Investment in U.S. Power Generation Facilities Under Regulation and Natural Gas Price Uncertainty: Timing of Plant Retirement and New Technology Choice

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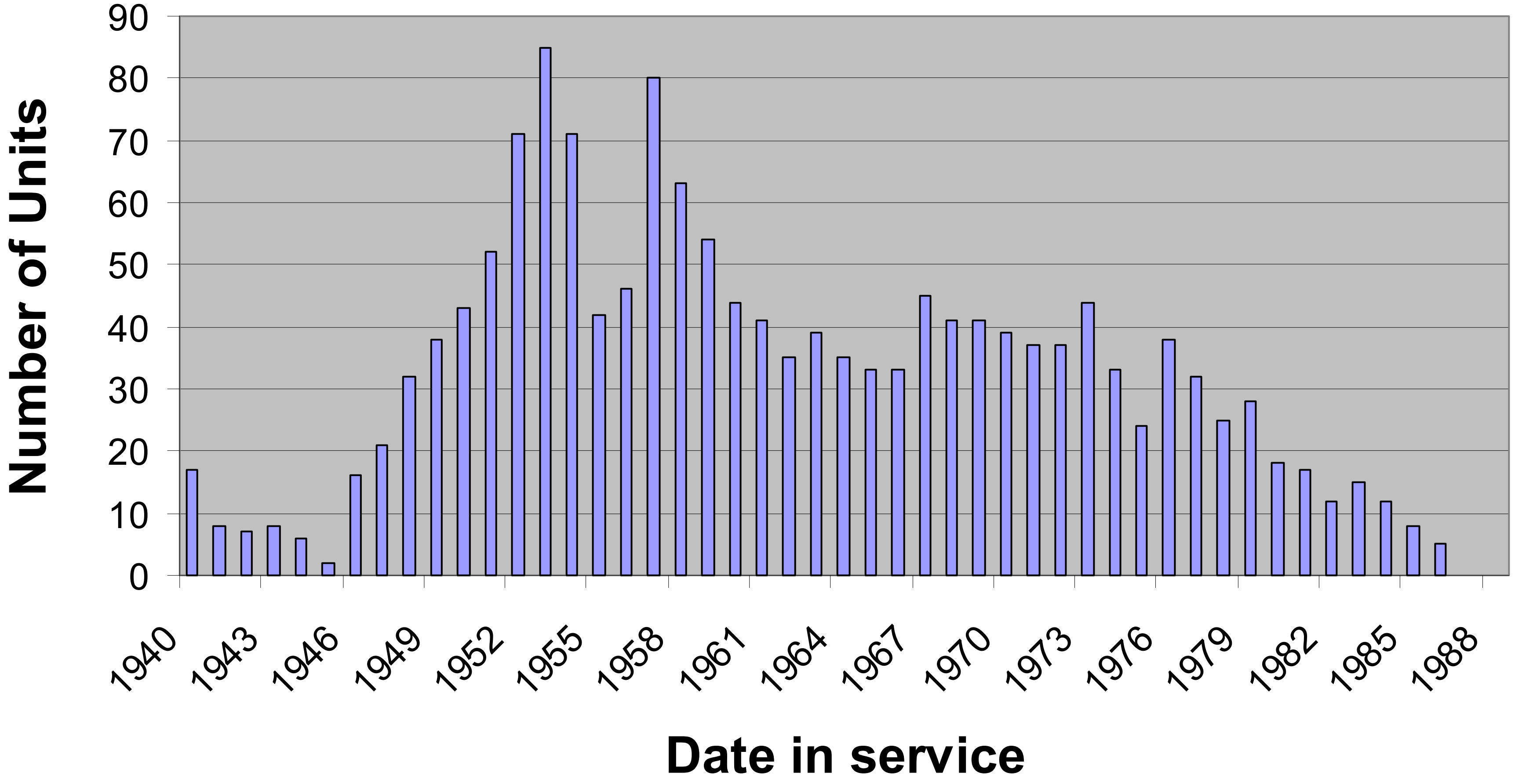
Like the rest of us, coal plant’s are not getting any younger….

Age distribution of 1200 coal plants larger than 50 MW



What to do with the coal fleet?

Current status in the US

1. Large aging fleet accounts of >50% of US generation.
2. New source review, and related regulatory uncertainty, high-S → low-S, and combustion related NOx control have all played a role in long plant lifetimes.
3. Plant level regulatory uncertainties: 3P and CO_2.
4. Factor cost uncertainties: NG price. IGCC cost & performance.

Climate policy and the future of coal-fired electricity

- We will regulate carbon but timing and structure of regulations is uncertain.

- Lots of new coal will be built in next few decades
  - In US, the coal fleet is aging. Substantial new builds likely absent climate policy.
  - In developing world (China) many 100's of GW are planed, huge build up already underway.

- Options for reducing CO_2 emissions
  - Coal with CO_2 capture and storage (CCS), nuclear and wind have high capital costs but low operating cost (under a carbon price).
  - Gas has low capital cost but gas prices rising and volatile.
  - IGCC more expensive (and/or risky) than conventional coal but offers relatively cheap upgrade path to CCS.

Questions

1. How does the threat of future restrictions on carbon emissions affect current private investment decisions?
2. Does regulatory uncertainty combined with irreversible investment create an incentive to delay retirement of existing coal plants with associated power generation cost and pollution consequences?
3. How valuable is the flexibility that arises from building IGCC plants for which the cost of later CCS retrofits is comparatively small?
4. What is the social cost of regulatory uncertainties?
5. How is the cost effectiveness of CO2 reductions influence by regulatory uncertainty and the flexibility provided by CCS retrofits?

Minimize Present Value Cost of Electricity Generation

Minimize the Expected Present Value Cost of Electricity Generation Using Stochastic Dynamic Programming Methods

Initial Condition: Firm begins with an aging PC plant

Action Space: Each period the firm must make an investment choice

1) keep existing plant,
2) build Advanced PC plant (APC),
3) build NGCC plant,
4) build IGCC plant,
5) build IGCC + CCS plant,
6) retrofit existing IGCC plant with CCS

Minimize Present Value Cost of Electricity Generation

State Space: Prior investment, market prices, and CO_2 regulations define the state of the firm's power generation operation each period

1) technology
2) plant age
3) P_{NG}
4) P_{carbon}

Cost Each Period a Function of

1) Capital Investment (technology)
2) FOM (plant age, technology)
3) VOM (technology)
4) Fuel Cost (time, technology)
5) Regulation Cost (price of carbon, technology)

Summary of Model Parameters

Technology	*PC*	*APC*	*NGCC*	*IGCC*	*IGCC+CCS*
Capital Cost ($/kW)	0	1200	450	1200+C_{rp}	1600+C_{rp}
Initial Fixed O&M ($/kW)	30	22	15	22	26
Fixed O&M annual increase (%)	**15%**	2%	2%	2%	2%
Variable O&M ($/MWh)	5.0	3.6	0.5	3.6	4.3
Thermal Efficiency (%)	30%	38%	55%	38%	30%
Emissions intensity (tC/MWhr)	0.29	0.22	0.09	0.22	0.02
COE @ 14% CCF, 70% dispatch over 20-year lifetime					
capital	0	30	11	30	39
fuel	13	10	30	10	13
VOM	5	4	1	4	4
FOM	16	4	3	4	5
Carbon Storage					7
Total ($/MWhr)	34	48	45	48	68

Illustrative cost of electricity calculation

Coal price	Fixed at 1.1 $/GJ
Natural gas price	4 $/GJ initial price 0.1 $/GJ-yr increase 0.2 $/GJ annual random standard deviation
Carbon price	20% chance of regulation in 2010, with 2/3 and 1/3 probability of 50 and 200 $/tC. Chance of regulation increases 20% each period it does not occur so that it's certain by 2030
Discount rate	14%
Conventional pollutants	PC is forced out by annual FOM increase as proxy for increasingly stringent regulation of air pollutants.

Minimize Expected Present Value Cost under Uncertainty

Stochastic Dynamic Programming Solution Concept:

At any time, no matter what state a firm finds itself in, it will minimize expected costs to the end of the planning horizon from that state.

Formal Solution:

Let

$V_t(s_t)$ = minimum PV cost to end of time horizon from state s_t at time t
$a^*_t(s_t)$ = optimal decision at time t from state s_t
$c(s_t, a_t)$ = current period cost given state s_t and decision a_t at time t
β = discount factor

Final Period

Minimum PV cost to end of time horizon at beginning of last period

$$V_T(s_T) = \min_{a_T \in A}\left[c(s_T, a_T) - \beta \cdot \text{salvage}(s_{T+1}) \right]$$

where s_T and $a_T \Rightarrow s_{T+1}$

Minimize Expected Present Value Cost under Uncertainty

Backward Induction to Initial Period

For t = T – 1, …, 0

$$
\begin{aligned}
V_t(s_t) &= \min_{a_t \in A}\left[c(s_t, a_t) + E\left[\beta V_{t+1}(s_{t+1}) \right] \right] \\
&= \min_{a_t \in A}\left[c(s_t, a_t) + \beta \int V_{t+1}(s_{t+1}) p(ds_{t+1} \mid s_t, a_t) \right]
\end{aligned}
$$

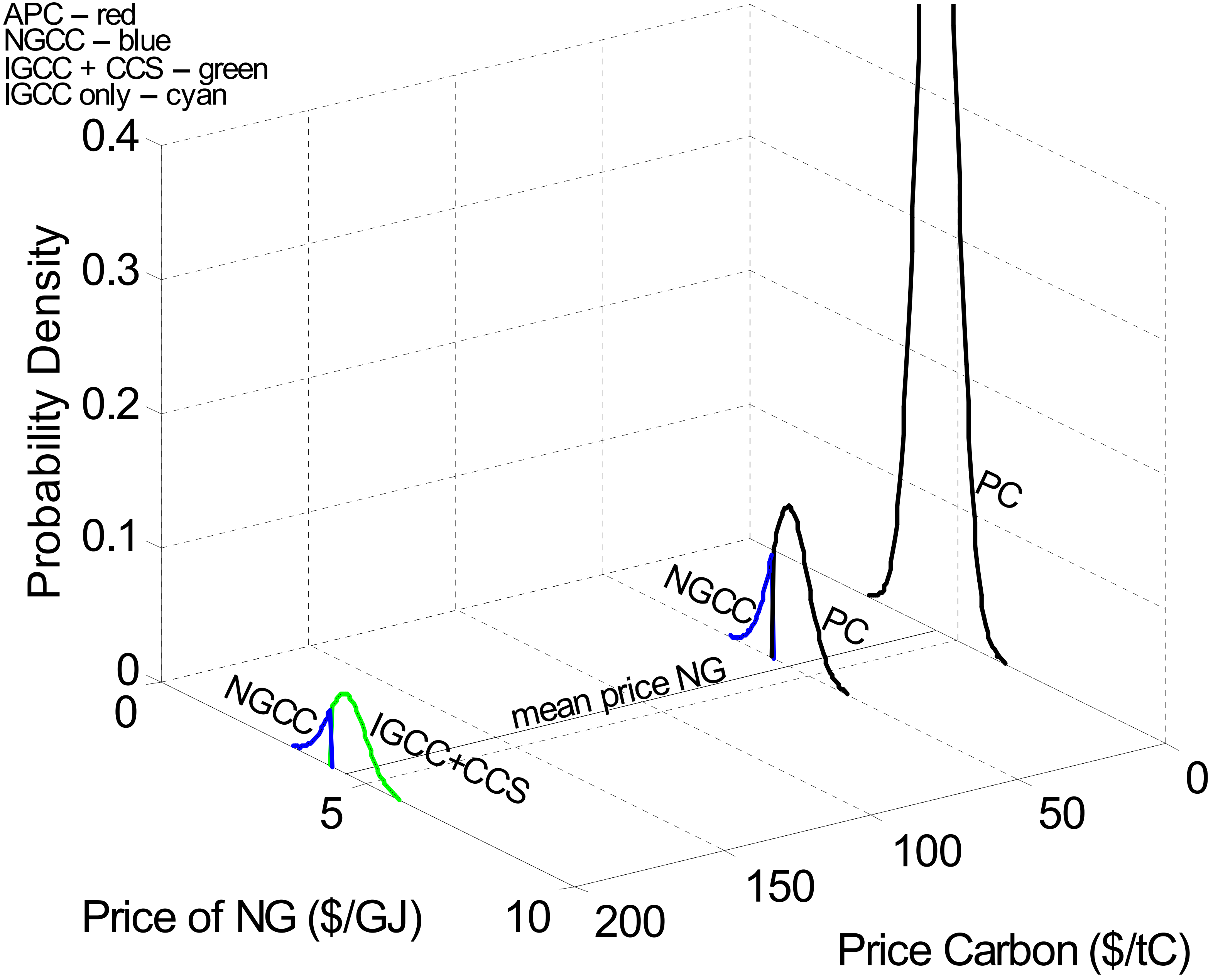
Optimal Solution

$V_0(s_0)$ = Minimum Expected PV cost to end of time horizon from state s_0 at t = 0

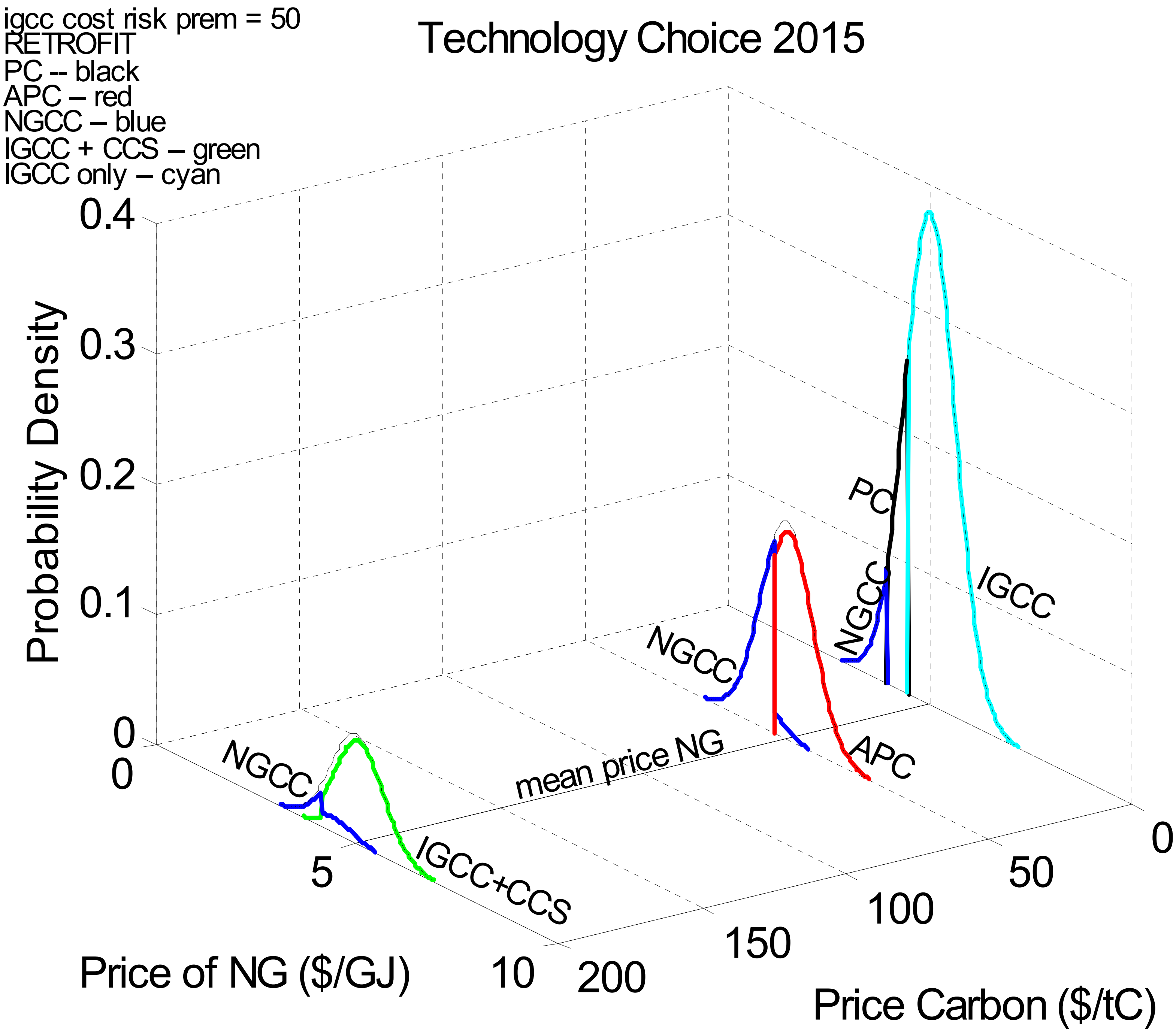
$\left[a_0^*(s_0), a_1^*(s_1), a_2^*(s_1), \ldots, a_T^*(s_T) \right]$ = optimal policy (contingent decision sequence)

Future decisions contingent on future states including P_{NG} and P_{carbon}

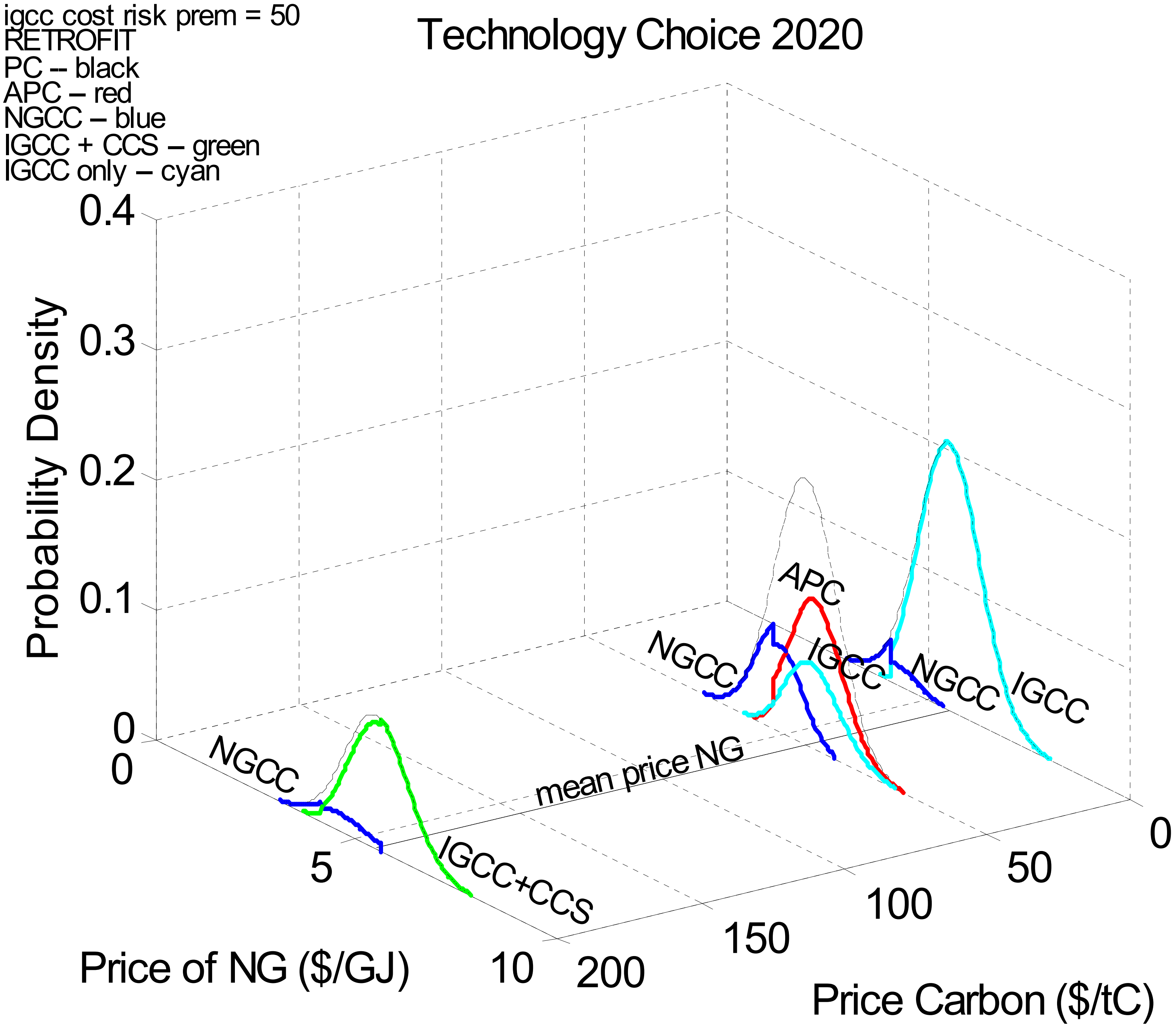
Technology Choice 2010



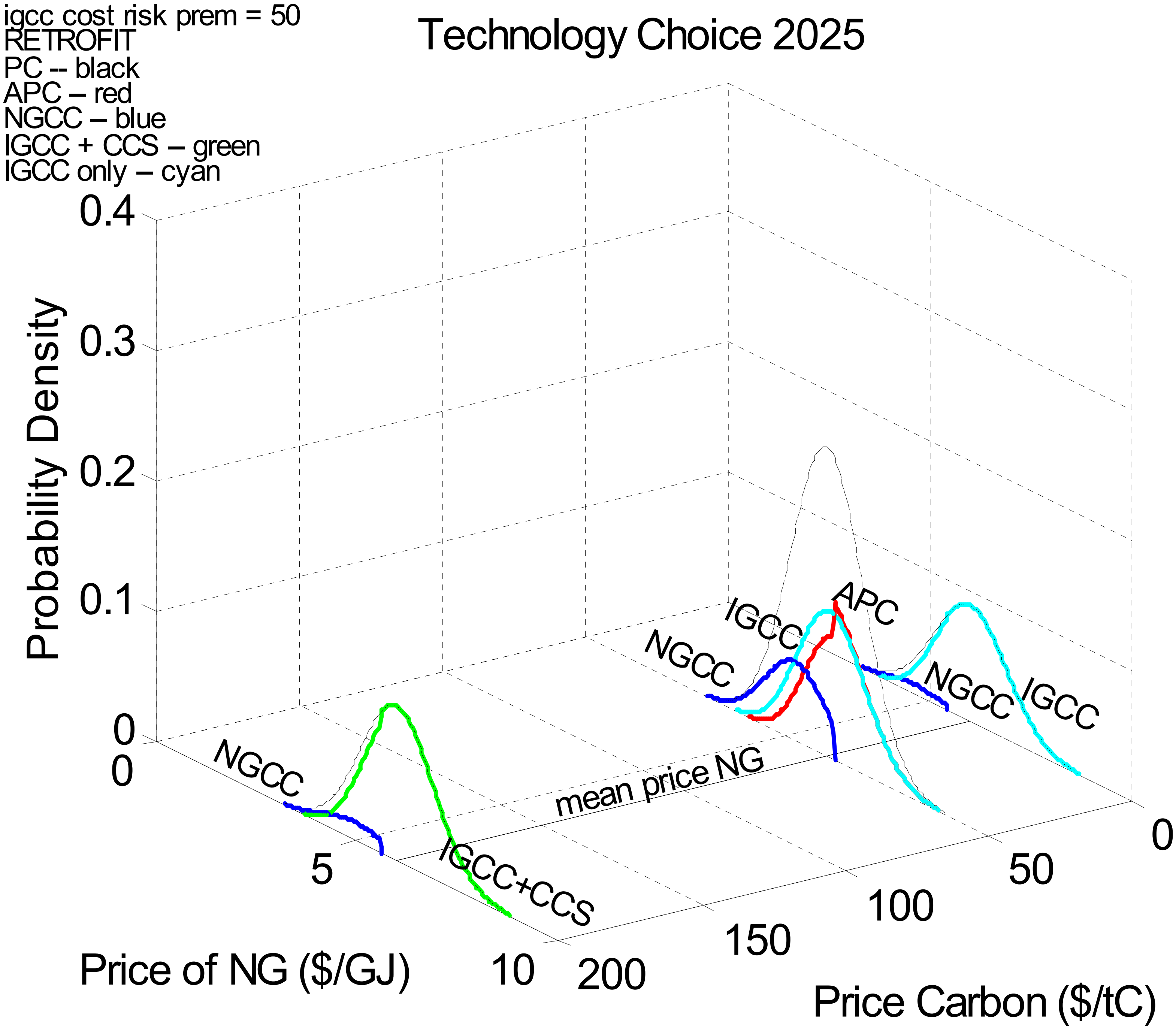
igcc cost risk prem = 50
RETROFIT
PC -- black
APC – red
NGCC – blue
IGCC + CCS – green
IGCC only – cyan


igcc cost risk prem = 50
RETROFIT
PC -- black
APC – red
NGCC – blue
IGCC + CCS – green
IGCC only – cyan
Technology Choice 2015
Probability Density
0.4
0.3
0.2
0.1
0
0
5
10
Price of NG ($/GJ)
200
150
100
50
0
Price Carbon ($/tC)
NGCC
IGCC+CCS
mean price NG
NGCC
APC
NGCC
PC
IGCC

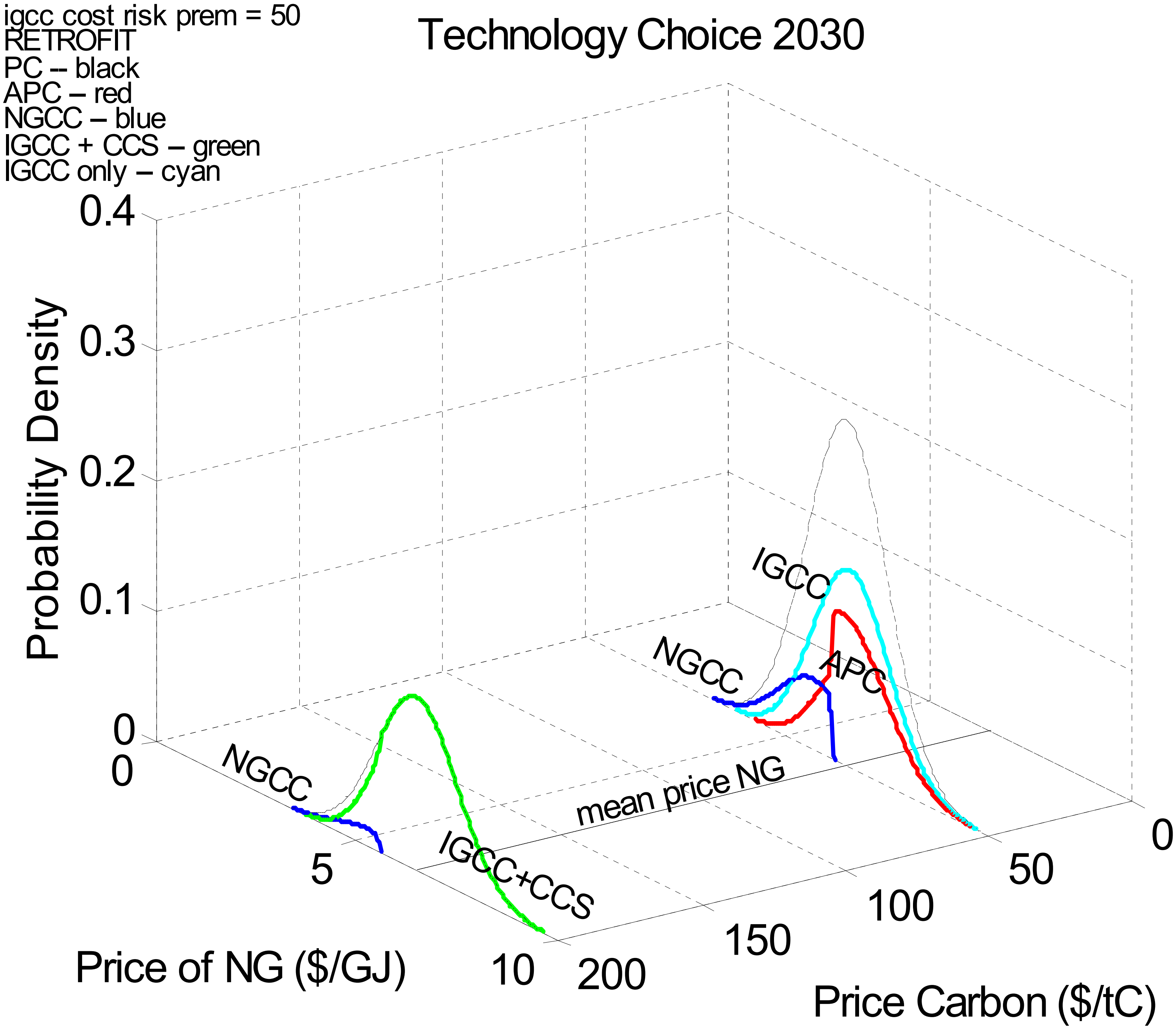
Technology Choice 2020



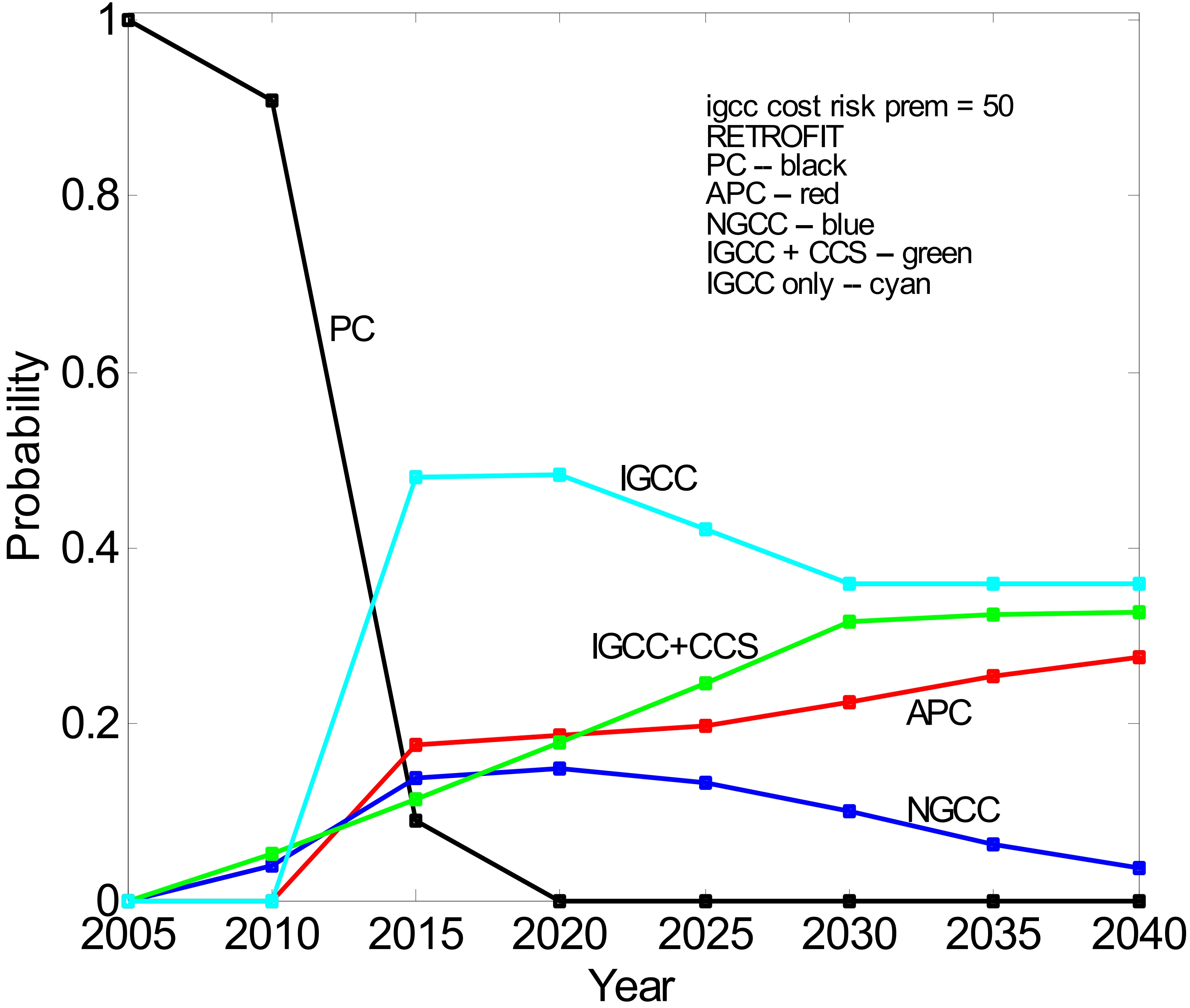
Technology Choice 2025

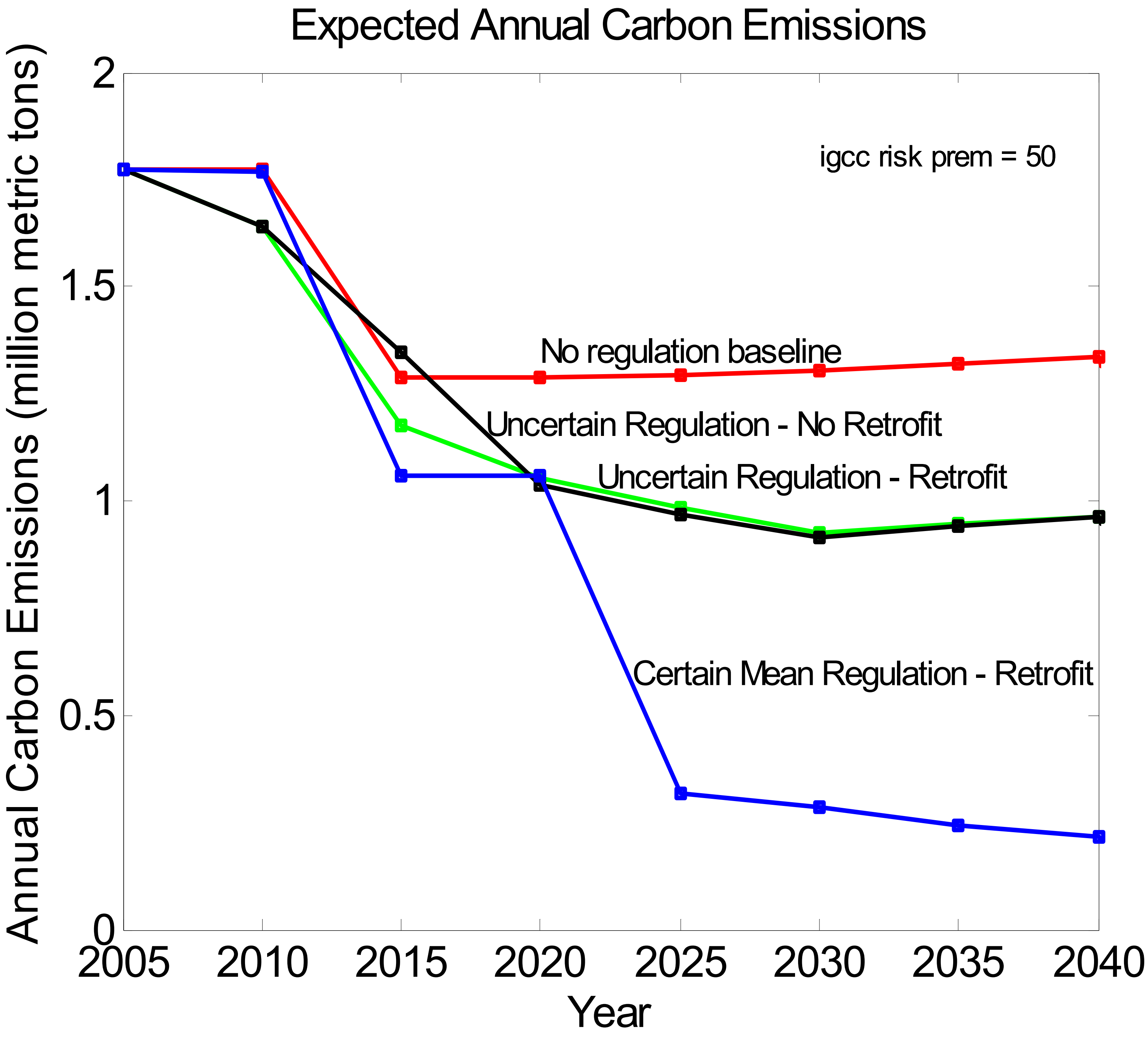


Technology Choice 2030



Technology Probability




Expected Annual Carbon Emissions
Annual Carbon Emissions (million metric tons)
2
1.5
1
0.5
0
2005
2010
2015
2020
2025
2030
2035
2040
Year
igcc risk prem = 50
No regulation baseline
Uncertain Regulation - No Retrofit
Uncertain Regulation - Retrofit
Certain Mean Regulation - Retrofit

CO_2 Abatement Cost Effectiveness Under Regulatory Uncertainty

Numerical measure to quantify the tradeoff between higher electricity generation cost and lower emissions

Expected Social Present Value Cost of Abatement =

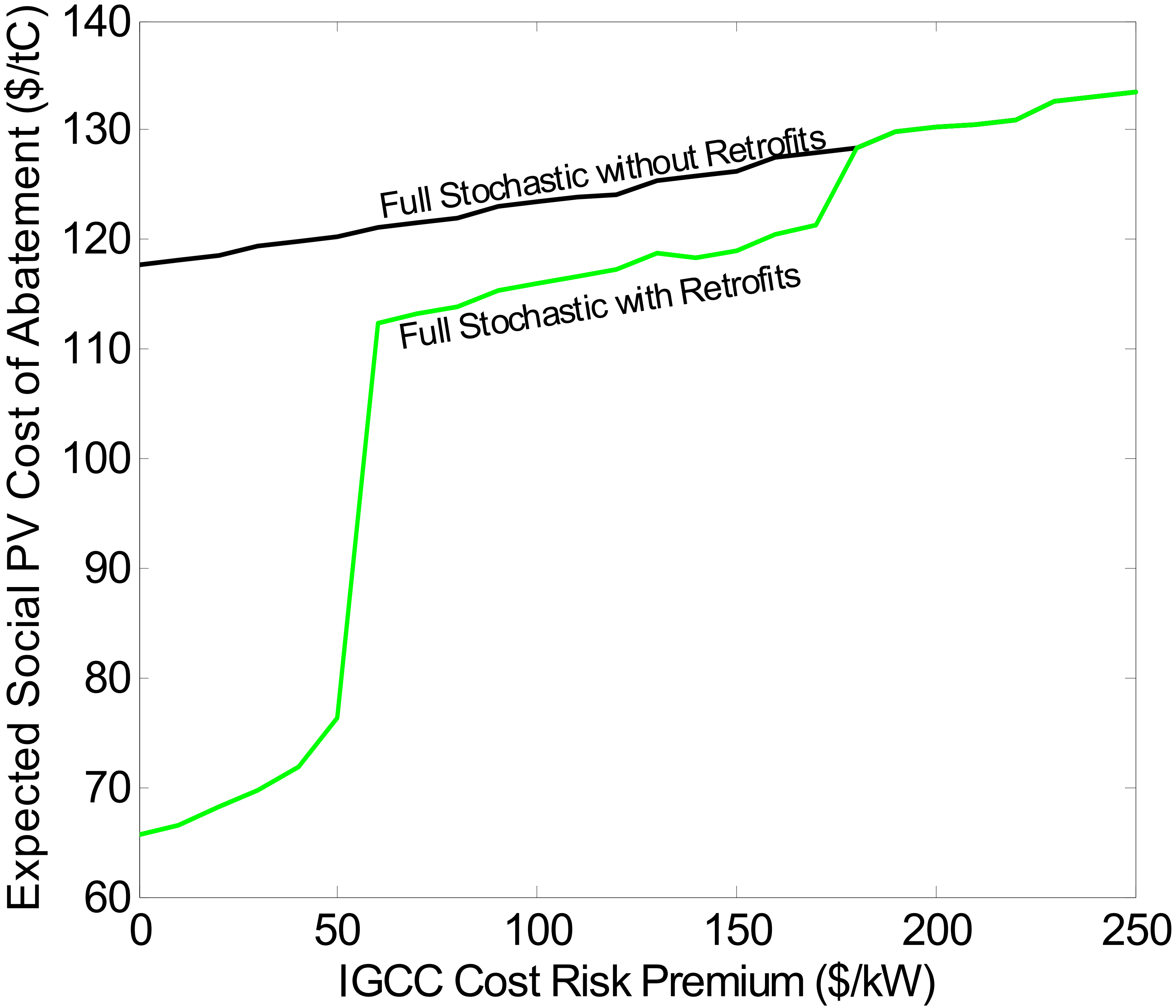
$$\frac{\text{Increase in PV cost of private decisions evaluated at social discount rate}}{\text{Reduction in PV } CO_2 \text{ emissions evaluated at social discount rate}}$$

Base case: $76/tC

The Value of Retrofit Flexibility

Graphical presentation of the relative competitiveness of IGCC and the value of retrofit flexibility as measure by the social cost effectiveness of abatement

Expected Social PV Cost of Abatement



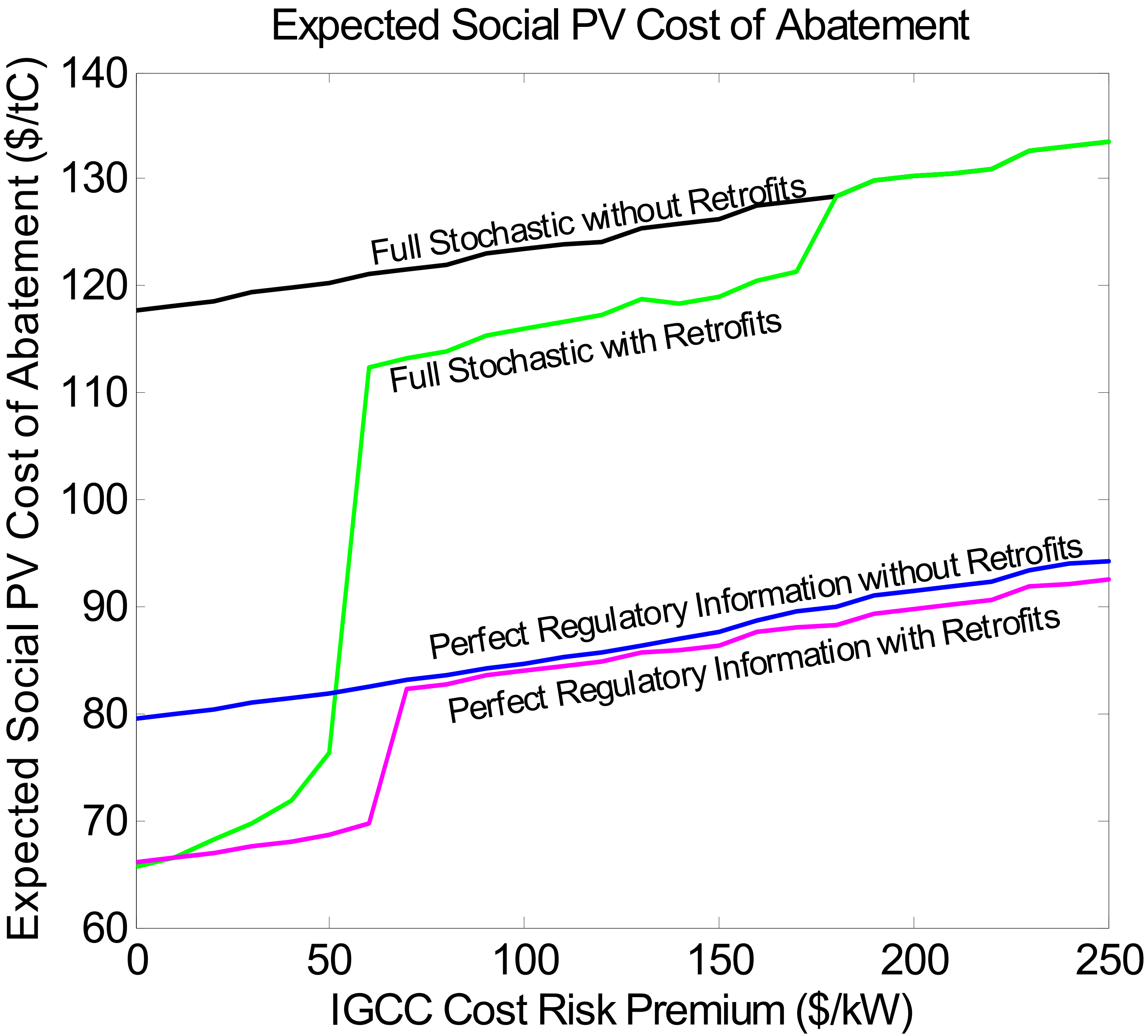
Expected PV Cost with Perfect Information on Future Regulation

Stochastic Dynamic Programming Expected Solution of
Perfect Regulation Information and Uncertain Price of Natural Gas

Backward Induction to Initial Period

For t = T – 1, …, 0

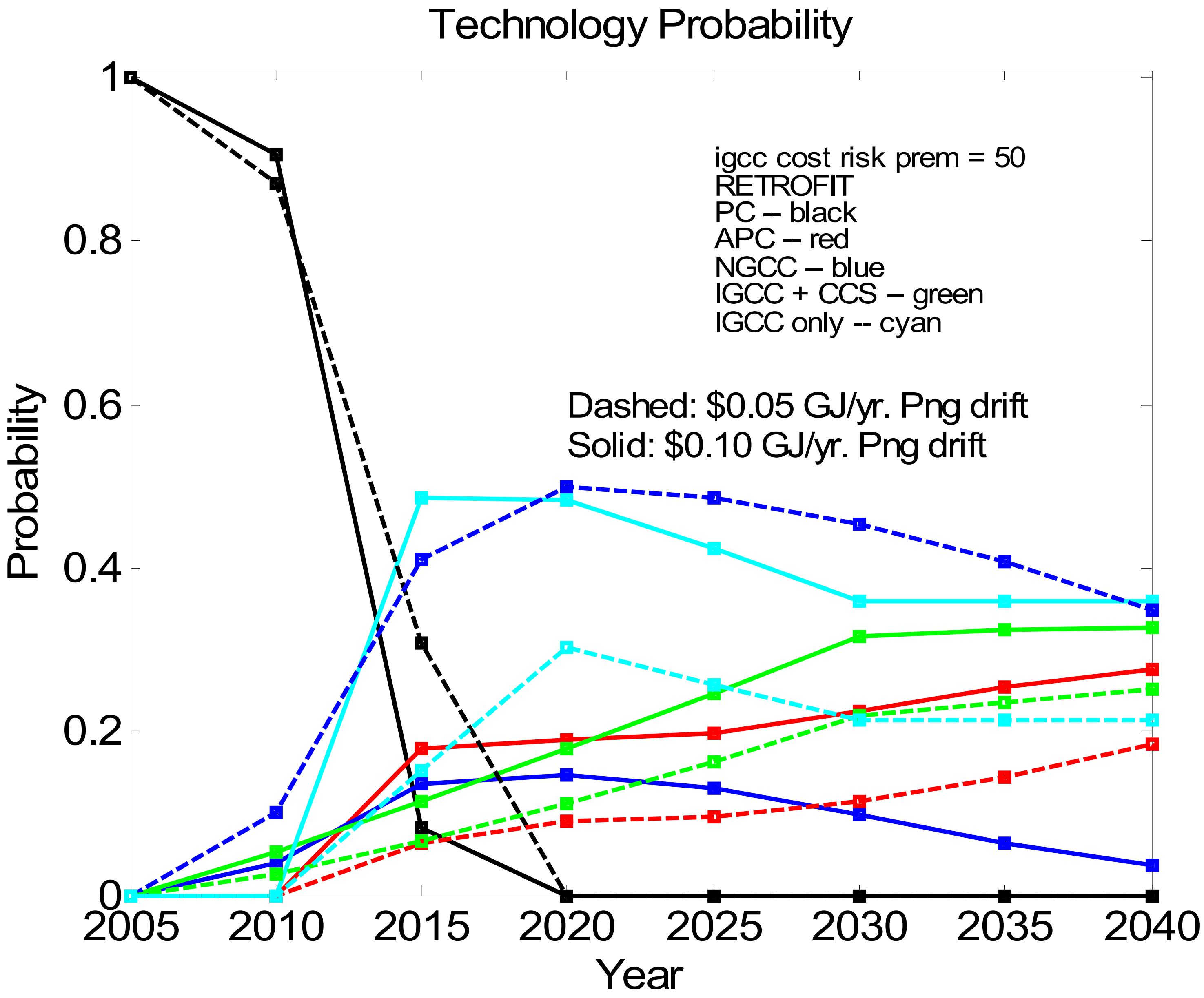
$$V_t(s_t) = E^{P_{carbon}}\left[\min_{a_t \in A}\left[c(s_t, a_t) + E^{P_{NG}}\left[\beta V_{t+1}(s_{t+1})\right]\right]\right]$$

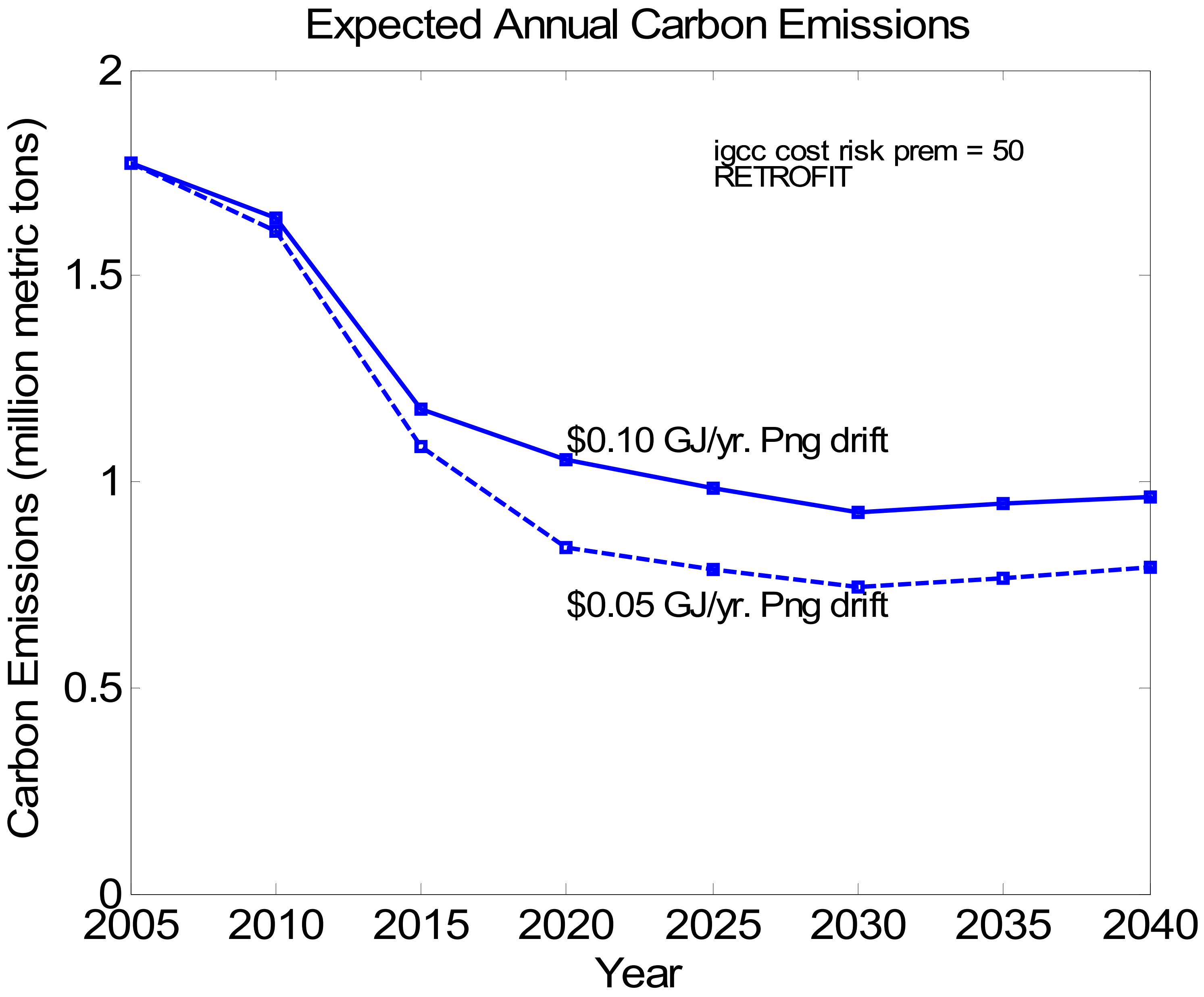

Expected Social PV Cost of Abatement
Expected Social PV Cost of Abatement ($/tC)
140
130
120
110
100
90
80
70
60
0
50
100
150
200
250
IGCC Cost Risk Premium ($/kW)
Full Stochastic without Retrofits
Full Stochastic with Retrofits
Perfect Regulatory Information without Retrofits
Perfect Regulatory Information with Retrofits

Sensitivity of Optimal Investment to Natural Gas Price Ramp

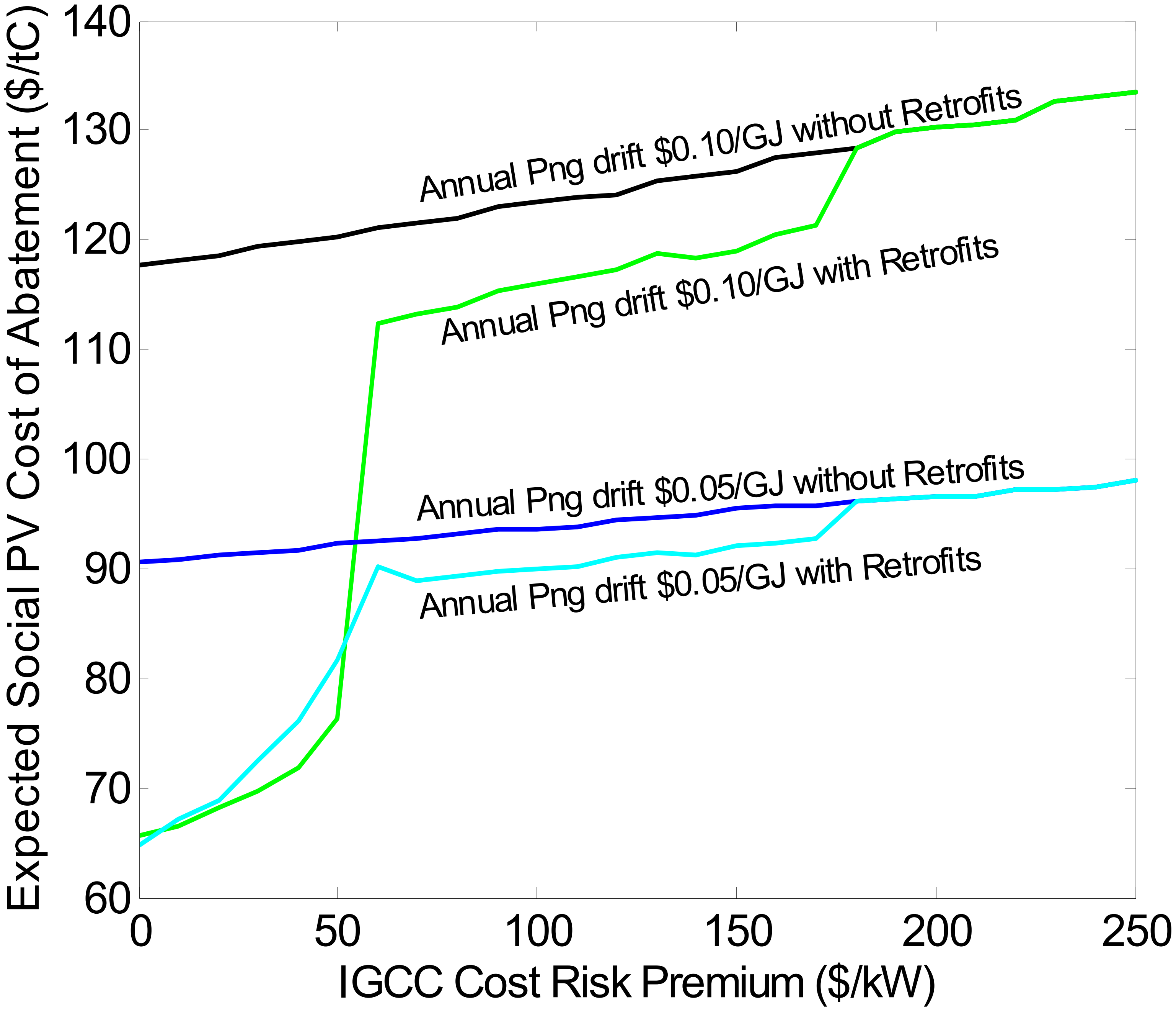
Lower Price of Natural Gas Drift

from $.10 GJ/yr. to $0.05 GJ/yr.


Technology Probability
Probability
Year
0
0.2
0.4
0.6
0.8
1
2005
2010
2015
2020
2025
2030
2035
2040
igcc cost risk prem = 50
RETROFIT
PC -- black
APC -- red
NGCC – blue
IGCC + CCS – green
IGCC only -- cyan
Dashed: $0.05 GJ/yr. Png drift
Solid: $0.10 GJ/yr. Png drift


Expected Annual Carbon Emissions
igcc cost risk prem = 50
RETROFIT
$0.10 GJ/yr. Png drift
$0.05 GJ/yr. Png drift
Carbon Emissions (million metric tons)
0
0.5
1
1.5
2
2005
2010
2015
2020
2025
2030
2035
2040
Year

Png Drift and Expected Social PV Cost of Abatement



Summary and Caveats

Summary

1. Regulatory uncertainty not costly in NPV terms (a few %).
2. Without retrofit technological flexibility, regulatory uncertainty delays retirement of PC plants, temporarily raising emissions above even the certain no regulation case, and greatly increases the social cost of abatement.
3. If a technology with retrofit capabilities is closely competitive with alternative technologies, regulatory uncertainty does not cause serious damage to the social cost effectiveness of abatement.
4. If regulators foresee continued delay of CO_2 regulations due to economy-wide cost considerations, they should pursue narrower technological policies that enhance the competitiveness of technologies with low cost retrofit capabilities to avoid technological traps that lead to high eventual abatement costs.

Summary and Caveats

Caveats

1. This method assumes fixed dispatch, and does not address changes in price electricity price structure that arise from decisions made by other actors.
2. Regulation of conventional pollutants
3. Technological change
4. Nuclear
5. Time lags
6. CO_2 regulation assumptions

Why is the electric sector the focus for emissions mitigation?

Electric power plants are among the largest point sources of CO_2.

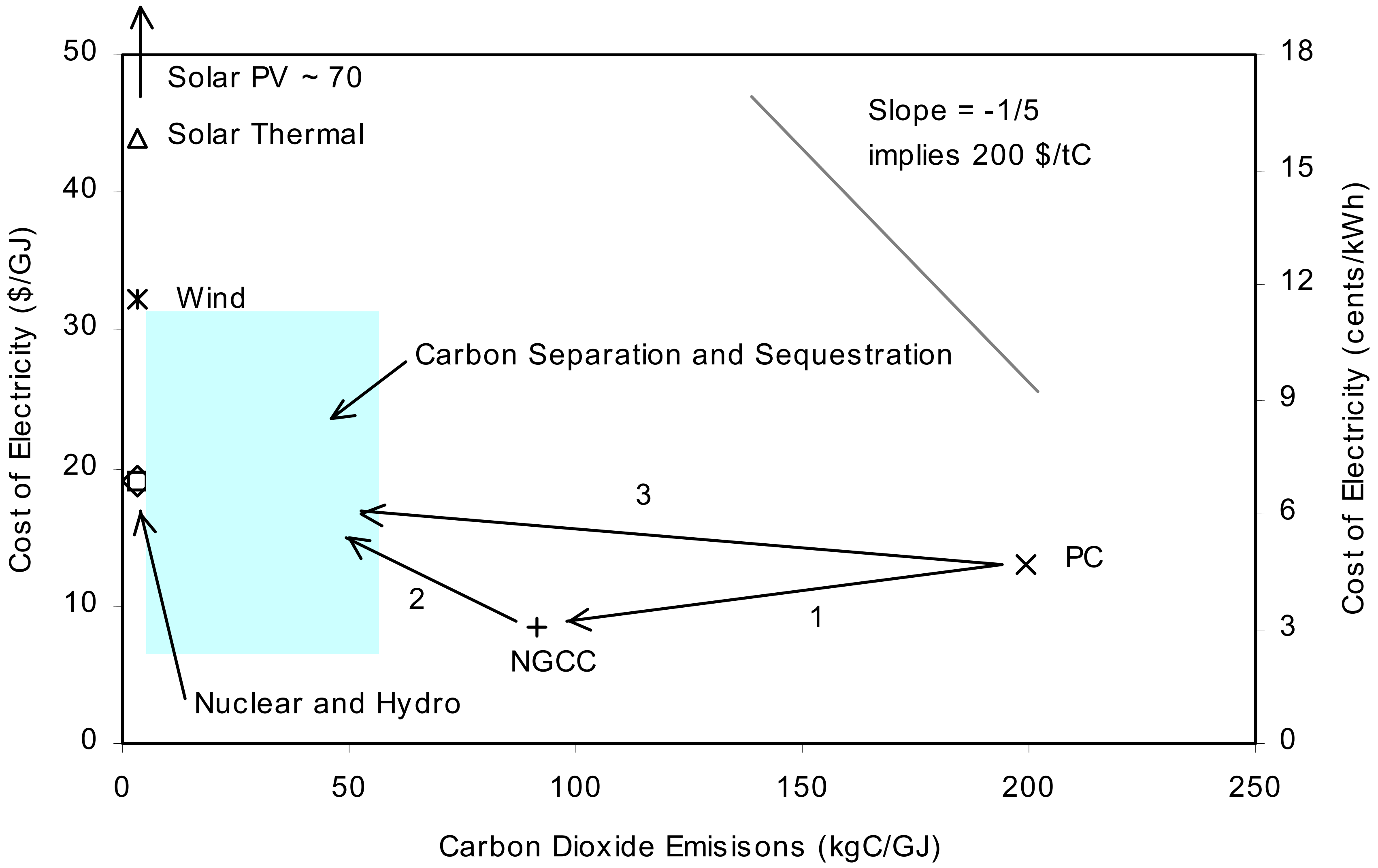
Deep reductions in emissions can be achieved without requiring system-wide changes end use equipment.

Most coal is used for electric generation, and coal is the fuel with the highest carbon-to-energy ratio.

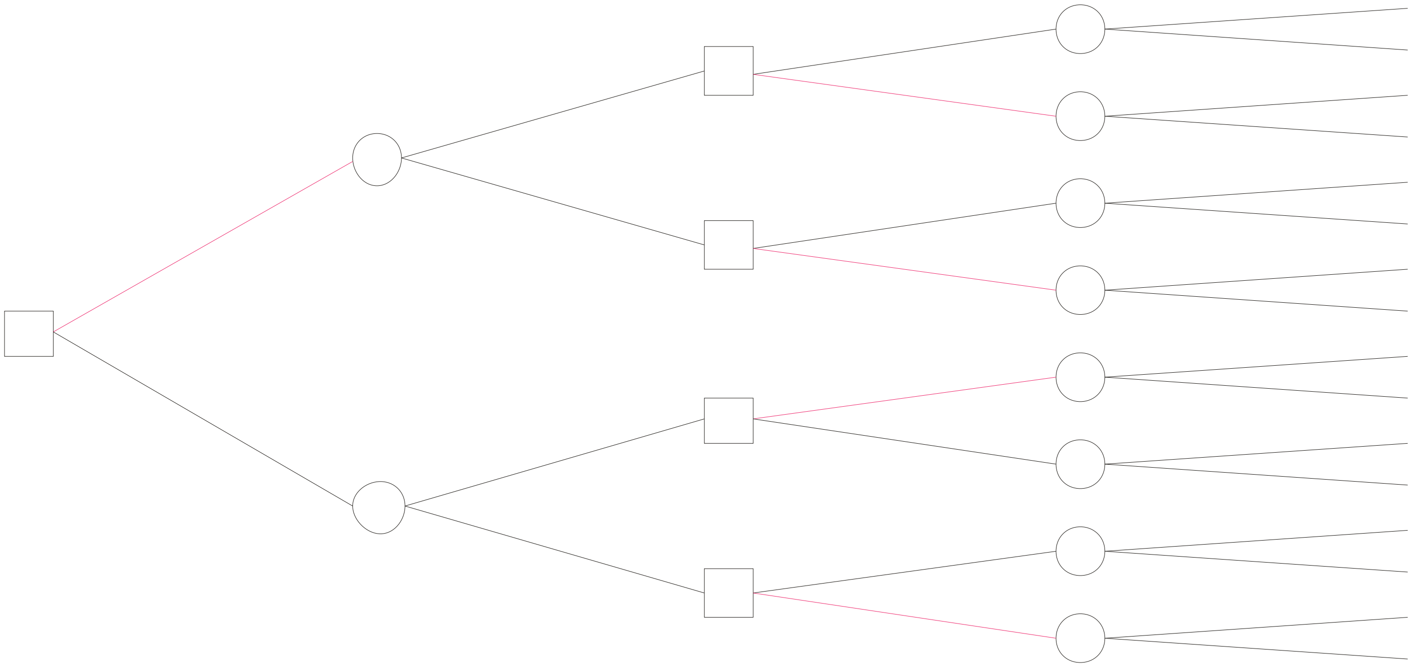
The centralization of capital and management in electric production makes regulatory implementation simpler than for end-use sectors---utilities are used to being regulated.

International trade in electricity is limited, so government action that raises prices in the electric sector will be less likely to cause producers to move offshore that is the in other industrial sectors.

Cost of Electricity vs Carbon Intensity



Stochastic-dynamic programming



Information

Information

Decision

Decision

Outcome

Time →

Backward induction ←