Getting Carbon Regulation Right(er):
The Implications of Capital Malleability

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Bait and Switch

"GTAP-WiNDC Framework: Applied trade policy analysis with a focus on the geographic and household impacts of policy" will be present as part of the GTAP Virtual Seminar Series.

May 19, 2022, 11:00-11:50 am (EDT)

See `http://windc.wisc.edu`

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 future research

Key Idea of Integrated Assessment

Frameworks for application of integrated assessment:

- Costs benefit analysis, or
- Cost effectiveness analysis.

NB!

IAMs are often *equilibrium* models solved using large-scale constrained optimization methods (e.g., GAMS/CONOPT). They incorporate multiple independent, optimizing agents who interact through markets in which allocations are mediated by prices.

Virtues of Integrated Assessment Models

1. Explicit representation of the problem to be addressed, incorporating behavioral responses.
2. Framework for assessing alternative approaches to the climate problem, with an explicit assessments of efficiency and equity.
3. Logical appeal of general equilibrium foundations.
4. Explicit climate and technology constraints.
5. Address issues of risk and uncertainty which are centrally involved in climate policy design.

Drawbacks of an Integrated Assessment Models

1. Misrepresentation and/or misunderstanding of model capabilities on the part of policy makers. Modesty is warranted. For starters, we don't have a reliable and parsimonious model of how policy interventions affect economic growth.
2. The modeling framework does less well when we abandon the simplifying assumption of selfish, optimizing agents.
3. Effective application requires detailed understanding of the underlying economic theory, climate dynamics and energy technologies.
4. The black box approach can easily backfire.

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.

IAMs and Economic Theory

Integrated assessment models a stylized story of how markets work and the nature of agent interactions:

1. Theory of the consumer (demand), including inter-temporal choice.
2. Production and cost theory (supply), possibly based on (bottom-up) activity analysis – engineering estimates of cost functions.
3. The neoclassical paradigm: individual elements of the economy (consumers, firms, workers) are rational agents with objectives which can be expressed as quantitative functions to be optimized subject to constraints.
4. The microeconomic theory underlying this framework has not been a core element of graduate economics classes for over 20 years.

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.

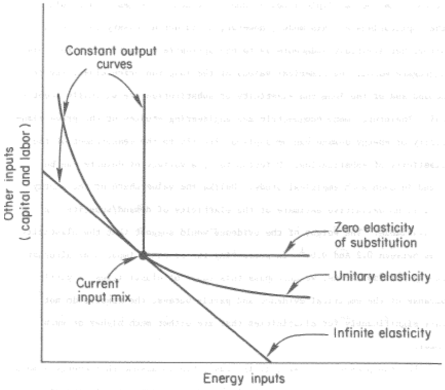
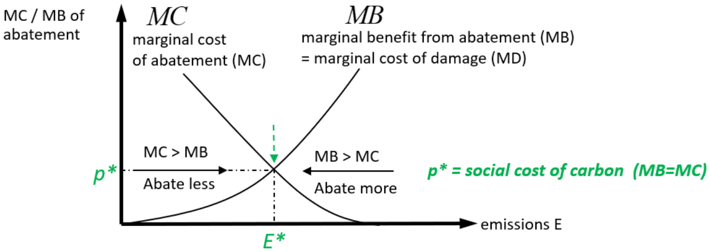


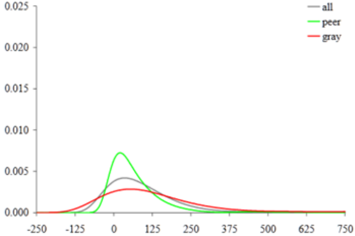
FIGURE 1. THE ELASTICITY OF SUBSTITUTION CONCEPT

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?



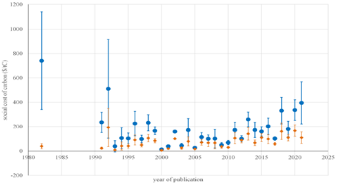
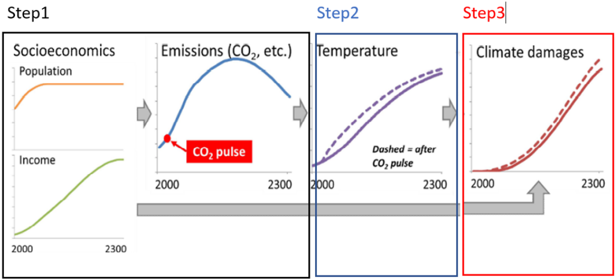


Figure 1: Average social cost of carbon by publication year. Orange diamonds are as reported, blue dots are corrected for inflation and year of emission. Error bars are plus and minus the standard deviation of the published estimates. Estimates are quality weighted and censored.

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

Nordhaus RICE-DICE Family of IAMs

History:

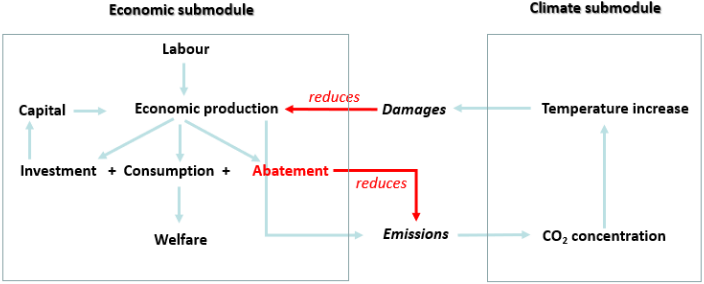
- First vintage 1992
- Latest versions:
    - Global aggregate (DICE 2013)
    - Regional (RICE 2010)
- Special cases (probabilistic, with R&D, with learning, with catastrophic thresholds)

DICE Model Structure

- Economic module
  - Ramsey-Cass-Koopmans model with labor, capital, carbon emissions and climate damages
  - Climate variable is externality and market underinvests in climate capital
- Environmental module
  - Emissions $= f$(output, carbon price, time)
  - Concentrations $= g$(emissions, 3 C reserviors)
  - Temperature change $= h$(GHG forcing, lagged T)
  - Economic damage $= F$(output, T, $CO2$, sea level rise)

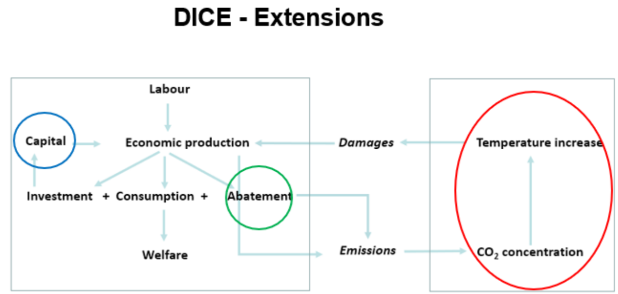
Dice Model Structure

DICE - *Dynamic Integrated model of Climate and the Economy*



- Economic submodule
  - Intertemporal Ramsey model of (exogenous) economic growth
- Climate submodule
  - Reduced-form model of climate dynamics
- Policy analysis
  - No climate policy: CO_2 market externality (no abatement)
  - Cost-benefit mode: Optimal abatement
  - Cost-effectiveness mode: Emissions or temperature targets

Extending Dice



- Structural extensions as compared to DICE-2016r:
  - Climate cycle (FAIR)
  - Technological change (negative emissions technologies - NETs)
  - Capital malleability (putty-clay)

The Ramsey Model

We begin from the DICE model, a Ramsey-growth model which is combined with a simple climate model in order to provide a framework for cost-benefit assessment. Our implementation of DICE remains close to the 2016 version of the model which Nordhaus has provided. The novelty in our implementation is that we focus on two alternative macro models: putty-clay and putty-putty. These differ in their representation of both production and abatement technologies. In both models, emissions are determined jointly by the scale of output and the expenditure on abatement measures. In the putty-clay model emissions rates per unit of output are determined in the year that capital is installed. In the putty-putty model emission rates are determine independently in each year, and there is no distinction between production based on old versus new capital.

The Demand Side

Our demand side of the model is identical to DICE 2016 featuring consumption and savings choices which maximize intertemporal welfare:

$$W = \left(\sum_t \Delta_t L_t \left(\frac{C_t}{L_t} \right)^{1-\eta} \right)^{1/(1-\eta)}$$

in which Δ_t is the discount factor to year t:

$$\Delta_t = \left(\frac{1}{1+\rho} \right)^{t-2015}$$

where ρ is the pure rate of time preference (=0.015), and L_t is the exogenously-give population in year t.

Macro Market and Capital

Focusing first on the pure Ramsey growth model without carbon emissions or climate damages, market clearance in year t relates output to consumption plus investment:

$$C_t + I_t = Y_t$$

Capital depreciates at annual rate δ and is incremented by investment:[1]

$$K_{t+1} = (1 - \delta) K_t + I_t$$

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[1] One difference in our model as compared with DICE2016 is that we work with annual rather than 5-year time steps.

Production Structure

In the *putty-putty* model, macro output in year t is a function of the exogenous labor force (L_t) and the capital stock:

$$Y_t = \phi_t K_t^{\gamma} L_t^{1-\gamma}$$

In the putty-clay model we distinction between three sources of macro supply in year t:

$$Y_t = Y_t^X + Y_t^N + Y_t^V$$

corresponding to *extant production*, *new vintage production* and *old vintaged production* installed in first year of the model or later.

Putty-Clay Production

Details of these three categories of macro supply are as follows:

i. *Extant production* is indexed by capital vintages installed prior to 2015 (the first year of the model):

$$Y_t^X = \sum_{v<2015} y_{vt}^x$$

in which supply by vintage v is bounded by decisions about abandonment between year 2015 and t:

$$y_{v\tau}^x \leq (1-\delta) y_{v,\tau-1}^x \quad y_{v\tau}^x \geq 0 \quad \tau \in [2015, \ldots, t]$$

Putty-Clay Production (cont.)

i. *New vintage output* depends on new vintage labor and new vintage capital (investments in the previous period):

$$Y_t^N = \phi_t(\ell_t^N)^{1-\gamma} I_{t-1}^{\gamma}$$

in which ℓ_t^N is the level of employment associated with technologies introduced in year t,

ii. Aggregate production by vintages installed between 2015 and $t-1$ which is represented by Y_t^V. Vintaged output is subject to evaporative decay:

$$Y_t^V \leq (1-\delta)\left(Y_{t-1}^N + Y_{t-1}^V\right)$$

Labor Market in Putty-Clay

Labor is fully employed in new vintaged production, older vintaged production or in extant vintages:

$$L_t = \ell_t^N + \ell_t^V + \ell_t^X$$

Extant vintages have fixed coefficient:

$$\ell_t^X = \sum_v a_v^L X_{vt}$$

As extant vintages decay, vintaged labor demand declines proportionally:

$$\ell_t^V = (1 - \delta)\left(\ell_{t-1}^N + \ell_{t-1}^V\right)$$

Market Equilibrium: Optimal Growth

The intemporal growth model is formulated as a nonlinear program which maximizes W subject to the labor endowment, initial capital endowment and exogenously specified model parameters (ρ, L_t, δ, ϕ_t, γ, $y^x_{v,2015}$, a^L_v. In the putty-putty model the entering capital stock K_{2015} is given exogously whereas in the putty-clay model I_{2014} is given exogenously and K_t plays no role.

Emissions and Abatement Cost

Carbon emissions in the DICE model are proportional to output net of mitigation measures. In the putty-putty model we have:

$$E_t = \sigma_t Y_t (1 - \mu_t) + \mathcal{E}_t$$

in which σ_t is the emissions coefficient, μ_t is the emissions control rate and $\mathcal{E}_t$ represents carbon emissions from deforestation and land-use.
The integrated assessment model represents both the costs and benefits of mitigation measures. In the putty-putty model costs and benefits both enter the market-clearance condition. Aggregate demand (for consumption plus investment) is equated to macro output net of abatement cost (A_t) and damage (D_t):

$$C_t + I_t = Y_t (1 - A_t)(1 - D_t)$$

in which abatement cost is an increasing function of mitigation:

$$AC_t = \tilde{c}_t \mu_t^{\epsilon}$$

Damage

Climate damage is an increasing function of atmospheric temperature:

$$D_t = a_1 T_t + a_2 T_t^{a_3}$$

in which T_t is atmospheric temperature anomaly in year t measured as degrees centigrade above the pre-industrial (1900) average. Model parameters $\tilde{c}_t$ and ϵ characterize the cost of abatement which a_1, a_2 and a_3 describe the cost of climate damage. The cost-benefit trade-off then depends on the manner in which emissions at time t affect temperature in subsequent years:

$$T_t = f_t(\xi_{2015}, E_{2015}, E_{2016}, \ldots, E_{t-1})$$

in which f represents the climate model which translates initial conditions (ξ_{2015} and carbon emissions from years $\tau \in [2015, \ldots, t-1]$ into current temperature T_t.

Damages and Abatement in Putty-Clay

The putty-clay model begins from the assumption that climate damages affect supply from all sources:

$$C_t + I_t = Y_t(1 - D_t)$$

whereas abatement costs in year t are born solely by new vintage production, i.e.

$$Y_t = Y_t^X + Y_t^N(1 - A_t) + Y_t^V$$

Carbon Emissions in Putty-Clay

Emission rates in year t from vintages installed prior to that year are fixed:

$$E_t = E_t^X + E_t^N + E_t^V + \mathcal{E}_t$$

in which

$$E_t^X = \sum_v \sigma_v^X y_{vt}^x$$

$$E_t^N = \sigma_t^N Y_t^N (1 - \mu_t)$$

and

$$E_t^V = (1 - \delta) \left(E_{t-1}^V + E_{t-1}^N \right)$$

In the putty-clay framework there are two sources of emission reductions: emission controls for *new vintage* production (μ_t) and pre-mature retirement of *extant* vintages.

GAMS Code: The Putty-Putty Model

```
VARIABLES
        Y(t)                Gross output (trillions 2010 USD)
        K(t)                Capital stock (trillions 2010 USD),
        C(t)                Aggregate consumption (2010 USD)
        I(t)                Investment (trillions 2005 USD)
        W                   Welfare function (CIES form),
        AC(t)               Abatement cost margin
        D(t)                Damage margin;

nonnegative variables I, K;
```

GAMS Code: The Putty-Putty Model (cont.)

```
equations               wdef, cdef, ydef, market, kdef, sdef;

wdef..          W =e= w0 * sum(t, thetac(t) *(C(t)/cref(t))**(1-elasmu))**(1/(1-elasmu));

ydef(t)..       Y(t) =e= al(t) * (L(t)/1000)**(1-gama) * K(t)**gama;

market(t)..     C(t) + I(t) =e= Y(t) * (1-AC(t))*(1-D(t));

kdef(t+1)..     K(t+1) =e= (1-dk) * K(t) + I(t);

sdef(tterm(t)).. I(t) =e= optlrsav * Y(t);

edef(t)..       E(t) =e= sigma(t)*Y(t)*(1-MIU(t)) + etree(t);
```

GAMS Code: The Putty-Clay Model

```
VARIABLES
        Y(t)            Gross output (trillions 2010 USD)
        YV(t)           Vintaged output (trillions 2010 USD)
        YX(t,xv)        Extant output (trillions 2010 USD)
        YN(t)           New vintage output,
        LN(t)           New vintage labor,
        LV(t)           Vintaged labor,
        C(t)            Aggregate consumption (2010 USD)
        I(t)            Investment (trillions 2005 USD)
        KN(t)           New vintage capital (trillions 2005 USD)
        W               Welfare function (CIES form),
        AC(t)           Abatement cost margin
        D(t)            Damage margin;

nonnegative variables I, YX, LN, LV;
```

GAMS Code: The Putty-Clay Model (cont.)

```
equations                wdef, cdef, ydef, yvdef, yxdef, yndef, kndef, lndef, lvdef, market, sdef;

wdef..          W =e= w0 * sum(t, thetac(t) * (C(t)/cref(t))**(1-elasmu))**(1/(1-elasmu));

ydef(t)..       Y(t) =e= YN(t) + YV(t) + sum(xv,YX(t,xv));

yvdef(t+1)..    YV(t+1) =e= (1-dk) * (YV(t) + YN(t));

yndef(t)..      YN(t) =e= aln(t) * (LN(t)/1000)**(1-gama) * KN(t)**gama * (1-AC(t));

yxdef(t+1,xv).. YX(t+1,xv) =L= YX(t,xv) * (1-dk);

kndef(t+1)..    KN(t+1) =e= I(t);

lndef(t)..      L(t) =e= LN(t)  + LV(t) + sum(xv,aLx(xv)*YX(t,xv));
```

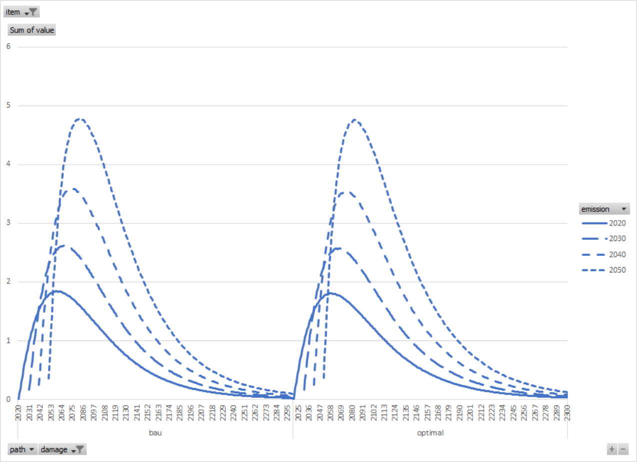
GAMS Code: The Putty-Clay Model (cont.)

```
lvdef(t)..       LV(t) =e= (1-dk) * (LV(t-1) + LN(t-1));

market(t)..      C(t) + I(t) =e= Y(t)*(1-D(t));

sdef(tterm(t)).. I(t) =e= optlrsav * Y(t);

evdef(t+1)..     EV(t+1) =e= (1-dk) * (EV(t) + sigman(t)*YN(t)*(1-MIU(t)));

edef(t)..        E(t) =e= sigman(t) * YN(t) * (1-MIU(t)) + EV(t) + sum(xv,sigmax(xv)*YX(t,xv)) + etree(t);
```

Steps in Calculating the SCC

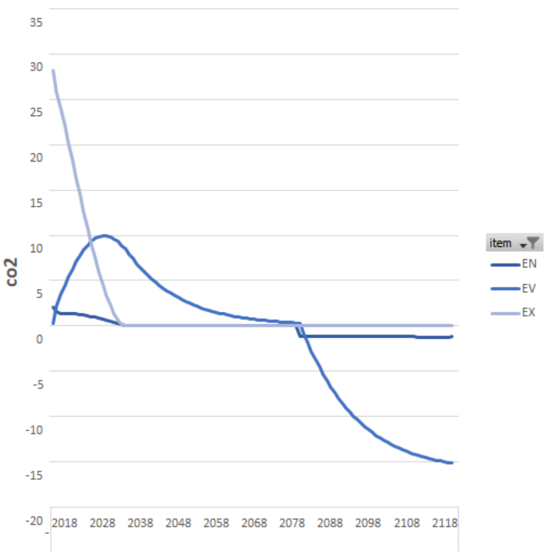
1. Project future emissions based on population, economic growth, etc.
2. Assess future climate responses such as temperature increase.
3. Assess the economic impacts of climatic changes, converting future damages into their present-day value
4. Run steps 1-3 to obtain a baseline value for the damages 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.

Decomposing the Social Cost of Carbon

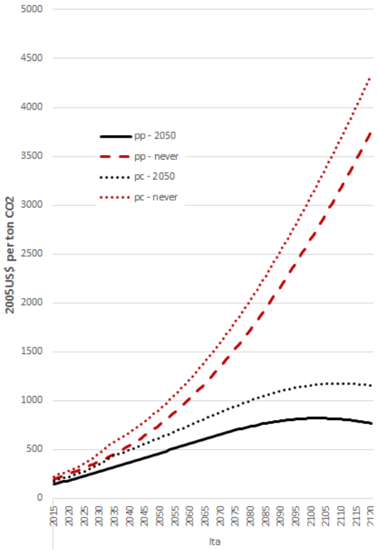


N.B. Here we compare present-value marginal damage curves normalized by marginal damage at the point of emissions. The social cost of carbon rises over time, but the normalized trajectory approaches a stationary distribution in the DICE climate model.

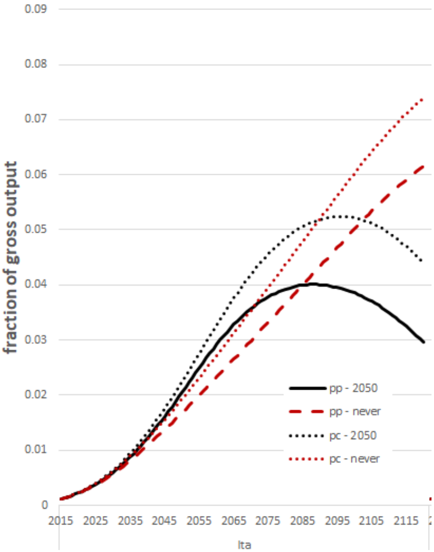
Emission by Vintage



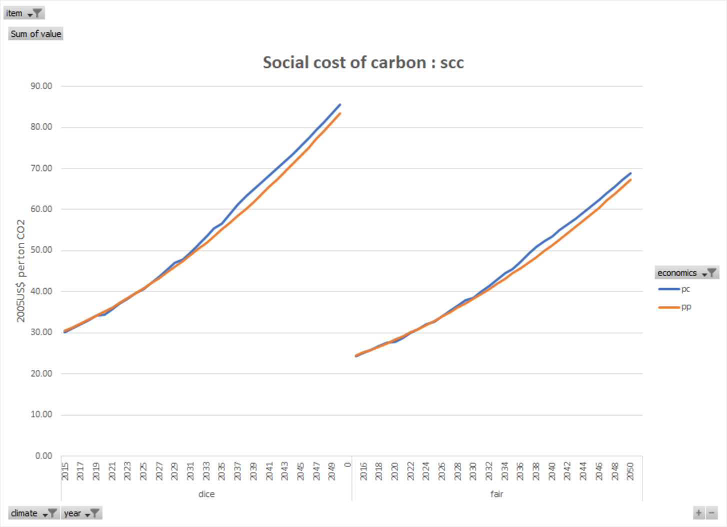
Social Cost of Carbon



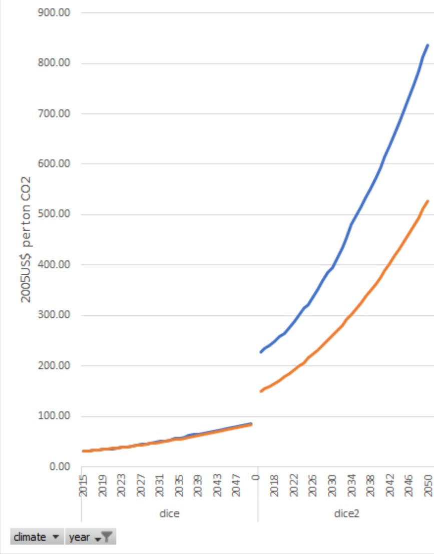
Climate Damage



Social Cost of Carbon: Dice Damage Path



Social Cost of Carbon



The Way Forward

- Structural Estimation of Climate Dynamics
- Negative Emission Technologies (NETs – Tavoni et al)
- Discounting and Climate Damage
- Overlapping Generations (Sequential Recalibration Method)
- Risk and Uncertainty – Stochastic Control