# How Grid Integration Costs Impact the Optimal R&D Portfolio into Electricity Supply Technologies in the Face of Climate Change

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# Motivation

R&D into renewable energy makes reducing CO2 emissions cheaper and easier, but…

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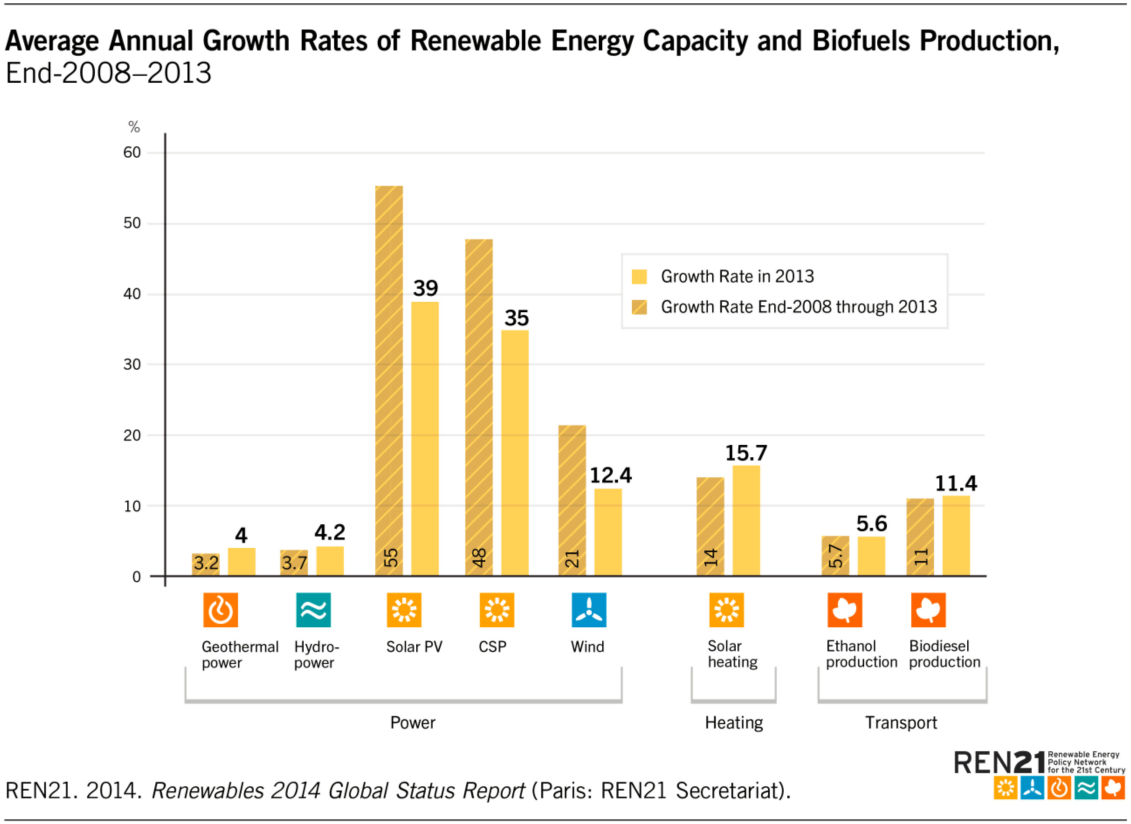
R&D into renewable energy makes reducing CO2 emissions cheaper and easier, but…

Non-dispatchable generation creates problems for the grid.

Modeling grid integration is difficult and expensive.

We would like to place bounds on the value of problem before we embark on a costly modeling exercise.



# Strategy

- Construct a pair of two-stage stochastic models
  - The Budget Constrained Model (BCM).
  - The Overall Optimal Model (OOM).

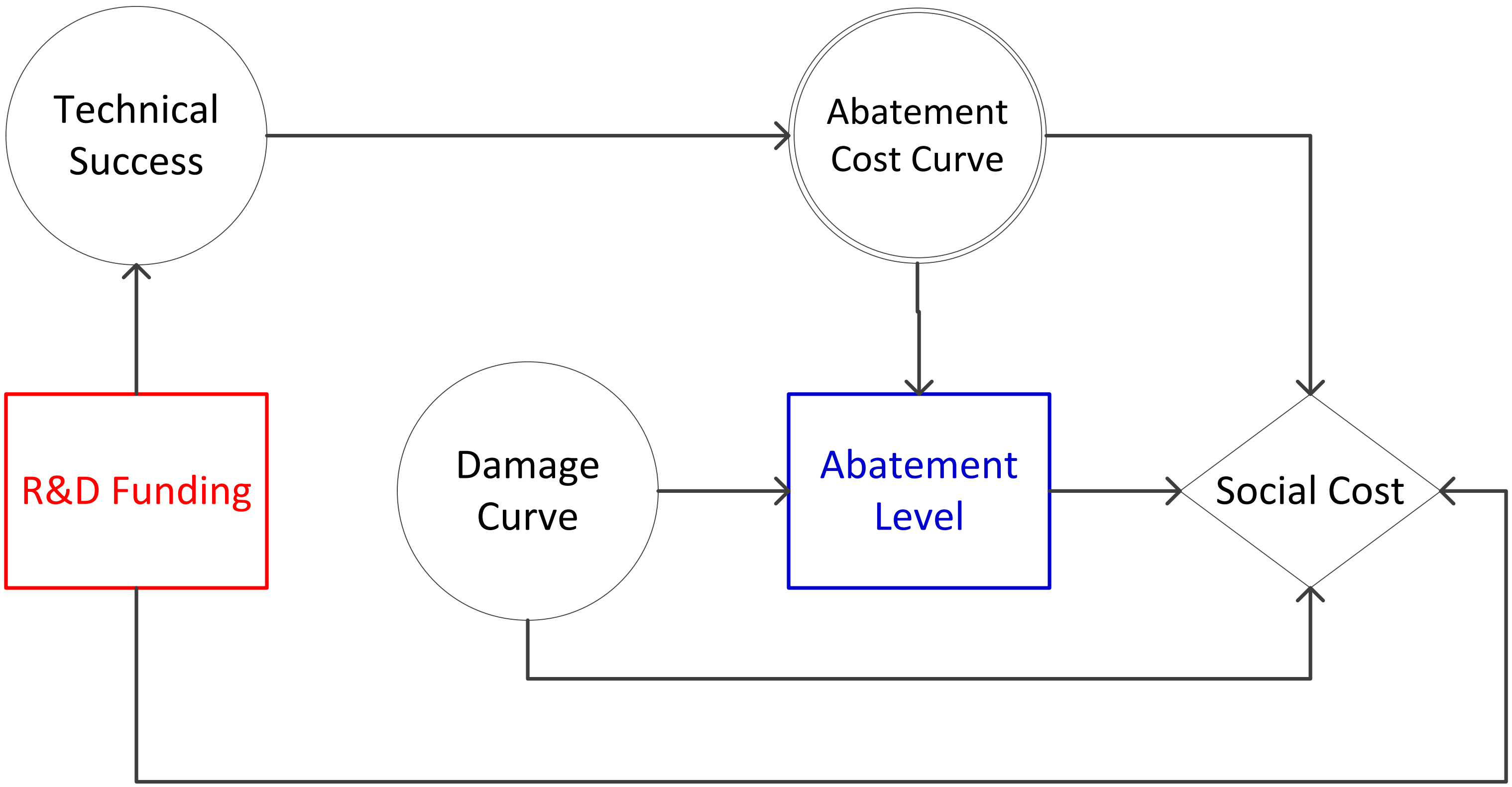
- Use GCAM to estimate the effect of technological change and integration costs on the cost of abatement.

- Run the stochastic models under two extreme assumptions about grid integration costs.
  - Costly Integration
  - Free Integration

# Influence Diagram

Two Stage Model

- Stage 1: Choose R&D portfolio.
- Stage 2: Choose abatement.

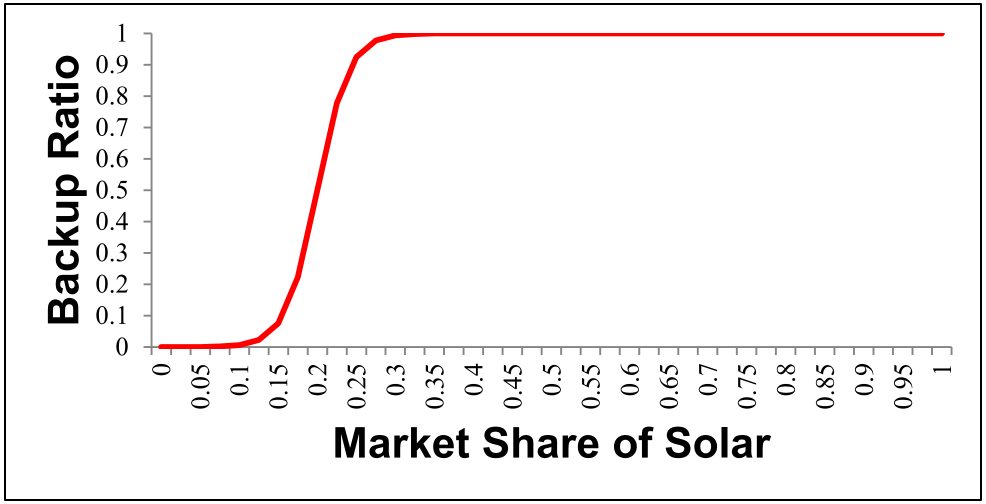


# Grid Integration Assumptions

**Costly Storage Assumption (CSA)**

The GCAM default integration cost model.

- Two competing options for intermittency.
- Backup requires gas fired backup.




- Storage assumes PV is paired with storage at some additional cost

**Free Storage Assumption (FSA)**

Sets the cost of energy storage in GCAM to zero.

# The R&D Menu and Portfolio

- Elicitations done by Baker, Chon and Kiesler (2008, 2008a, 2008b)
- DM chooses one funding level for each project.
- The resulting vector $\boldsymbol{x} = [x_{ijk}] \forall ijk$ is the *Investment Portfolio.*

| Technology (i) | Project (j) | Funding Level (MM 2008 $) (k) | | | |
|---|---|---|---|---|---|
| | | High (1) | Medium (2) | Low (3) | None (4) |
| 1: Solar | 1: Organic | 386 | 154 | 39 | 0 |
| | 2: Inorganic | 56 | 38 | 19 | 0 |
| | 3: 3rd Gen | 519 | 224 | 52 | 0 |
| 2: Nuclear | 1: Light Water Reactor | 346 | 260 | 173 | 0 |
| | 2: High Temperature Reactor | 3089 | 1544 | 772 | 0 |
| | 3: Fast Reactor | 15443 | 4633 | 1158 | 0 |
| 3: CCS | 1: Pre Combustion | N/A | 830 | 116 | 0 |
| | 2: Chemical Loop | N/A | 77 | 39 | 0 |
| | 3: Post Combustion | N/A | N/A | 386 | 0 |

# Effect of R&D on Abatement Cost

Given our investment portfolio $\boldsymbol{x}$ define a binary random indicator variable

$$Y_{ij}(\boldsymbol{x}) = \begin{cases} 1 \; if \; project \; ij \; is \; successful \\ 0 \; otherwise \end{cases}$$

and $a_{ij}$, a parameter that represents the effect of success in project $i, j$ on the MAC.

Now, define a vector $\boldsymbol{s} = (s_1, s_2, \dots, s_i); s_i = \max_j [a_{ij} y_{ij}]$ to represent the state of technology.

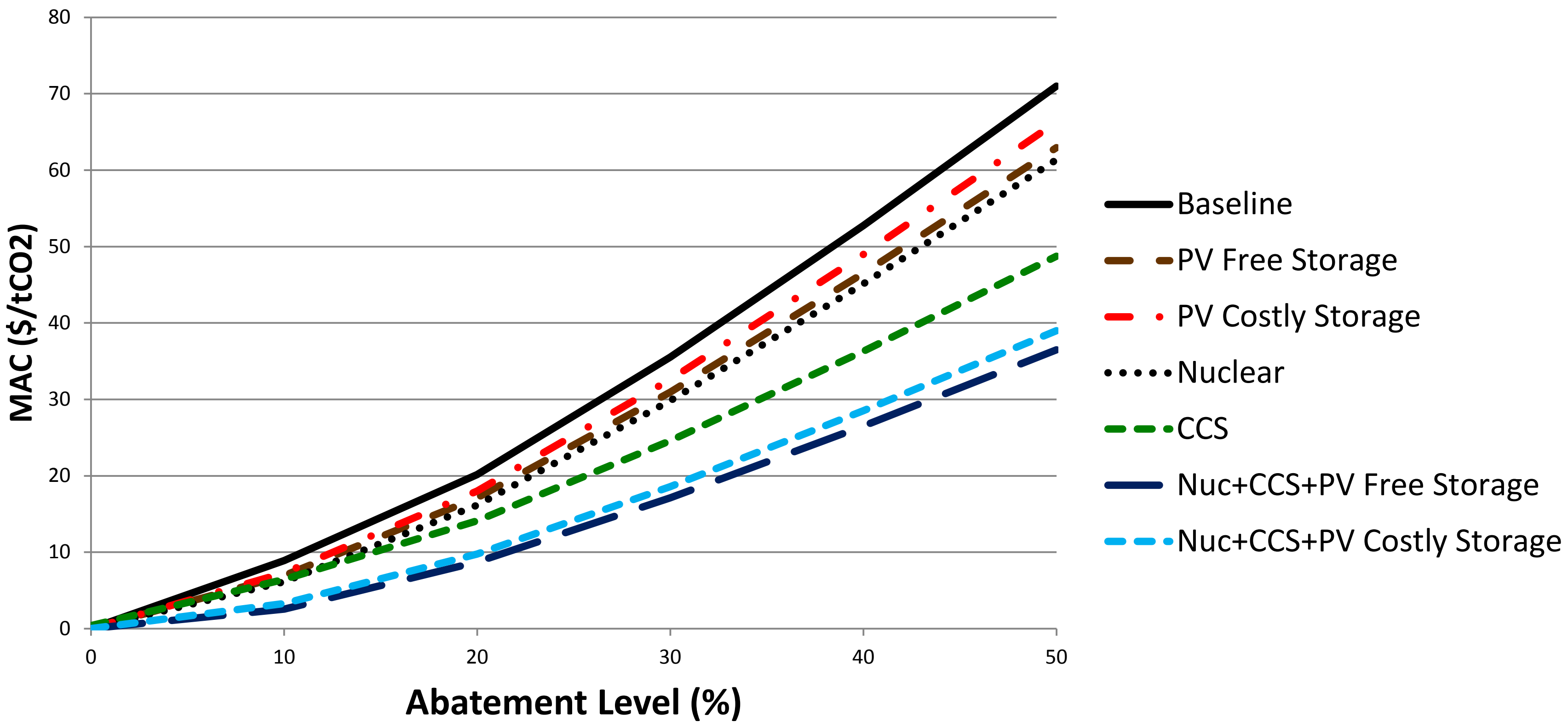
Let $\alpha(\boldsymbol{s})$ and $h(\boldsymbol{s})$ be random scalars that represent the combined effect of all of the technological successes corresponding to technological state $\boldsymbol{s}$, on the Marginal Abatement Cost (MAC).

Now, define the MAC:

$$\widetilde{MAC}\big(\mu\!: \alpha(\boldsymbol{s}), h(\boldsymbol{s})\big) = \big(1 - \alpha(\boldsymbol{s})\big)\big(MAC(\mu) - h(\boldsymbol{s})MAC(0.5)\big)$$

# Estimating Technology's Effect on the MAC Curve

$$\widetilde{MAC}(\mu\colon \alpha(\boldsymbol{s}), h(\boldsymbol{s})) = (1-\alpha(\boldsymbol{s}))(MAC(\mu) - h(\boldsymbol{s})MAC(0.5))$$




(After Baker and Solak, 2011)

# The Budget Constrained Model (BCM)

$$\min_{x_{ijk}} \left( E_{S,Z} \left[ \min_{\mu} [C(\mu: \alpha(\mathbf{s}), h(\mathbf{s})) + ZD(\mu)] \right] \right)$$

s.t.

$$\sum_{ijk} x_{ijk} F_{ijk} \leq B$$

$$\sum_{k} x_{ijk} = 1 \; \forall \, i, j$$

$$x_{ijk} \in \{0,1\}$$

Where

| | |
|---|---|
| $B$ | Budget Constraint |
| $Z$ | Stochastic damage risk multiplier |
| $\alpha, h$ | Technological change parameters |
| $x_{ijk}$ | Binary decision variable to fund project $ijk$ |
| $F_{ijk}$ | Cost of funding project $ijk$ |
| $\boldsymbol{s}$ | Vector representing the state of technology |

# The Overall Optimal Model

$$\underset{x_{ijk}}{\text{Min}}\left(\beta\sum\nolimits_{ijk} x_{ijk}F_{ijk} + E_{S,Z}\left[\min_{\mu}[C(\mu:\alpha(\boldsymbol{s}),h(\boldsymbol{s})) + ZD(\mu)]\right]\right)$$

st

$$\sum\nolimits_{k} x_{ijk} = 1 \ \forall \ i,j$$

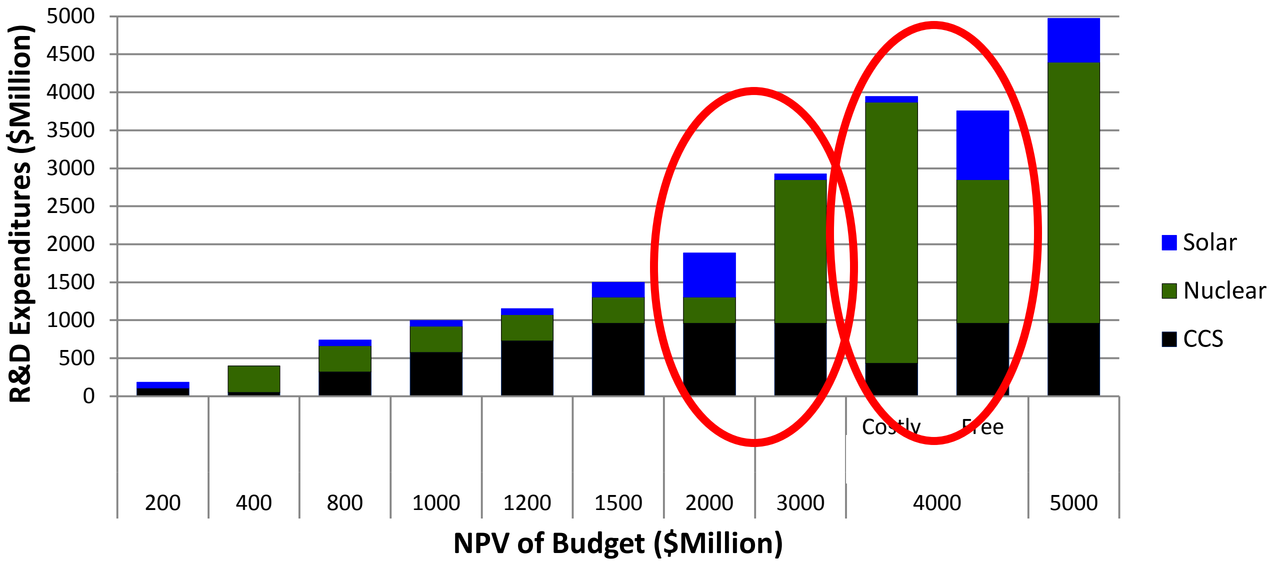
$$x_{ijk} \in \{0,1\}$$

Where

$\beta$ is an opportunity cost multiplier that reflects the opportunity cost of R&D investments.

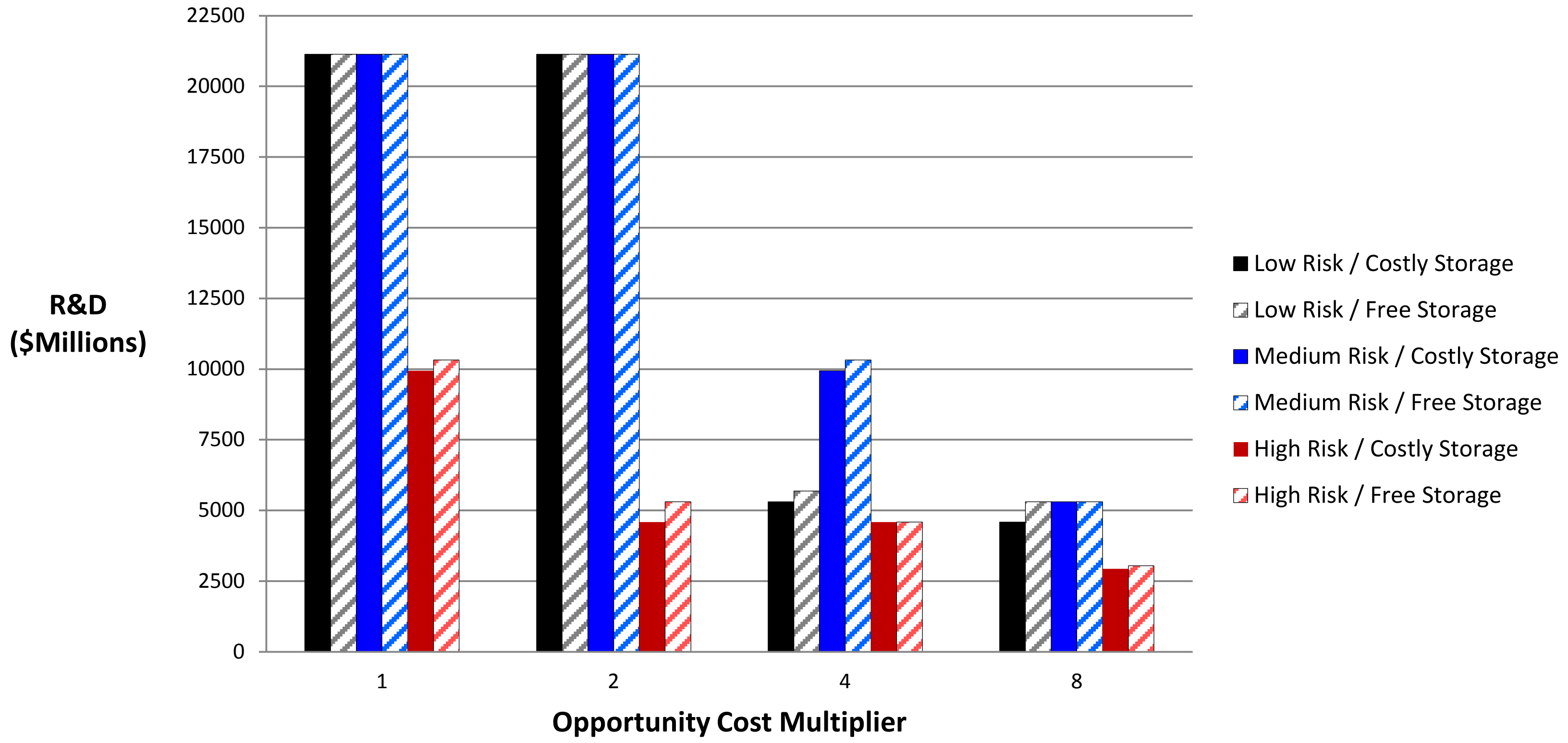
The OOM moves the budget constraint to the objective function and adds an opportunity cost multiplier.

# Budget Constrained Model




- Grid integration assumptions have little impact – only one difference.
- Lumpy problem – moving from 2000-3000 greatly increases nuclear at the expense of solar.

# Overall Optimal Model




- Grid integration assumptions make a difference here.

# Overall Optimal Model

| | | | CCS | | | Nuclear | | | Solar | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Climate Damage Risk Level** | **Cost Multiplier** | **Integration Cost** | **Pre Combustion** | **Chemical Looping** | **Post Combustion** | **Light Water Reactors** | **High Temp. Reactors** | **Fast reactors** | **Organic** | **Inorganic** | **3rd Gen.** | **Total R&D cost ($ MM)** |
| **Low** | **1** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | **2** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | **4** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | ***0*** | 5303 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | 386 | 5689 |
| | **8** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 0 | ***116*** | 77 | 0 | 4589 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | 0 | 5303 |
| **Medium** | **1** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | **2** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 15443 | 830 | 77 | 386 | 21132 |
| | **4** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 4633 | 830 | 77 | ***0*** | 9936 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 4633 | 830 | 77 | 386 | 10322 |
| | **8** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | 0 | 5303 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | 0 | 5303 |
| **High** | **1** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 4633 | 830 | 77 | ***0*** | 9936 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 4633 | 830 | 77 | 386 | 10322 |
| | **2** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 0 | ***116*** | 77 | 0 | 4589 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 0 | 830 | 77 | 0 | 5303 |
| | **4** | **Costly** | 386 | 56 | 519 | 346 | 3089 | 0 | 116 | 77 | 0 | 4589 |
| | | **Free** | 386 | 56 | 519 | 346 | 3089 | 0 | 116 | 77 | 0 | 4589 |
| | **8** | **Costly** | 386 | 56 | 519 | 346 | 1544 | 0 | ***0*** | 77 | 0 | 2928 |
| | | **Free** | 386 | 56 | 519 | 346 | 1544 | 0 | 116 | 77 | 0 | 3044 |

- Investments in Organic and 3rd gen solar increase under the FSA

# Conclusions

- Under a budget constraint grid integration assumptions have little impact on the optimal R&D portfolio.
- In the absence of a budget constraint grid integration assumptions do make a difference.
- Getting grid integration costs right depends on the question being asked: how to allocate a exogenously specified budget, or what size the budget should be.

# Questions?

# References

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# Definitions

| | |
|---|---|
| **DICE:** | The Dynamic Integrated Model of the Climate and Economy (Nordhaus 2008). |
| **GCAM:** | The Global Change Assessment Model (JGCRI 2012). |
| **Integration Cost:** | Any cost imposed by intermittency. |
| **Abatement:** | A reduction in emissions below the business-as-usual baseline. |

# Abatement and Damage Functions

- Damages

$$D(\mu) = M_0(Q - M_1\mu)$$

Where $M_0, M_1$: Parameters of the damage function.
$Q$: BAU quantity of carbon emissions.
$\mu$: Abatement as a proportion of BAU emissions

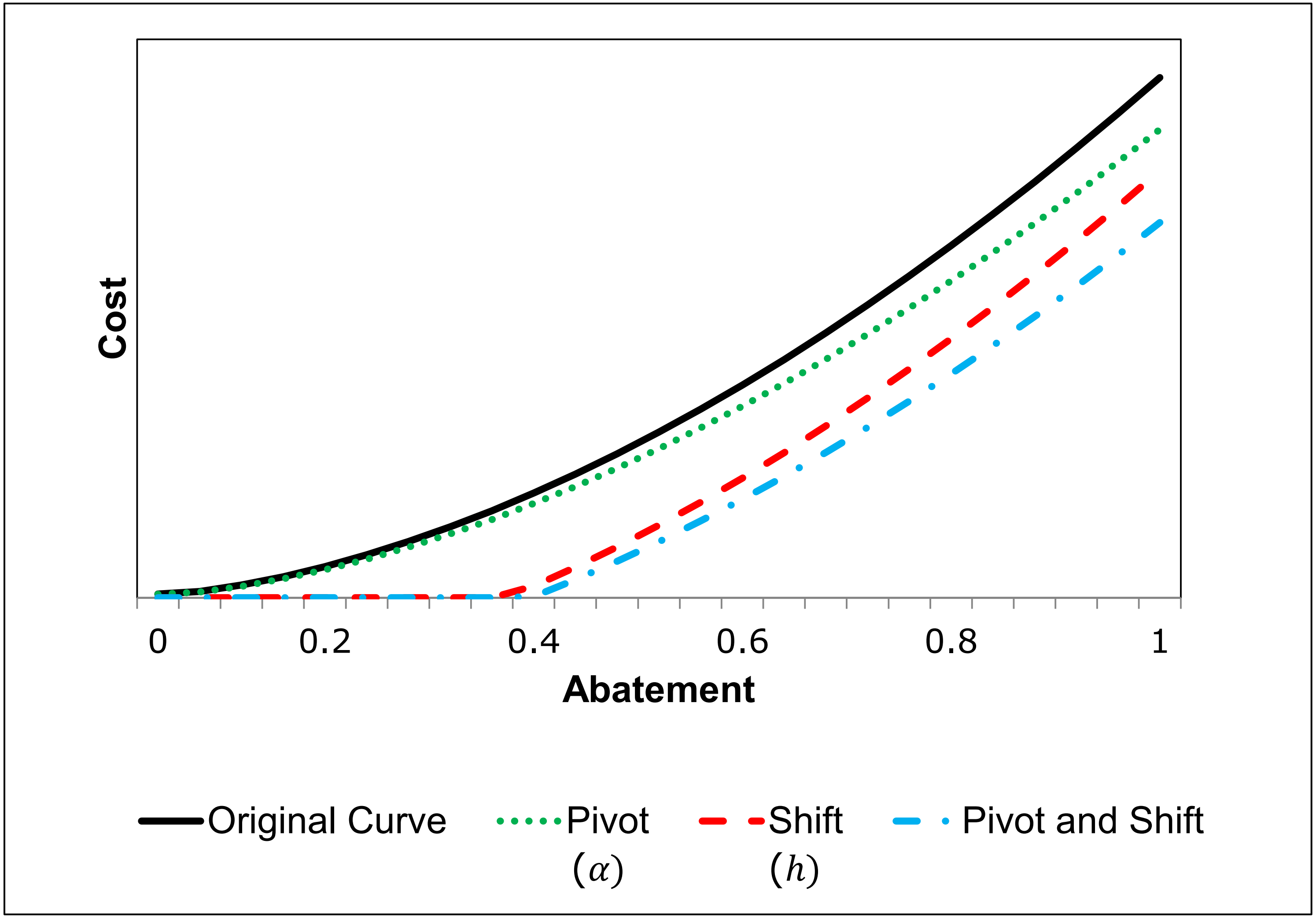
- Abatement Cost

$$C(\mu) = b_0\mu^{b_1}$$

Where $b_0$,$b_1$ are calibration parameters.

This work considers abatement cost in terms of the Marginal Abatement Cost (MAC).

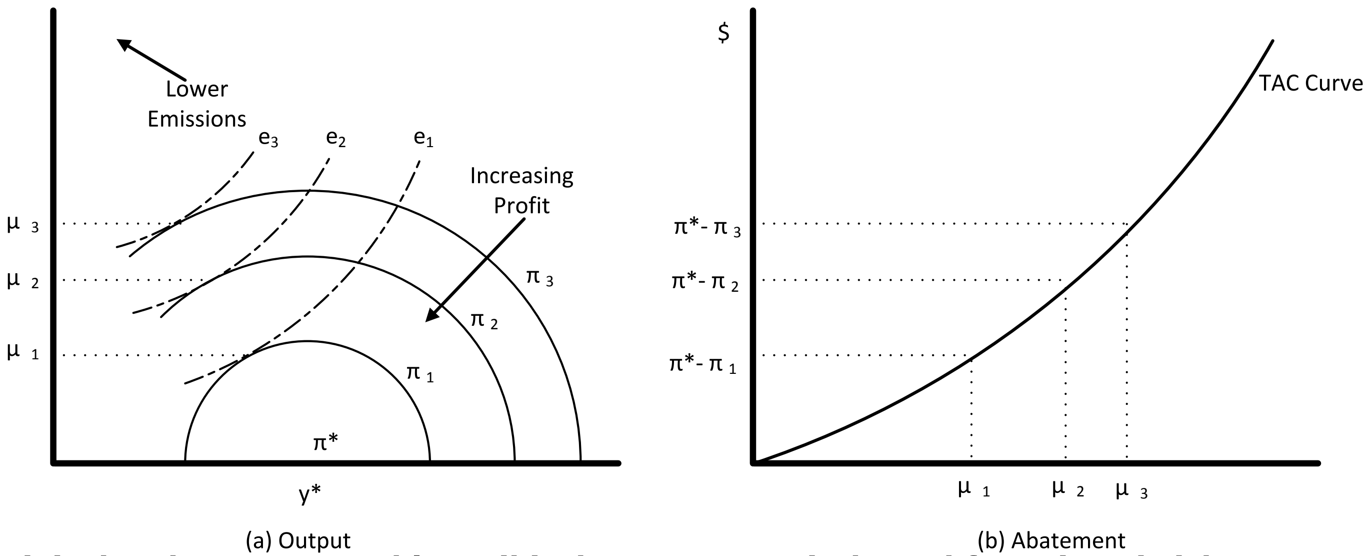
# Technological Change and the Abatement Cost Function



# The Abatement Cost Function

Abatement: Reduction in emissions below some baseline.

Abatement cost: Difference in profit/GDP with and without an emissions constraint, WRT abatement level.




**(a) The abatement problem, (b) The TAC curve (Adapted from (McKitrick 1999, 306-314)).**

Marginal Abatement Cost (MAC): $MAC(\mu) = TAC'(\mu)$

# Calibration

- After Peng (2010)

$$D(\mu) = M_0(S - M_1\mu)^2$$

Where $S$ is the initial emissions stock ($2.5 \times 10\text{^}12$ tc) and under the BAU ($\mu = 0$) scenario the NPV of damages is $17.7 trillion.

$$D(\mu = 0) = M_0 S^2 = \$17.7 \times 10^{12} \rightarrow M_0 = 2.74$$

Now let $\mu_0 = 0.462$ be average abatement from 2005-2095 in the optimal case, and the NPV of damages be $13.54 trillion.

$$D(\mu_0) = 2.74(S - M_1\mu_0)^2 = \$13.54 \times 10^{12} \rightarrow M_1 = 0.6$$

# Calibration

- Abatement cost in DICE is given by

$$c(\mu) = b_0 \mu^{b_1}$$

Recognize that in the optimal case $\frac{\partial c(\mu)}{\partial \mu} = \frac{\partial D(\mu)}{\partial \mu} = 0$

From DICE $b^1 = 2.8$

Solving yields $b_0 = 10.43$ and

$$C(\mu) = 10.43\mu^{2.8}$$