Climate-related macro-financial modelling (I)

Climate macro & finance course 2022 - Lecture 3

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Communication on assessment

- Types of paper to be written:
  - Critical reflection on a specific literature
  - Preliminary development of research ideas
  - Or a combination of both
- Topics:
  - Some specific issue among the ones studied in the course
  - Eg. What is the overview of exposure of physical/financial assets at risk of stranding?
  - Eg. How to effectively capture transition-related expectations among households/firms/investors?
  - Happy to suggest topics (remember SMOOTH?) but you need to have genuine interest
- Timeline
  - Topics by 15 March
  - Deadline: 30 March

Last lectures

- Conceptual and empirical research on climate-related macro-financial dynamics
    - Strategy: reduce GHG emissions
    - However, decarbonisation could come with costs
    - Common conceptual framework: drivers → costs for firms → costs for financial institutions → macro-financial disruptions
- Empirical research
    - Calculate exposure to risks (e.g. physical/financial asset stranding)
    - Capture climate-related 'sentiments' (asset pricing, text analysis, surveys, experiments)
- Today:
    - What could the future look like? How should we intervene?
    - → Prospective modelling methods

Outline of today's lecture

- Basic modelling blocks
  - Key modelling decisions to take
  - How to put climate and transition in
  - Equilibrium vs non-equilibrium methods
- Overview of modelling strategies
  - 1. Use climate economic modelling (IAMs, CGE)
  - 2. Use neoclassical macro modelling (DSGE, CAPM)
  - 3. Use non-neoclassical macro modelling (SFC, ABM)
- The DICE model
  - Modelling structure and main results
- Large-scale numerical IAMs
  - → Rebecca's presentation on Gambhir et al. (2021)
  - → Carmen's presentation on Moore et al. (2022)

In the next lecture

- Analytical IAMs
- Computable General Equilibrium (CGE) models
- Dynamic Stochastic General Equilibrium (DSGE) models
- Capital Asset Pricing Models (CAPM)
- Stock-Flow Consistent (SFC) models
  - $\rightarrow$ Angela's presentation on Dafermos et al. (2021)
- Agent-Based Models (ABM)
  - $\rightarrow$ Adrianna's presentation on Rengs et al. (2020)

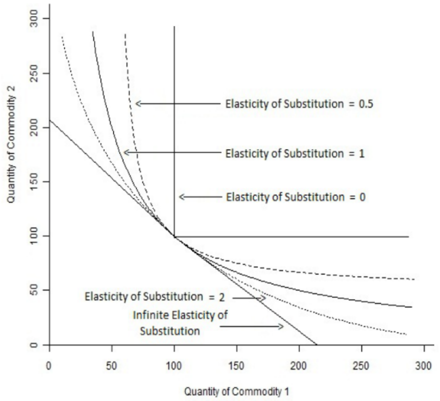
Key modelling decisions to make

Outline of the section

- Some key economic modelling decisions
  - Production function (supply- vs demand-side)
  - Welfare function or not
  - Optimisation vs macro-econometric behavioural functions
  - Forward- vs backward-looking expectations
- Putting climate-related dimensions in
  - Economy $\rightarrow$ Environment (e.g. GHG emissions)
  - Abatement mechanisms
    - Abatement technologies decreasing emissions
    - Structural change from dirty to clean capital
  - Environment $\rightarrow$ Economy
    - Climate damages to output/productivity/utility..
    - Emission/temperature constraints
  - Adaptation mechanisms

Production function choice

- How is output produced?
  - Supply side: input factors $\rightarrow$ output (demand accepts)
  - Demand side: demand sources $\rightarrow$ output (supply provides)
- Ultimately a choice about elasticity of substitution
  - Change in $\frac{x_1}{x_2}$ when $\frac{p_1}{p_2}$ changes?



Types of production functions. Figure source

Supply-side production functions

- Cobb-Douglas (CD)
  - $Y = AK^{\alpha}L^{\beta}$
  - Elasticity constant and equal to 1
  - Include energy? $\rightarrow Y = AK^{\alpha}L^{\beta}E^{\gamma}$
- Constant elasticity of substitution (CES)
  - $Y = A(\alpha K^{\rho} + (1-\alpha)L^{\rho})^{\frac{1}{\rho}}$
  - Elasticity of substitution: $\sigma = \dfrac{1}{1-\rho}$
  - CES nesting:
    $Y = A\left[\alpha\left(\alpha_1 K^{\rho_1} + (1-\alpha_1)L^{\rho_1}\right)^{\frac{\rho}{\rho_1}} + (1-\alpha)ES^{\rho}\right]^{\frac{1}{\rho}}$
  - Possible to include intermediate inputs

Demand-side production function

- Demand for goods determines production
  - $Y = C + I + G$ (consumption+investment+public expenditure)
  - Sometimes supply bottlenecks considered
- Ultimately a Leontief production function:
  - $Y = \min(\xi_K uK; \xi_L \lambda L)$
  - ξ_K and ξ_L: productivities
  - u and λ: input utilisation rates
- $Y \rightarrow$ Input factor utilisation
  - $u = \frac{Y}{\xi_K K}$; $\lambda = \frac{Y}{\xi_L L}$

Welfare function choice

- Are we interested in measuring utility/welfare?
    - Yes, if we then try to maximise it
    - Otherwise, societal welfare inferred from macro variables (GDP, employment, environmental quality, etc.)
- Most common utility function:

$$u(c) = \begin{cases} \frac{c^{1-\eta}-1}{1-\eta} & \eta \geq 0, \eta \neq 1 \\ ln(c) & \eta = 1 \end{cases}$$

    - Isoelastic (i.e. with constant elasticity), power, or CRRA (constant relative risk aversion) utility function
    - η is the elasticity of marginal utility of consumption
    - η interpreted as relative inter-generational inequality aversion, with intertemporal elasticity of substitution (IES) $\frac{1}{\eta}$
    - η also coincides with the degree of relative risk aversion here

Welfare function choice

- What else can appear into the utility function?
  - Relatively common: leisure (i.e. the opposite of working). E.g. $U(c_t, l_t) = c_t^{\nu} l^{1-\nu}$
  - Sometimes there is an environmental dimension:
    - E.g. Acemoglu et al. 2012: $u = \frac{(\phi(S_t)C_t)^{1-\sigma}}{1-\sigma}$ where S is the quality of the environment
- Epstein-Zinn preferences (recursive utility):
  - Allows to separate IES and risk aversion, and to account for uncertainty
  - E.g. $U_t = \left[c_t^{\rho} + \beta \mathbb{E} U_{t+1}^{\rho}\right]^{\frac{1}{\rho}}$

Optimisation vs macro-econometric approach

- Optimisation
  - Maximisation of (inter-temporal) welfare
    - eg. $W = \sum_{t=1}^{T} \beta^t U(C_t)$, where $\beta = \dfrac{1}{(1+\rho)^t}$ is discount factor
  - Minimisation of (inter-temporal) (energy/abatement) costs
  - $\rightarrow$ Optimal consumption and investment paths
- Behavioural functions
  - Consumption and investment choices modelled as (linear) functions of other variables
  - e.g. $I = \eta_0 + \eta_1 u + \eta_2 \Pi$
  - Underlying theoretical assumptions + econometric estimation
  - Non-neoclassical schools of thought

Forward- vs backward-looking expectations

- Forward-looking expectations
  - Agents formulate (correct?) expectations about the future and act accordingly
  - Usually (but not necessarily) combined with optimisation
  - To what extent agents look into the future? $\rightarrow$ Infinite vs finite planning horizons
- Backward-looking expectations
  - Choices under radical uncertainty: agents cannot formulate reliable expectations
  - They look at the present/past, and linearly extrapolate into the next period
  - e.g. $I_t = \eta_0 + \eta_1 u_{t-1} + \eta_2 \Pi_{t-1}$

A large number of additional choices to make

- How many sectors, and how are they distinguished?
- How many households/populations, and how are they distinguished?
- Are there banks and/or non-bank financial institutions?
- Do we consider production or financial networks?
- Are there sources of uncertainty in the model?
- Is there a government? What policies can it implement?
- Is there a central bank? What policies can it implement?
- Etc. etc. etc....

Putting climate and transition in

1. Economy to environment links

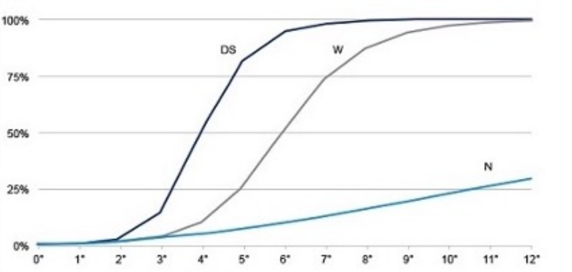
- Typically GHG emissions function of output/capital/energy
  - e.g. $E = \psi Y$ where ψ is carbon intensity
  - How does ψ move? Exogenous and endogenous innovation
- Sometimes also resource use
  - Production leads to resource depletion $\dot{R}_t = -q_t$
  - Focus on energy/material intensity

2. Abatement mechanisms

- Abatement technologies decreasing emissions
  - e.g. $E = \mu\psi Y$ where μ is abatement parameter
  - Abatement cost function
- Structural change from dirty to clean capital ($K_d \rightarrow K_c$)
  - Shift to cleaner technologies decreases emissions
  - Capital stock inertia? $\rightarrow$ Irreversibility or adjustment costs
  - Abatement cost linked to differences across technologies (e.g. different productivities/prices)
  - $\rightarrow$ Underutilisation of capital stocks?

3. Environment to economy links

- Climate damages
  - Environmental externality creates costs to output/growth/productivity/utility
  - Cost-benefit analysis: trade off benefits and costs of polluting to find optimal behaviour
- The debate around damage function specifications



Climate damage functions by Dietz and Stern (2014), Weitzman (2012) and Nordhaus (2013). Source: Schroeders (2015)

3. Environment to economy links

- Constraints
  - Focus on objectives
    - Temperature goals: 1.5-2°C upper limits
    - Carbon budget (cumulative emissions)
    - Overshoot or not; Negative emission technologies or not
  - Cost-effectiveness analysis
    - Reach/respect constraint optimising welfare or minimising GDP/energy/abatement costs
- Alternative: take some climate-related dimensions as exogenous
  - Carbon price policy scenario
  - Emission reduction schedule (e.g. to net-zero by 2050)

Climate/transition modelling approaches

Two main methodological avenues

	Equilibrium	Non equilibrium
Behaviour drivers	Intertemporal optimisation of a welfare function	Macro-econometric relations
Determination of output	Supply-driven: output (production) is allocated between different uses (consumption and investment) Y=AKL	Demand-driven: output (income) is determined by the expenditure desires (consumption and investment) Y=C+I+G
Expectations	Forward-looking expectations by rational agents	Adaptive expectations by agents in a context of deep uncertainty
Decisions	Rational	Routines in a context of deep uncertainty
Equilibrium	The system moves to an equilibrium state (balanced growth path)	There is not necessarily an equilibrium (cycles, emergent behaviours)
Money	Money as a 'veil' (banks as intermediaries)	Endogenous money (credit creation by commercial banks)
Modelling approaches	IAM, CGE, DSGE, CAPM	SD, SFC, ABM
Communities	Economics, Finance, Environmental/Energy Economics	Social sciences, Ecological/Evolutionary Economics

First strategy: Use climate economic modelling

- Integrated Assessment Modelling
  - Aim: assess in an integrated manner interactions between economy, energy systems and climate
  - The father of IAMs: the DICE model
- Types of IAMs
  - Large-scale numerical IAMs
  - Analytical IAMs
  - Computable General Equilibrium (CGE) models
- Traditionally small economy modules and no finance
  - Can they expand to include macro-financial dimensions?
  - Analytical IAMs might be the most flexible
  - Also a matter of definition of IAMs

Second strategy: Use macro-financial modelling

- Neoclassical 'equilibrium' modelling
  - Dynamic Stochastic General Equilibrium (DSGE) models
  - Capital Asset Pricing Models (CAPM)
  - Growth theory ($\rightarrow$ Analytical IAMs)
- Non-neoclassical 'disequilibrium' modelling
  - Stock-Flow Consistent (SFC) models
  - Agent-Based Models (ABMs)
  - Diffusion / discrete choice theory

Alternative taxonomies: Mercure et al. (2019)

Table 1. Schools of economic thought.

	School Name		Micro-foundations: Rationality / Agent	Money	Parameter-isation method	Innovation Technology	Economic change
Equilibrium/Supply-led	Neoclassical	Solow[1]	Rational expectations/ Representative Agent	Commodity	Optimization	Exogenous	Capital accumulation
		Endogenous Growth[2]	Rational Expectations/ Representative Agent	Commodity	Optimization	Knowledge in production functions	Capital & knowledge accumulation
		General[3] Equilibrium	Rational Expectations/ Representative Agent	Commodity	Optimization	Knowledge in production functions, learning curves, knowledge spillovers[10]	Capital & knowledge accumulation
Non-equilibrium/ demand-led	Post-Schumeterian	Evolutionary Economics[4]	Behavioural[8] Heterogeneous	Asset (Credit creation)	Dynamical systems, Historical approach[9]	Knowledge networks, Diffusion, learning	Entrepreneur, Innovation clustering, creative destruction
		Transitions Theory[5]				Historical	
		Technology Innovation Systems[6]				Case studies	
	Post-Keynesian[7]	Horizontalists	Behavioural[8] Heterogeneous	Asset (Credit creation)	Time series Econometrics	Sectoral tech. progress functions	Cumulative causation of knowledge accumulation
		Structuralists					
	Behavioural[8]		Numerous agents	–	Empirical	–	–
	Marxian		Classes	–	Econometrics	–	–

Representative Models: [1]RICE/DICE (Nordhaus, 2013), [2]REMIND (PIK, 2016), [3]IMACLIM (CIRED, 2018), AIM (NIES, 2012), GEM-E3 (E3MLab, 2018a), [4]Evolutionary Economics (Safarzyńska & van den Bergh, 2010), [5]Geels (Geels, 2002), [6]Technology Innovation Systems (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007), [7]E3ME-FTT (Mercure et al., 2018a), GINFORS (Lutz, Meyer, & Wolter, 2009), Giraud stock-Flow (Giraud, Mc Isaac, Bovari, & Zatsepina, 2016), DEFINE (Dafermos et al., 2017), MINSKY (Keen, 1995), [8]Prospect theory (Kahneman & Tversky, 1979), Discrete choice theory (Domencich & McFadden, 1975), [9]historical approach (Freeman & Louçã, 2001; Geels, 2002), [10]Note that although the method is in use (e.g. in GEM-E3), some but not all GE models feature learning curves or knowledge spillovers.

Source: Mercure et al. (2019)

Alternative taxonomies: Mercure et al. (2019)

Table 2. Types of macro-models and summary of their assumptions regarding energy-related innovation and investment behaviour.

	Assumption type		Micro innovation	Macro innovation	Micro agent	Macro agent
Supply-led / Optimization	Optimal growth[1]		Does not have detailed disaggregated sectors	Knowledge accumulation in economy production function	Normative social planner optimizing utility inter-temporally	
	General Equilibrium	Computable General Equilibrium[2]	Can be linked to detailed technology models	Endogenous productivity in sectoral production functions	Representative agent with rational expectations (deterministic) optimizing utility, prices adjust to clear all markets	
		Dynamic Stochastic General Equilibrium	Can be linked to detailed technology models	Exogenous technological change	Heterogeneous stochastic representative agent	
	Partial equilibrium Cost-optimisation[3]		Learning curves, exogenous diffusion rates, vintage capital	Productivity not defined, can be linked to a CGE model	Can be heterogeneous, market segments	The normative social planner
Demand-led / Simulation	Macro-econometric[4]		Can be linked to detailed technology models	Technology progress indicators (fn. of cumulative investment)	Can be linked to detailed technology models	Investment behaviour derived econometrically
	Systems Dynamics	Discrete choice[5]	Vintage capital (fleets), learning curves	Productivity not defined, but can be linked to any macro-model	Multinomial logit regressions, heterogeneous agents	Can be linked to macro-model
		Diffusion[6]	Selection-diffusion evolutionary model, learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model
	Agent-based	Sectoral[7]	Vintage capital (fleets), learning curves	Can be linked to a path-dependent economic model	Decision-making under bounded rationality, social influence	Can be linked to macro-model

Model examples: [1]RICE/DICE (Nordhaus, 2013), FUND (Anthoff & Tol, 2014), QUEST (DG ECFIN, 2015), [2]GEM-E3 (E3MLab, 2018a), IMACLIM (CIRED, 2018), [3]MESSAGE (IIASA, 2014), (PNNL, 2017), TIMES (IEA/ETSAP, 2016), PRIMES (E3MLab, 2018b), [4]E3ME (Mercure et al., 2018a), GINFORS (Lutz et al., 2009) Giraud stock-Flow (Giraud et al., 2016), DEFINE (Dafermos et al., 2017), EIRIN (Monasterolo & Raberto, 2018) [5]IMAGE-TIMER (Bouwman et al., 2006) [6]FTT (Mercure et al., 2014) [7]MATISSE (Köhler et al., 2009).

Source: Mercure et al. (2019)

Alternative taxonomies: Ciarli and Savona (2019)

Table 2
Aspects of structural change in different modelling traditions. Some models are better equipped than others to capture the relation between aspects of structural change and environmental impact. In particular those that do not require a closed form solution in equilibrium.

Models	Aspects of structural change					
	Sectors	**IO**	**Technical change**	**Employment**	**Demand**	**Institutions**
IAM	No: aggregate & exogenous – no sectoral changes	No	Partial: Exogenous, LBD, induced TC, but aggregate	No	Limited: time preferences change with pollution	No (policy experiments)
CGE	Partial: many sectors, with technical change that may affect GHG	No: I/O maps diversification, but static	Partial: Semi-exogenous, LBD, induced TC, but aggregate	No	Limited: change consumption patterns, not preferences	No (policy experiments)
SCM	Yes	Yes, but only a couple of models	Yes, but only a couple of models	No	Limited: two populations	No (policy experiments)
EMK	Partial: labour composition	Not yet	No	Yes	Limited: wage distribution	No (policy experiments)
EABM 1	Partial: weaker on the environmental effects	Limited: firm size & industrial dynamics	Largely Yes	Yes	Yes, although not developed	Partial: interaction & response to policies
EABM 2	No	Limited: mainly industrial dynamics	Yes	No	Yes	Partial: evolution of power and tech. opportunities

Notes: IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM 1: evolutionary and multi agent models (macro); EABM 2: evolutionary and multi agent models (innovations).

Source: Ciarli and Savona (2019)

Alternative taxonomies: Nikas et al (2019)

Category	Economy	Impacts	Energy	Climate
Optimal growth models	Neoclassical growth Highly aggregated Tracks long-term trajectory of economy (dynamic) Single production function Single representative agent Policy optimisation Global	Highly aggregated monetary damage function that translates temperature change to loss of GDP All damages in monetary terms	Aggregated energy sector (top-down)	Reduced-form equations linking emissions to temperature
General equilibrium models	Multisectoral (multiple production functions) Single representative agent Optimising behaviour of producers and consumers Global, regional, national, local More difficult to incorporate dynamics	Shocks introduced into production functions, e.g. reduction in crop yields reflected in agricultural production function leading to a shift in supply Shocks can be based on expert judgements or drawn from biophysical or statistical models of impacts	Often detailed description of energy system (multiple energy sources explicitly modelled) Often linked to bottom-up energy system models	Climate scenarios are exogenous and used to drive climate variables and impacts
Partial equilibrium models	Detailed modelling of a single sector, e.g. agriculture Static and dynamic Often combined or linked with other top-down models	(a) Detailed biophysical model of impacts to specific sector relating key climate variables to impacts (b) Statistical analysis leading directly to monetary value of impacts	Little or no representation of energy sector	Exogenous climate scenarios used to drive impacts
Energy system models	Can be considered as a subcategory of partial equilibrium models (with some instances including a macro feedback) Often linked to top-down models (making them "hybrid")	Used to assess costs of reducing emissions; no need to represent impacts	Detailed representation of alternative energy technologies and mitigation opportunities and policies	Focus on emissions rather than climate change
Macroeconometric models	Input-output econometric (multisectoral) Macroeconomy components Simulation: agents not assumed to feature optimising behaviour "Keynesian" Dynamic	Used primarily to evaluate mitigation and adaptation policies rather than evaluate damages arising from climate change	Detailed description of energy system	Exogenous scenarios
Other models	Various simple representations of economy or exogenous scenarios of economic growth	Variety of detailed representations of impacts and damages both physical and monetary	Various aggregated and detailed energy models	Reduced-form equations linking emissions to temperature and other variables

Source: Nikas et al. (2019)

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 is an ethical question: 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

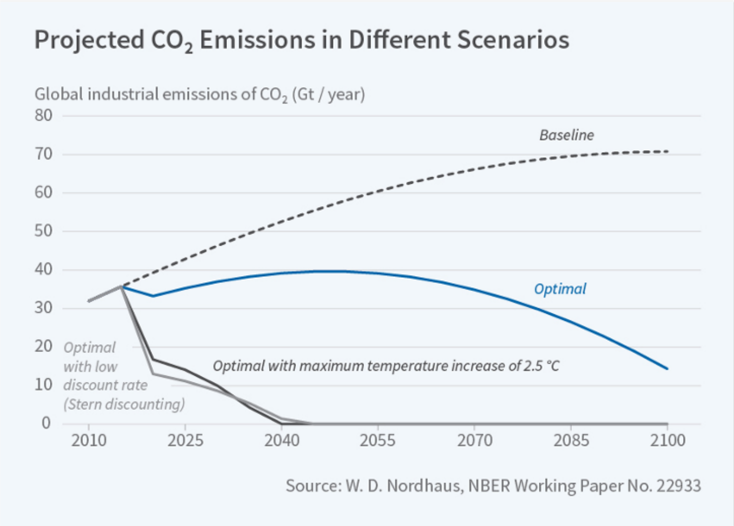
Macro variables

- 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

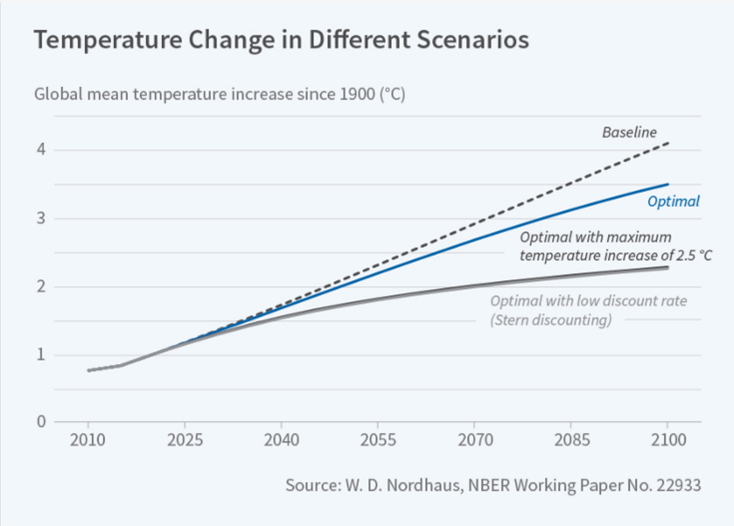
- Baseline (or ‘BAU’)
  - μ set to zero for entire simulations
- Optimal run
  - μ is a decision variable
  - It can be used to derive the social cost of carbon
- Temperature constraints
  - Set peak or average temperature to respect a threshold (e.g. 2°C)
- Change in parameters
  - E.g. Higher/lower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

DICE results - Emission paths



Source: Nordhaus (2017)

DICE results - Temperature paths



Source: Nordhaus (2017)

The social cost of carbon (SCC)

- SCC computes monetary present value of all net future damages deriving from emitting an additional tonne of CO_2.
- Nordhaus calculates it as a shadow price (cost of emitting an additional unit of CO_2 in terms of consumption)

$$SCC_t \equiv \frac{\partial W}{\partial E_t} \Big/ \frac{\partial W}{\partial C} \equiv \frac{\partial C_t}{\partial E_t}$$

- This is used in US as optimal carbon price to apply
  - Europe and others just set targets (on temperature, emissions, etc)

The social cost of carbon (SCC)

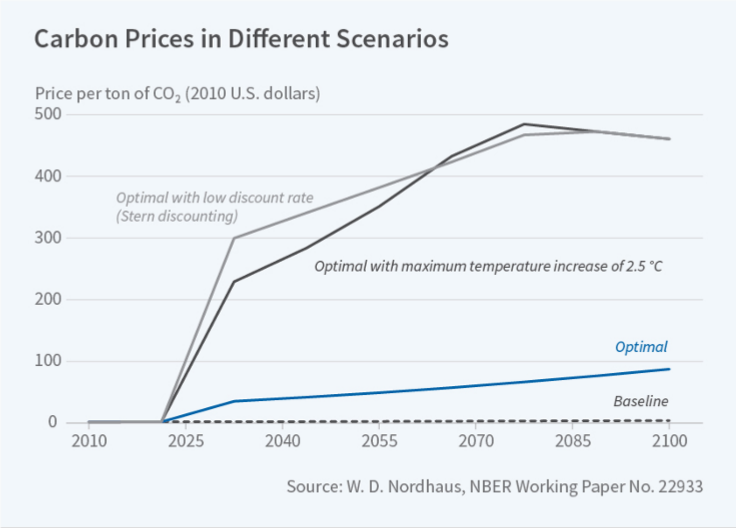
Table 3. Estimates of SCC for 2020 from US Interagency Working Group and comparison with DICE model in 2010 US$

Model and scenario	5% per year discount rate on goods	DICE	4% per year discount rate on goods	3% per year discount rate on goods	2.5% per year discount rate on goods
Estimates of 2020 SCC from US Working Group, 2013 (2010$)					
DICE-2010	12	na	na	40	59
PAGE	23	na	na	74	105
FUND	3	na	na	22	37
Average	13	na	na	**45**	67
Estimates for different DICE model versions (2010$)					
DICE-2013R	15	24	26	50	74
DICE-2016R	23	**37**	41	87	140

Upper rows show estimates of the 2020 SCC from the IAWG. The three models have harmonized outputs, emissions, populations, and ETS distribution and use constant discount rates. Lower rows show the results of the estimates from the two latest versions of the DICE model for the baseline (Table 1) and using constant discount rates.

Estimates of SCC for 2020. 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

Dietz et al. (2016) using DICE

- 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 $\rightarrow$ 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%

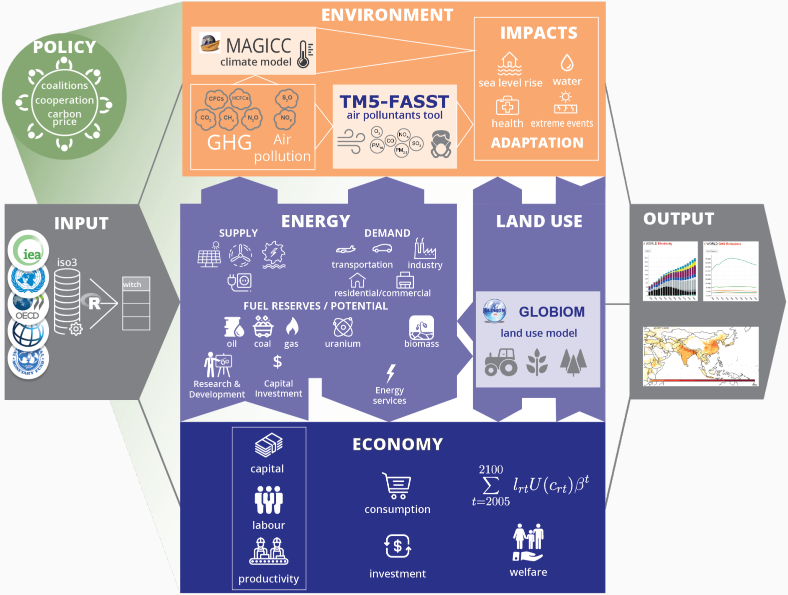
Source: Dietz et al. (2016)

Large-scale numerical IAMs

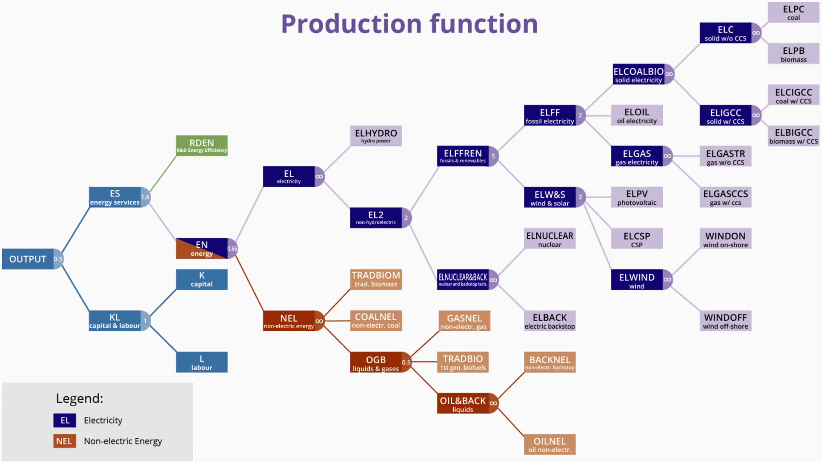
Large-scale numerical IAMs

- 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

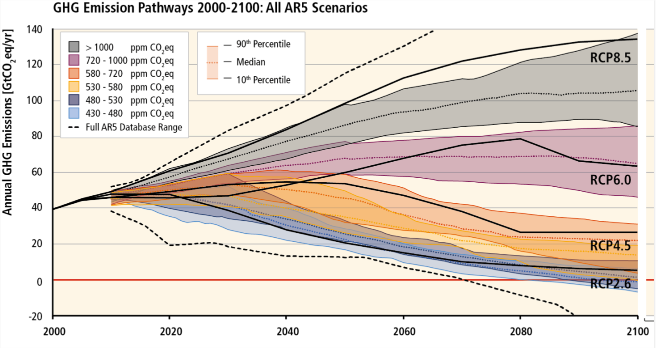
- More details in the WITCH documentation

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

Common scenarios: RCPs

- IPCC AR5: Representative Concentration Pathways (RCPs)
  - Based on radiative forcing in 2100; expressed in W/m2
  - RCP2.6 (stringent mitigation); RCP4.5; RCP6.0; RCP8.5 (high emissions)
  - Now also RCP1.9 (≈1.5°C) and RCP3.4 scenarios



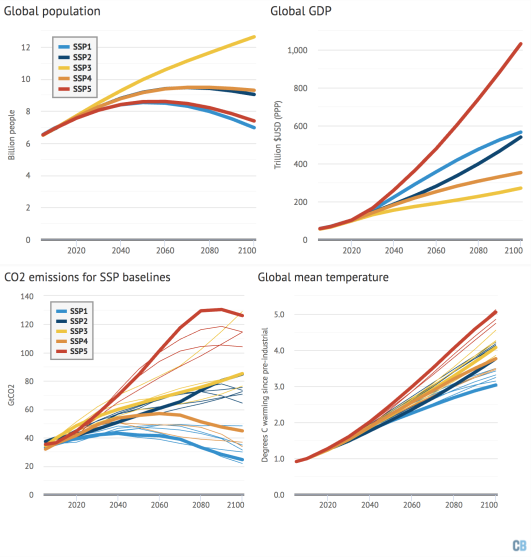
Representative Concentration Pathways (RCPs). Source: IPCC (2014)

Common scenarios: SSPs

- IPCC AR6: Shared Socioeconomic Pathways (SSPs)
  - Based on socio-economic narratives (irrespective of policy)
  - Population, urbanization, GDP, technology..

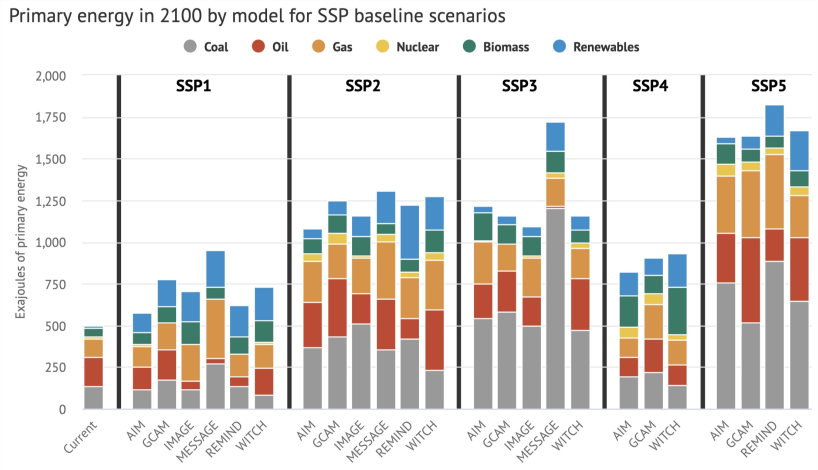
Source: O'Neill et al. (2017) and Rihai et al. (2017)

SSP scenario dynamics



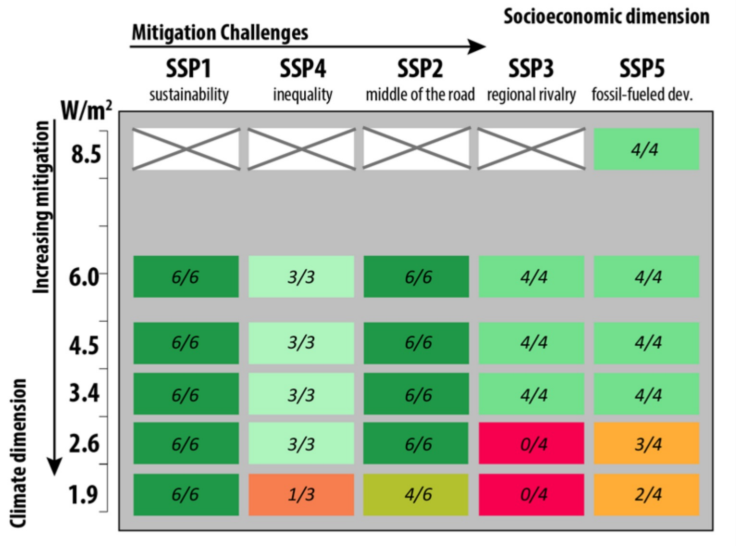
Source: Carbon Brief (2018)

SSP energy implications



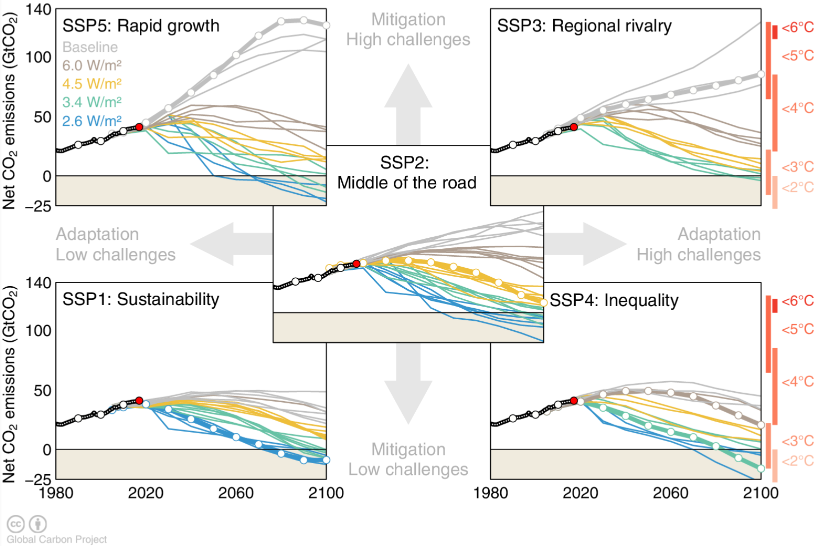
Source: Carbon Brief (2018)

Combining RCPs with SSPs



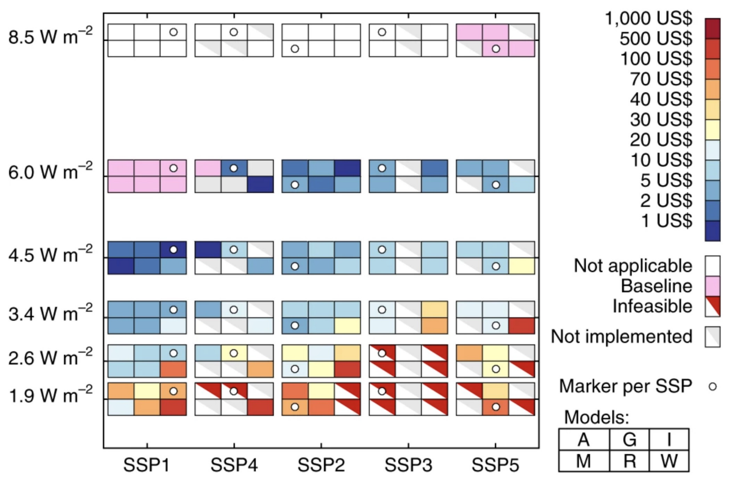
In cells: numbers of models with feasible scenarios. Source: Rogelj et al. (2018)

Combining RCPs with SSPs



Source: Peters (2017)

Combining RCPs with SSPs



Average global average carbon prices over the 2020–2100 period discounted to 2010 with a 5% discount rate. Source: Rogelj et al. (2018)

McGlade and Ekins (2015) on Nature

- 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%

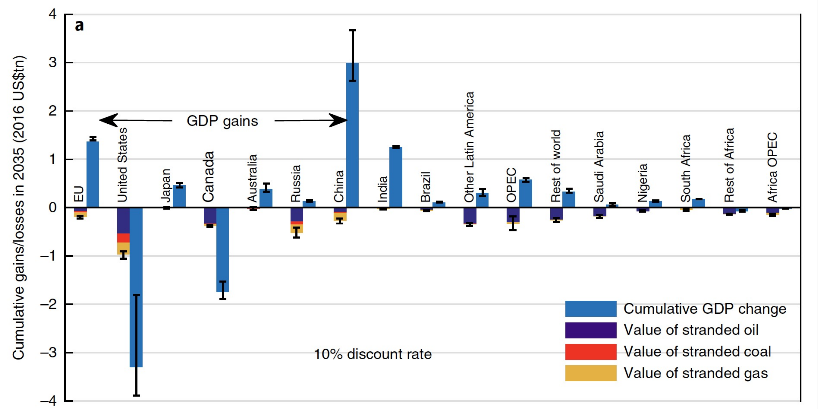
FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3; %, Reserves unburnable before 2050 as a percentage of current reserves.

Source: McGlade and Ekins (2015)

Mercure et al. (2018) on Nature CC

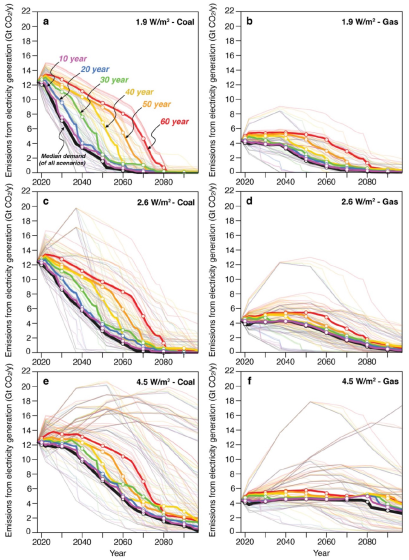
- Combination of E3ME (macroeconometrics), FTT (diffusion) and GENIE (Earth systems) models
- Two drivers of stranding: 2°C climate policy or technological diffusion
  - Fossil stranding can happen even without policies
  - Drop in demand for fossil fuels ($\rightarrow$ can trigger a 'sell out')
- Focus 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

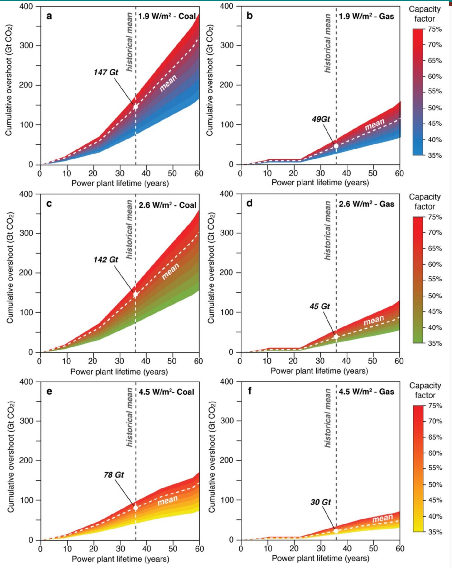
Fossil stranded assets across regions



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

Fofrich et al. (2020) on ERL using six IAMs



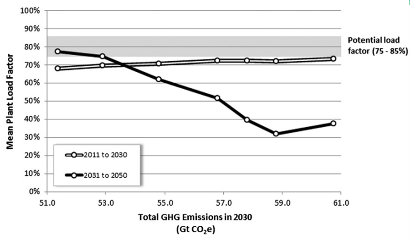


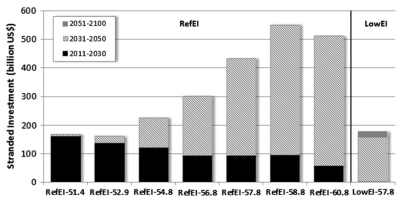
Left: future emission scenarios. Right: excess emissions. Source: Fofrich et al. (2020)

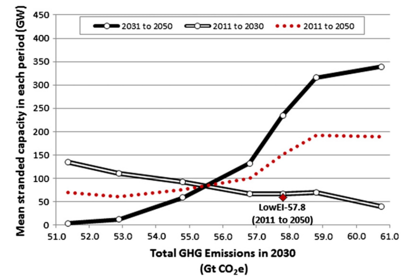
Johnson et al. (2015) on Tech.Forec.Soc.Change

- MESSAGE-MACRO IAM model at IIASA
  - Linear optimization model minimising energy system costs
- They compare:
  - Different near-term (2030) emission targets..
  - .. with common long-term target (2 °C)
- Capital stranding
  - Focus on coal-powered electricity plants without CCS
  - Stranding as unutilised capacity
- Results:
  - Loose near-term targets → Larger coal capacity investment (esp. in China/India) → Stronger stranding after 2030
- Possible policies
  - Extend lifetime of existing assets (default: 30 years)

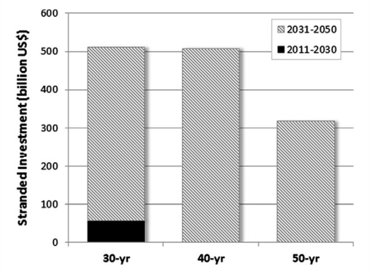
Johnson et al. (2015) results







Above: mean load factors. Below: mean stranded capacity.



Stranded investments. Below: RefEI60.8 scenario. Source: Johnson et al. (2015)

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
  - Non-neoclassical: disequilibrium; scenario analysis; demand-side; behavioural functions; heterogeneity; complexity; adaptive expectations
- 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
- Integrated Assessment Models (IAMs)
  - DICE
  - Large-scale numerical IAMs