Innovation, responsiveness and inertia in energy-economic systems:

Some evidence and a mathematical exploration

Michael Grubb, University College London (UCL), Institute for Sustainable Resources

Modelling: with **Pablo Salas** (CEENRG, Univ.Cambridge), **R.J.Lange** (Econometric Institute, Erasmus University Rotterdam), **J-F Mercure** (Radboud University Nijmegen)

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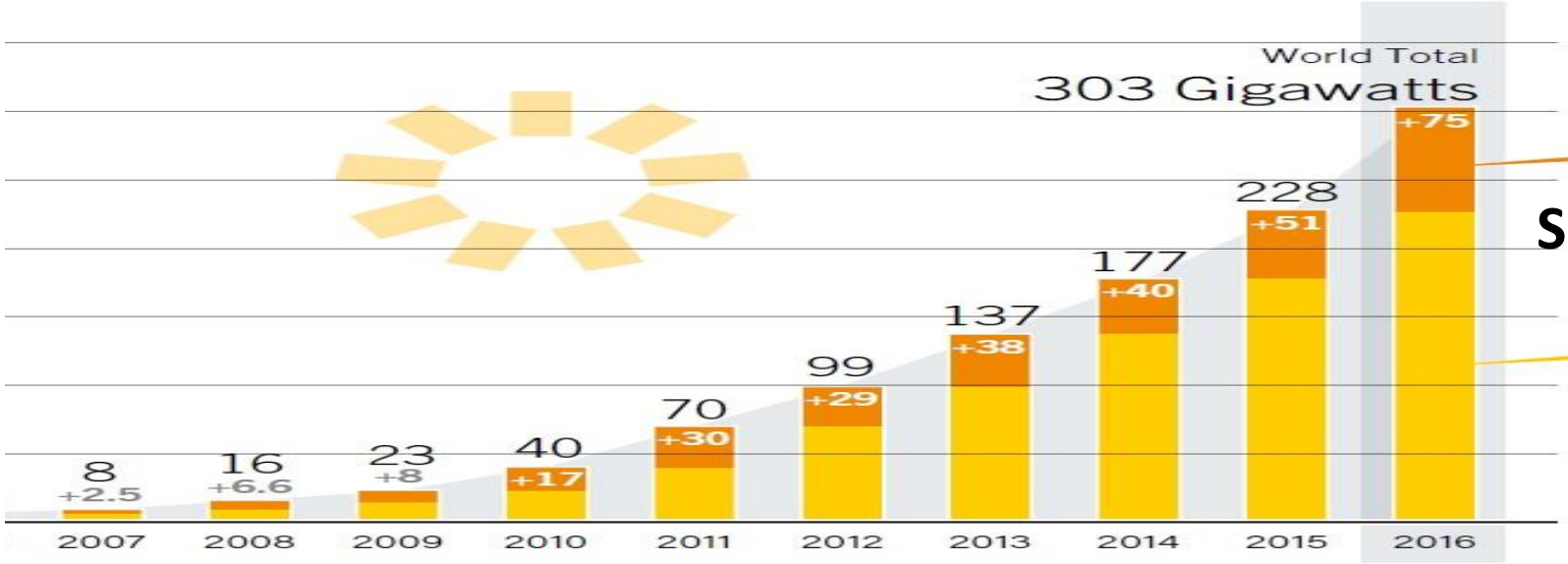
Introduction

- Innovation is
  - central to economic development (eg. Schumpeter, Solow Residual, etc)
  - inescapable in deep CO2 emission reductions
- 'Learning-by-doing' is
  - empirically documented for hundreds of energy-related technologies, complemented by rich literature on innovation systems
  - Explored analytically half a century ago (Arrow, 1963)
- Yet many economic models and policy recommendations continue to ignore what we know about learning & innovation
- THIS MATTERS

Huge market growth + cost reductions in solar PV



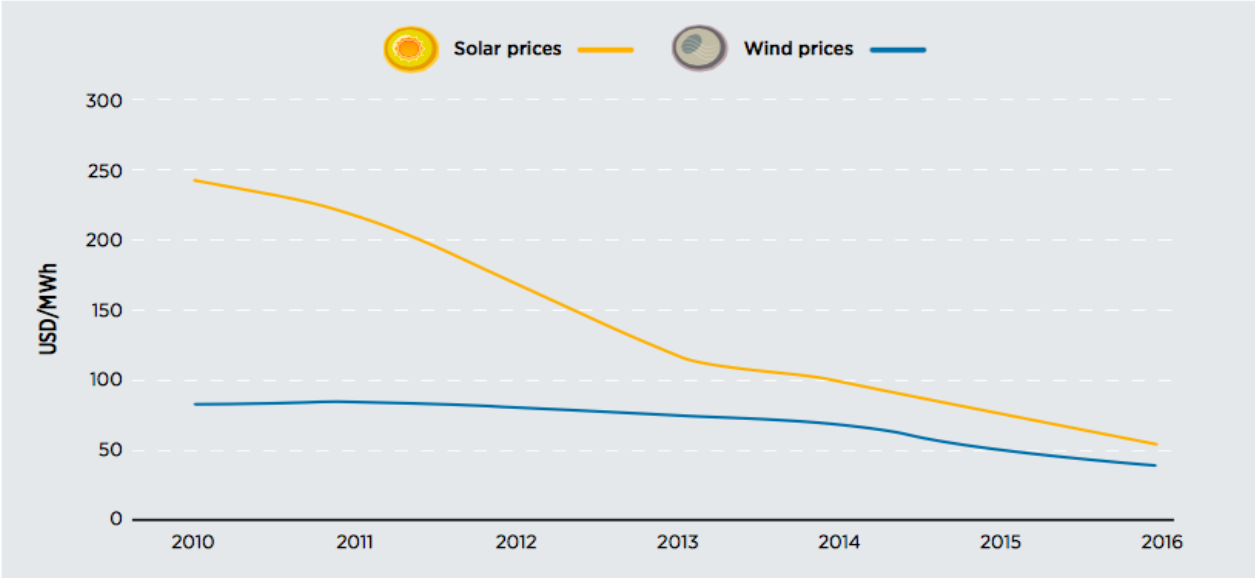
Solar PV 'strategic deployment'

Annual additions

Previous year's capacity

Source: IEA PVPS. See endnote 3 for this section.

Figure 1 Average prices resulting from auctions, 2010-16



.. accompanied by cost reductions, to 'learning curve' expectations – growth over 2-3 decades

- .. documented across wide range of other supply and demand-side technologies including w.r.t. energy efficiency

… and much else in energy systems

" solar power is by far the most expensive way of reducing carbon emissions …. the CO2 price would have to rise to $185 a tonne …." - *The Economist,* **2014. Err ……**

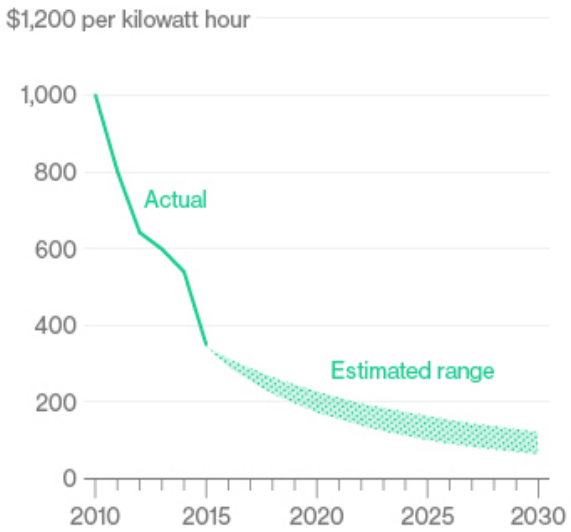
PV: 2016, installed power prices **below wholesale** *elec* **prices** in many sunny regions

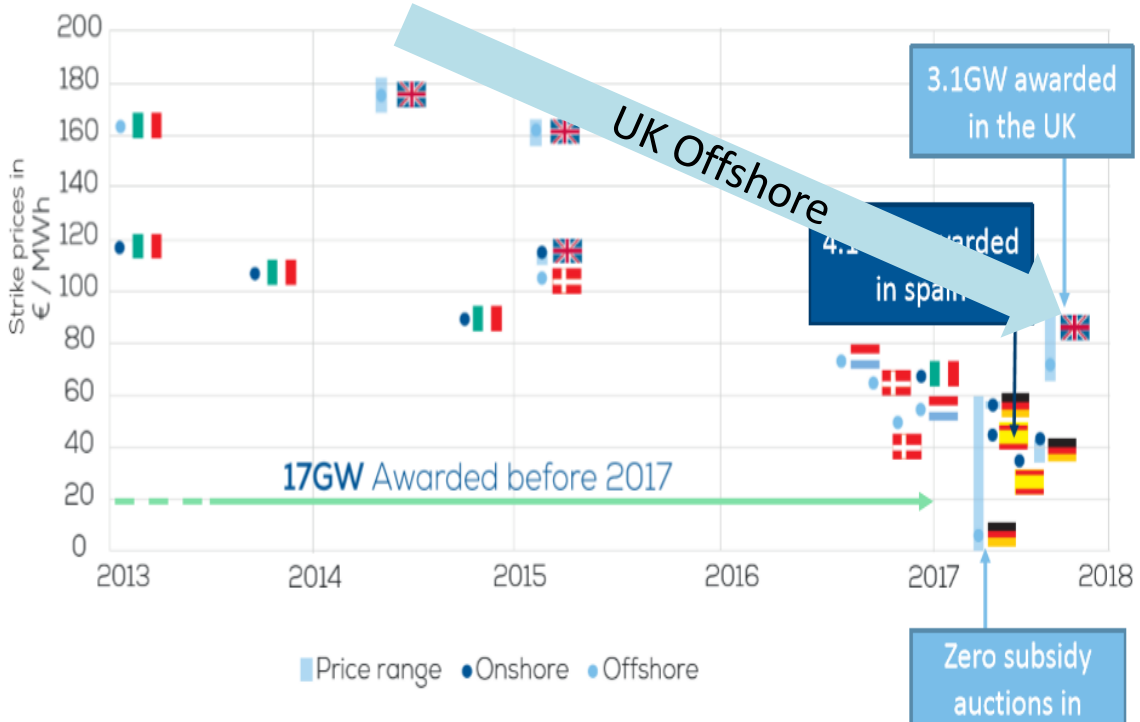
Chile	= $30/MWh
Masdar	= $25/MWh
Abu Dhabi	= $24/MWh

Module costs: -29% in 2016 to $0.39/Watt

Even offshore wind energy: series of auctions across Europe have seen prices tumble to about half that of 5 years ago

Batteries also …





‘The perils of the learning model…?’ (Nordhaus, 2013)

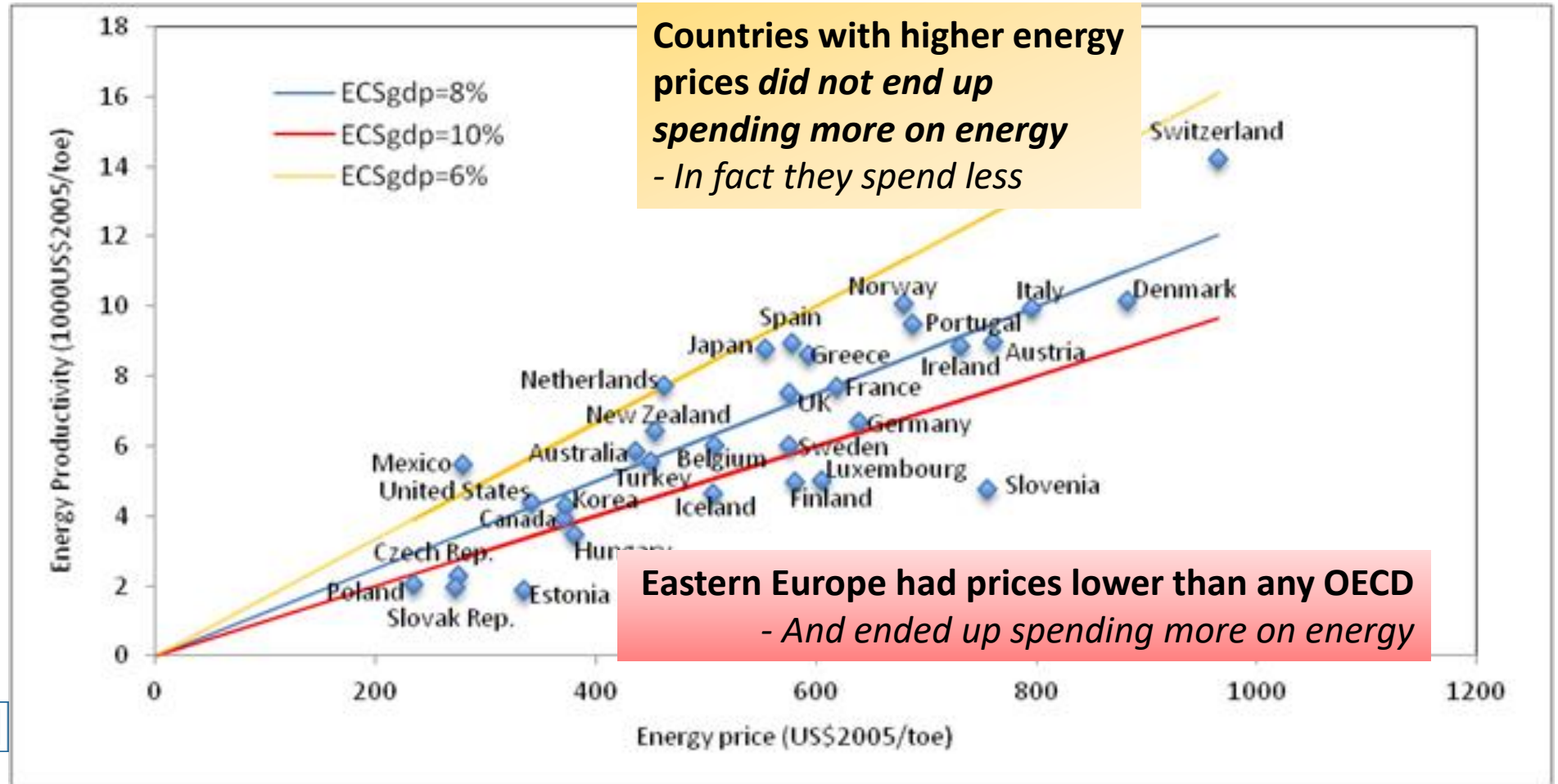
- Critique centred on data uncertainties and ‘correlation is not causation’ – price reductions would also drive growth. **But:**
  - Timing – capacity growth has generally led cost reductions, clearly the two reinforce each other *
  - Surge in private patents as markets grew *
  - Common sense:
    - Technology learning-by-doing
    - Private sector revenues resource private R&D
    - Economies of scale in both unit size and production volume
    - Development of supply chains & infrastructure
    - Experience and improved financial confidence in capital-intensive sectors drive big reductions in cost of finance
- **Assuming ‘zero’ is an unacceptable approximation to something we know to be positive and crucially important**
- Recent analyses (eg. Newbery 2016) have finally begun to derive the formal economics of policy taking account of learning-by-doing
  - suggesting that eg. renewables deployment was indeed good economic policymaking (and the earlier the action, the better the cost/benefit)

* Bettencourt et al (2013) document ‘A sharp increase in rates of patenting [during 2000-2009], particularly in renewable technologies, despite continued low levels of R&D funding. …. reveals a regular relationship between patents, R&D funding, and growing markets across technologies … growing markets have formed a vital complement to public R&D in driving innovative activity.’

The issues are wider: multiple other lines of evidence point to the capacity of energy/economic systems to adjust, given time

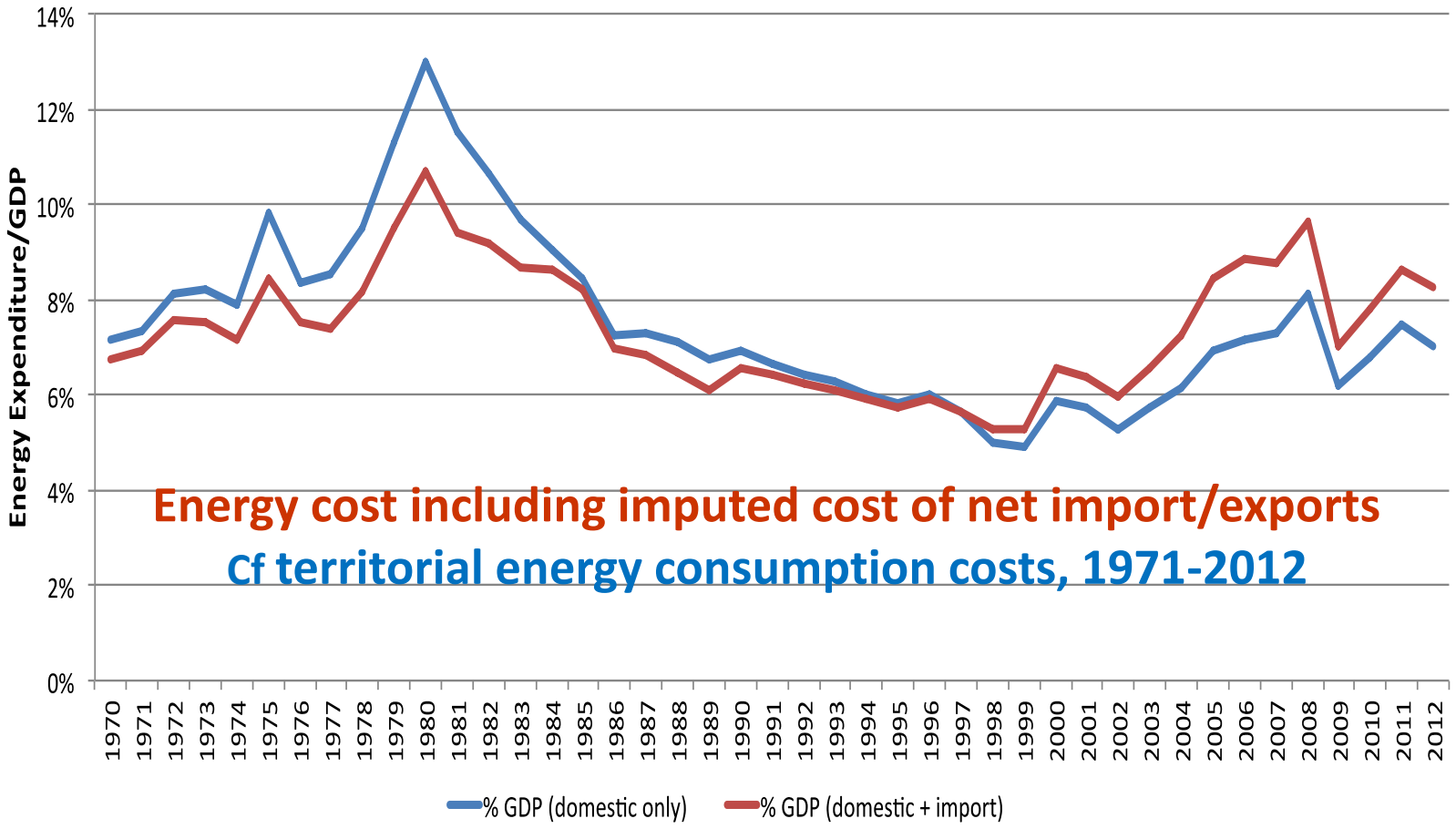
– they are '***pliable***' in the sense of *responding* to policies and external forces in ways that endure

- eg. relative constancy of long-run energy expenditure despite big price variations



However the timescales of adjustment are long

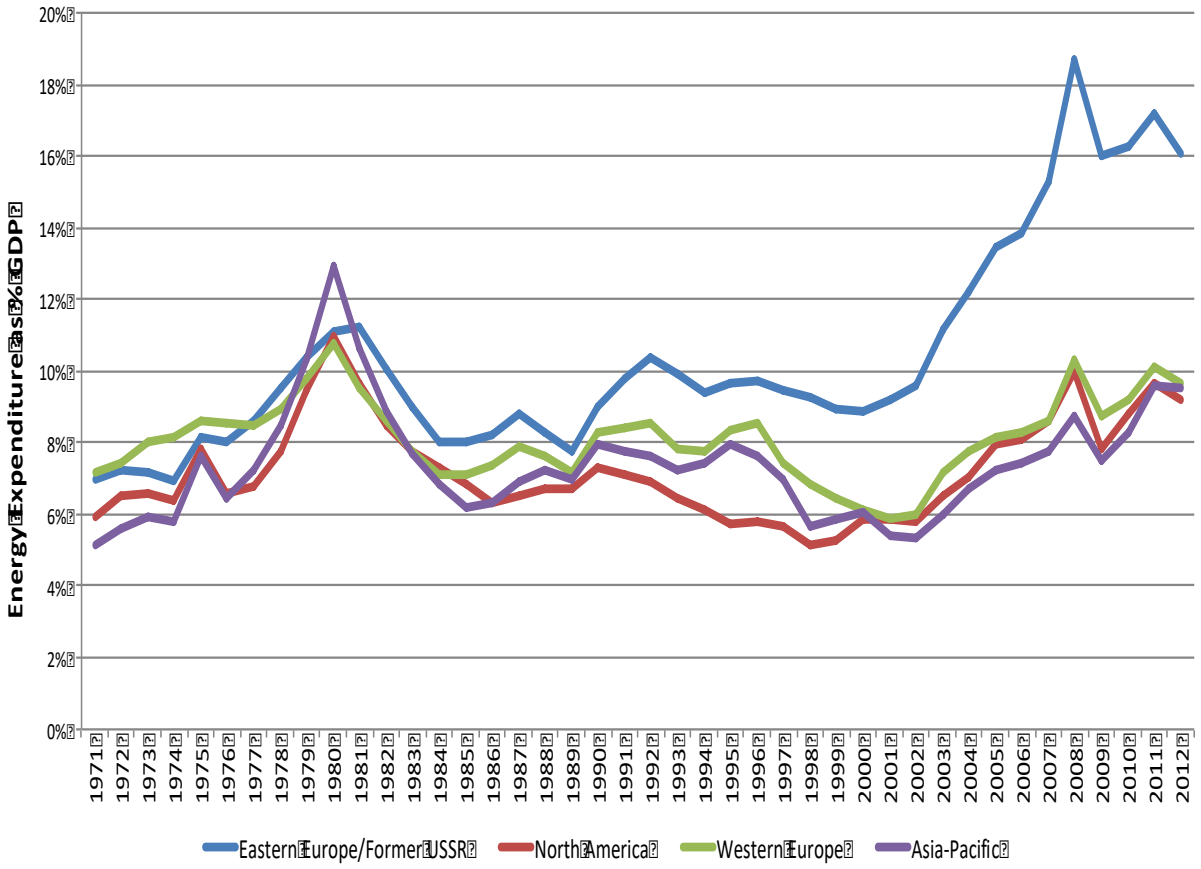
- the US took c. 25 years to adjust to 1970s oil shocks, & part of this was structural trade adjustment



Impact of trade: long-term slow decline of US energy expenditure intensity dis-appears when 'trade-adjusted' *(ie rough correction made for shift of US from net exporter to importer of energy intensive goods)*

Trade data source from www.carboncap.eu

… & eastern European countries couldn't adjust to the shock of market prices any faster ..



Central/Eastern Europe historical energy prices lower than any OECD – the result:

- *Ended up spending much **more** on energy as they sought to develop market systems and prices in joining the EU*
- *Energy expenditure/GDP hit over 14%, twice level of western Europe*
- *'It took 40 years for their energy intensity to reach double that of the west – may take as long to reverse..'*

- **Informs an adjustment timescale**

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Motivations for the modelling

- Huge literature on global trajectories, some cost/benefit, but relatively little attention to the dynamics and induced innovation
- The Paris Aims are some way outside the frame of traditional 'cost-benefit' assessments, most of which point to > 3 deg.C unless assume v. non-linear / cliff damage
  - Limited science-economics dialogue
- Seemingly big discrepancies between different views of the urgency of climate action & cost of delay
  - Eg. Nordhaus vs International Energy Agency
- Proposition that this due not only to different specifications of damage, but also assumed characteristics of emitting systems
- Vast majority of stylised global economic models assume mitigation relative to degree of abatement from 'reference projection' at time *t*
- This has no underlying history – no inertia or induced tech

  $\Rightarrow$ eg. DICE equations

Modelling approach – component analysis – learning (responsiveness)

Represent abatement cost curve in terms of ***sectors*** of abatement k

Integrate *investment* I_k over sectors with capacity U_k as abatement proceeds

$$\sum_k \int_0^{U_k} I_k(U_k')dU_k' = \sum_k \frac{1}{\beta_k}\int_{\varepsilon_{k-1}}^{\varepsilon_k} \alpha_I {\varepsilon_k'}^{\gamma} d\varepsilon_k' = \sum_k \frac{\alpha_I}{(\gamma+1)\beta_k} {\varepsilon_k'}^{\gamma+1}\Big|_{\varepsilon_{k-1}}^{\varepsilon_k}. \quad (1)$$

Learning rate b reduces the absolute value of the investment cost, and also reduces the non-linearity of the marginal cost curve – after various manipulations & simplifications:

Static (enduring) abatement cost $\approx \frac{\alpha_I(\beta W^0)^b}{(\gamma+1-b)\beta}\varepsilon^{\gamma+1-b}$ *Simplified form* $\approx c_A \boldsymbol{\varepsilon}^2$

Where $\mathbf{c_A}$ **expresses (enduring) cost after learning and adjustment,** $\boldsymbol{\varepsilon}$(t) is abatement at time t, βW^0 emission reductions associated with the *existing* capacities of the abatement technologies; learning *b* lowers total costs, *and* exponent $\gamma + 1 - b$ of the cost curve: if marginal *ex-ante* curve is slightly convex ($\gamma > 1$), ie. curve slightly steeper than quadratic, then learning tends to pull the *ex-post* curve back towards DICE-like assumptions of linear marginal and quadratic total costs.

Modelling approach – inertia

From same basic structure we examine the properties of three sources of inertia:

Early scrapping of capital stock	$\alpha_{ES}\dot{\boldsymbol{\varepsilon}}^{\mathbf{2}} - c_0^{ES}\left(\varepsilon_0^{ES}\right)$		Rate of abatement, non-linear	$/tCO$_2$/y^2
Transforming production capital	$\frac{\alpha_B(\beta W^{N0})^{b_N}}{(\gamma+1-b_N)\beta}\dot{\varepsilon}^{\gamma+1-b_N}$	*(simple form)* $\frac{\alpha_B(\beta W^{N0})^{b_N}}{2\beta}\dot{\boldsymbol{\varepsilon}}^{\mathbf{2}}$	Rate of abatement, non-linear	$/tCO$_2$/y^2
Diffusion / utilisation capability	$c_M = \frac{\alpha_M}{2\beta_k}\dot{\boldsymbol{\varepsilon}}^{\mathbf{2}}$		Rate of abatement, non-linear	$/tCO$_2$/y^2

In each case, the cost form appears quadratically increasing with the ***rate*** of abatement

Illustrative model

- Simple, transparent *stylised reduced-form model* to illustrate the main themes and sensitivities
- Drawing on above insights, mitigation (abatement) costs defined to depend on both the ***degree*** and the ***rate*** of abatement, each with

$$C(t) = c_A \varepsilon(\mathrm{t})^2 + c_B \left(\frac{d\varepsilon(t)}{dt}\right)^2$$

  - Degree of deviation from baseline is classical, DICE-like formulation, learning is reflected in (a) reduction of parameter c_A, implying a more ***responsive*** energy system
  - And rate-dependent term, with parameter c_B which expresses the ***transitional costs*** of both (b) *learning-by-doing investment* in currently costly sources, and cost of overcoming *inertia*
  - The ratio of the two reflects **adaptive capacity, or *pliability (0<ϱ<1)*** of the system* – scale of learning etc investment and overcoming inertia, compared to enduring loss from abatement
- Climate damage assumed to be direct function of T approximated through **cumulative CO2 emissions,** damage function proportional to T^2

Results in quartic differential equation, analytic solutions to Euler-Lagrange conditions

* Then takes the form $C(t) = \mathrm{Ca_}[(1-\varrho).\varepsilon(\mathrm{t})^2 + \varrho.\frac{H^2}{3}\dot{\varepsilon}(t)^2]$, where H is the **characteristic time constant of system adjustment, est 35 yrs.**

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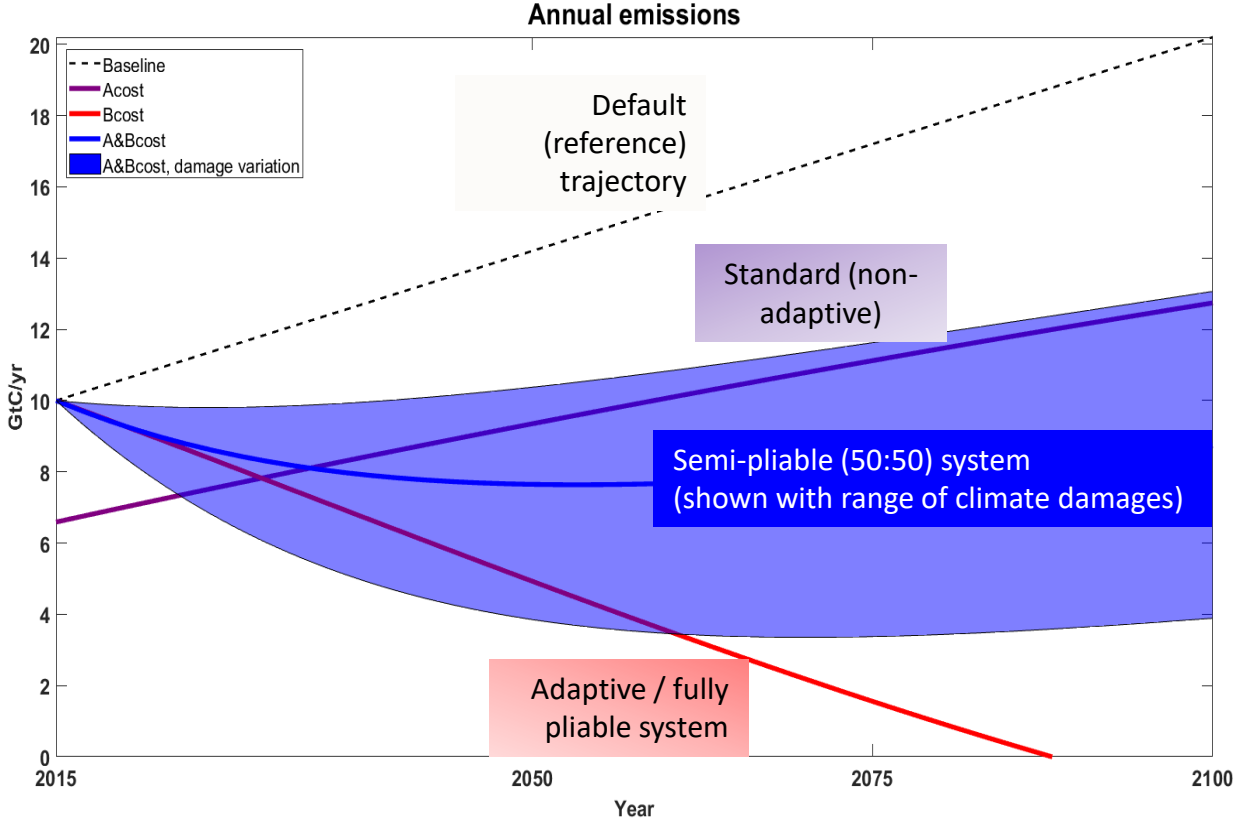
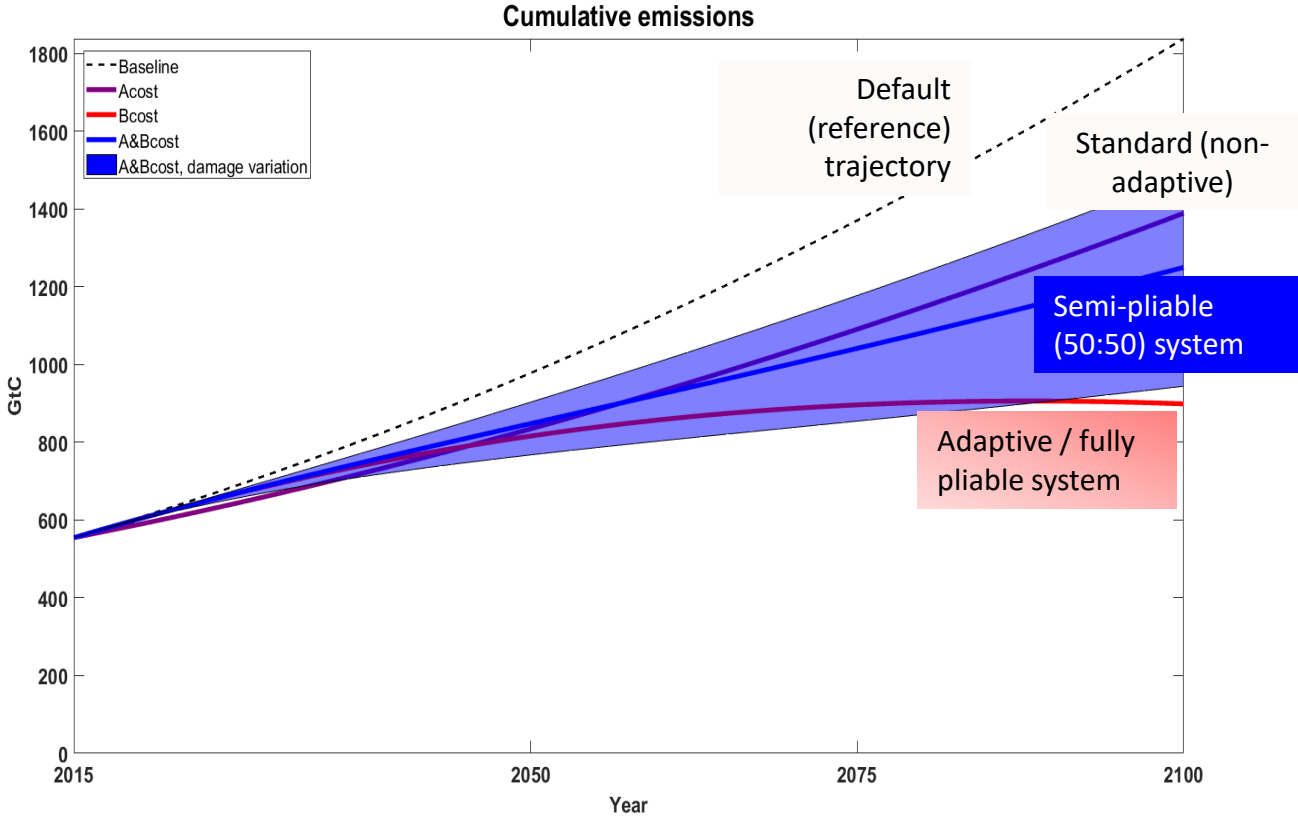
The 'global optimal trajectory' is radically different for an adaptive / pliable energy system, given 'typical'* damage & discounting assumptions





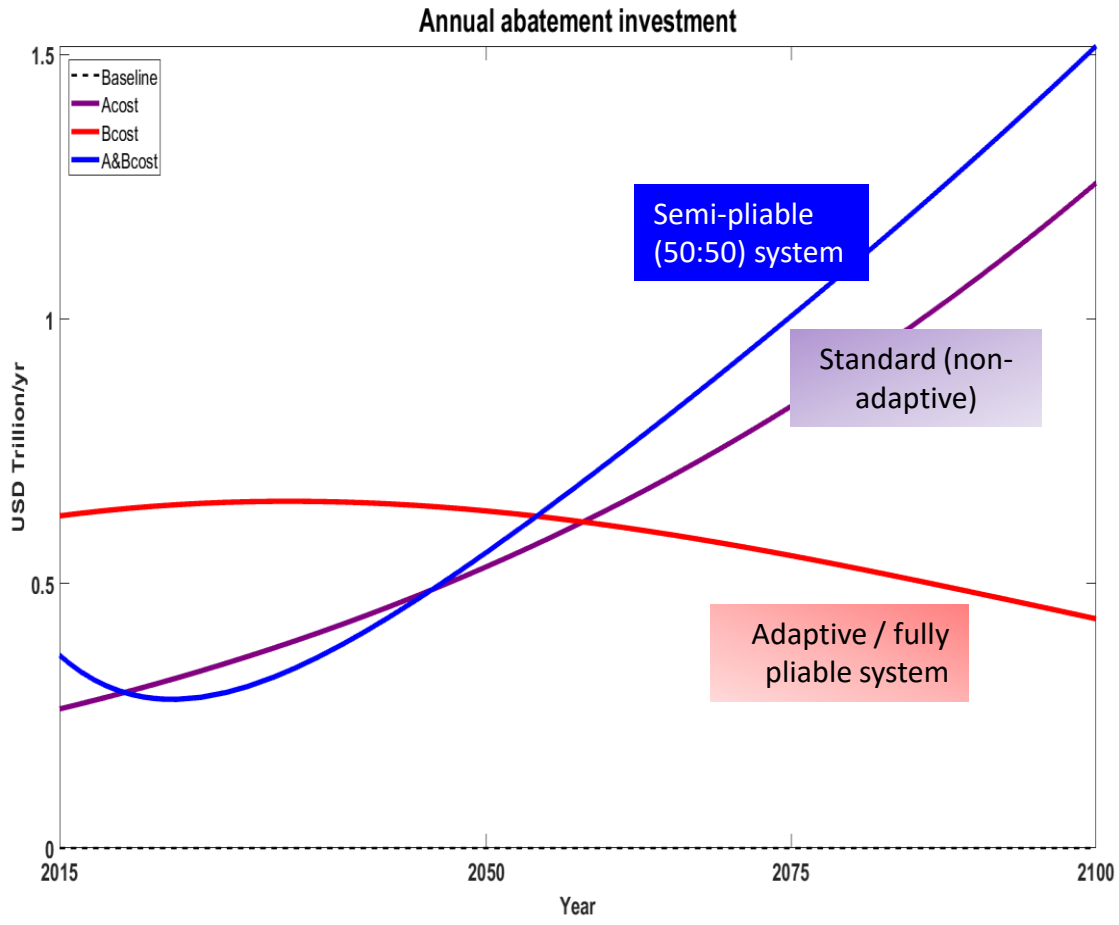
Emissions: if emissions system adaptive/pliable, steady decline: sustained almost linear if fully adaptive

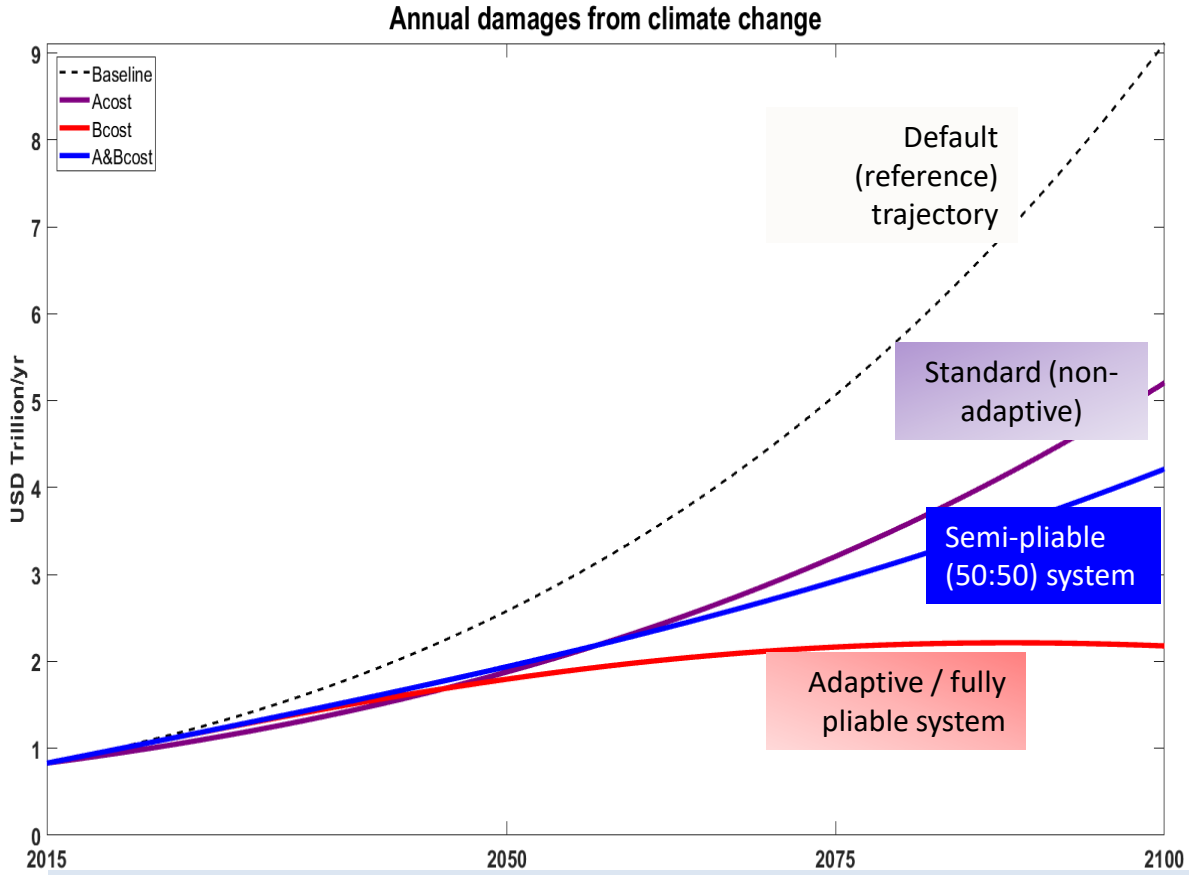
'Ambition': with these parameters, cumulative emissions c. +350GtC, if high damages, *or* if system highly pliable (in which case, stabilises atmosphere)

Blue range: with semi-pliable ('A&B cost': ϱ = 0.5) emission system, shows emissions range for damage sensitivities x 2 & 0.5 respectively

* See Annex for assumptions: many parameters reflect typical DICE parameters

Measures which steadily adjust the pathway are optimal at much higher effort / 'cost of carbon'





Effort: If adaptive / pliable system, much bigger early efforts because they have much higher benefit

Timely investment: Optimal global investment < $1trn/yr can cut annual costs (abatement + damage) towards end of century by at least 5 times as much

Conclusions

- Overwhelming evidence of induced learning and capacity of energy technologies and systems to adapt in response to policies and external forces ("pliability")
- But coupled with high inertia – several decades for major transitions
- Consider Dynamics
  - 'Optimal' response does not just depend on assumed scale and non-linearity of impacts and discount rate! Also depends on responsiveness and inertia and adaptive capacity (pliability) of emitting systems
  - Standard frameworks imply sharply rising costs – both damages and mitigation costs - over the century
  - Adaptability / pliability is a major driver of the net benefits of early action – will vary by specific options and would justify diversity in apparent mitigation costs
- The combination can lead to 'cost benefit' effort levels similar to a risk-averse strategy dominated by non-linearly / threshold assumptions, may almost stabilise gross costs
- **Annex:** Some background to model & parameter assumptions

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Optimising Model Fundamentals 1: Mitigation costs

- Mitigation (abatement) costs defined to depend on both the ***degree*** and the ***rate*** of abatement relative to ref projection:
  - Degree of deviation from baseline is classical, DICE-like formulation
  - Rate-dependent costs reflect the *inertia* of change – investment in changing the underlying pathway or overcoming political obstacles
  - The Ratio of the two reflects the adaptive capacity of the system

- Each rises *non-linearly*: the model assumes quadratic dependence (like DICE for the enduring cost term):

Abatement cost at time t = C_a x (**degree** of abatement)² + C_b x (**rate** of abatement)²

Or more specifically :

Abatement cost = $C(t) = c_A \varepsilon(\mathrm{t})^2 + c_B \left(\frac{d\varepsilon(t)}{dt}\right)^2$

where ε(t) is the degree of cutback

Model Fundamentals 2: Climate damage

- Climate Damage: a simplified approach, inspired by observation from model ensembles of a closely linear relationship between cumulative CO2 emissions and global temperature change at a given point in time
  - central estimate that 500GtC cumulative emissions increases global temperature by about 1 deg.C (time lags are minor significance for most practical emission trajectories).
- Generally accepted non-linear relationship between temperature change and damage

Present model assumes that global damage increases in proportion to the square of temperature change:

Annual damage from climate change at time t,

d(t) proportional to (temperature change) ^{2} = $(E(t)/500)^2$

Where E(t) is the cumulative CO_2 emissions (in GtC) at time t.
Central case, $3trn/yr damage for 500GtC emissions = 1 degC temperature rise

Some key assumptions

Real discount rate 2.5%/yr.

Climate change damage $3trn/yr for an additional 500GtC emission. – cf global GDP mid Century typically projected in range $85-150 trn/yr

Reference emissions growth linear 120MtC/yr (1.2% of 2015 emissions)

Abatement costs parameters

- Purely enduring costs (C_b =0): 50% cut in global CO_2 emissions in 2050 costs 1.5% of projected GDP (c. 1.9 US$trn).

- Purely transitional costs (C_a =0): the same cutback, on a linear trajectory of abatement, results in the same total (undiscounted) integrated cost over the 35-year period to 2050, but these are now attributed as transitional costs of reorienting the energy system over these decades.