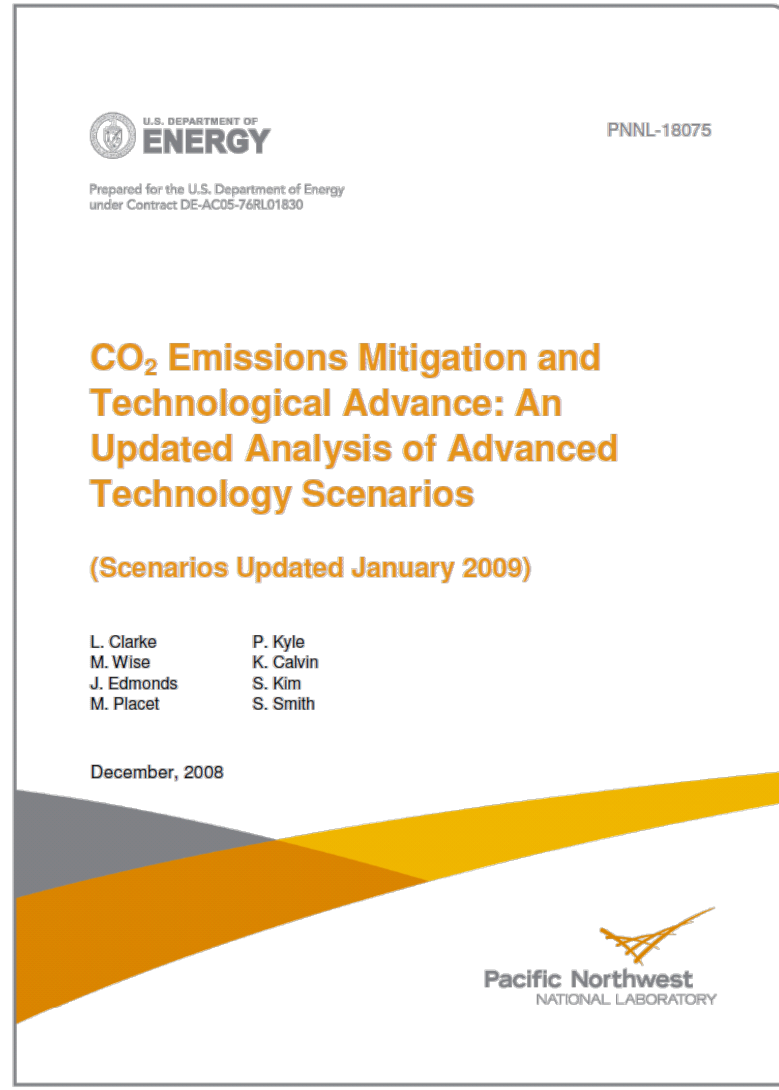
PNNL-16078

Climate Change Mitigation: An Analysis of Advanced Technology Scenarios

L. Clarke, M. Wise, M. Placet, C. Izaurralde, J. Lurz, S. Kim, S. Smith, A. Thomson

September 2006
(Addendum added April 2007)

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830


U.S. DEPARTMENT OF ENERGY

PNNL-18075

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

CO_2 Emissions Mitigation and Technological Advance: An Updated Analysis of Advanced Technology Scenarios

(Scenarios Updated January 2009)

L. Clarke, M. Wise, J. Edmonds, M. Placet, P. Kyle, K. Calvin, S. Kim, S. Smith

December, 2008

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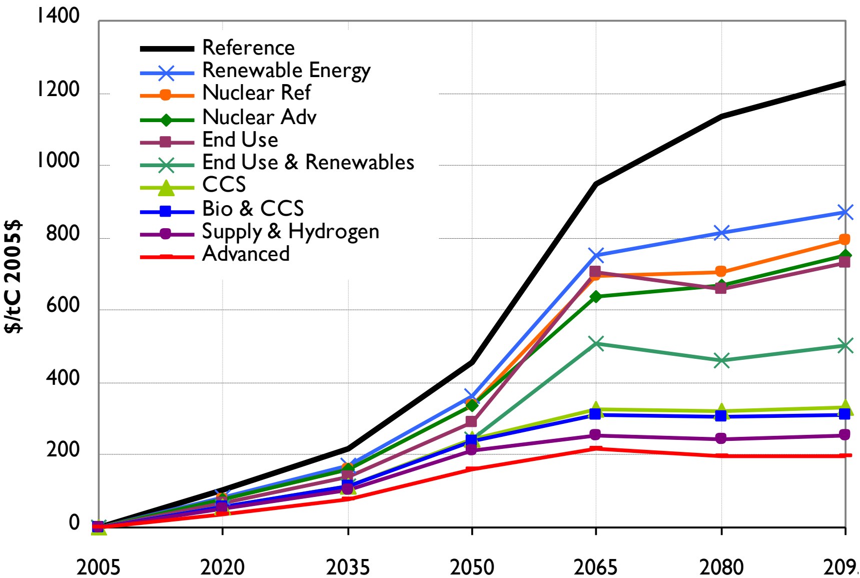
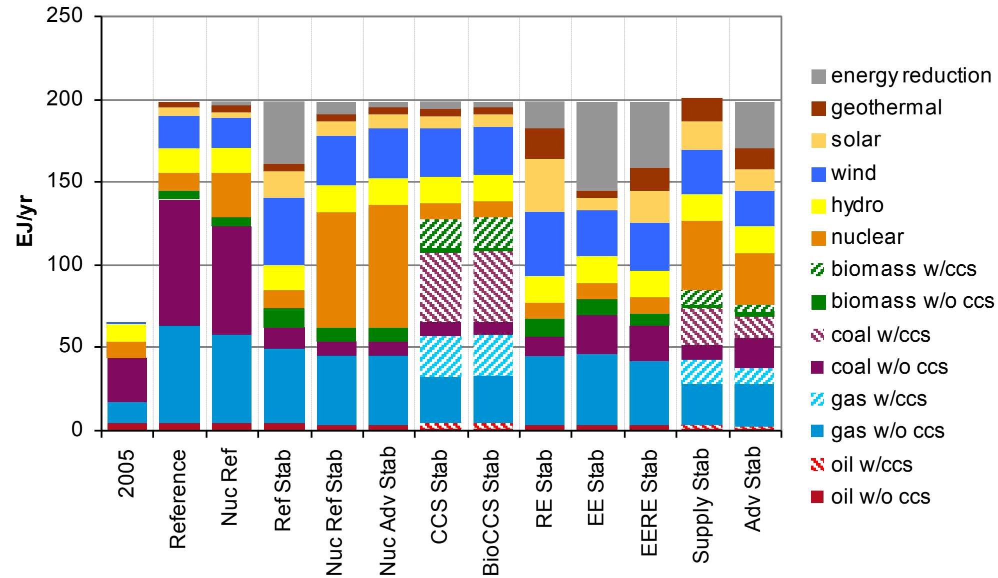
Technologies Affect the Cost of CO_2 Stabilization in a Non-Linear Non-Modular Way

Carbon Prices across Scenarios



Primary Energy Production in 2050 across Scenarios (450 ppmv CO_2)



	450 ppmv	550 ppmv
Reference	11.6	2.5
Renewable Energy	8.5	1.6
Nuclear Ref	7.8	1.5
Nuclear Adv	7.4	1.4
End Use	5.6	0.6
End Use & Renewables	4.1	0.4
CCS	5.6	1.3
Bio & CCS	5.5	1.3
Supply & Hydrogen	3.9	0.6
Advanced	1.9	0.1

Mitigation Costs (Cumulative through 2095) across Scenarios

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The 768 Scenario Dataset

- Developing large number of technology combination scenarios
- Assessing the impact of each technology on the stabilization cost under varying other technology assumptions

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Technology interactions among low-carbon energy technologies: What can we learn from a large number of scenarios?

Haewon C. McJeon [a,*], Leon Clarke [a], Page Kyle [a], Marshall Wise [a], Andrew Hackbarth [b], Benjamin P. Bryant [b], Robert J. Lempert [b]

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[b] *RAND Corporation, Santa Monica, CA, USA*

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Q48

A B S T R A C T

Advanced low-carbon energy technologies can substantially reduce the cost of stabilizing atmospheric carbon dioxide concentrations. Understanding the interactions between these technologies and their impact on the costs of stabilization can help inform energy policy decisions. Many previous studies have addressed this challenge by exploring a small number of representative scenarios that represent particular combinations of future technology developments. This paper uses a combinatorial approach in which scenarios are created for all combinations of the technology development assumptions that underlie a smaller, representative set of scenarios. We estimate stabilization costs for 768 runs of the Global Change Assessment Model (GCAM), based on 384 different combinations of assumptions about the future performance of technologies and two

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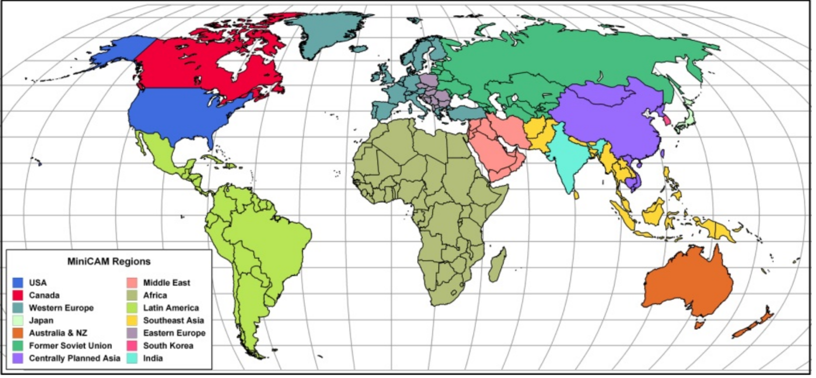
Exploring All Possible Combinations of CCTP 2008 Technology Components

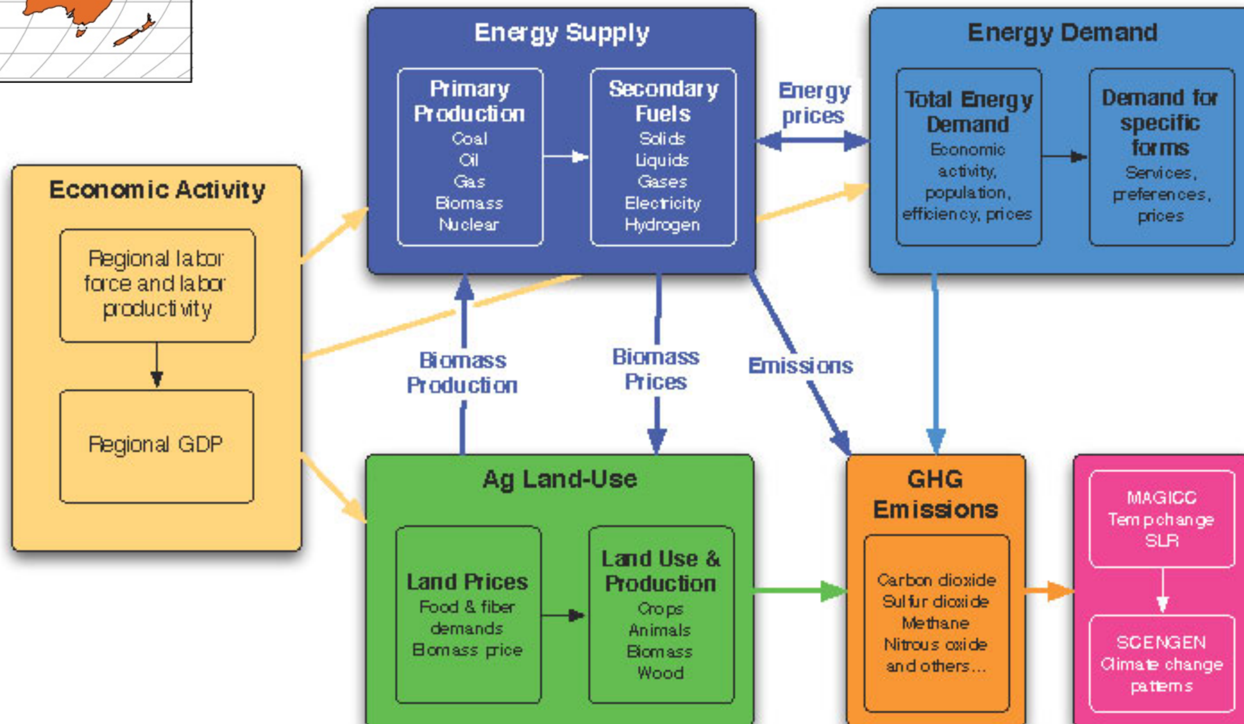
		0: FIXED	1: REF	2: ADV	
Supply Technology	**Solar**	N/A	Capital costs drop by 1%-2% per year 2005-2050	Capital costs drop by 2%-3.5% per year 2005-2050	2
	Wind	N/A	Capital costs drop by 0.25% per year 2005-2050	Capital costs drop by 0.5% per year 2005-2050	2
	CCS	No CCS in any applications	CCS available in electricity, hydrogen, and cement sectors (starting at about $40 / t CO2)	N/A	2
	Nuclear	Nuclear power generation fixed at 2005 levels	Nuclear power available at $2300/kW in 2020, decreasing at 0.1% per year	Nuclear power available at $2300/kW in 2020, decreasing at 0.3% per year	3
End-Use Technology	**Buildings**	N/A	Improvement in building technologies and shells based on EIA (2007)	Accelerated improvement in costs and performance of energy-saving technologies and building shells	2
	Transport	N/A	Improvement in transportation technologies based on EIA (2007)	Accelerated improvements in conventional technologies, and availability of low-cost electric and fuel-cell light duty vehicles	2
	Industry	N/A	Technology efficiencies improve at 0.1% per year; process intensities improve at 0.35% per year	Boiler and motor system efficiencies improve by 10% and 25% by 2035; best available practices from IEA (2007) are in use by 2035	2
Other	**Other**	N/A	Long-term agricultural productivity improvement: 0.25% per year. Engineered geothermal systems (EGS) not available.	Long-term agricultural productivity: 0.5% per year. Accelerated improvements in hydrogen production. EGS available	2

Total combinations: $2^7 \cdot 3 = 384$ tech combinations per stabilization level



Research Platform:
Global Change Assessment Model

- Energy-Agriculture-Economy Market Equilibrium
- 14 Global Regions – Fully Integrated
- Explicit Energy Technologies – All Regions



- Fully Integrated Agriculture and Land Use Model
  - 15 Greenhouse Gases and Short-lived Species
    - Typically Runs to 2095 in 5-year time steps

Evergreen Cluster

The Evergreen cluster provides a platform for massively parallel processing of integrated assessment models like GCAM.

Commodity Cluster Solution, Integrated by PNNL and UM

Compute

284 compute nodes
- Dual Quad/Hex-core Intel 2.8 Ghz
- 48GB per node

2512 Cores: ~28 TFLOPS

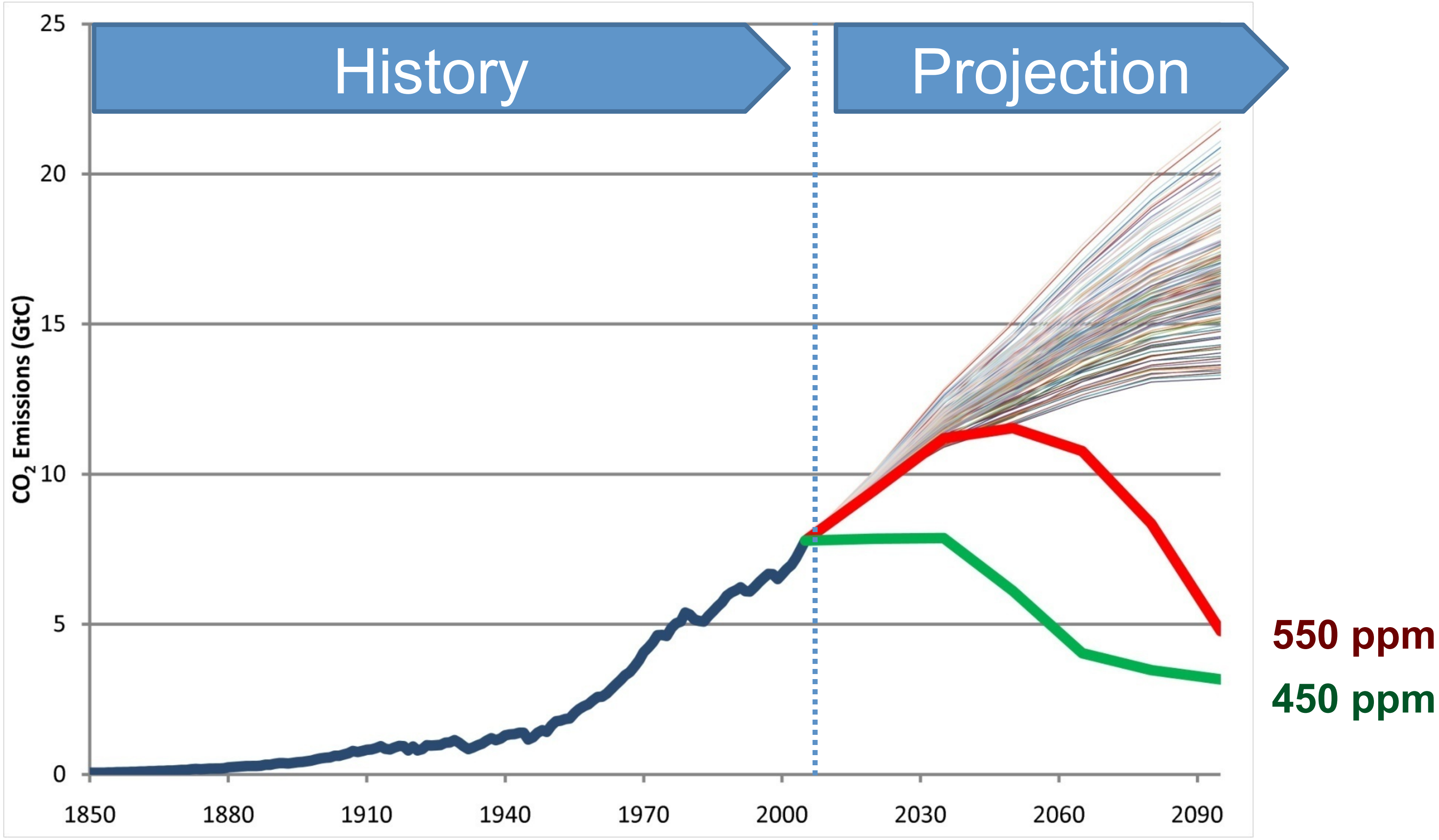
Storage

1.4 Petabytes
- Lustre
- 20GB/second

Network

Voltaire QDR (40 gigabit) InfiniBand

Baseline Emissions and Stabilization Constraints



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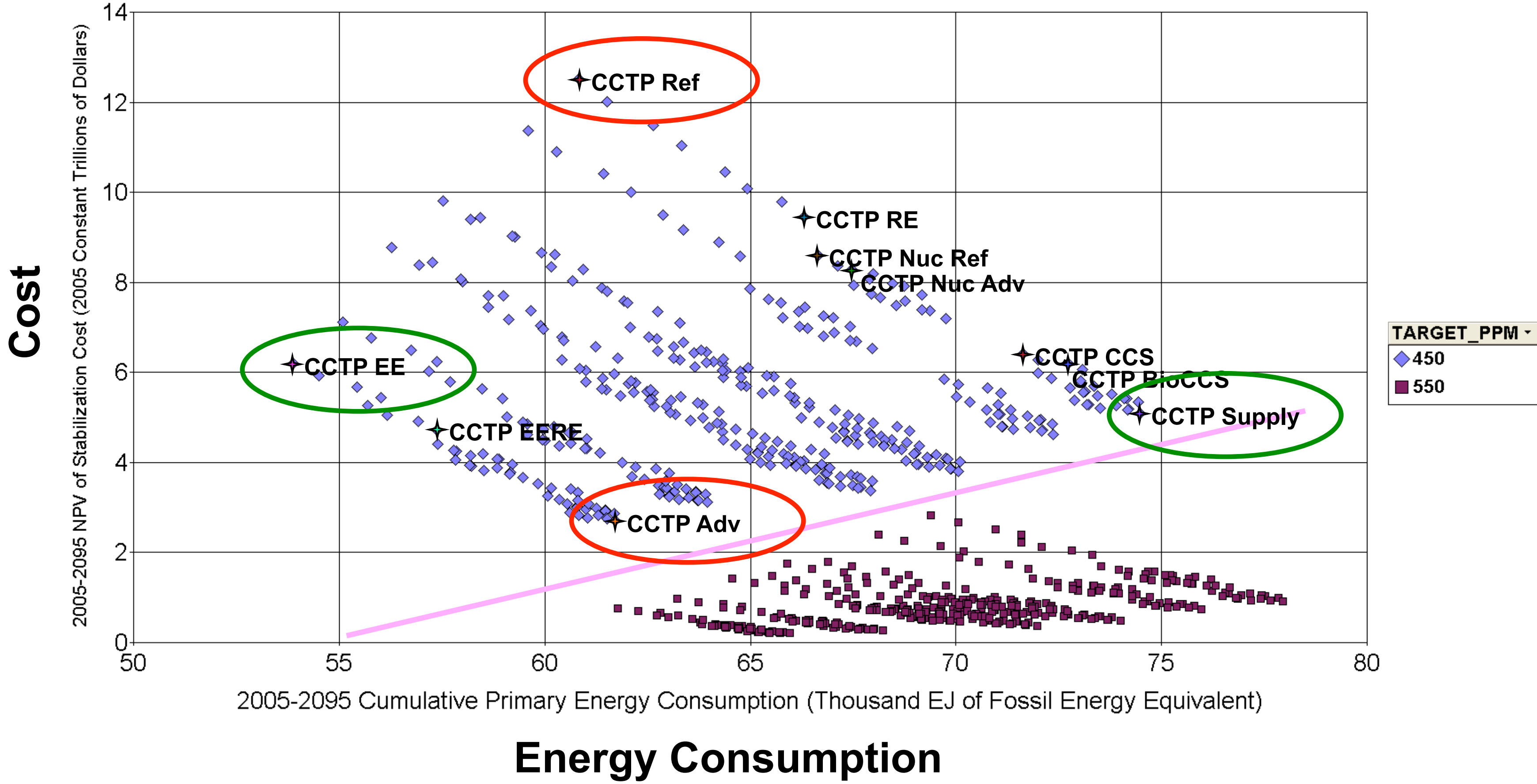
Revealing the Interior of the Technology Space: a Plot of 768 Scenarios



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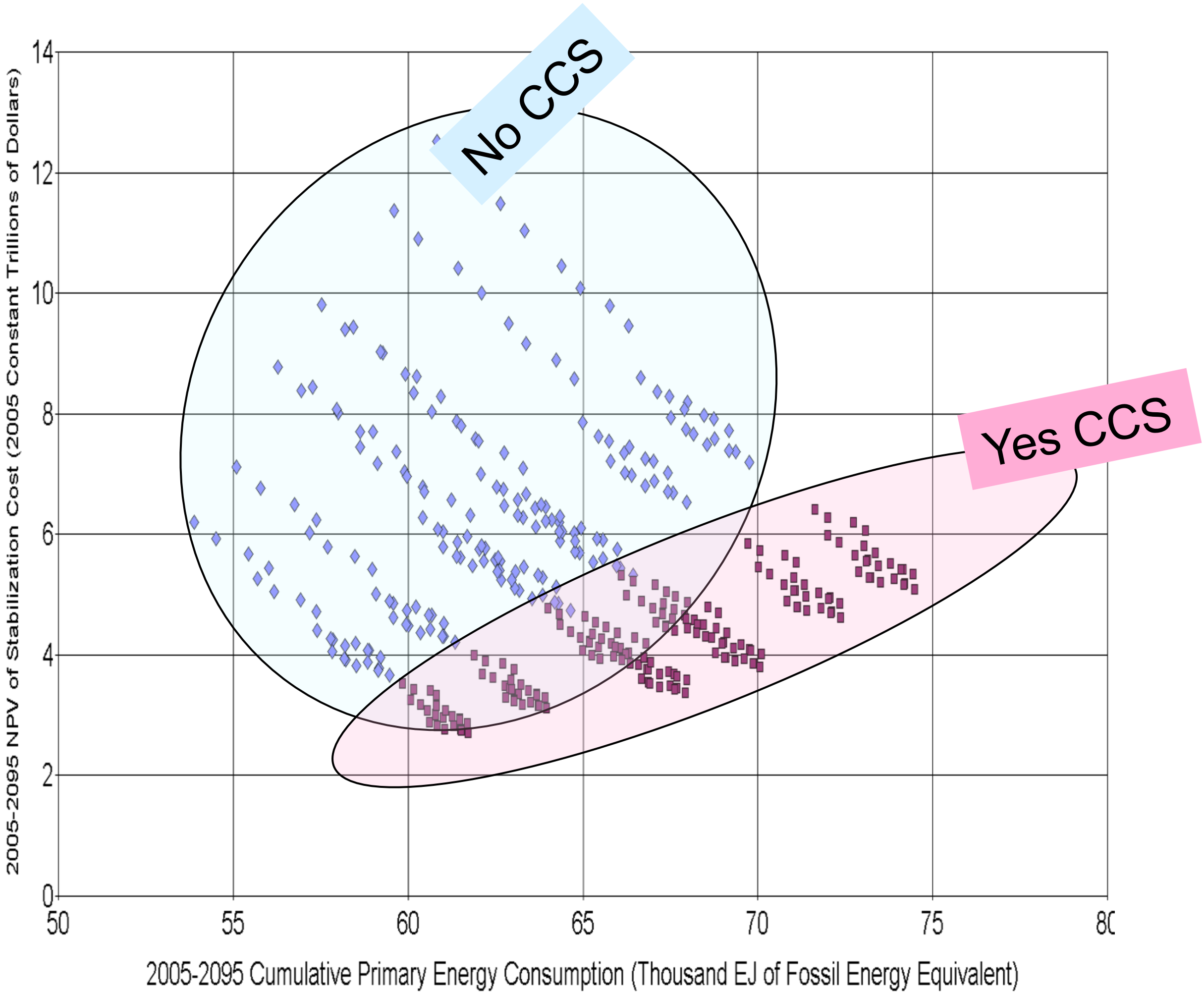
Stabilization Cost Distribution Associated with Each Technology Type



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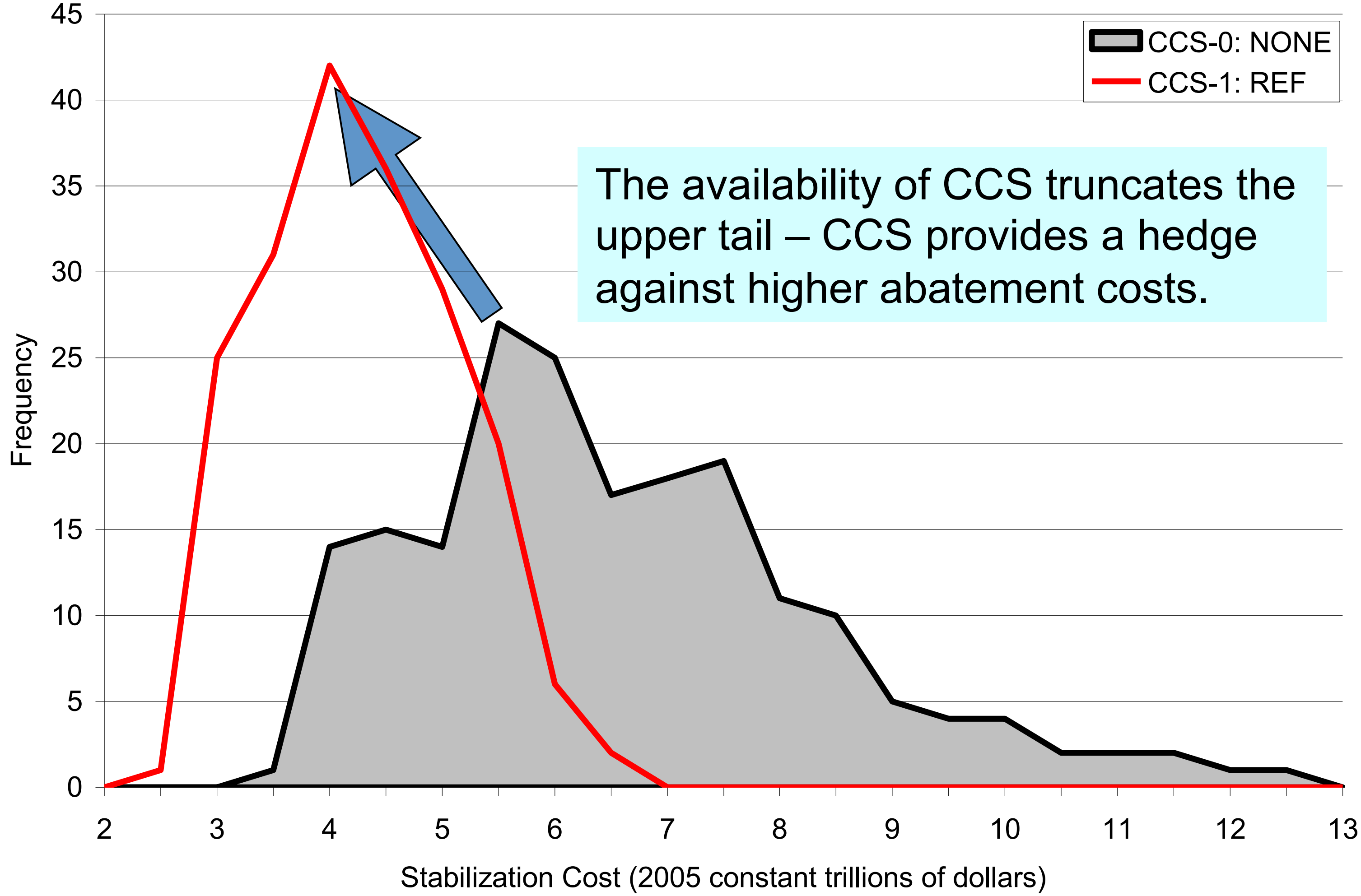
450 ppm Histogram – CCS focus



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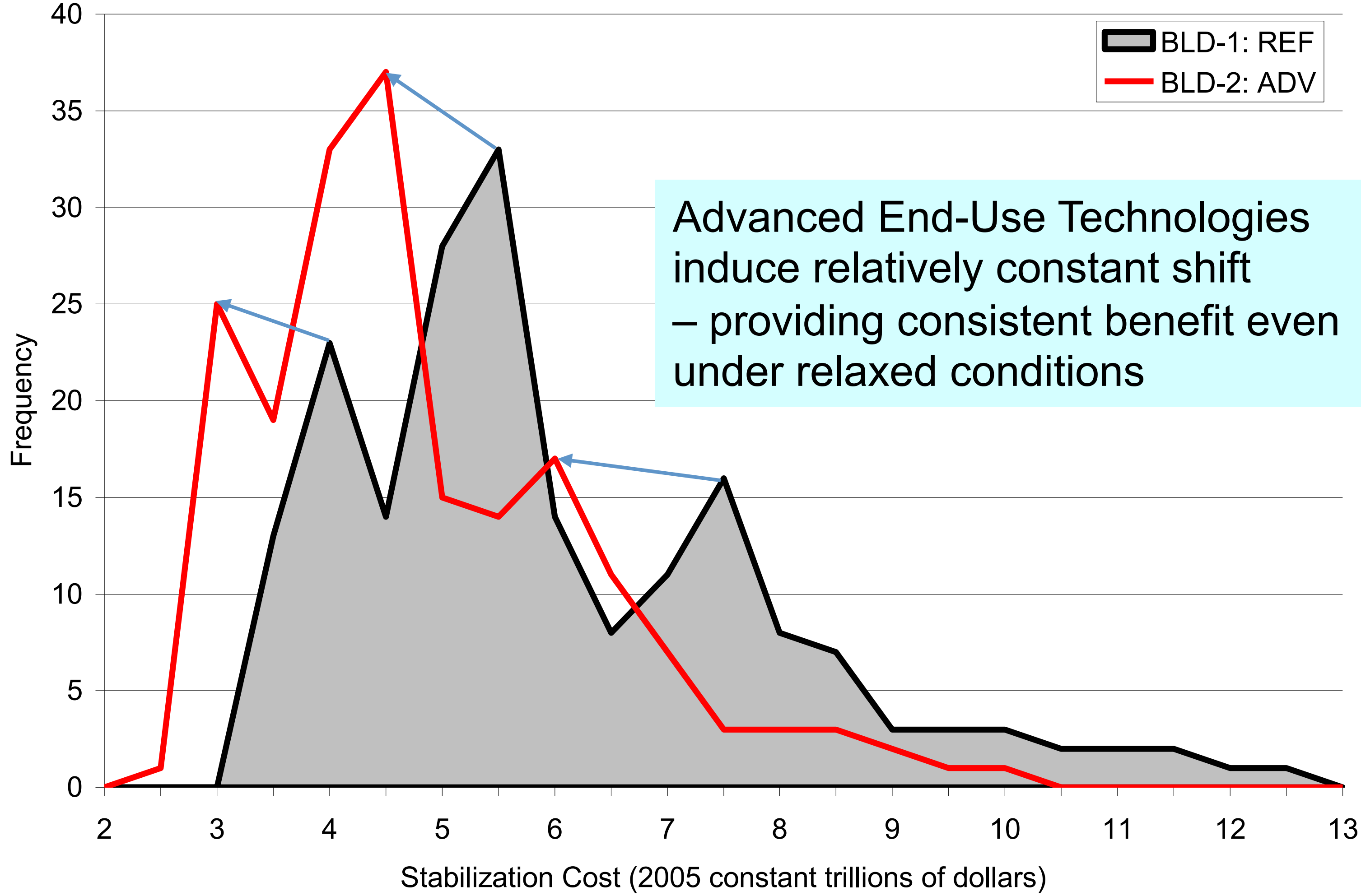
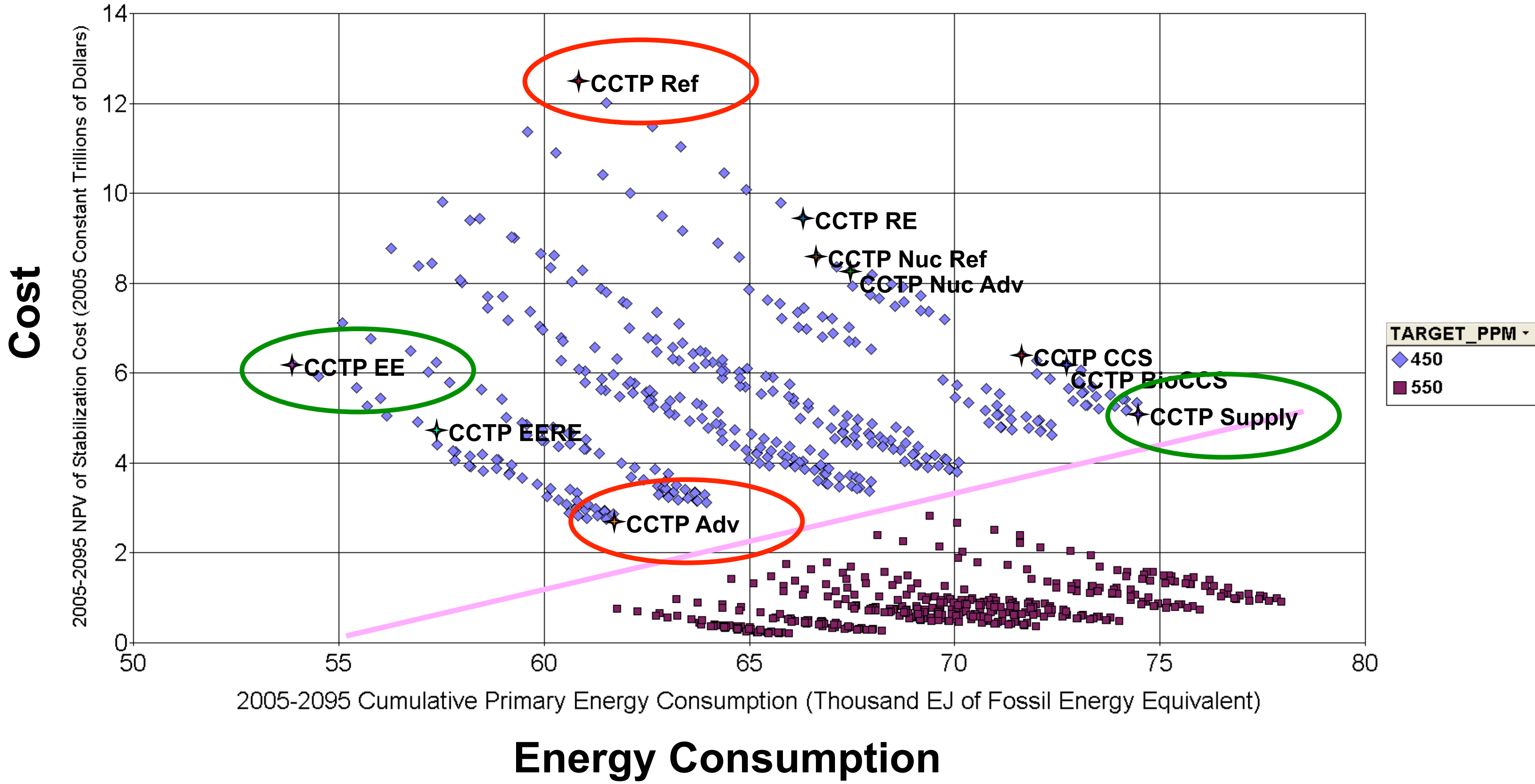
450 ppm Histogram – Buildings focus

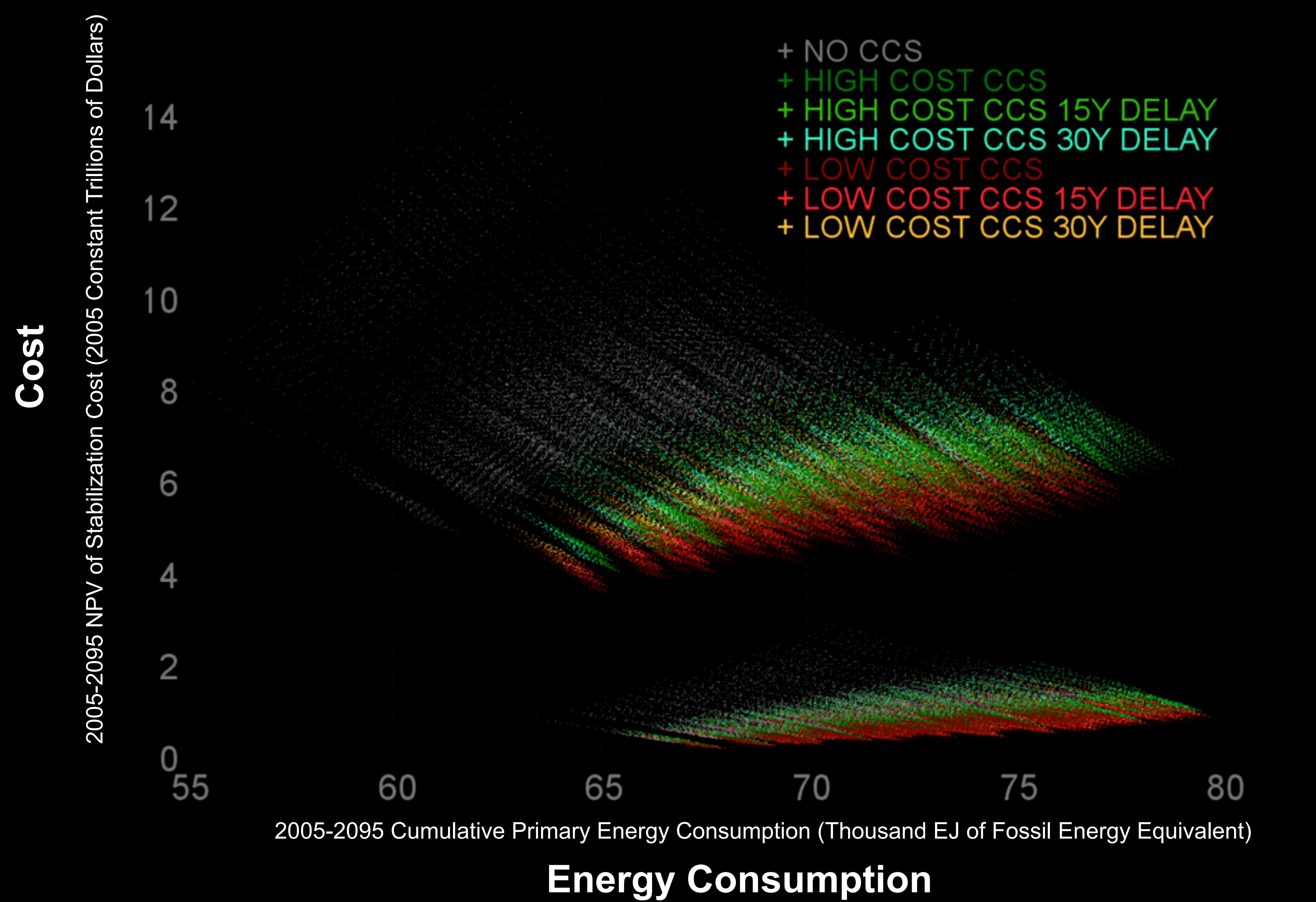


Advanced End-Use Technologies induce relatively constant shift – providing consistent benefit even under relaxed conditions

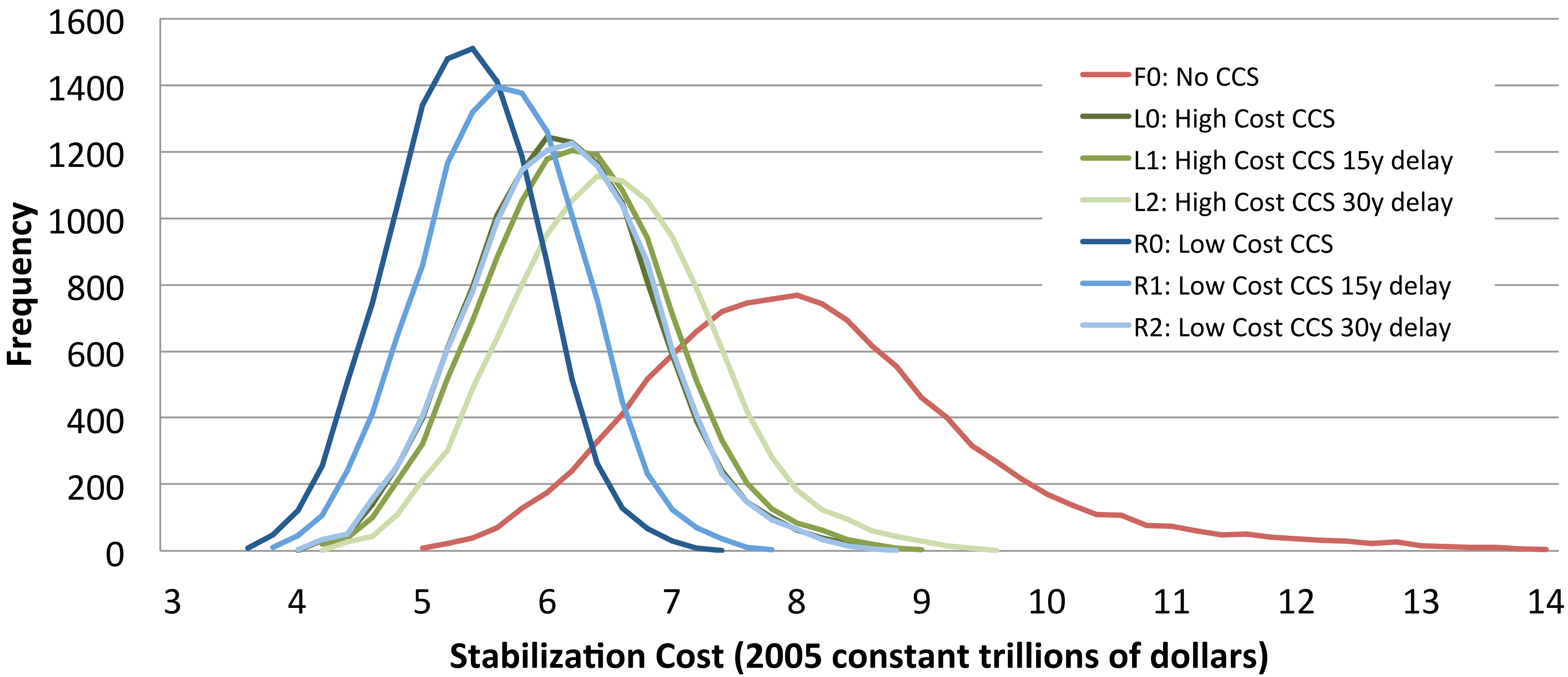
What if the advanced technology developments are delayed?

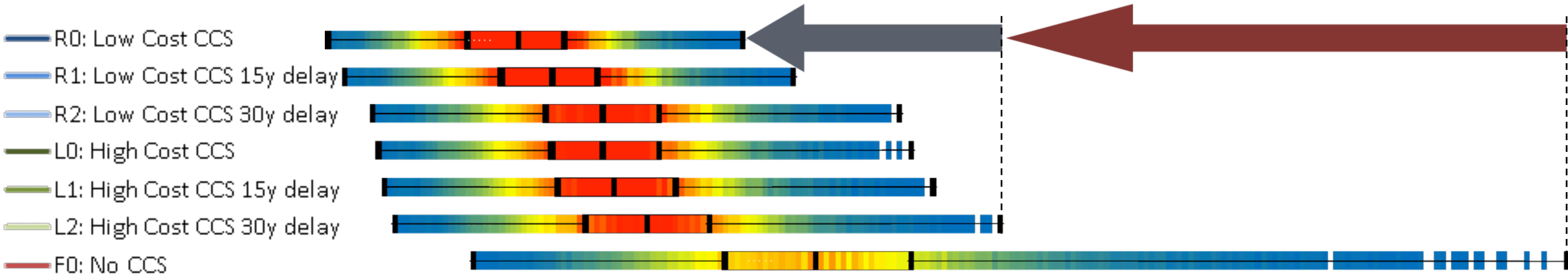


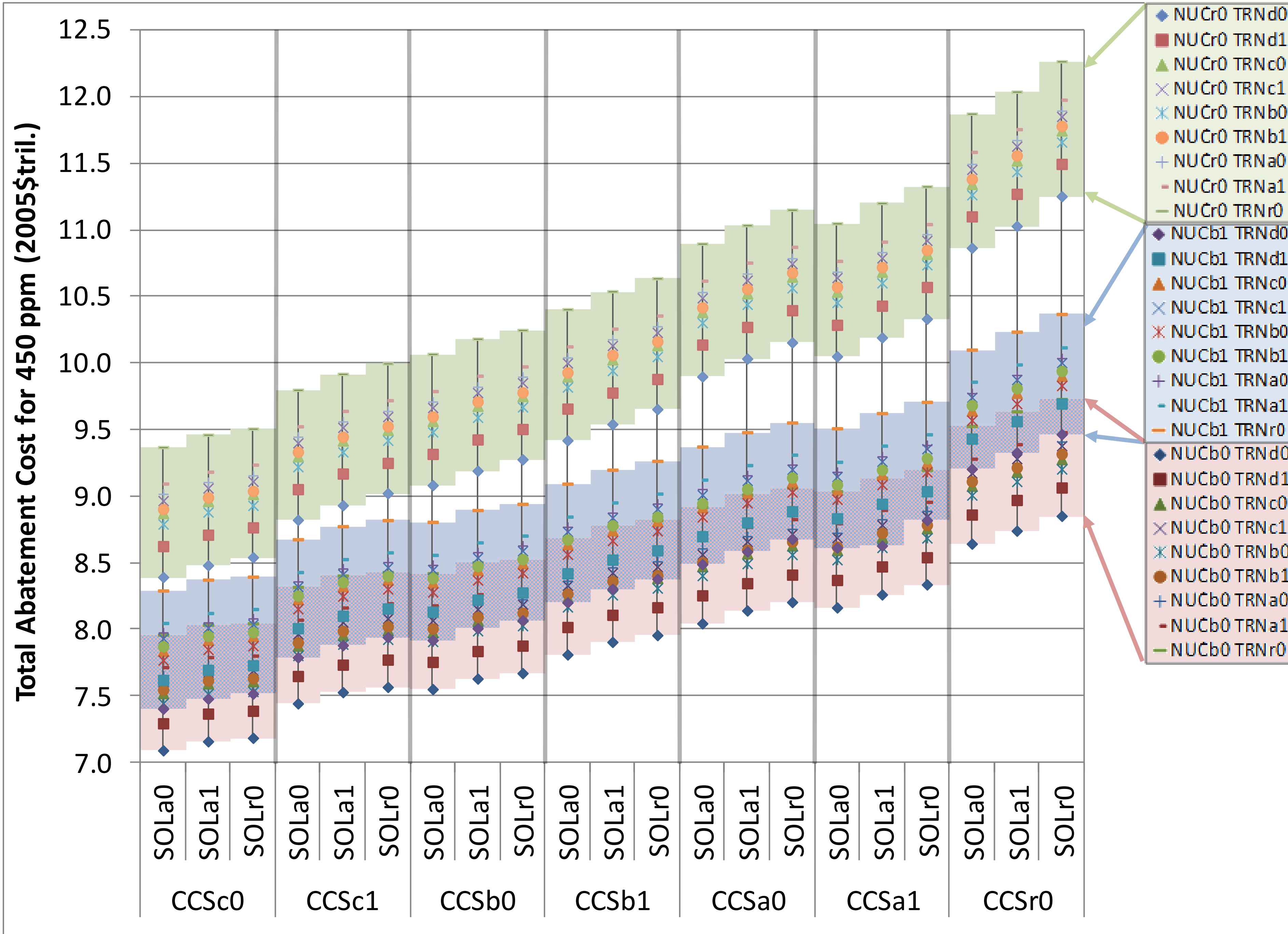
The Galaxy of 161k Technology Combinations



The Galaxy of 161k Technology Combinations

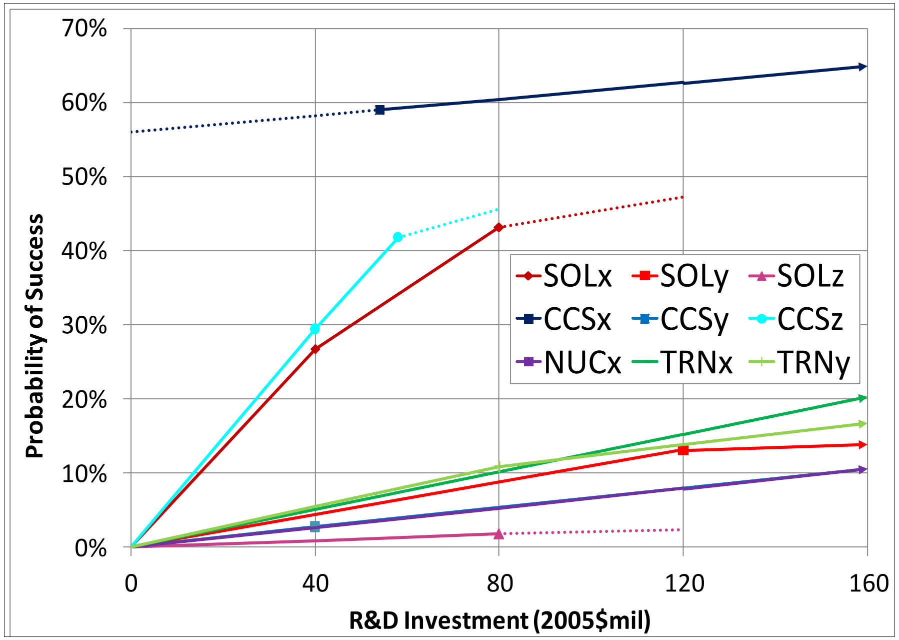




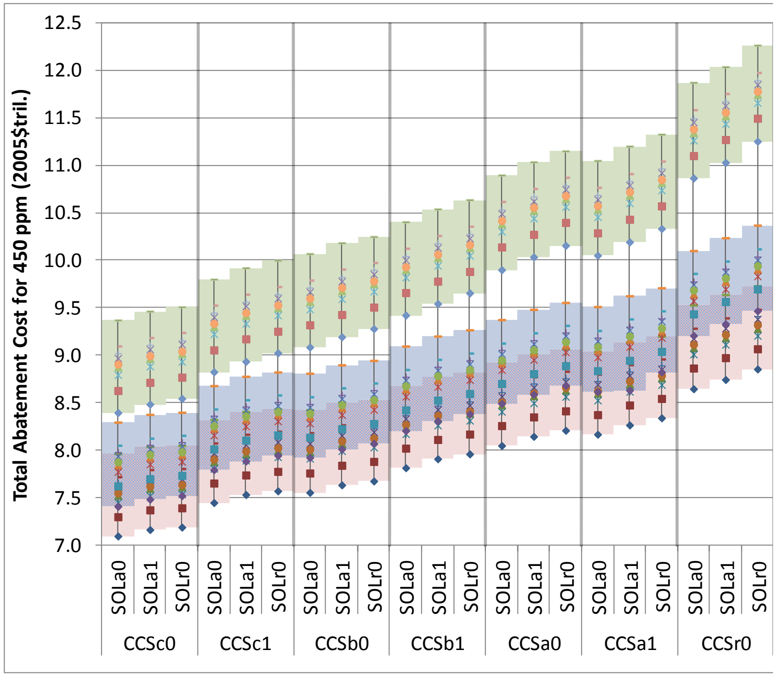

Total Abatement Cost for 450 ppm (2005$tril.)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
SOLa0
SOLa1
SOLr0
CCSc0
CCSc1
CCSb0
CCSb1
CCSa0
CCSa1
CCSr0
NUCr0 TRNd0
NUCr0 TRNd1
NUCr0 TRNc0
NUCr0 TRNc1
NUCr0 TRNb0
NUCr0 TRNb1
NUCr0 TRNa0
NUCr0 TRNa1
NUCr0 TRNr0
NUCb1 TRNd0
NUCb1 TRNd1
NUCb1 TRNc0
NUCb1 TRNc1
NUCb1 TRNb0
NUCb1 TRNb1
NUCb1 TRNa0
NUCb1 TRNa1
NUCb1 TRNr0
NUCb0 TRNd0
NUCb0 TRNd1
NUCb0 TRNc0
NUCb0 TRNc1
NUCb0 TRNb0
NUCb0 TRNb1
NUCb0 TRNa0
NUCb0 TRNa1
NUCb0 TRNr0

Combining the Two Studies in a Stochastic Dynamic Programming Framework

Probabilities of Technology Success



CO_2 Stabilization Cost

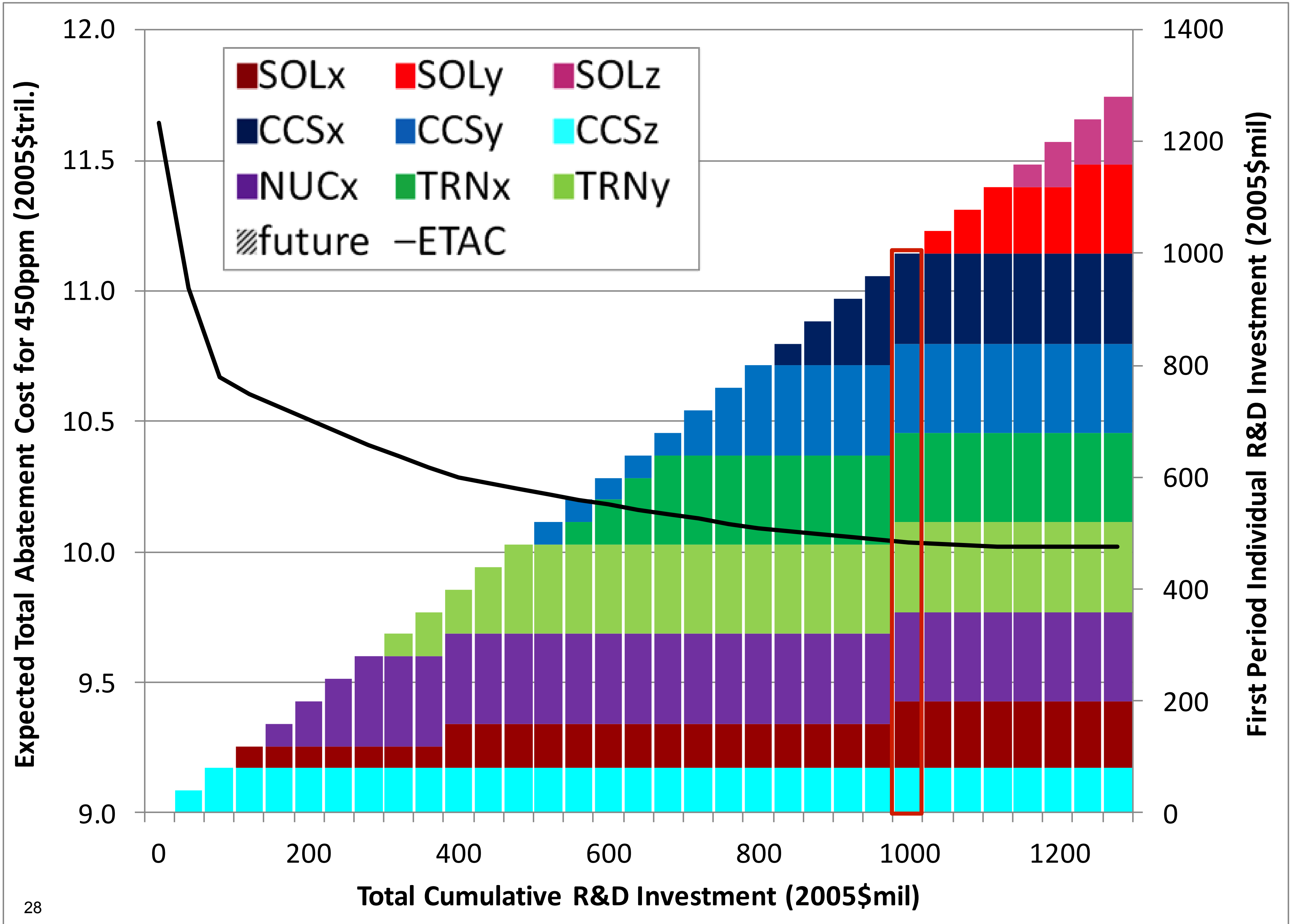


Baker, Chon, and Keisler, Research Series on Combining Economic Analysis with Expert Elicitations to Inform Climate Policy, 2006-Present.

McJeon, Clarke, et al., Technology Interactions among Low-Carbon Energy Technologies, 2009-Present.

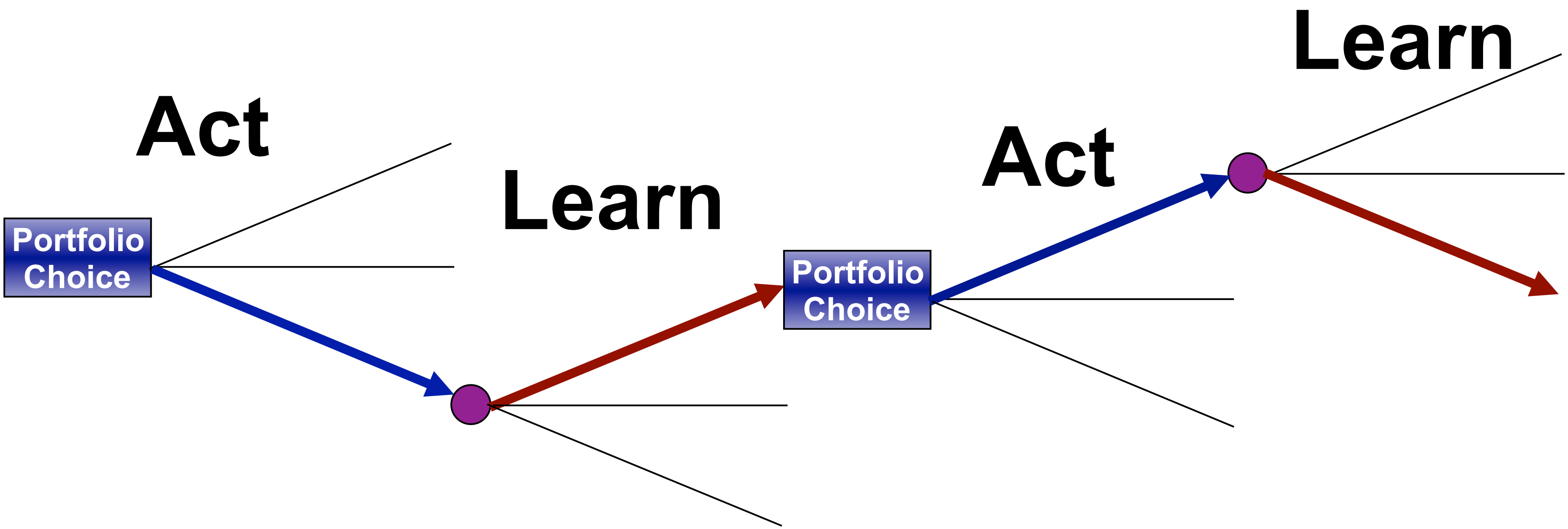
Model 1: Single-Period Allocation

- Minimize: NPV of abatement cost
- Subject to:
  - Probability of success depends on funding
  - Limited total budget
  - Stabilization level parameter
- Parametric optimization:
  - Budget as a varying parameter
  - How funding share changes as total budget changes



SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
ETAC
Expected Total Abatement Cost for 450ppm (2005$tril.)
First Period Individual R&D Investment (2005$mil)
Total Cumulative R&D Investment (2005$mil)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200

Model 2: Introducing the Act-Then-Learn Strategy



- Stochastic Dynamic Programming Approach
- Which technology should we invest now, and which should we wait until later?
- The cost of waiting and the benefit of learning from success and failure.
- Value of information can only be understood in a multi-period framework.

Model 2: Stochastic Dynamic Programming Approach

State of the system at period *t*:

$$C_t \in \left(\prod_{i \in I} S_t \right), e.g., (success, fail, fail, success)$$

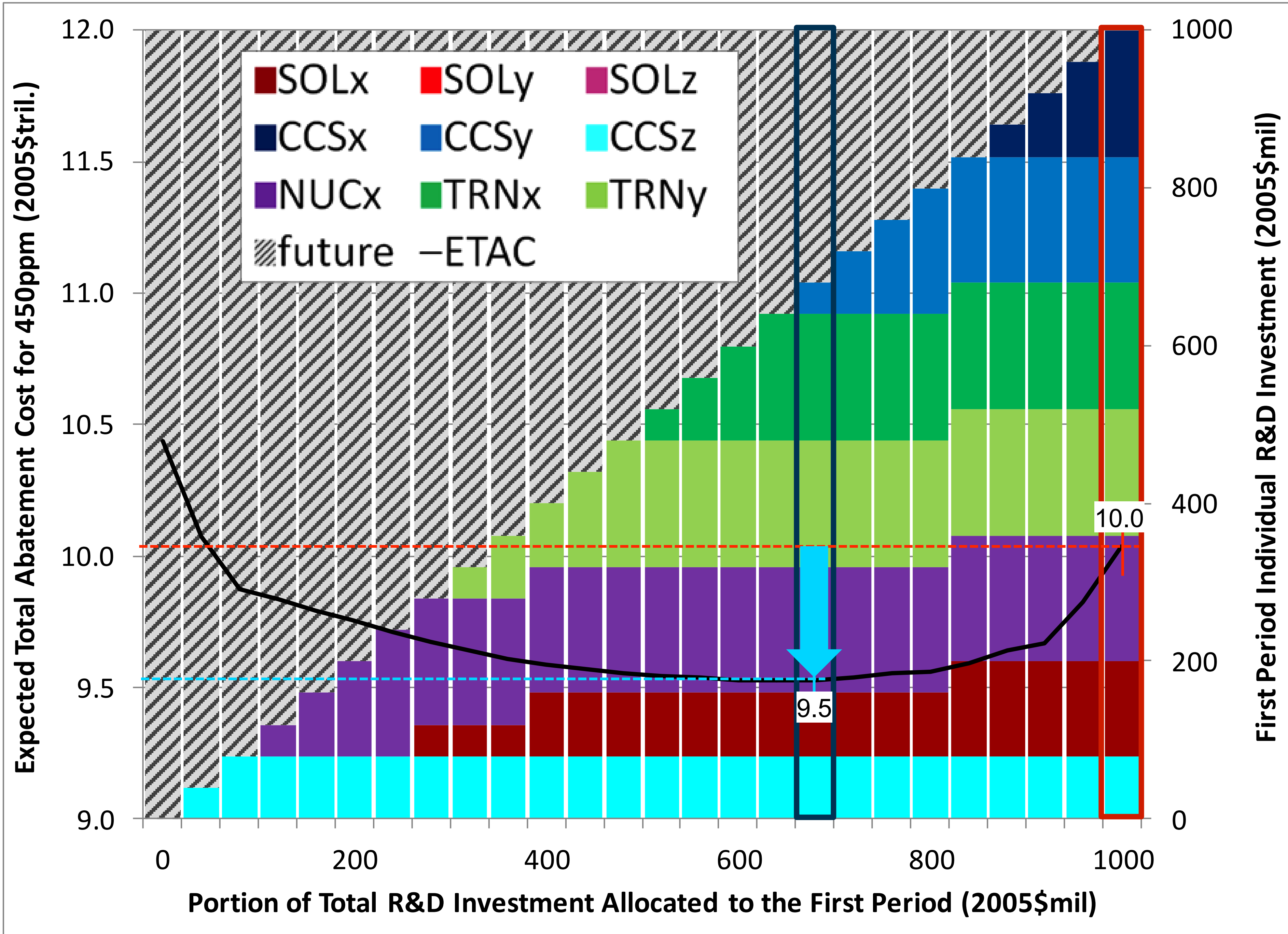
Set of feasible funding decisions:

$$X(C_t) = \left\{ X_t \in \{0, \alpha_{low}, \alpha_{med}, \alpha_{high}\}^I \mid : \sum_{i \in I} X_{it} \leq B_t \right\}$$

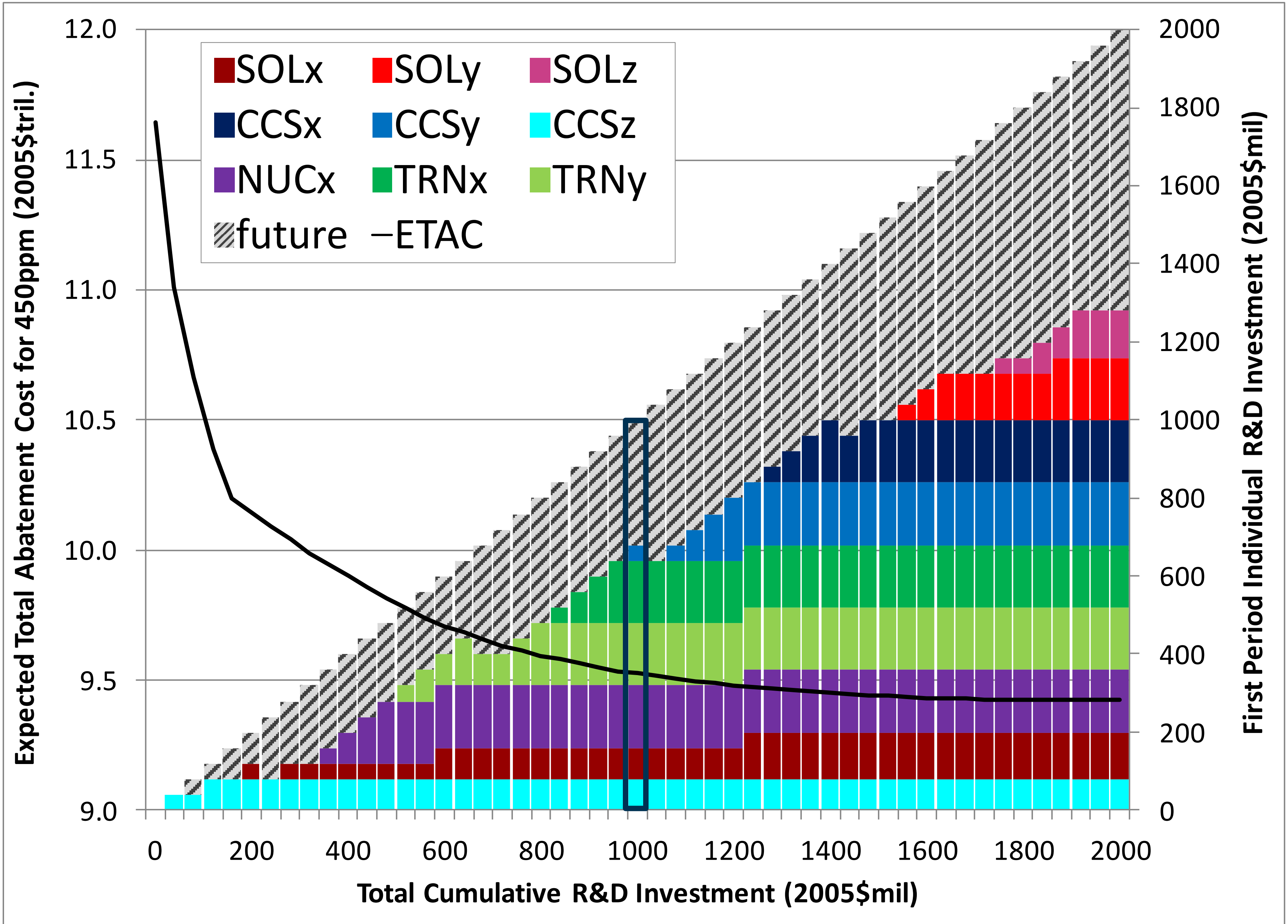
Recursively solve the stochastic dynamic program:

$$V_t(C_t) = \min_{X_t \in X(C_t)} E\{V_{t+1}(C_{t+1}) \mid C_t, X_t\}$$

Where the value function is the net present value of total abatement cost, given technology development level.



SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
ETAC
12.0
11.5
11.0
10.5
10.0
9.5
9.0
1000
800
600
400
200
0
0
200
400
600
800
1000
10.0
9.5
Expected Total Abatement Cost for 450ppm (2005$tril.)
First Period Individual R&D Investment (2005$mil)
Portion of Total R&D Investment Allocated to the First Period (2005$mil)



SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
ETAC
Expected Total Abatement Cost for 450ppm (2005$tril.)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
First Period Individual R&D Investment (2005$mil)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Total Cumulative R&D Investment (2005$mil)

Is this Better than Back-of-the-Envelope?

- R&D investment order is significantly different from the order generated by either stabilization cost reduction potential or probability of success alone
- However, it is marginally different from the order generated by product of the two data
- Specifically, the two TRN technologies switch places with the immediately preceding CCS technologies
  - The maximum impact measurement systematically underestimates the strength of end-use technologies (McJeon et al. 2011)
- Within TRN technologies, the available funding is concentrated to a single technology: TRNy

Rank	max impact		Marginal P of Success		max impact * Marginal P		SDP1		SDP2	
1	CCSz	40	CCSz	40	CCSz	40	CCSz	40	CCSz	40
2	CCSz	80	SOLx	40	CCSz	80	CCSz	80	CCSz	80
3	NUCx	40	SOLx	80	SOLx	40	SOLx	40	SOLx	40
4	NUCx	80	CCSz	80	NUCx	40	NUCx	40	NUCx	40
5	NUCx	120	TRNy	40	NUCx	80	NUCx	80	NUCx	80
6	NUCx	160	TRNy	80	NUCx	120	NUCx	120	NUCx	120
7	CCSy	40	TRNx	40	NUCx	160	NUCx	160	NUCx	160
8	CCSy	80	TRNx	80	SOLx	80	TRNy	40	TRNy	40
9	CCSy	120	TRNx	120	CCSy	40	TRNy	80	TRNy	80
10	CCSy	160	TRNx	160	CCSy	80	SOLx	80	SOLx	80
11	CCSx	40	SOLy	40	CCSy	120	TRNy	120	TRNy	120
12	CCSx	80	SOLy	80	CCSy	160	TRNy	160	TRNy	160
13	CCSx	120	SOLy	120	TRNy	40	CCSy	40	TRNx	40
14	CCSx	160	SOLx	120	TRNy	80	TRNx	40	TRNx	80
15	TRNy	40	TRNy	120	CCSx	40	TRNx	80	TRNx	120
16	TRNy	80	TRNy	160	CCSx	80	TRNx	120	TRNx	160
17	TRNy	120	CCSy	40	CCSx	120	TRNx	160	CCSy	40
18	TRNy	160	NUCx	40	CCSx	160	CCSy	80	CCSy	80
19	TRNx	40	NUCx	80	TRNx	40	CCSy	120	CCSy	120
20	TRNx	80	NUCx	120	TRNx	80	CCSy	160	CCSy	160
21	TRNx	120	NUCx	160	TRNx	120	CCSx	40	SOLx	120
22	TRNx	160	CCSy	80	TRNx	160	CCSx	80	CCSx	40
23	SOLx	40	CCSy	120	TRNy	120	CCSx	120	CCSx	80
24	SOLx	80	CCSy	160	TRNy	160	CCSx	160	CCSx	120
25	SOLx	120	CCSx	40	SOLy	40	SOLx	120	CCSx	160
26	SOLy	40	CCSx	80	SOLy	80	SOLy	40	SOLy	40
27	SOLy	80	CCSx	120	SOLy	120	SOLy	80	SOLy	80
28	SOLy	120	CCSx	160	SOLx	120	SOLy	120	SOLy	120
29	SOLy	160	SOLz	40	SOLz	40	SOLz	40	SOLz	40
30	SOLz	40	SOLz	80	SOLz	80	SOLz	80	SOLz	80
31	SOLz	80	SOLy	160	SOLy	160	SOLy	160	SOLy	160
32	SOLz	120	SOLz	120	SOLz	120	SOLz	120	SOLz	120

Is this Better than Back-of-the-Envelope?

- A nominal evidence of diversification across different technology groups is observed by SOLx overtaking CCSx
- This is driven by the relatively high value of wait-and-see option for CCSx
- Last but not least, SDP results tell us the optimal balance between current and future investment

Rank	max impact		Marginal P of Success		max impact * Marginal P		SDP1		SDP2	
1	CCSz	40	CCSz	40	CCSz	40	CCSz	40	CCSz	40
2	CCSz	80	SOLx	40	CCSz	80	CCSz	80	CCSz	80
3	NUCx	40	SOLx	80	SOLx	40	SOLx	40	SOLx	40
4	NUCx	80	CCSz	80	NUCx	40	NUCx	40	NUCx	40
5	NUCx	120	TRNy	40	NUCx	80	NUCx	80	NUCx	80
6	NUCx	160	TRNy	80	NUCx	120	NUCx	120	NUCx	120
7	CCSy	40	TRNx	40	NUCx	160	NUCx	160	NUCx	160
8	CCSy	80	TRNx	80	SOLx	80	TRNy	40	TRNy	40
9	CCSy	120	TRNx	120	CCSy	40	TRNy	80	TRNy	80
10	CCSy	160	TRNx	160	CCSy	80	SOLx	80	SOLx	80
11	CCSx	40	SOLy	40	CCSy	120	TRNy	120	TRNy	120
12	CCSx	80	SOLy	80	CCSy	160	TRNy	160	TRNy	160
13	CCSx	120	SOLy	120	TRNy	40	CCSy	40	TRNx	40
14	CCSx	160	SOLx	120	TRNy	80	TRNx	40	TRNx	80
15	TRNy	40	TRNy	120	CCSx	40	TRNx	80	TRNx	120
16	TRNy	80	TRNy	160	CCSx	80	TRNx	120	TRNx	160
17	TRNy	120	CCSy	40	CCSx	120	TRNx	160	CCSy	40
18	TRNy	160	NUCx	40	CCSx	160	CCSy	80	CCSy	80
19	TRNx	40	NUCx	80	TRNx	40	CCSy	120	CCSy	120
20	TRNx	80	NUCx	120	TRNx	80	CCSy	160	CCSy	160
21	TRNx	120	NUCx	160	TRNx	120	CCSx	40	SOLx	120
22	TRNx	160	CCSy	80	TRNx	160	CCSx	80	CCSx	40
23	SOLx	40	CCSy	120	TRNy	120	CCSx	120	CCSx	80
24	SOLx	80	CCSy	160	TRNy	160	CCSx	160	CCSx	120
25	SOLx	120	CCSx	40	SOLy	40	SOLx	120	CCSx	160
26	SOLy	40	CCSx	80	SOLy	80	SOLy	40	SOLy	40
27	SOLy	80	CCSx	120	SOLy	120	SOLy	80	SOLy	80
28	SOLy	120	CCSx	160	SOLx	120	SOLy	120	SOLy	120
29	SOLy	160	SOLz	40	SOLz	40	SOLz	40	SOLz	40
30	SOLz	40	SOLz	80	SOLz	80	SOLz	80	SOLz	80
31	SOLz	80	SOLy	160	SOLy	160	SOLy	160	SOLy	160
32	SOLz	120	SOLz	120	SOLz	120	SOLz	120	SOLz	120

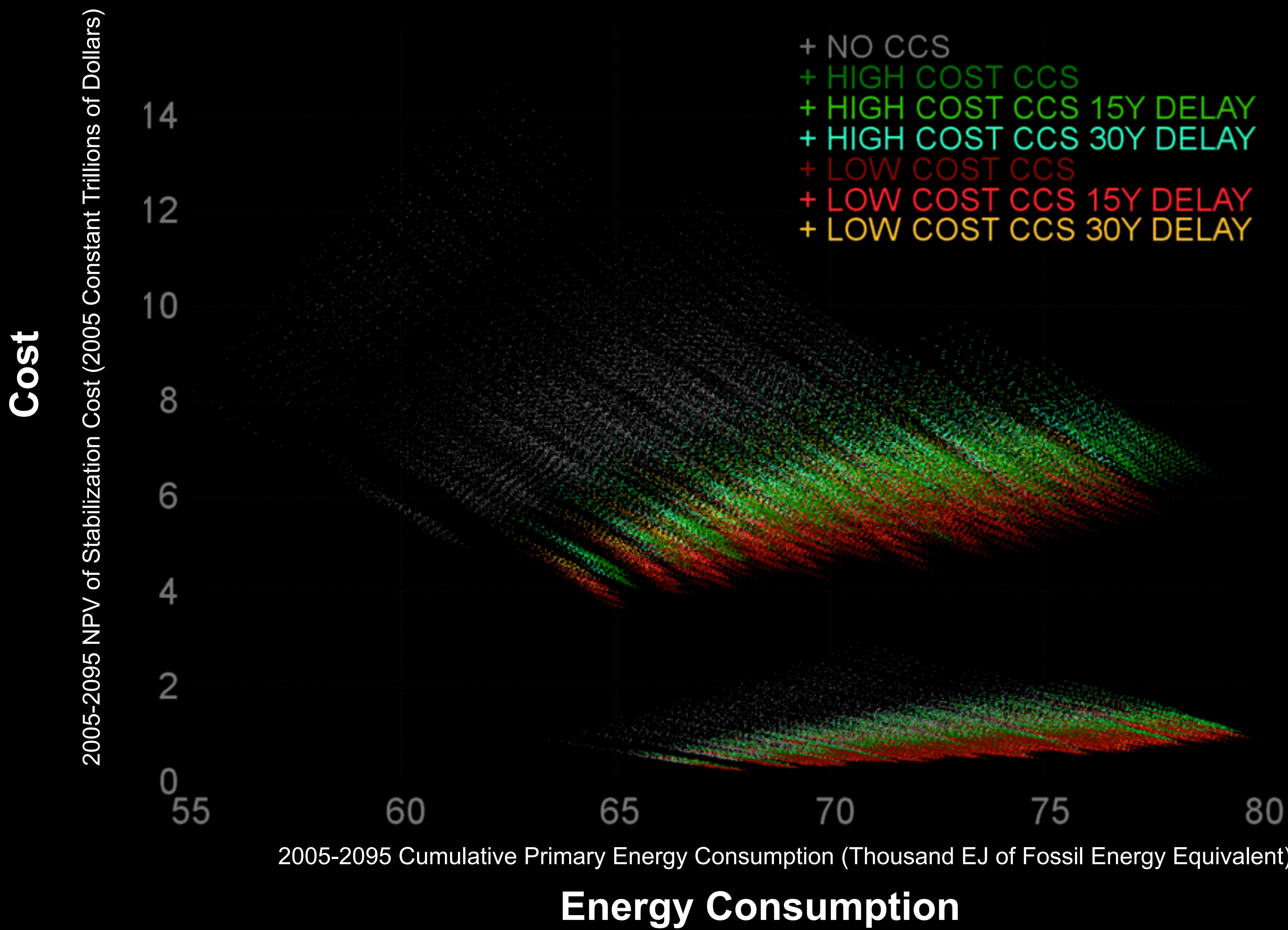
Synthesis and Discussion

- We have been getting some high quality data from the two front:
  - Probabilities of Technology Success
  - Stabilization cost estimates from technologically detailed models
- A natural choice of the decision making framework incorporating the two datasets is stochastic dynamic programming
- From the first analysis performed here, we understand that the likely contributions of this research are:
  - to provide insights into the balance of current and future R&D investments
  - and to point out the technologies that are best fit for the wait-and-see strategy
- Hence, the future research should focus on better representing the effect of delayed R&D investment

Future Work

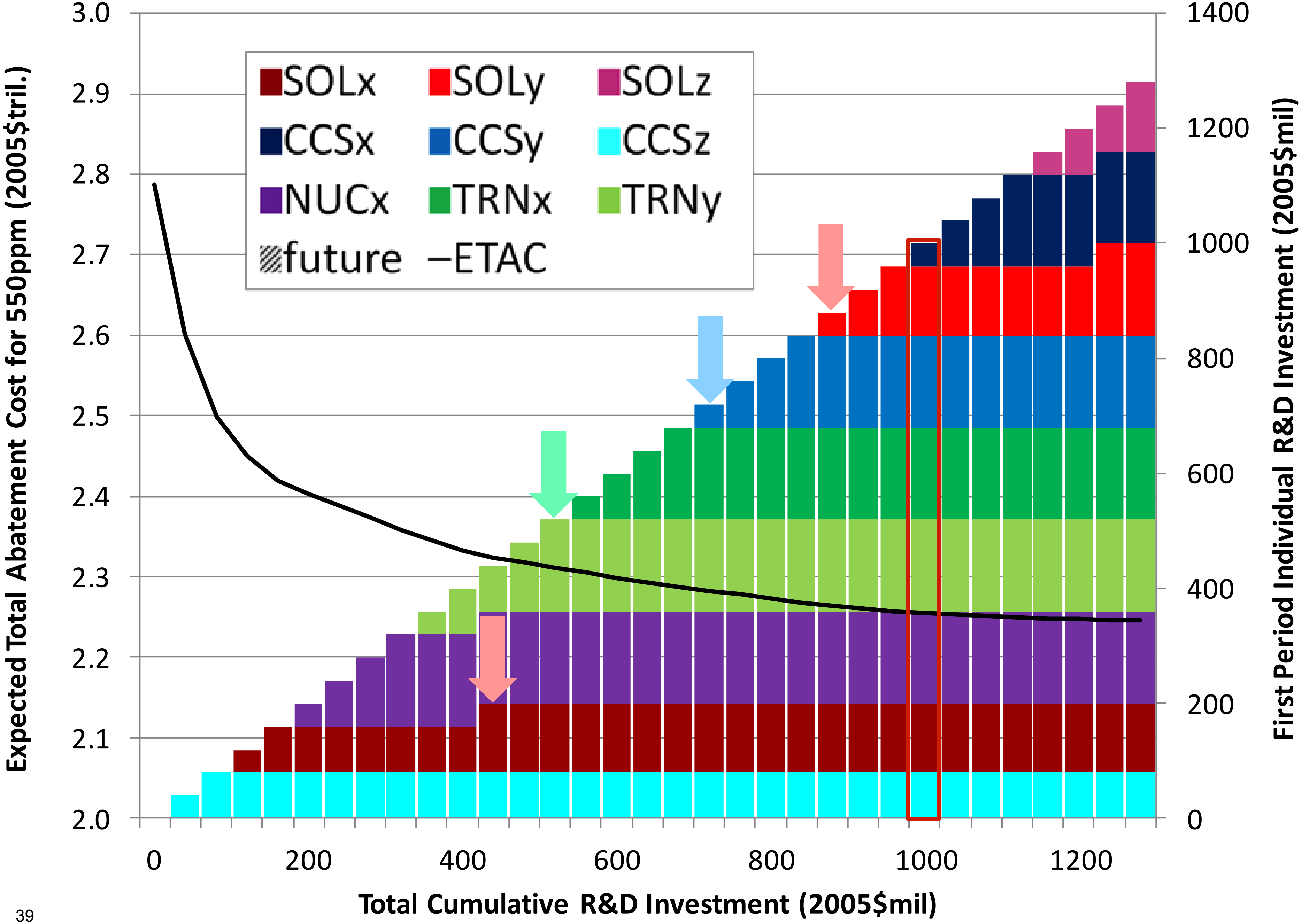
- Broader technology sets
- Realistic representations of uncertainty resolution
- Better understanding of learning from failure effect
- Non-economic aspects of a technology
  - Probability of political / institutional acceptance
- Interactions with other uncertainties in the system
  - Climate policy uncertainty
  - Socioeconomic uncertainty

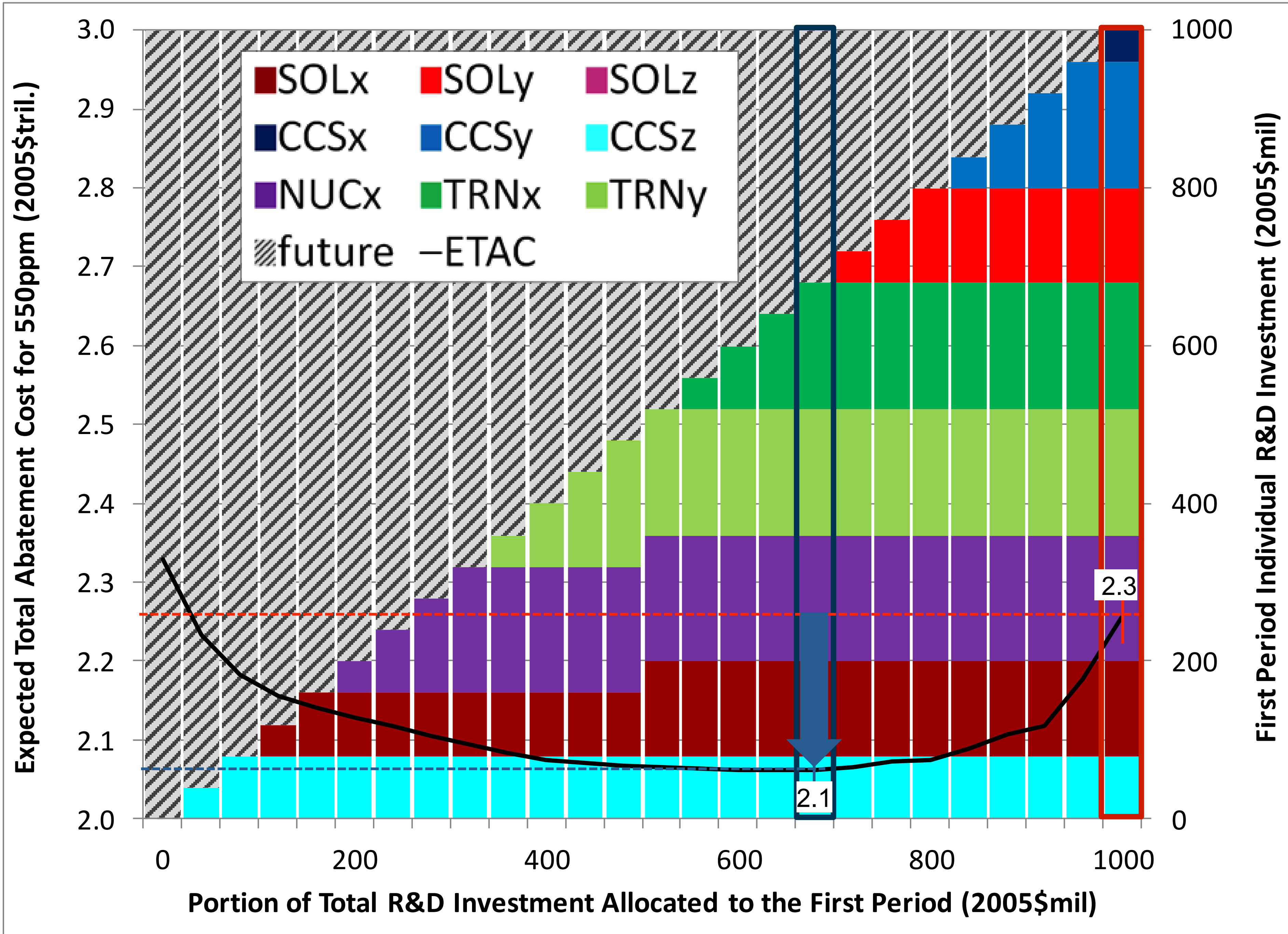
Thank You from the Galaxy Far Far Away



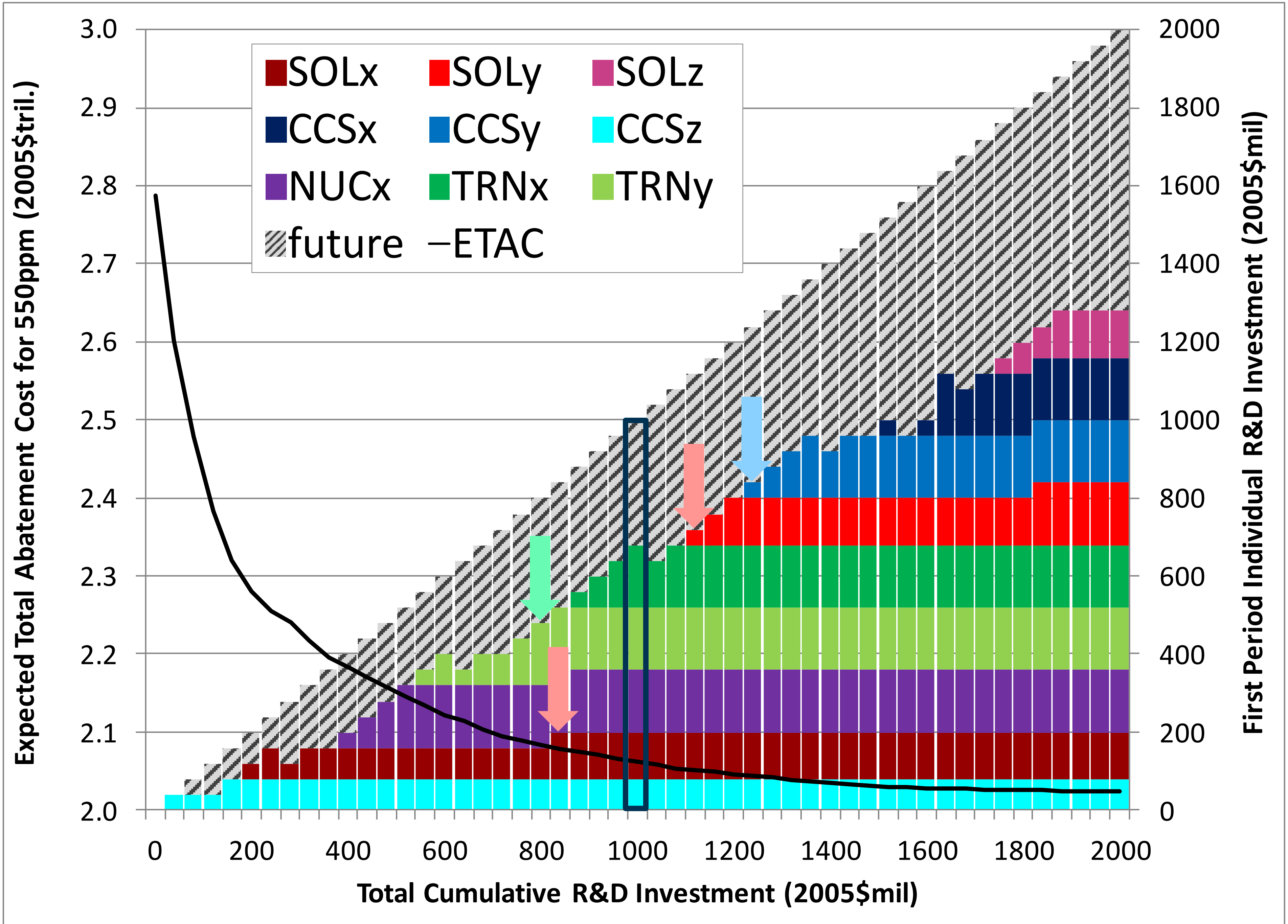
Does target stringency matter?

Rank	max impact 450		max impact 550		Marginal P of Success		SDP1 450		SDP1 550		SDP2 450		SDP2 550	
1	CCSz	40	NUCx	40	CCSz	40	CCSz	40	CCSz	40	CCSz	40	CCSz	40
2	CCSz	80	NUCx	80	SOLx	40	CCSz	80	CCSz	80	CCSz	80	CCSz	80
3	NUCx	40	NUCx	120	SOLx	80	SOLx	40	SOLx	40	SOLx	40	SOLx	40
4	NUCx	80	NUCx	160	CCSz	80	NUCx	40	SOLx	80	NUCx	40	SOLx	80
5	NUCx	120	CCSz	40	TRNy	40	NUCx	80	NUCx	40	NUCx	80	NUCx	40
6	NUCx	160	CCSz	80	TRNy	80	NUCx	120	NUCx	80	NUCx	120	NUCx	80
7	CCSy	40	CCSy	40	TRNx	40	NUCx	160	NUCx	120	NUCx	160	NUCx	120
8	CCSy	80	CCSy	80	TRNx	80	TRNy	40	NUCx	160	TRNy	40	NUCx	160
9	CCSy	120	CCSy	120	TRNx	120	TRNy	80	TRNy	40	TRNy	80	TRNy	40
10	CCSy	160	CCSy	160	TRNx	160	SOLx	80	TRNy	80	SOLx	80	TRNy	80
11	CCSx	40	TRNy	40	SOLy	40	TRNy	120	SOLx	120	TRNy	120	TRNy	120
12	CCSx	80	TRNy	80	SOLy	80	TRNy	160	TRNy	120	TRNy	160	TRNy	160
13	CCSx	120	TRNy	120	SOLy	120	CCSy	40	TRNy	160	TRNx	40	SOLx	120
14	CCSx	160	TRNy	160	SOLx	120	TRNx	40	TRNx	40	TRNx	80	TRNx	40
15	TRNy	40	SOLx	40	TRNy	120	TRNx	80	TRNx	80	TRNx	120	TRNx	80
16	TRNy	80	SOLx	80	TRNy	160	TRNx	120	TRNx	120	TRNx	160	TRNx	120
17	TRNy	120	SOLx	120	CCSy	40	TRNx	160	TRNx	160	CCSy	40	TRNx	160
18	TRNy	160	SOLy	40	NUCx	40	CCSy	80	CCSy	40	CCSy	80	SOLy	40
19	TRNx	40	SOLy	80	NUCx	80	CCSy	120	CCSy	80	CCSy	120	SOLy	80
20	TRNx	80	SOLy	120	NUCx	120	CCSy	160	CCSy	120	CCSy	160	SOLy	120
21	TRNx	120	SOLy	160	NUCx	160	CCSx	40	CCSy	160	SOLx	120	CCSy	40
22	TRNx	160	SOLz	40	CCSy	80	CCSx	80	SOLy	40	CCSx	40	CCSy	80
23	SOLx	40	SOLz	80	CCSy	120	CCSx	120	SOLy	80	CCSx	80	CCSy	120
24	SOLx	80	SOLz	120	CCSy	160	CCSx	160	SOLy	120	CCSx	120	CCSy	160
25	SOLx	120	CCSx	40	CCSx	40	SOLx	120	CCSx	40	CCSx	160	CCSx	40
26	SOLy	40	CCSx	80	CCSx	80	SOLy	40	CCSx	80	SOLy	40	CCSx	80
27	SOLy	80	CCSx	120	CCSx	120	SOLy	80	CCSx	120	SOLy	80	CCSx	120
28	SOLy	120	CCSx	160	CCSx	160	SOLy	120	CCSx	160	SOLy	120	CCSx	160
29	SOLy	160	TRNx	40	SOLz	40	SOLz	40	SOLz	40	SOLz	40	SOLz	40
30	SOLz	40	TRNx	80	SOLz	80	SOLz	80	SOLz	80	SOLz	80	SOLz	80
31	SOLz	80	TRNx	120	SOLy	160	SOLy	160	SOLy	160	SOLy	160	SOLy	160
32	SOLz	120	TRNx	160	SOLz	120	SOLz	120	SOLz	120	SOLz	120	SOLz	120


SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
ETAC
Expected Total Abatement Cost for 550ppm (2005$tril.)
First Period Individual R&D Investment (2005$mil)
Total Cumulative R&D Investment (2005$mil)
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200



SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
−ETAC
2.3
2.1
Expected Total Abatement Cost for 550ppm (2005$tril.)
First Period Individual R&D Investment (2005$mil)
Portion of Total R&D Investment Allocated to the First Period (2005$mil)
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1000
800
600
400
200
0
0
200
400
600
800
1000



SOLx
SOLy
SOLz
CCSx
CCSy
CCSz
NUCx
TRNx
TRNy
future
ETAC
Expected Total Abatement Cost for 550ppm (2005$tril.)
First Period Individual R&D Investment (2005$mil)
Total Cumulative R&D Investment (2005$mil)
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
2000
1800
1600
1400
1200
1000
800
600
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200
0
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200
400
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1000
1200
1400
1600
1800
2000