AAE 706

Getting Started with Integrated Assessment: The Social Cost of Carbon

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Revised Lecture Schedule (to Spring Break)

Mon 2/20	Integrated Assessment
Wed 2/22	Dynamic Economic Equilbrium Models
Mon 2/27	Probability
Wed 3/1	Elicitation and Bayes Rule
Mon 3/6	Expected Utility
Wed 3/8	Axioms and Applications of Expected Utility

Homework Assignment from Wednesday

The *isoelastic* demand function is an alternative functional form:

$$d(p) = ap^b$$

1. Derive values of a and b which produce a demand function which is locally consistent with the following *linear* demand curve at $p = \bar{p}$:

$$d(p) = \bar{d}\left(1 - |\epsilon|\left(\frac{p}{\bar{p}} - 1\right)\right)$$

We need to solve for values of a and b which match the reference demand and the elasticity of demand at the reference price:

$$d(p) = ap^b = \bar{d}$$

and

$$\left.\frac{\mathrm{d}d(p)}{\mathrm{p}}\right|_{p=\bar{p}} \frac{\bar{p}}{\bar{d}} = ab\bar{p}^{b-1}\frac{\bar{p}}{\bar{d}} = -|\epsilon|$$

The solution is:

$$a = \bar{d}\bar{p}^{|\epsilon|}, \quad b = -|\epsilon|$$

Homework Assignment from Wednesday

2. Formulate a representation of the isoelastic demand based on $\bar{q}$, $\bar{p}$ and ϵ rather than a and b.
   Substituting for a and b we have:

$$d(p) = ap^b = \bar{d}\left(\frac{p}{\bar{p}}\right)^{-\epsilon}$$

Homework Assignment from Wednesday (cont.)

3. Produce MCP and NLP models with iso-elastic demand, and demonstrate that these are calibrated.
   For the equilibrium model, we only need to replace the linear demand function:

```
aggdemand(i,s)..

  D(i,s) =e= dref(i,s) * (1 - epsilon(i)*(P(s)/pref(s)-1));
```

   by the isoelastic demand function:

```
aggdemand(i,s)..

  D(i,s) =e= dref(i,s) * (P(s)/pref(s))**(-epsilon(i));
```

Homework Assignment from Wednesday (cont.)

3. Produce MCP and NLP models with iso-elastic demand, and demonstrate that these are calibrated.
   We need to derive the consumer surplus function for the NLP model:

$$CS(q) = \int \bar{p} \left(\frac{q}{\bar{q}}\right)^{-1/|\epsilon|} = \frac{\bar{q}\bar{p}}{1 - 1/|\epsilon|} \left(\frac{q}{\bar{q}}\right)^{1-1/|\epsilon|}$$

   This enters the GAMS code in the equation which defines surplus:

```
surplusdef..

 SURPLUS =e= sum((i,s), pref(s)*dref(i,s)/(1-1/epsilon(i)) *

        (D(i,s)/dref(i,s))**(1-1/epsilon(i))) -  TOTCOST;
```

Homework Assignment from Wednesday (cont.)

4. Impose a supply shock (a phase out of coal generation) and compare results from the linear and isoelastic models.
   Renaming the original `qpdispatch.gms` file `linear.gms`, and name the new file (with isoelastic demand) `isoelastic.gms`.
   The counterfactual solution can be added to the model following the solution of the `SAMUELSON` model at the benchmark point. The following statements implement the counterfactual:

```
cap("coal") = 0;
D.LO(i,s) = 1e-5;
SOLVE samuelson USING nlp MAXIMIZING surplus;
```

   Results can be compared by extracting values from the solution listing.

Reporting Prices

The shadow-price on the supply-demand constraint for each load segment corresponds to the equilibrium price.

```
supplydemand(s)..       sum(j,Y(j,s)) =e= sum(i,D(i,s));
```

An increase in the right-hand-side of this constraint effectively decreases the supply of electricity and thereby lowers consumer surplus. Hence we expect that the Lagrange multiplier on this constraint will be *negative*.
A phase-out of coal generation will raise prices in all of the load segments in which coal is supplied. We find the shadow-price reported in the solution listing:

```
---- EQU supplydemand

             LOWER          LEVEL          UPPER        MARGINAL

s1             .              .              .          -20.2500
s2             .              .              .           -9.0000
...
```

Comparing Prices

A few copy-paste steps produces the following table of marginal values:

	Linear		Isoelastic	
	Benchmark	Phaseout	Benchmark	Phaseout
s1	-9.0000	-20.2500	-9.0000	-39.5958
s2	-7.0000	-9.0000	-7.0000	-9.0000
s3	-6.0000	-9.0000	-6.0000	-9.0000
s4	-6.0000	-7.0000	-6.0000	-7.0000
s5	-6.0000	-7.0000	-6.0000	-7.0000
s6	-6.0000	-7.0000	-6.0000	-7.0000
s7	-6.0000	-7.0000	-6.0000	-7.0000
s8	-4.0000	-4.0000	-4.0000	-4.0000
s9	-4.0000	-4.0000	-4.0000	-4.0000

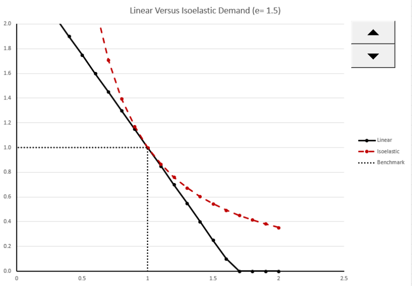
Note that the price impact of the phaseout in segment 1 is higher in the isoelastic model than in the linear model, yet the price impact is the same in all of the other load segments. *Why is this the case?*

Impacts in Load Segment 1 are Easily Explained

W1

Linear Versus Isoelastic Demand (e= 1.5)

	A	B	C	D
1				
2	epsilon	1.5		15
3				
4				
5				
6		Linear	Isoelastic	
7	0.1	2.4	31.6	
8	0.2	2.2	11.2	
9	0.3	2.1	6.1	
10	0.4	1.9	4.0	
11	0.5	1.8	2.8	
12	0.6	1.6	2.2	
13	0.7	1.5	1.7	
14	0.8	1.3	1.4	
15	0.9	1.2	1.2	
16	1	1.0	1.0	
17	1.1	0.9	0.9	
18	1.2	0.7	0.8	
19	1.3	0.6	0.7	
20	1.4	0.4	0.6	
21	1.5	0.3	0.5	
22	1.6	0.1	0.5	
23	1.7	0.0	0.5	
24	1.8	0.0	0.4	
25	1.9	0.0	0.4	
26	2	0.0	0.4	
27				
28				
29	1	0		
30	1	1		
31	0	1		
32				
33				



Reporting in GAMS with Parameters

```
SOLVE samuelson USING nlp MAXIMIZING surplus;

parameter       report          Summary report;

report("P",s,"bmk") = -supplydemand.m(s);
report(j,s,"bmk") = Y.L(j,s);
report(i,s,"bmk") = D.L(i,s);

cap("coal") = 0;
D.LO(i,s) = 1e-5;
SOLVE samuelson USING nlp MAXIMIZING surplus;

report("P",s,"phaseout") = -supplydemand.m(s);
report(j,s,"phaseout") = Y.L(j,s);
report(i,s,"phaseout") = D.L(i,s);

option report:3:2:1;
display report;
```

Reporting in GAMS with Parameters

The report parameter can be displayed to the listing file, but for an indexed model, scrutinizing results can be tedious.

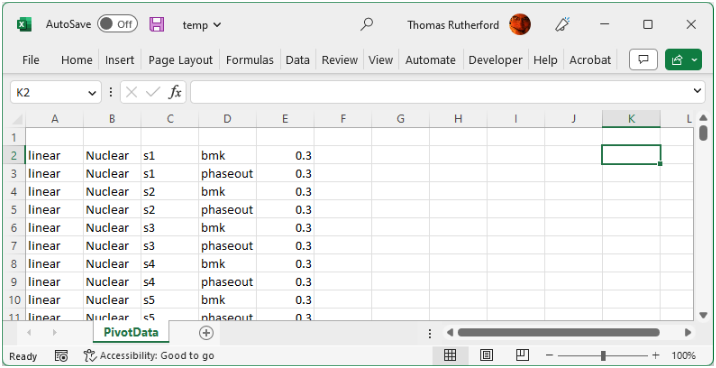
```
----    143 PARAMETER report  Summary report

                       bmk    phaseout

Nuclear.s1           0.300       0.300
Nuclear.s2           0.300       0.300
Nuclear.s3           0.300       0.300
Nuclear.s4           0.300       0.300
Nuclear.s5           0.300       0.300
Nuclear.s6           0.300       0.300
Nuclear.s7           0.300       0.300
Nuclear.s8           0.280       0.280
Nuclear.s9           0.230       0.230
Coal   .s1           0.300
Coal   .s2           0.300
Coal   .s3           0.290
Coal   .s4           0.200
Coal   .s5           0.140
Coal   .s6           0.100
Coal   .s7           0.050
Gas    .s1           0.200       0.200
Gas    .s2           0.190       0.200
Gas    .s3                       0.200
Gas    .s4                       0.179
Gas    .s5                       0.119
Gas    .s6                       0.078
Gas    .s7                       0.028
...
```

Pivot Tables are Helpful

After inserting the same report code in both `linear.gms` and `isoelastic.gms` we make the following command:

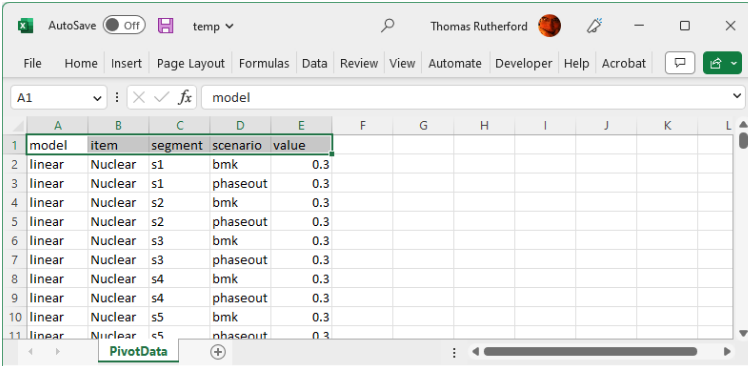
```
gams linear gdx=linear
gams isoelastic gdx=isoelastic

gdxmerge linear.gdx isoelastic.gdx id=report

gdxxrw i=merged.gdx o=report.xlsx par=report rng=PivotData!a2
```

report.xlsx with Pivot Data



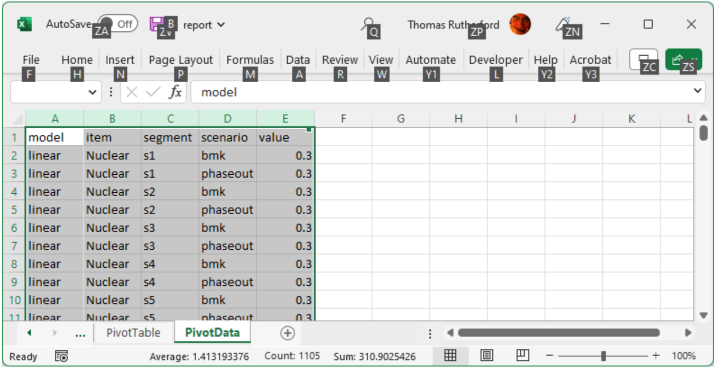
	A	B	C	D	E
1					
2	linear	Nuclear	s1	bmk	0.3
3	linear	Nuclear	s1	phaseout	0.3
4	linear	Nuclear	s2	bmk	0.3
5	linear	Nuclear	s2	phaseout	0.3
6	linear	Nuclear	s3	bmk	0.3
7	linear	Nuclear	s3	phaseout	0.3
8	linear	Nuclear	s4	bmk	0.3
9	linear	Nuclear	s4	phaseout	0.3
10	linear	Nuclear	s5	bmk	0.3
11	linear	Nuclear	s5	phaseout	0.3

`report.xlsx` with Pivot Data Headers

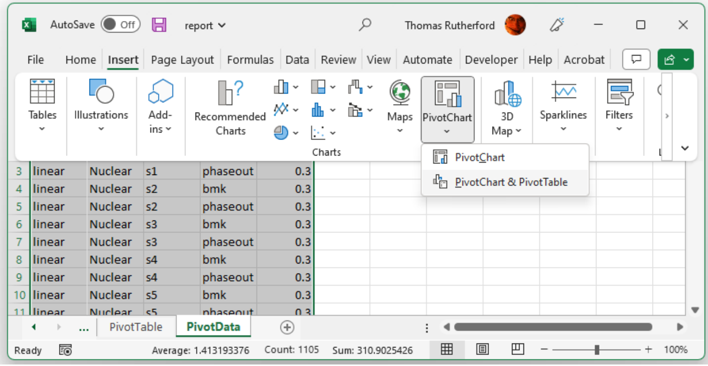


model	item	segment	scenario	value
linear	Nuclear	s1	bmk	0.3
linear	Nuclear	s1	phaseout	0.3
linear	Nuclear	s2	bmk	0.3
linear	Nuclear	s2	phaseout	0.3
linear	Nuclear	s3	bmk	0.3
linear	Nuclear	s3	phaseout	0.3
linear	Nuclear	s4	bmk	0.3
linear	Nuclear	s4	phaseout	0.3
linear	Nuclear	s5	bmk	0.3
linear	Nuclear	s5	phaseout	0.3

Highlight Columns



Insert Pivot Table/Chart (Windows)



Pivot Tables: Learning Objectives

- Understand data organization and sources that are appropriate for use with PivotTables
- Be able to use basic PivotTable techniques for data exploration
- Create charts and tabular reports using PivotTables with appropriate formatting

PivotTable terms and concepts

- PivotTable report source data types
- Creating a PivotTable report using the PivotTable report wizard
- Adding/removing fields to a PivotTable report
- Changing the layout of a PivotTable report
- Refreshing the PivotTable data
- Showing/hiding the field list in a PivotTable report
- Formatting a PivotTable report

What is an Excel Pivot Table?

- An interactive worksheet table
- Provides a powerful tool for summarizing large amounts of tabular data
- Similar to a cross-tabulation table
- A pivot table classifies numeric data in a list based on other fields in the list
- General purpose:
    - Quickly summarize data from a worksheet or from an external source
    - Calculate totals, averages, counts, etc. based on any numeric fields in your table
- Generate charts from your pivot tables

Pivot Table Advantages

- Interactive: easily rearrange them by moving, adding, or deleting fields
- Dynamic: results are automatically recalculated whenever fields are added or dropped, or whenever categories are hidden or displayed
- Easy to update: “refreshable” if the original worksheet data changes

Appropriate Data for Pivot Tables

- Data arranged in a list:
  - Columns represent fields
  - Columns contain one sort of data
  - Rows represent a record of related data
  - First row = column label
- Remove subtotals (use caution working with subtotals)
- De-normalized database extracts are great for pivoting!

Potential Uses of Pivot Tables

- Ad hoc reporting with "refreshable" summary table reports
- Data validation and checking
- Web reporting
- Data exploration

Create a PivotTable

1. Select any cell in the worksheet that contains data, or select all the data and columns you want to include in the report. On the Data menu, click PivotTable and PivotChart Report.
2. In Step 1 of the wizard, make sure that Microsoft Excel list or database is selected.
3. Under *What kind of report do you want to create?*, make sure that PivotTable is selected.
4. Click *Next*.

When Creating Your PivotTable:

- Understand your data
- Ask yourself what you want to know
- Remember the rules of where to place data fields:
  1. *Row Fields*: display data vertically, in rows
  2. *Column Fields*: display data horizontally, across columns
  3. *Data Items*: numerical data to be summarized
  4. *Page Fields*: display data as pages and allows you to filter to a single item
- Changing the layout takes only seconds, so don't worry about making it perfect the first time
- Note: If the field list is hidden, click Show Field List on the PivotTable toolbar.

Overview

- Climate policy: social cost of carbon (SCC) and cost-benefit analysis
- SCC calculus: key uncertainties
- Integrated assessment modeling: DICE and extensions
- Systematic sensitivity analysis on SCC: results and policy implications
- Outlook: priorities for our semester's research program

Role of IAMs in Policy Dialogue

- Stylized models provide a framework for “second order agreement”.
- IAMs can focus policy discussions on issues which matter.
- Supportive IAM results should be a *necessary but not a sufficient* condition for candidate climate policy proposals.

An Analogy: Assessing Bridge Safety

When the Golden Gate Bridge was opened to pedestrian traffic as part of the 50th anniversary of the bridge opening in 1937, there were real concerns regarding structural safety. Two methods of analysis were employed:

1. *Reduced form*: strain gauges were used to evaluate how the bridge responded to vehicle loads.
2. *Structural*: finite element models based on simple physical principles (Hook's law) were evaluated numerically to assess response of the structure to pedestrian loads.

These analysis of representative of *ex-post* and *ex-ante* analysis of economic policy.

From David Luenberger's microeconomics class, Stanford University, 1981.

Vehicles: 150 kg/m^2

Pedestrians: 450 kg/m^2

The Bridge Crew in 1978

Opening of Syange Bridge

Syange Bridge in 1985

Syange Bridge in 2016

With Natalie at Ngadi Khola Bridge

The Indian Fable

The Blind Men and the Elephant John Godfrey Saxe (1816-1887)

```
It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind

The First approached the Elephant,
And happening to fall
Against his broad and sturdy side,
At once began to bawl:
"God bless me! but the Elephant
Is very like a wall!"
```

The Blind Men and the Elephant – (cont.)

```
The Second, feeling of the tusk,
Cried, "Ho! what have we here
So very round and smooth and sharp?
To me 'tis mighty clear
This wonder of an Elephant
Is very like a spear!"

The Third approached the animal,
And happening to take
The squirming trunk within his hands,
Thus boldly up and spake:
"I see," quoth he, "the Elephant
Is very like a snake!"
```

The Blind Men and the Elephant – (cont.)

```
The Fourth reached out his eager hand,
And felt about the knee.
"What most this wondrous beast is like
Is mighty plain," quoth he;
"'Tis clear enough the Elephant
Is very like a tree!"

The Fifth, who chanced to touch the ear,
Said: "E'en the blindest man
Can tell what this resembles most;
Deny the fact who can,
This marvel of an Elephant
Is very like a fan!"
```

The Blind Men and the Elephant – (cont.)

```
The Sixth no sooner had begun
About the beast to grope,
Than, seizing on the swinging tail
That fell within his scope,
"I see," quoth he, "the Elephant
Is very like a rope!"

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!
```

The Blind Men and the Elephant – (cont.)

```
MORAL.

So, oft in theologic wars
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean,
And prate about an Elephant
Not one of them has seen!
```

An Ontological Parable

The poem by John Godfrey Saxe is based on a folk tale which originated in ancient India. The parable of the blind men and an elephant is a story of a group of blind men who have never come across an elephant before and who learn and imagine what the elephant is like by touching it. Each blind man feels a different part of the elephant's body, but only one part, such as the side or the tusk. They then describe the elephant based on their limited experience and their descriptions of the elephant are different from each other. In some versions, they come to suspect that the other person is dishonest and they come to blows. The moral of the parable is that humans have a tendency to claim absolute truth based on their limited, subjective experience as they ignore other people's limited, subjective experiences which may be equally true.

The Elephant and the Rabbit (Manne and Hogan)

- The energy value share of GDP is typically on the order of 4-5% in industrial countries.
- This is something like *elephant-rabbit stew*. If such a recipe contains just one rabbit (the energy sector) and one elephant (the rest of the economy), doesn't it still taste very much like elephant stew?
- But what if energy prices double, triple or quadruple, and there is sufficient time for the economy to respond? How much will this cost the rest of the economy?
- For large reductions in energy use, the value share of energy in aggregate output need not remain fixed. If the value share rises, the metaphor of the elephant and the rabbit may no longer be appropriate.

Substitution

- Production processes are not fixed immutably. Insulation, energy efficiency improvements and "input juggling" in production processes can all alter the energy requirements for a given level of output.
- *Flexibility* in energy utilization is the next essential element after the energy value share in measuring the magnitude of energy-economy feedback.
- Economists describe the responsiveness of technology by the *elasticity of substitution*.
- There are significant differences between *long-run* and *short-run* elasticities. Here we focus on the former.

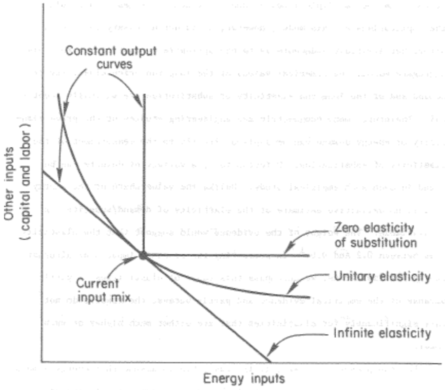


FIGURE 1. THE ELASTICITY OF SUBSTITUTION CONCEPT

Empirics

- If we focus on models with a constant elasticity of substitution (CES), we can build a coherent, self-consistent model of energy-economy interactions.
- Most empirical estimates of the elasticity value converge on values between 0.2 and 0.6.
- It is a reasonable assumption in many economies to assume constant energy intensity in the absence of policy measures: if the price of energy remains unchanged, energy demand grows proportionally to GDP.

Policy Context *in 1977*

- Multiple motivations for policy measures leading to energy conservation: environmental protection, national security and *sustainability*.
- Feedback issues are central when we consider two questions:
  (i) What size of tax is required to achieve a target reduction in energy use? and
  (ii) What is the resulting impact on GDP?
- Formally, focus on a future economy (2010) in which the steady-state forecast energy demand is 220 quadrillion BTU.
- Contemplate policy measures which lead to a substantial reduction in energy demand

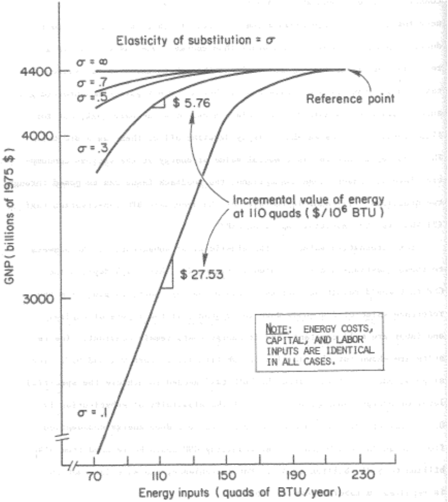


FIGURE 2. ECONOMIC IMPACTS OF ENERGY REDUCTIONS IN THE YEAR 2010

Contemporary Relevance

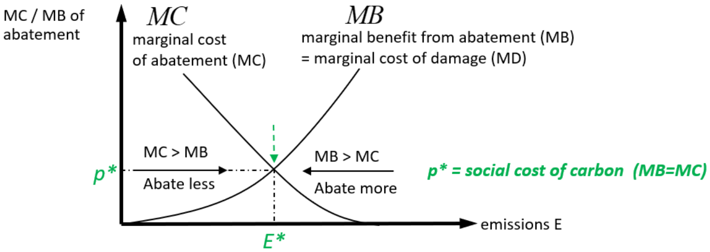
- The thematic and policy dimensions of Manne and Hogan's 1977 paper remain topical nearly 40 years after publication: energy security, environmental cost and sustainability are all at the forefront of the academic research agenda in energy economics.
- What may be less obvious about this paper is its methodological relevance. The CES demand system introduce here continues to be a workhorse of theoretical and applied economic equilibrium analysis.
- The CES function is a key component in multi-sectoral general equilibrium models which exploit the inherent global convexity and local flexibility.

Positive versus Normative

- In economics, *positive* statements are factual statements whose truth or falsehood can be verified by empirical study, logic or careful computer programming.
- Conversely, *normative* statements involve value judgments and cannot be verified by empirical study or logic.

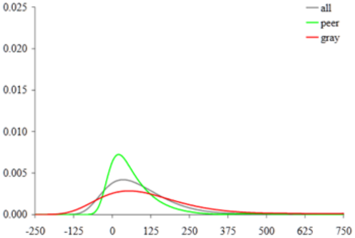
IAMs are typically used to provide logical implications of specific assumptions. Model results may provide the basis for normative conclusions.

Cost-Benefit Analysis and the Social Cost of Carbon



- The social cost of carbon (SCC) is the marginal cost of the damages created by one extra ton of carbon dioxide emissions (or carbon dioxide equivalent) at any point in time.
- Cost-benefit appraisal of public policy: SCC puts the “right” (Pigouvian) price on the carbon externality $\Rightarrow MC = MB$

The Policymakers' Dilemma: What is the Right SCC?



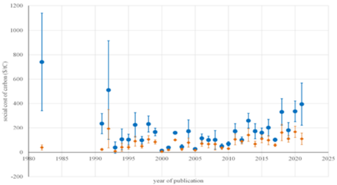
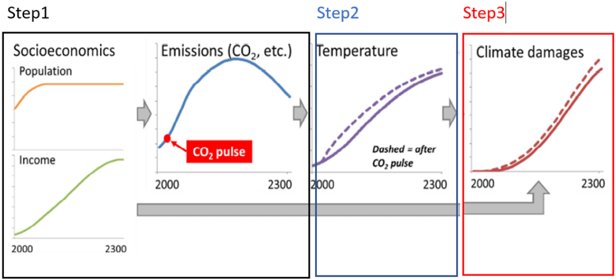


Figure 1: Average social cost of carbon by publication year. Orange diamonds are as reported, blue dots are corrected for inflation and year of emission. Error bars are plus and minus the standard deviation of the published estimates. Estimates are quality weighted and censored.

The social cost of carbon should guide policymakers about where to set the carbon price. Yet: The discrepancies in SCC estimates are huge and may "confuse" the policymakers' choice.

Tol (2007) provides an early meta-analysis, and Tol (2021) is more recent. The upward-sloping SCC trend is evident.

Calculus of the Social Cost of Carbon (SCC)

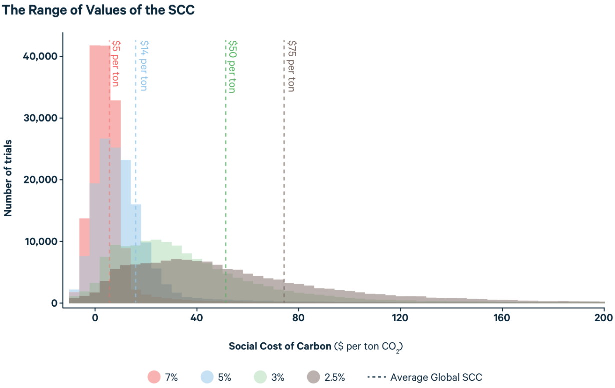


SCC is the present value of future global climate change impacts from one additional net global metric ton of carbon dioxide emitted to the atmosphere at a specific point in time. For example, SCC in 2020 is the discounted value of the additional net damages from the marginal emissions increase in 2020

Steps in Calculating the SCC

1. Project future emissions based on population, economic growth, etc.
2. Assess future climate responses such as temperature increase.
3. Assess the economic impacts of climatic changes, converting future damages into their present-day value
4. Run steps 1-3 to obtain a baseline value for the damages of emissions in the absence of climate policy. Then, repeat 1-3 with a CO2 pulse of emissions at a specific point it time to determine the change in damage cost, i.e. the SCC.

RFF Estimates of SCC from 2019 (Rennert and Kingdon)



Latest RFF Estimates of the SCC

Article

Comprehensive evidence implies a higher social cost of CO_2

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Open access

Kevin Rennert[1], Frank Errickson[2,15], Brian C. Prest[1,15], Lisa Rennels[3,15], Richard G. Newell[1], William Pizer[1], Cora Kingdon[3], Jordan Wingenroth[1], Roger Cooke[1], Bryan Parthum[4], David Smith[4], Kevin Cromar[5,6], Delavane Diaz[7], Frances C. Moore[8], Ulrich K. Müller[9], Richard J. Plevin[10], Adrian E. Raftery[11], Hana Ševčíková[12], Hannah Sheets[13], James H. Stock[14], Tammy Tan[4], Mark Watson[9], Tony E. Wong[13] & David Anthoff[3]✉

The social cost of carbon dioxide (SC-CO_2) measures the monetized value of the damages to society caused by an incremental metric tonne of CO_2 emissions and is a key metric informing climate policy. Used by governments and other decision-makers in benefit–cost analysis for over a decade, SC-CO_2 estimates draw on climate science,

RFF Estimates of SCC from 2022 (*Nature*)

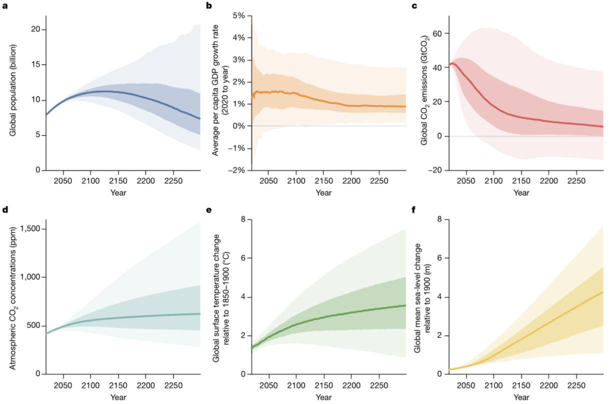

Fig. 1 | RFF-SP socioeconomic scenarios and the resulting climate system projections. a–c, Probabilistic socioeconomic projections for global population (**a**), per capita GDP growth rates (**b**), and carbon dioxide emission levels (**c**) from the RFF-SP scenarios. **d–f**, Corresponding climate system projections that account for parametric uncertainty in FaIR and BRICK for atmospheric carbon dioxide concentrations (**d**), global surface temperature changes relative to the 1850–1900 mean (**e**), and global mean sea-level changes relative to 1900 (**f**). In all panels, solid centre lines depict the median outcome, with darker shading spanning the 25%–75% quantile range and lighter shading spanning the 5%–95% quantile range.

RFF Estimates of SCC from 2022 (*Nature*)

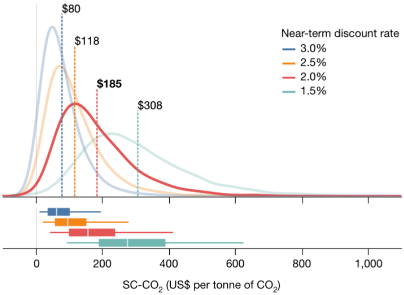

Fig. 2 | SC-CO_2 distributions vary with the choice of near-term discount rates. Distributions of the SC-CO_2 based on RFF-SP scenario samples, a stochastic, growth-linked discounting framework, uncertainty in the FaIR climate and BRICK sea-level models, and uncertainty in climate damage parameters. Colours correspond to near-term average discount rates of 3.0% (blue), 2.5% (orange), 2.0% (red, our preferred specification) and 1.5% (teal). Dashed vertical lines highlight mean SC-CO_2 values. Box and whisker plots along the bottom of the figure depict the median of each SC-CO_2 distribution (centre white line), 25%–75% quantile range (box width), and 5%–95% quantile range (coloured horizontal lines) values. All SC-CO_2 values are expressed in 2020 US dollars per metric tonne of CO_2.