Integrated assessment modelling

Climate macro & finance course 2022/23 - Lecture 7

Emanuele Campiglio

University of Bologna
Department of Economics (DSE)

Course communications

- Problem set n.5
    - Based on Global Energy Monitor data
    - Available on Virtuale from tomorrow
- Exam on 2 November
    - Exam preparation slides on Virtuale
    - Mock exam on Virtuale: replicate conditions
- Presentations
    - 15 mins per group: 12 presentation + 3 Q&A
    - Timing constraints strictly enforced!
    - Upload presentation on Virtuale by the start of the lecture

Lecture 10 presentation schedule

- 9.10 Role of policy uncertainty in shaping investment decisions
- 9.25 Metrics to evaluate country-level climate-related risks
- 9.40 Strategies to incentivise long-termist policy-making
- 10.05 Strategies to incentivise long-termist financial behaviour
- 10.20 Climate-related expectations/beliefs of fin. investors
- 10.35 International equity implications of low-carbon transition
- 11.00 Political discourse on climate change and transition
- 11.15 Obstacles/strategies to finance low-carbon innovation
- 11.30 Is inflation good or bad for climate mitigation?

Last lectures

- We want to explore possible futures
  - How could the transition play out, and what could be its macro-financial implications $\rightarrow$ We need models
- Strategies for climate/transition macro-financial modelling
  - Include macro-finance into climate economic models
  - Include climate/transition into neoclassical macro models
  - Include climate/transition into non-neoclassical macro models

Today's lecture

- Integrated Assessment Models (IAMs)
  - Integrate economy, energy and climate
- Nordhaus' DICE model
  - Structure, assumption and results
- Two main developments from there
  - Large-scale numerical IAMs (including CGEs) $\rightarrow$ Benedetta's presentation
  - Analytical IAMs
- $\rightarrow$ Unanswered questions on macro and finance

The DICE model

The ‘dynamic integrated climate economy’ (DICE) model

- Start: 1992 paper on Science
- Latest version:
  - DICE2016 (see code)
  - Available in GAMS and Excel
  - 2017 paper on PNAS
- 2018 Nobel Prize in Economics
  - “for integrating climate change into long-run macroeconomic analysis”
  - Nobel lecture (video) (AER article)

William Nordhaus (1941-)

Social welfare function

- Social welfare is the discounted sum of the future stream of population-weighted instantaneous utilities:

$$W = \sum_{t=1}^{T} \frac{U(c_t)L_t}{(1+\rho)^t}$$

- $U(c)$: utility as a function of per capita consumption
- L: population
- ρ: Pure rate of social time preference
    - Also called ‘rate of time impatience’ or ‘time discount rate’
    - Set to 1.5% in DICE; to 0.1% in the Stern Review
    - Choosing this value has ethical implications: how do we treat future generations compared to the present ones?
    - $SDR = \rho + \alpha g$

Utility function

- Isoelastic utility function

$$U(c_t) = \frac{c_t^{1-\alpha}}{1-\alpha}$$

- α: Elasticity of marginal utility of consumption (set to 1.45)
    - It can be interpreted as a measure of relative intergenerational inequality aversion
    - The intertemporal elasticity of substitution is $\frac{1}{\alpha}$
    - Coincides with risk aversion here, but different concepts (see Epstein and Zin preferences)

Production

- Cobb-Douglas production function

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

- Y: Gross output (before damages and mitigation)
- A: TFP parameter
  - TFP increases logistically in time (exogenous)
  - Hicks-neutral technological progress, i.e. $\frac{K}{L}$ is not affected
- K: Capital stock (endogenous)
- L: Population
  - L grows asymptotically to 11.5 billion
  - Population $=$ labour
- γ: elasticity of output with respect to the capital (set to 0.3)

Emissions

- Emissions result from production

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

- σ: Carbon intensity
  - $\sigma_{2015} \approx 0.35$
  - σ decreases exponentially, first rapidly (-1.5% per year) then more slowly (exogenous)
- μ: Emissions reduction rate (endogenous)
- Abating emissions is costly

$$\Lambda = \theta_{1,t}\mu_t^{\theta_2}$$

  - θ_1 is a function of the price of the backstop technology
  - $\theta_2 = 2.6$

Backstop technology

- Backstop technology concept
  - A technology capable of satisfying demand with a virtually infinite resource base
  - Fossil emissions: renewables, CCS, CDR, nuclear fusion, etc.
- Exogenous decrease in time

$$p_{b,t} = p_0(1 - g_b)^t$$

  - with $p_{b,2015} = 550\$$ per tCO2 and $g_b = 2.5\%$
- Calibrate $\theta_{1,t}$ so that marginal abatement cost when $\mu = 1$ equals $p_{b,t}$
  - Marginal abatement cost

$$\frac{\partial Q_t}{\partial E_t} = -\frac{\theta_{1,t}\theta_2}{\sigma_t}\mu^{\theta_2 - 1}$$

  - So we set

$$\theta_{1,t} = \frac{p_{b,t}\sigma}{\theta_2}$$

Climate damages

- Emissions enter the carbon cycle, made of three interacting reservoirs
  - Carbon in the atmosphere (M_{AT})
  - Carbon in the upper oceans and the biosphere (M_{UP})
  - Carbon in the deep oceans (M_{LO})
- M_{AT} affects radiative forcing F
  - F is a measure of the difference between incoming and outgoing solar radiation, relative to 1750 ($F_{1750} = 0$)
- Higher F warms the atmospheric layer (T_{AT})
- Finally, temperature creates damages

$$\Omega_t = \psi_1 T_{AT,t} + \psi_2 T_{AT,t}^2$$

  - where Ω is the damage ratio (damages/GDP)
  - with $\psi_1 = 0$ and $\psi_2 = 0.00236$
  - $\rightarrow$ 2.1% of GDP lost at 3°C; 8.5% at 6°C

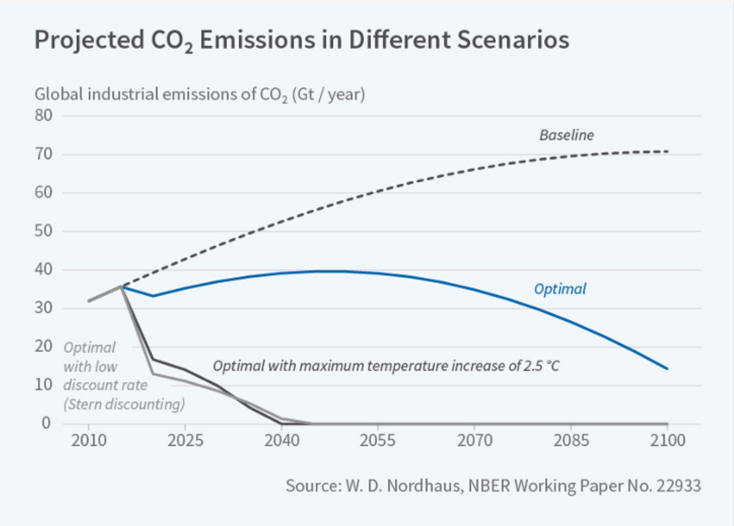
Macro variables

- Net output is equal to gross output less damages and abatement costs
$$Q_t = \frac{(1-\Lambda_t)Y_t}{1+\Omega_t}$$
- Net output is allocated between consumption and investments
$$Q_t = C_t + I_t$$
- Investments contribute to accumulating capital stock
$$K_{t+1} = (1-\delta_K)K_t + I_t$$

Scenarios

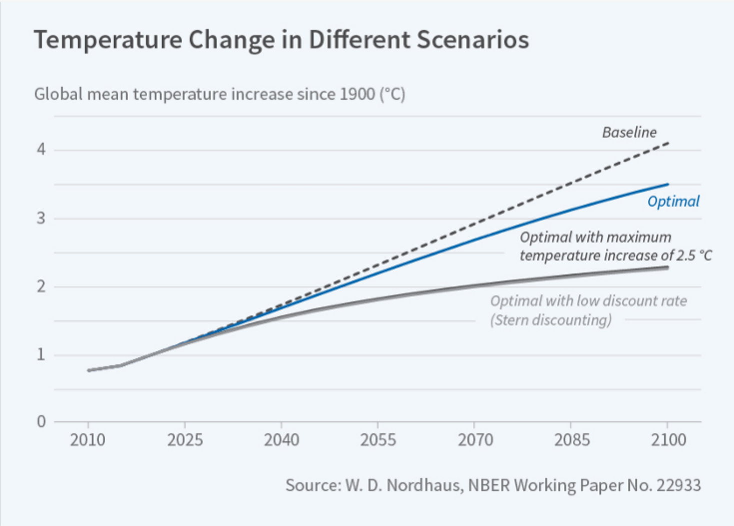
- Baseline (or ‘BAU’)
    - μ set to zero for entire simulations
- Optimal run
    - μ is a decision variable
    - It can be used to derive the social cost of carbon
- Temperature constraints
    - Set peak or average temperature to respect a threshold (e.g. 2° C)
- Change in parameters
    - E.g. Higher/lower discount rate

DICE results - Emission paths



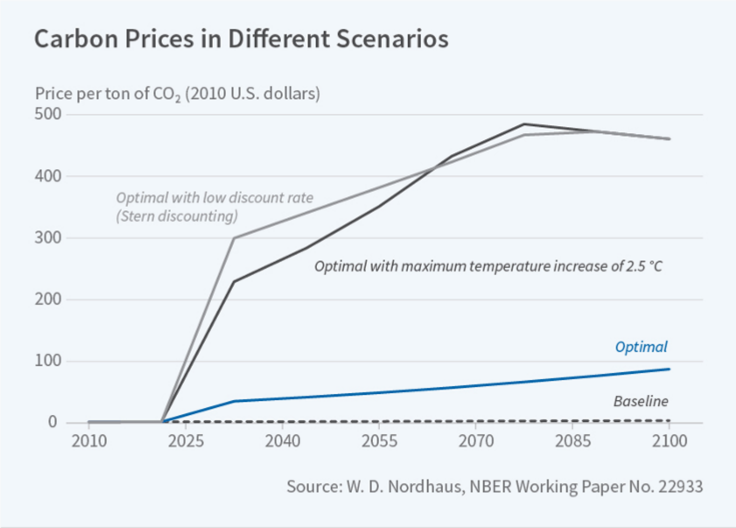
Source: Nordhaus (2017)

DICE results - Temperature paths



Source: Nordhaus (2017)

DICE results - Carbon price paths



Source: Nordhaus (2017)

Other IAMs

- Other well-known medium-scale models
  - FUND model by Richard Tol and collaborators
  - PAGE model by Chris Hope and collaborators
  - DICE, FUND and PAGE are used to calculate SCC in US
- Two main evolutions from this first generation
  - Go big: large-scale numerical models with multiple regions and detailed representation of technologies
  - Go small: simplified models aimed at deriving analytical solutions

An application to climate finance: Dietz et al. (2016)

- What would be the impact of climate change on asset values?
  - Value at Risk (VaR): potential portfolio loss over a given time horizon, at a given probability
- Starting point: DICE 2010
  - Modified climate damages: on both growth and capital stocks
- Some assumption
  - Asset values = NPV of discounted cash flows
  - Corporate earnings constant % of GDP → same growth rates
  - Debt and equity perfect substitutes

Table 1 | The present value at risk of global financial assets from climate change between 2015 and 2100—the climate VaR.

Emissions scenario	1st pctl.	5th	Mean	95th	99th
BAU (expected warming of 2.5 °C in 2100)	0.46%	0.54%	1.77%	4.76%	16.86%
Mitigation to limit warming to 2 °C with 2/3 probability	0.35%	0.41%	1.18%	2.92%	9.17%

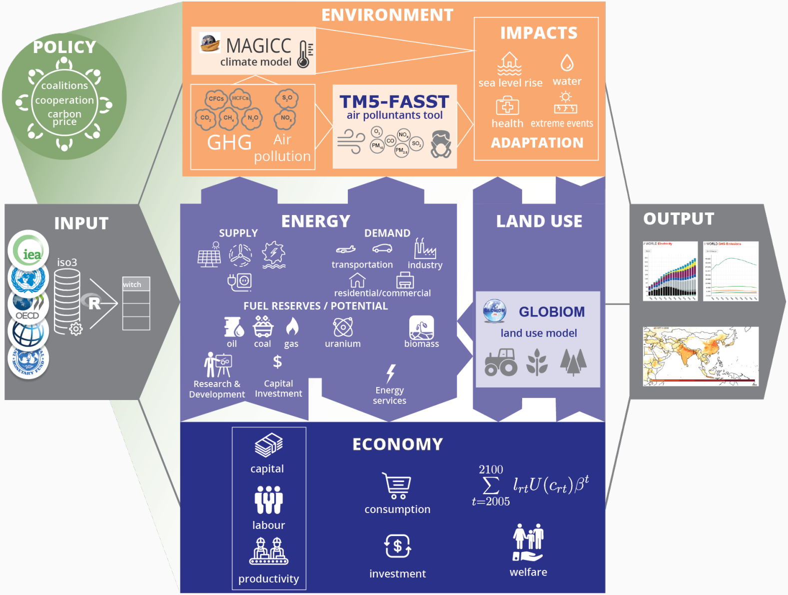
Source: Dietz et al. (2016)

Large-scale numerical IAMs

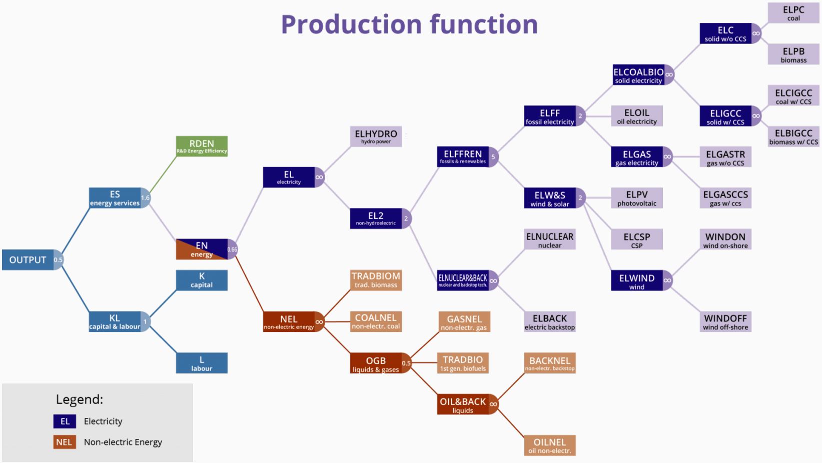
Large-scale numerical IAMs

- Common features across models
  - Multiple regions
    - Cooperative/non-cooperative behaviour; coalitions
    - Equity issues (burden-sharing, transfers)
  - Detailed energy sources/technologies and pollutants
  - Small climate modules (or links to larger climate models)
  - Economic modules also tend to be simple (or absent)
    - Exception: CGE models (are they IAMs?)
- But large variability across models
  - Partial vs general equilibrium
  - Simulation vs optimization
  - Recursive dynamic (myopic) vs intertemporal optimization (foresight)
  - Different representation of climate impacts, non-energy sectors, land use, regions..

An example: The WITCH model



The WITCH production function

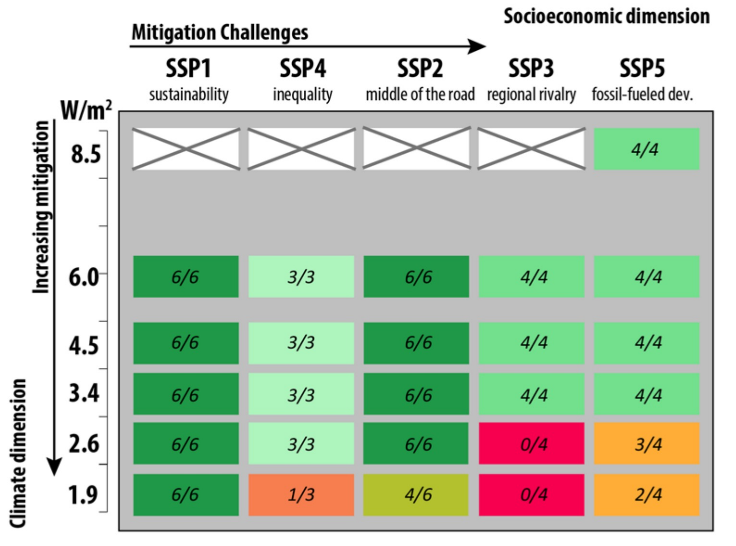


Source: WITCH website

- More details in the WITCH documentation

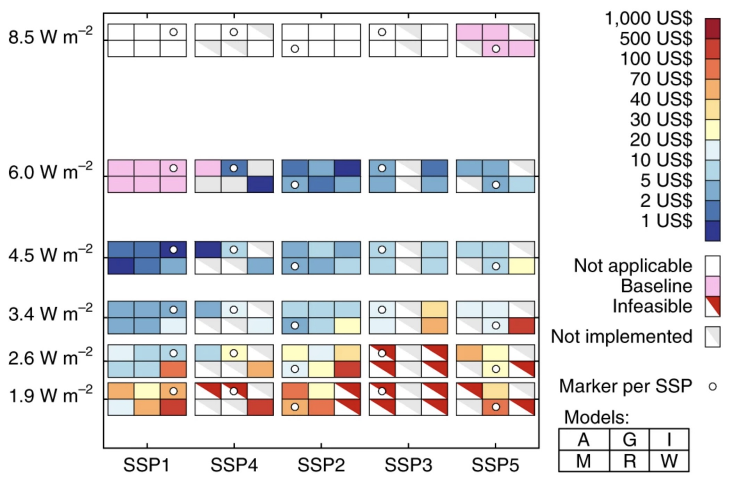
Many other large IAMs exist

- Other notable models:
  - MESSAGE model (IIASA, Austria)
  - GCAM model (JGCRI, United States)
  - IMAGE (PBL, Netherlands)
  - REMIND model (PIK, Germany)
  - IMACLIM (CIRED, France)
  - E3ME (Cambridge Econometrics, United Kingdom)
  - An overview: see the IAM Consortium Wiki paper
- Inter-model comparison exercises
  - Run the same scenarios and compare results
  - e.g. Rogelj et al. (2018): can we achieve 1.5°C? using six IAMs



In cells: numbers of models with feasible scenarios. Source: Rogelj et al. (2018)

Optimal carbon prices per RCP/SSP



Average global average carbon prices over 2020–2100 (discounted to 2010 with a 5% rate). A: AIM/CGE; G: GCAM4; I: IMAGE; M: MESSAGE-GLOBIOM; R: REMIND-MAgPIE; W: WITCH-GLOBIOM. Source: Rogelj et al. (2018)

Fossil stranding using TIAM-UCL

- TIAM-UCL regional model:
    - Partial equilibrium model with detailed representation of energy sources and systems
    - Driven by minimisation of energy system NPV costs to 2100
- What is the optimal geographical distribution of unnburnable carbon in a 2° scenario?

Table 1 | Regional distribution of reserves unburnable before 2050 for the 2 °C scenarios with and without CCS

	2 °C with CCS						2 °C without CCS					
	Oil		Gas		Coal		Oil		Gas		Coal	
Country or region	Billions of barrels	%	Trillions of cubic metres	%	Gt	%	Billions of barrels	%	Trillions of cubic metres	%	Gt	%
Africa	23	21%	4.4	33%	28	85%	28	26%	4.4	34%	30	90%
Canada	39	74%	0.3	24%	5.0	75%	40	75%	0.3	24%	5.4	82%
China and India	9	25%	2.9	63%	180	66%	9	25%	2.5	53%	207	77%
FSU	27	18%	31	50%	203	94%	28	19%	36	59%	209	97%
CSA	58	39%	4.8	53%	8	51%	63	42%	5.0	56%	11	73%
Europe	5.0	20%	0.6	11%	65	78%	5.3	21%	0.3	6%	74	89%
Middle East	263	38%	46	61%	3.4	99%	264	38%	47	61%	3.4	99%
OECD Pacific	2.1	37%	2.2	56%	83	93%	2.7	46%	2.0	51%	85	95%
ODA	2.0	9%	2.2	24%	10	34%	2.8	12%	2.1	22%	17	60%
United States of America	2.8	6%	0.3	4%	235	92%	4.6	9%	0.5	6%	245	95%
Global	431	33%	95	49%	819	82%	449	35%	100	52%	887	88%

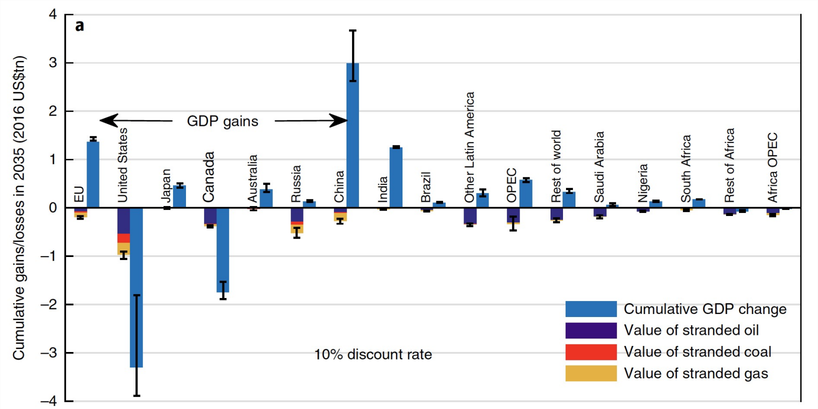
FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3; %, Reserves unburnable before 2050 as a percentage of current reserves.

Source: McGlade and Ekins (2015)

Fossil stranding using E3ME

- Combination of E3ME (macroeconometrics), FTT (diffusion) and GENIE (Earth systems) models
- Two stranding drivers: 2°C climate policy or technological diffusion
  - Fossil stranding can happen even without policies
  - Drop in demand for fossil fuels ($\rightarrow$ can trigger a 'sell out')
- Focus on geographical distribution of fossil stranding and macro implications
  - Net importers (e.g China, EU) may benefit from dynamics
  - Producers (Russia, US, Canada) will lose out
  - Global NPV wealth loss of US$1-4 trillion

Fossil stranded assets across regions



Cumulative GDP changes and discounted fossil fuel value loss to 2035 - 2 °C sell-out scenario vs IEA projections. Source: Mercure et al. (2018)

Computable General Equilibrium (CGE) models

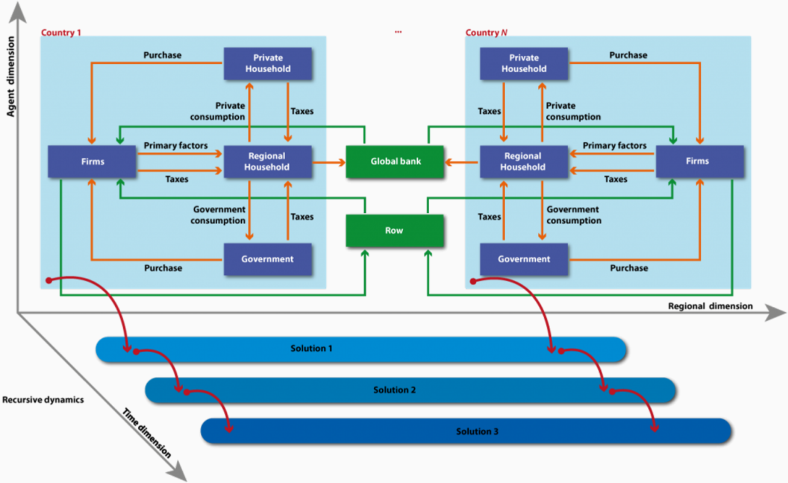
CGE models

- Start from actual data capturing economic inter-dependencies
  - Input-Output (IO) tables
  - Social Accounting Matrices (SAM) also include institutional accounts
  - e.g. GTAP Database
- Define a set of behavioural rules
  - Profit maximisation or cost minimisation by firms
  - Welfare maximisation by households
  - e.g. GTAP model
- Calibrate parameters on available data
  - E.g. Armington elasticity (of substitution between products of different countries)
- Introduce a change
  - E.g. a change in taxes or border tariffs
  - Observe how the system reacts to the change in prices

CGE models in climate economics

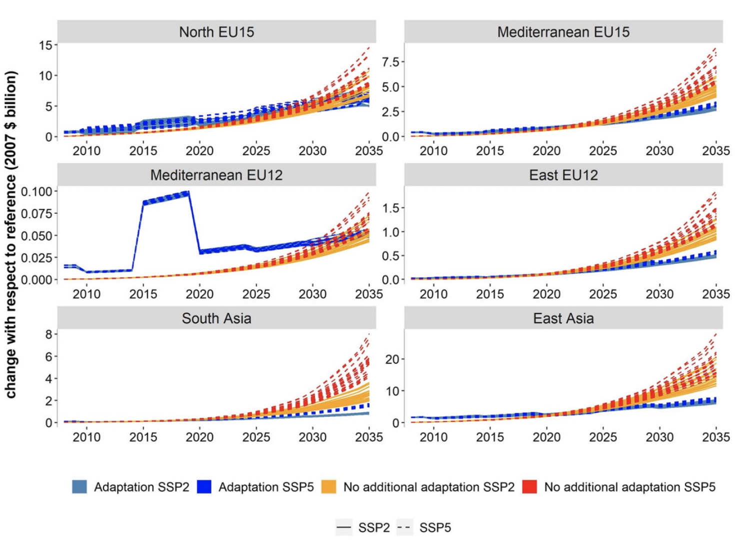
- They can adapted to include energy/environment
  - Impact of mitigation policies (carbon tax) or climate impacts
  - Multi-sectoral dimension is important (structural change)
  - Multi-regional dimension is important (trade impacts)
- Stylized representation of macro-financial dimension
  - All savings aggregated into a global banks that reallocates them according to relative returns
  - Crowding-out assumption (exogenous money)
- Example: ICES model (CMCC Venice)
  - Recursive model generating a sequence of static equilibria under myopic expectations
  - Derived from GTAP-E model
  - Cost-minimizing firms, representative household and government

An example: the ICES model



ICES model structure. Source: ICES website

An application: Public deficit and adaptation to sea level rise



Impacts on public deficit. Source: Parrado et al. (2020)

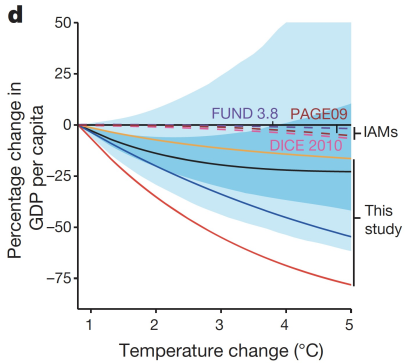
Analytical IAMs

Analytical IAMs

- Small-scale IAMs with simplified relations
- Usually aimed at deriving analytical rules for the SCC (i.e. optimal carbon price)..
  - Golosov et al. (2014) on Econometrica
  - Rezai and Van der Ploeg on JAERE
  - Gerlagh and Liski (2018) on EJ
  - Cai and Lontzek (2018) on JPE
  - van den Bijgaart et al (2016) on JEEM
- .. or cost-efficient paths to a temperature target / carbon budget
  - Lemoine and Rudik (2017) on AER
  - Rozenberg et al. (2020) on JEEM
- Let's look at an example from van der Ploeg (2020)

Damages from temperature

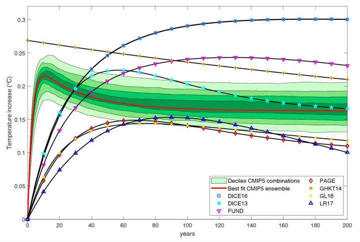
- Assumption:
  - Damages proportional to GDP
- Assumption:
  - Damage/GDP ratio linear function of temperature
  - Justification: Burke et al. (2015) on Nature
- Constant Marginal effect of temperature on damage ratios (MDR): $\frac{\partial \Omega}{\partial T}$

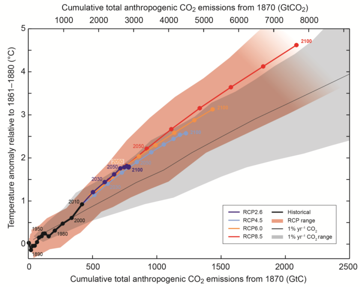


Source: Burke et al. (2015)

Effect of emissions on temperature

- We assume T to be a linear function of cumulative emissions (S)
- That is, $\frac{\partial T}{\partial S}$, the Transient Climate Response to Cumulative Emissions (TCRE), is independent of time and concentration M
- Assume TCRE≈1.8°C per tn tons of carbon (Matthews et al. 2018 give a 0.8-2.4°C range)





Source: Dietz et al. (2021) and IPCC (2013)

A simple formula for the SCC

- Further assuming:
  - Exponential discounting with RTI: rate of time impatience (ρ in DICE); and IIA: relative intergenerational inequality aversion (α in DICE)
  - Constant trend growth rate g
- We can write the optimal carbon price as

$$P_t = \frac{MDR * TCRE}{RTI + (IIA - 1)g} Y_t$$

- Depending on assumptions on damages, discount rate, IIA, etc. we can obtain a large range of optimal prices..
- P increases at rate g (adjusted for inflation)

Alternative: put constraint and find efficient path

- Hotelling structure applicable
  - Remember Hotelling rule: optimal net price ('Hotelling rent') of an exhaustible resources grows at the rate of interest
  - Remaining allowable CO2 emissions are like an exhaustible resource
- Optimal carbon price is a function of interest rate (or SDR) $P_t = e^{rt} P_0$
- Risk-adjusted interest rate is what we're interested in
  - Gollier et al. (2020): 3.75%
  - If it's too high, it means that, for a specific carbon budget, price today is too low

Growth theory on asset stranding

- Analytical Ramsey growth models can also be used to study optimal capital stranding
    - Stranding as loss of capacity utilisation ('endogenous capacity constraints')
- A selection of papers
    - Amigues et al. (2015) on JEDC (A+)
    - Vogt-Schilb et al. (2018) on JEEM (VS+)
    - Coulomb et al. (2019) on ERE (C+)
    - Baldwin et al. (2020) on JEEM (B+)
    - Rozenberg et al (2020) on JEEM (R+)

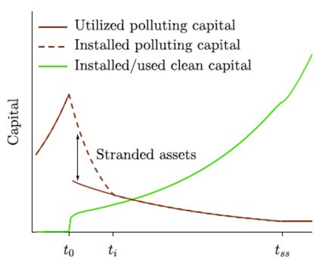
Common features

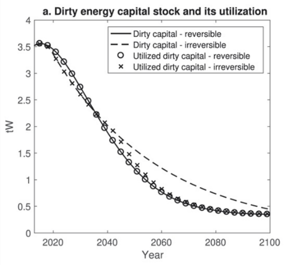
- Intertemporal maximisation of welfare $u(c_t)$
- Two (or more) technologies: clean and dirty capital (k_C, k_D)
    - Investments are irreversible: Jorgenson (1967), Arrow and Kurz (1970)
    - They allow for underutilisation of capital ($q_t \leq k_t$)
- Using k_D produces emissions: $e_t = F_t k_{D,t}$
    - where F is carbon intensity
- In the social planner programme, some constraint is imposed
    - Typically a carbon budget $\bar{m}$ (on resources or cum. emissions)
- No explicit financial considerations

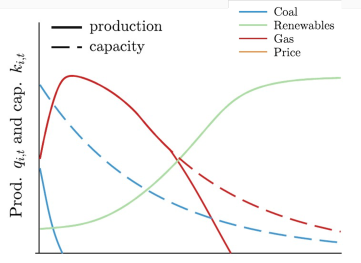
General results

- They then derive optimal paths for investments, utilisation rates, etc.
- $\rightarrow$ Optimal paths under carbon budgets would inevitably involve some stranding of capital stocks
  - A period in which it is optimal to leave some installed capital unutilised
- The exact features of the optimal transition depend on some crucial 'exogenous' values
  - eg. carbon budget, investment cost parameters
  - $\rightarrow$ a variety of possible optimal transition profiles (sequential vs overlapping, timing, stranding profiles)

Typical results concerning underutilisation



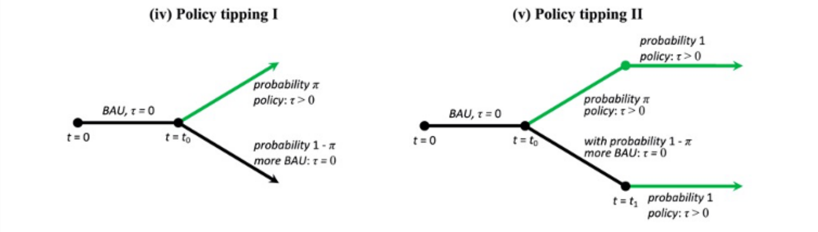




Source: Rozenberg et al. (2020), Baldwin et al. (2020) and Coulomb et al. (2019)

van der Ploeg & Rezai (2020) on JEEM

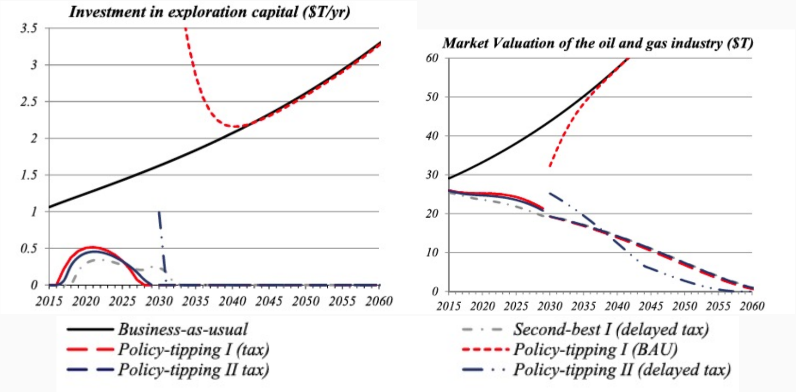
- Focus on the fossil fuel sector
  - A single type of capital to work with: extraction capital k
  - No underutilisation of capital allowed
- Market valuation of fossil firms given by future profits
  - They decide investments by maximising $V^R \equiv \int_0^\infty e^{-rt}\Pi^R$
- Policy tipping setting:



Source: van der Ploeg & Rezai (2020)

van der Ploeg & Rezai (2020): Results

- Uncertainty (and its resolution) affect transition profiles
  - I might go to zero but K continues to operate
  - $\rightarrow V$ moves more smoothly



Source: van der Ploeg & Rezai (2020)

Conclusions

Conclusions

- We want to explore climate-related macro-financial futures
  - $\rightarrow$ We need models
- Two broad methodological avenues
  - Neoclassical: equilibrium, optimisation, supply-side, rationality, homogeneity, forward-looking expectations
  - Behavioural: disequilibrium, scenario analysis, demand-side, behavioural functions, heterogeneity, complexity, adaptive expectations
- Integrated Assessment Models (IAMs)
  - DICE
  - Analytical IAMs
  - Large-scale numerical IAMs

Unanswered questions on macro and finance

- IAM/CGEs have no or little representation of macro-financial system
  - No banking or financial institutions
  - Production networks: yes in CGE; financial networks: no
  - No monetary/banking/financial policies
  - Physical/financial conflation (investments, capital)
  - Stranding possible only for fossil reserves
- Next lecture: alternative strategies
  - Include climate/transition into neoclassical macro models
  - Include climate/transition into non-neoclassical macro models