Session 1: Environmental drivers of the energy transition

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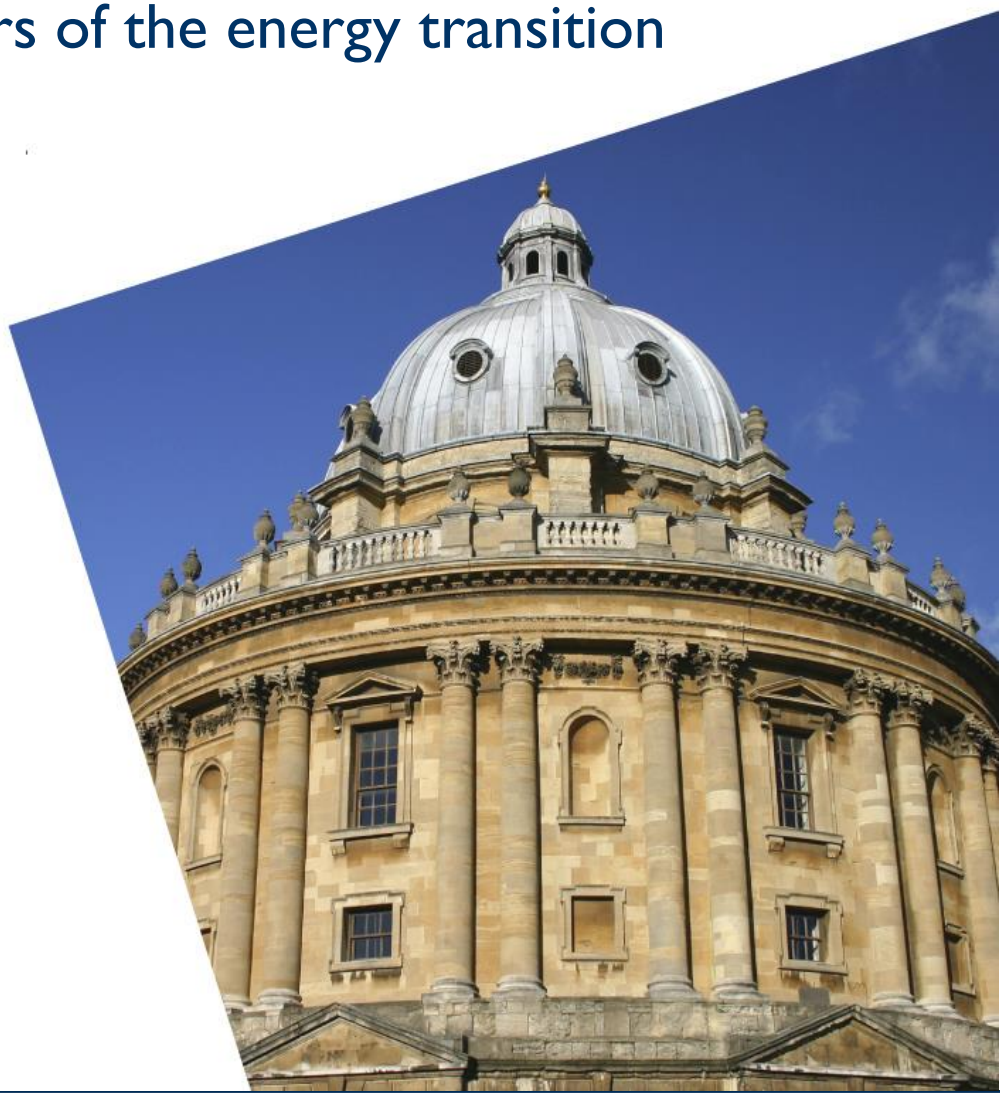


Tehran, Sunday 10 September 2017

Question for you

By what percentage must net emissions be reduced from today's levels to limit temperature increases to 3°C?

(A) 0-20%

(B) 20-80%

(C) 80-100%

Agenda for this session

1. Paris
2. Policy responses thus far
3. Arguments to slow action
4. Some economics of climate policies
5. Corporate responses

Next session

1. Technological progress and the energy transition
2. Will we get there in time?

There were four key commitments in Paris

- "…holding the increase in the global average temperature to **well below 2°C** above pre- industrial levels and **pursuing efforts to limit** the temperature increase **to 1.5°C**,…"

- "…to **achieve a balance** between anthropogenic emissions by sources and removals by sinks of greenhouse gases **in the second half of this century**…"

- "…communicate by 2020 a new nationally determined contribution and to do so **every five years** thereafter…"

- "…in this regard strongly urges developed country Parties **to scale up their level of financial support**, with a concrete roadmap to achieve the goal of **jointly providing USD 100 billion annually by 2020** for mitigation and adaptation…"

Sources: UNFCCC; C2ES; BBC

Also at Paris, a pledge to double clean energy R&D spend was launched as "Mission Innovation"

Each of the 20 participating countries will **seek to double** its governmental and/or state-directed clean energy research and development investment **over five years**.

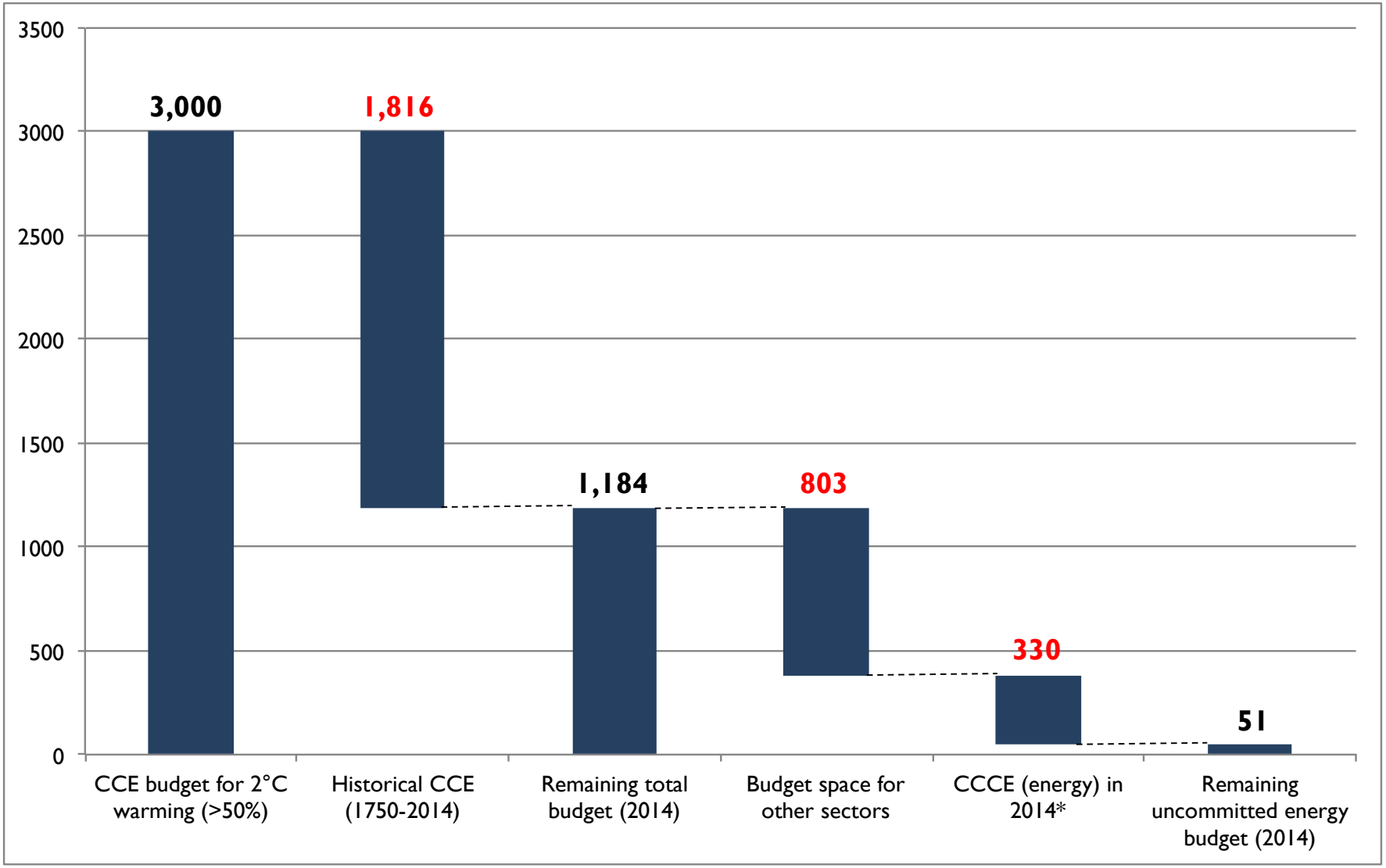
New investments will be focused on **transformational clean energy technology** innovations that can be scaled to varying economic and energy market conditions that exist in participating countries and in the broader world.

The carbon budgets can be described by the Oxford 'decarbonization equation'

$$\mathcal{B}(T) > \mathcal{E} + \mathcal{N} - \mathcal{S} - \mathcal{C}$$

B(T)	Budget: **remaining** carbon budget for a given warming/likelihood goal
E	Existing: Committed cumulative carbon emissions from today's existing capital stock
N	New: Committed cumulative carbon emissions from future (yet to be built) capital stock
S	Stranded: Committed cumulative carbon emissions from today's or future (yet to be built) capital stock that will not be emitted by retiring the respective capital stock early (stranding) before emissions have been realized
C	Captured: New atmospheric space that can be created to increase the remaining carbon budget (e.g. by reforestation, BECCS, etc.)

Our research on "baked in" emissions leaves little budget for new long-lived fossil infrastructure…



Sources: Pfeiffer et al. (2016) - The '2 C capital stock' for electricity generation

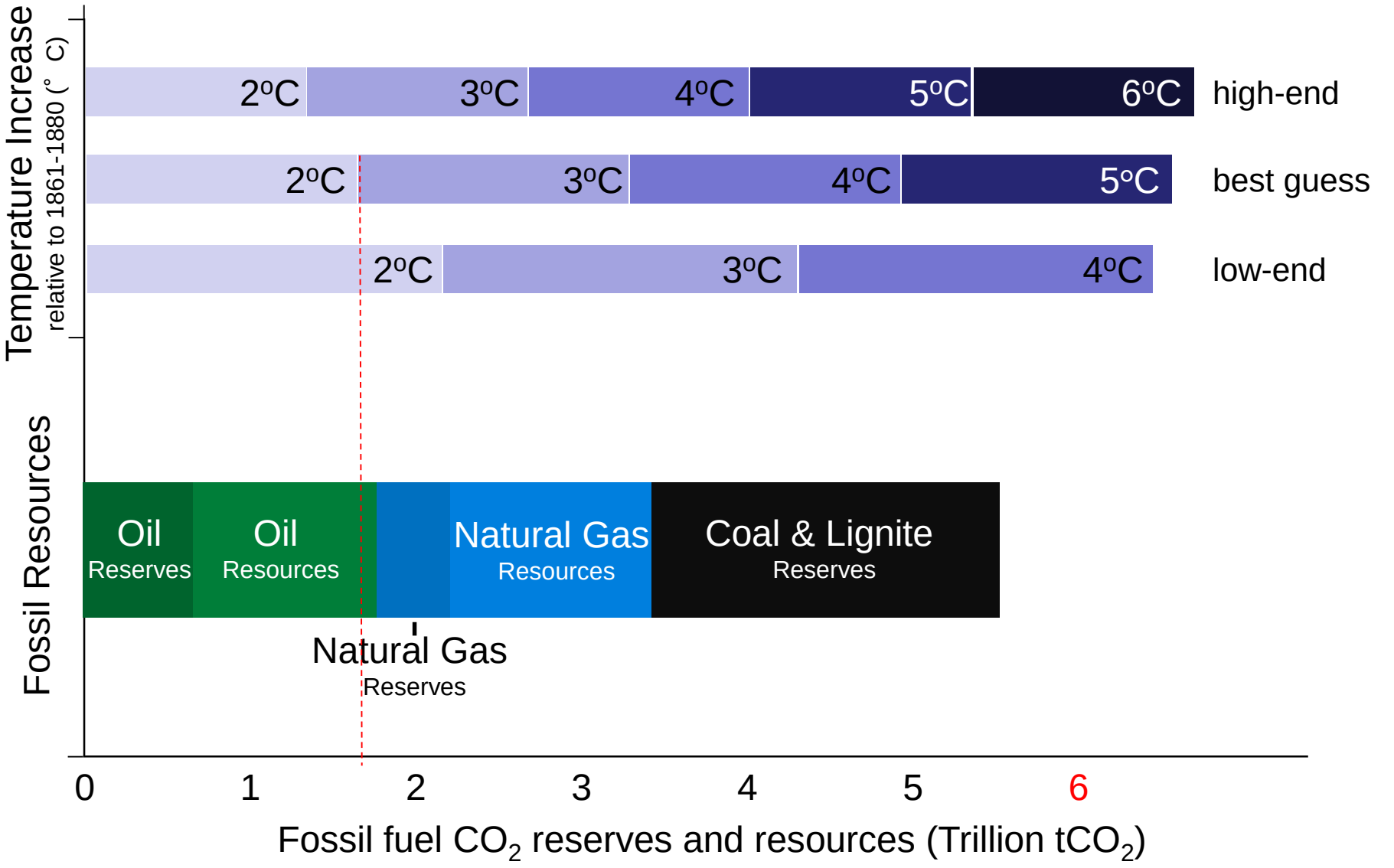
The implications are that for 50:50 odds of 2°C, we will have built the necessary capital stock by…

Smith School of Enterprise and the Environment

UNIVERSITY OF OXFORD

2017

We also have more coal, oil and gas in known, economically extractible reserves than we can burn



Source: Hepburn et al (2014) "Resilient and inclusive prosperity within planetary boundaries" China & World Economy

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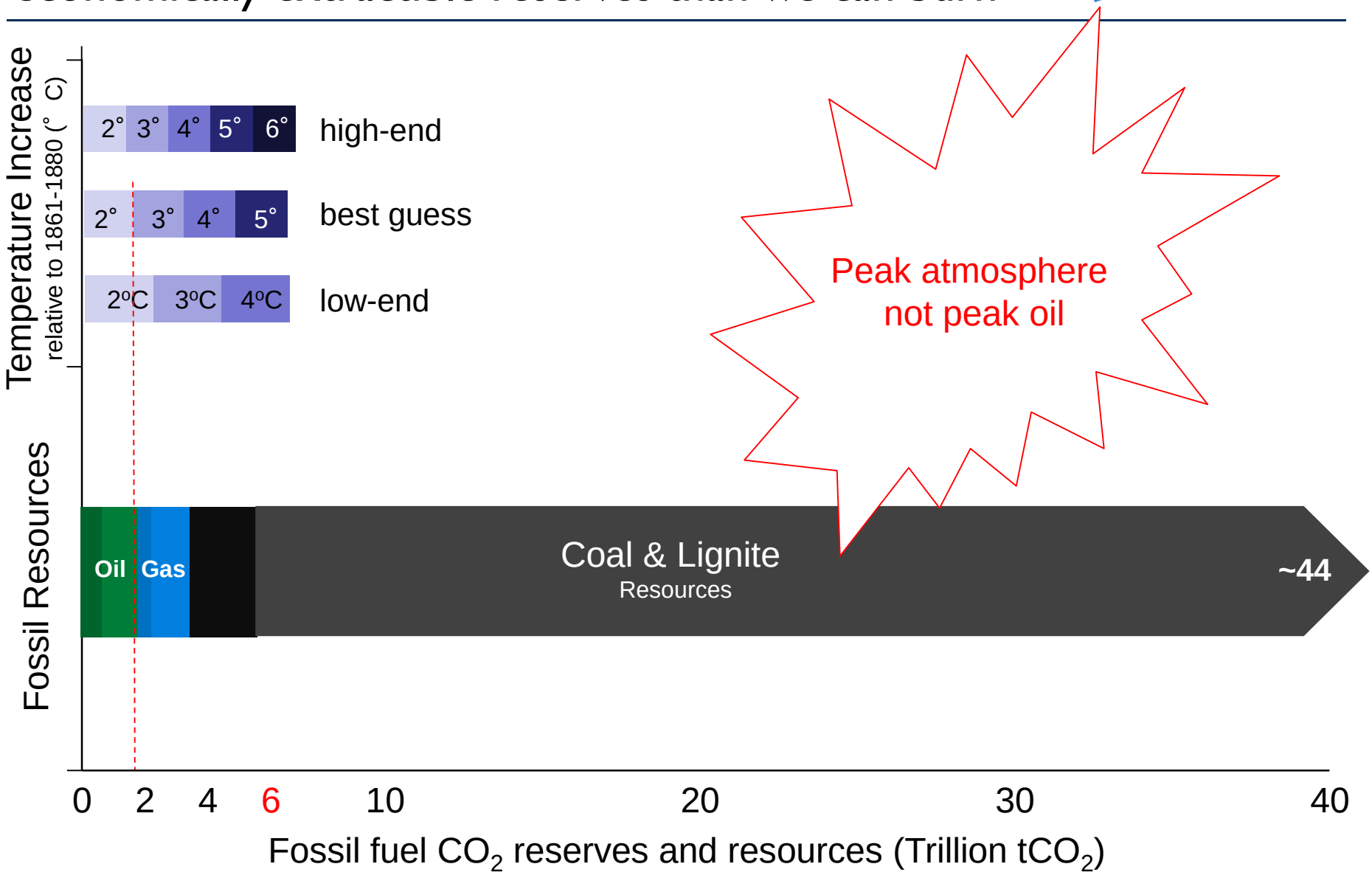

Source: Hepburn et al (2014) "Resilient and inclusive prosperity within planetary boundaries" China & World Economy

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Has Paris really solved it?

Skeptics say: "Countries are making pledges but not doing anything"

- It is true that not enough is being done; Earth is on track to warm 3°C or more
- But action is happening in every country on Earth (Climate Action Tracker).
- **China** announced in January 2017 that it will cancel 120 GW of coal-fired power (compared to the USA capacity of just over 300 GW).
- Chinese, Asian and global coal consumption is now falling (BP, 2016).
- The **USA** and **China** have decoupled emissions from economic growth (IEA, 2016).
- The **United Kingdom** has reduced emissions from around 800MtCO_2e in 1990 to around 500MtCO_2e, with a legal requirement to reduce emissions by 80% by 2050, shown in Figure 4.
- The UK Secretary of State announced in 2015 that coal-fired power will be phased out and closed entirely by 2025.

Has Paris really solved it?

"China is the worst polluter and they not doing anything"

- China is indeed the largest current polluter in total. However, per capita, China emits less than half that of America. Since the industrial revolution, America has the highest cumulative emissions (Matthews, 2015).
- China has the largest solar, wind, nuclear and hydro deployment programme in the world (IRENA, 2016) and will introduce a CO_2 trading scheme in 2017

"Other countries are not on board"

- 196 countries unanimously signed the Paris Agreement committing to keep temperatures "well below 2°C" and they will "pursue efforts" to 1.5°C.

"Trump has pulled America out"

- He has only said he will. He says lots of things. Actually doing it will take 4 years. The damage is the momentum lost with the absence of US Federal leadership

Has Paris solved it?

Skeptics say: "Countries are making pledges but not doing anything"

- Carbon prices are now in place in 40 countries and 24 subnational regions, raising $26 billion of revenue in 2015, see Figure 5. (World Bank, 2016).
- In 2016, more was invested in renewable energy than in fossil fuels. Mission Innovation will double clean energy R&D to $30 billion in 22 countries & the EU.

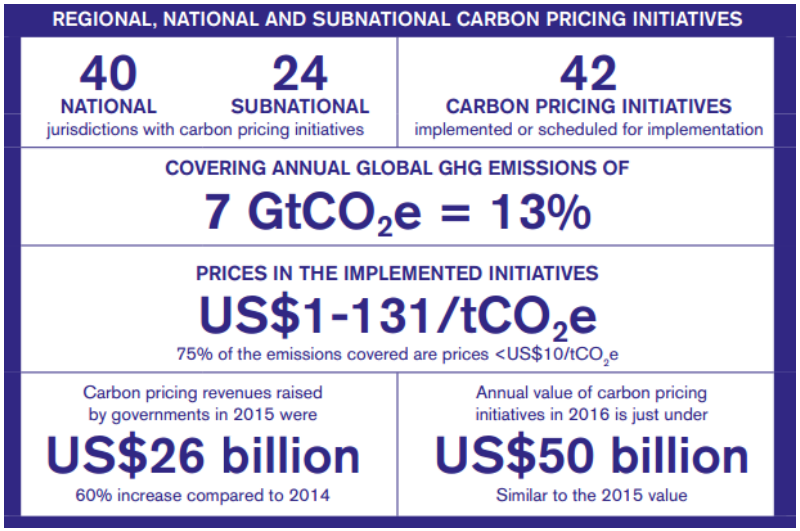


Figure 5. Source: World Bank (2016)

The UK is making progress, including on getting rid of coal from the system

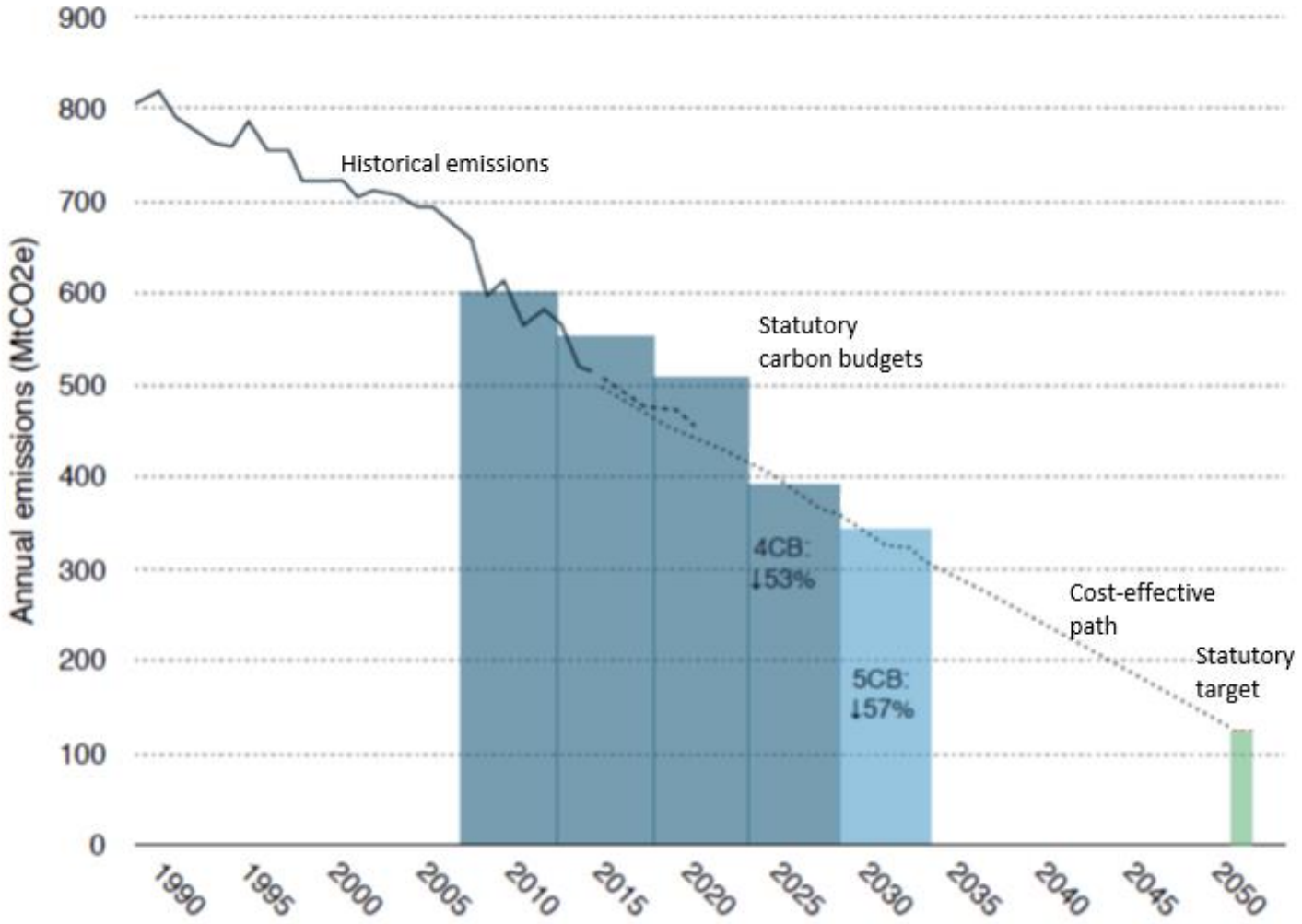
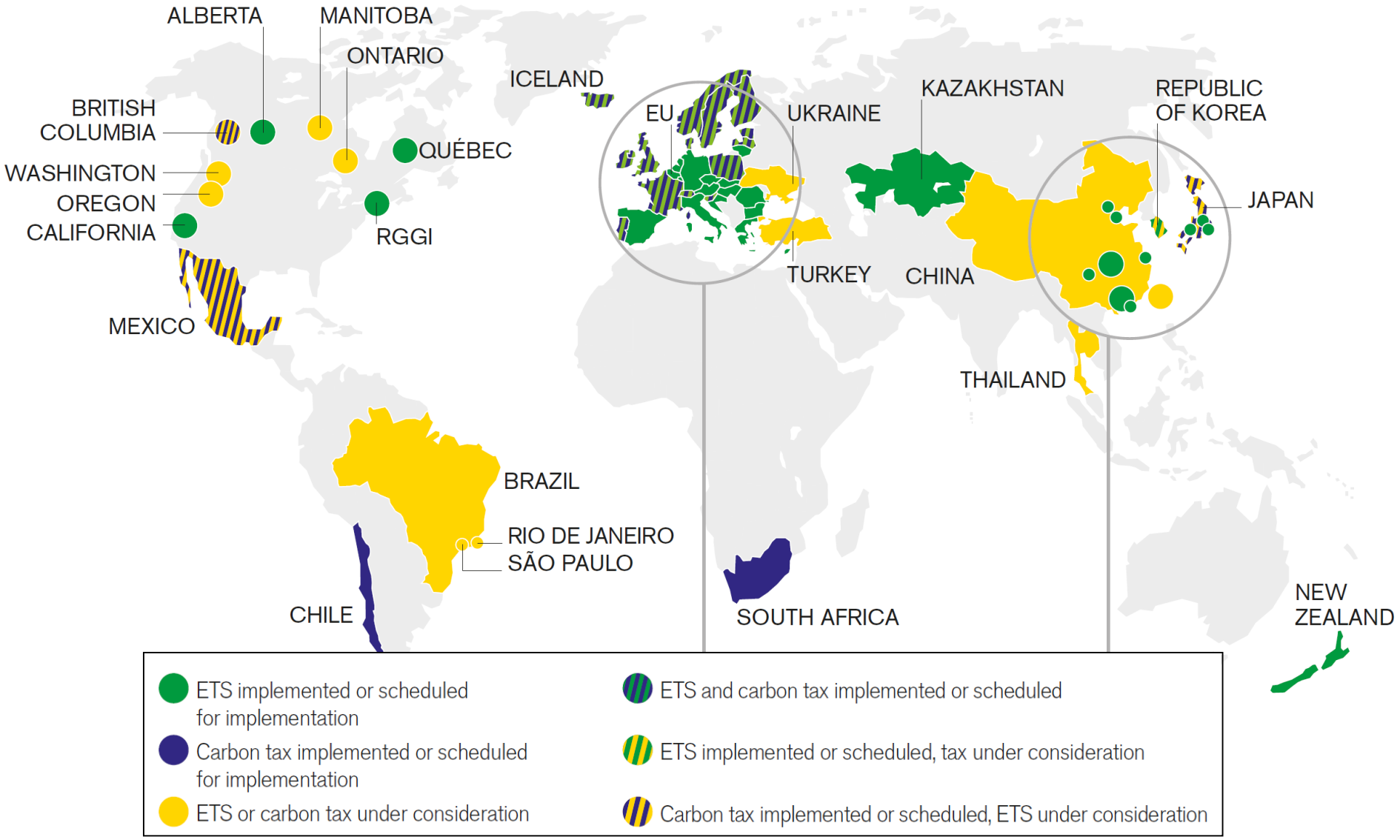


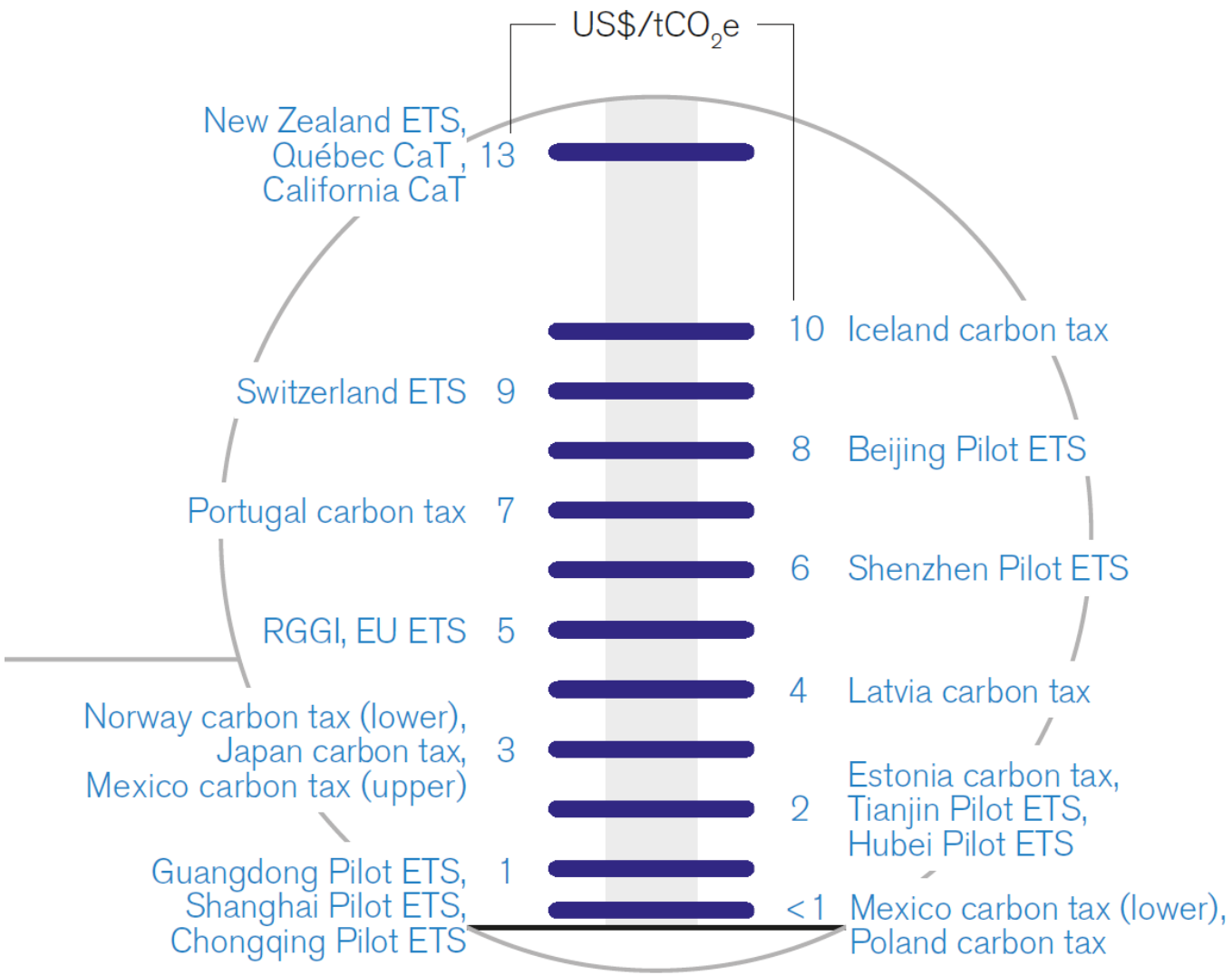
Figure 4. Source: Adapted from United Kingdom Committee on Climate Change (2015)

Carbon prices have sprung up in various parts of the world



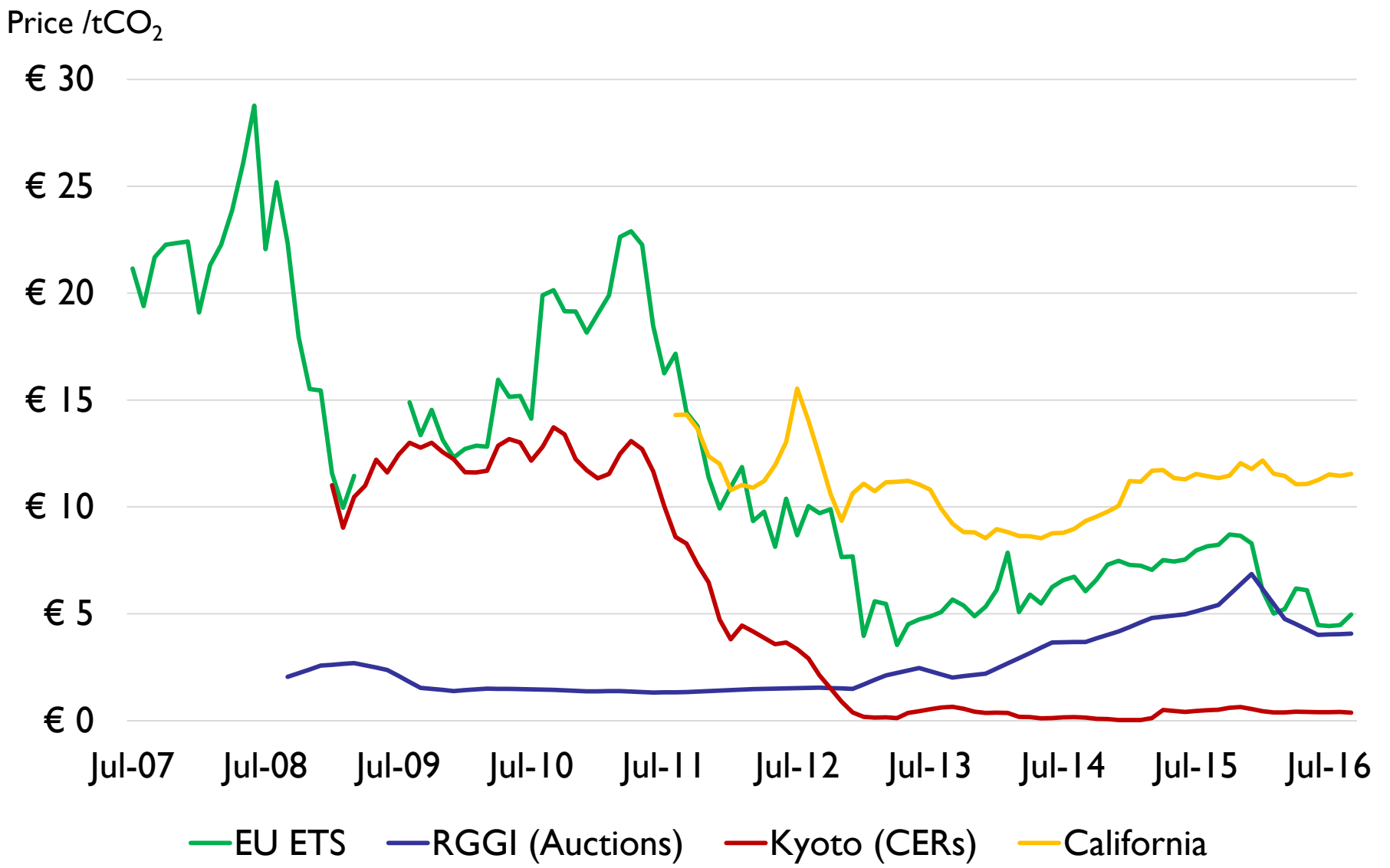
Source: World Bank (2015) State and Trends of Carbon Pricing

Carbon prices mostly remain below $10/tonne, which is well below social cost or national optimum

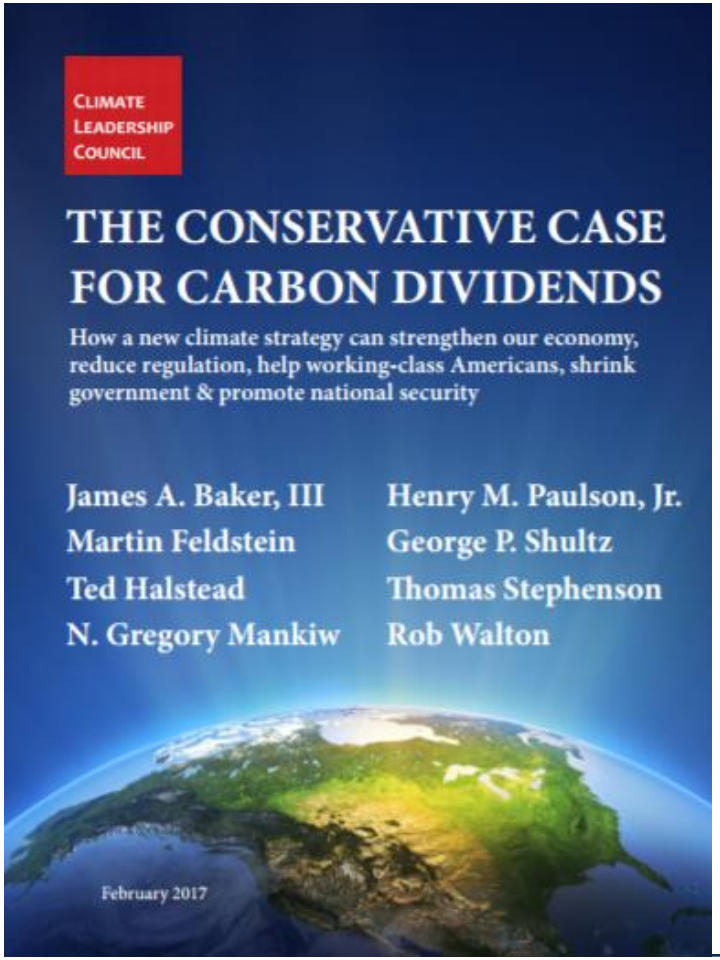


Source: World Bank (2016) State and Trends of Carbon Pricing

Carbon trading often leads to lower prices because policy makers don't count on the market innovating



Could carbon taxes see the light of day in the USA?



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Tuesday, June 20, 2017

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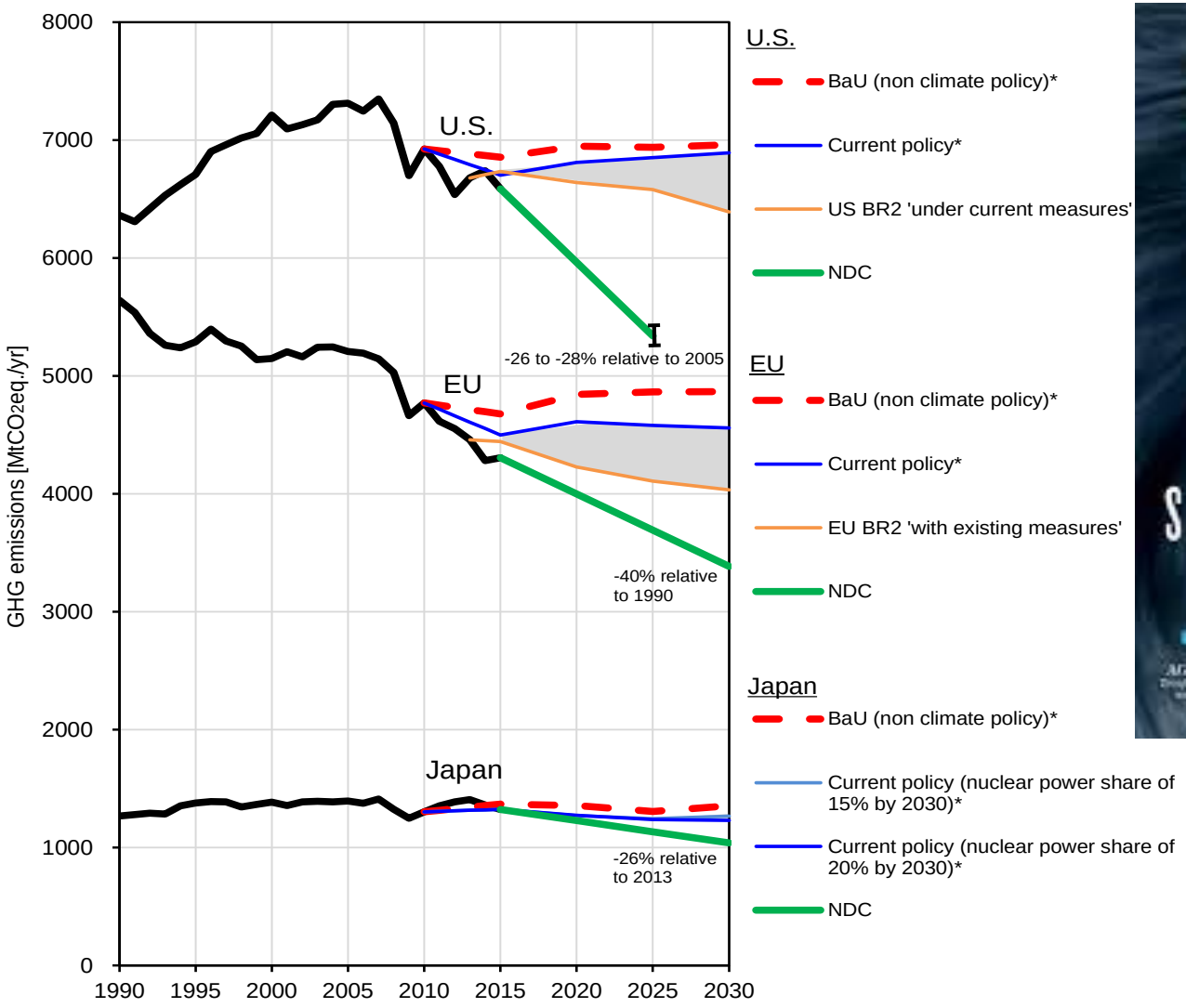
Overall, there is action but we are not on track to meet Paris pledges, which would take us above 3°C



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There are a wide range of sceptical arguments against action on climate change; there are responses to each

1. Climate change is not happening
2. Humans are not causing it
3. Any warming will be very modest
4. There are benefits from climate change
5. Any damages are small or uncertain
6. Humans will be able to adapt
7. The cost of reducing emissions are very high
8. Other countries are not playing their part

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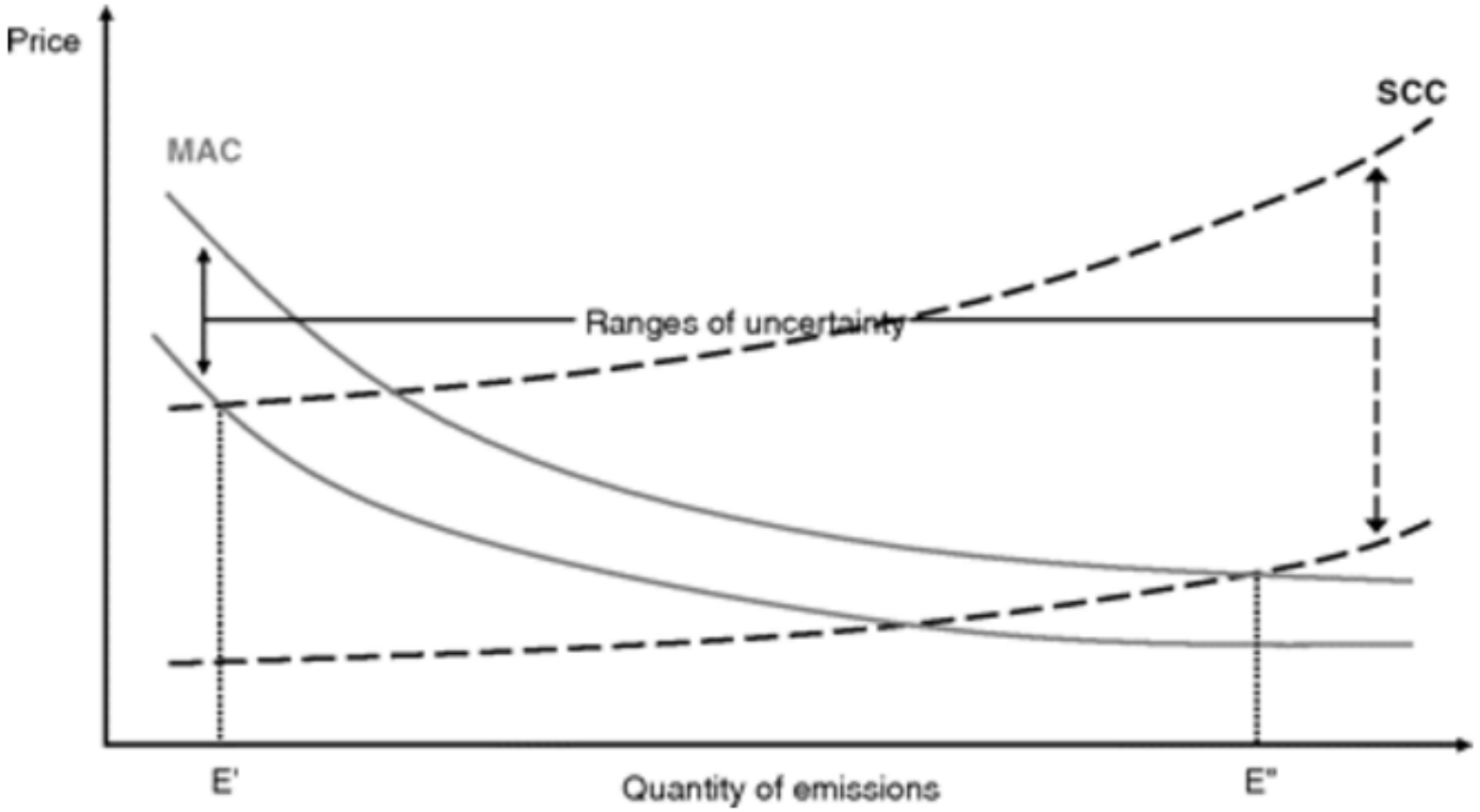
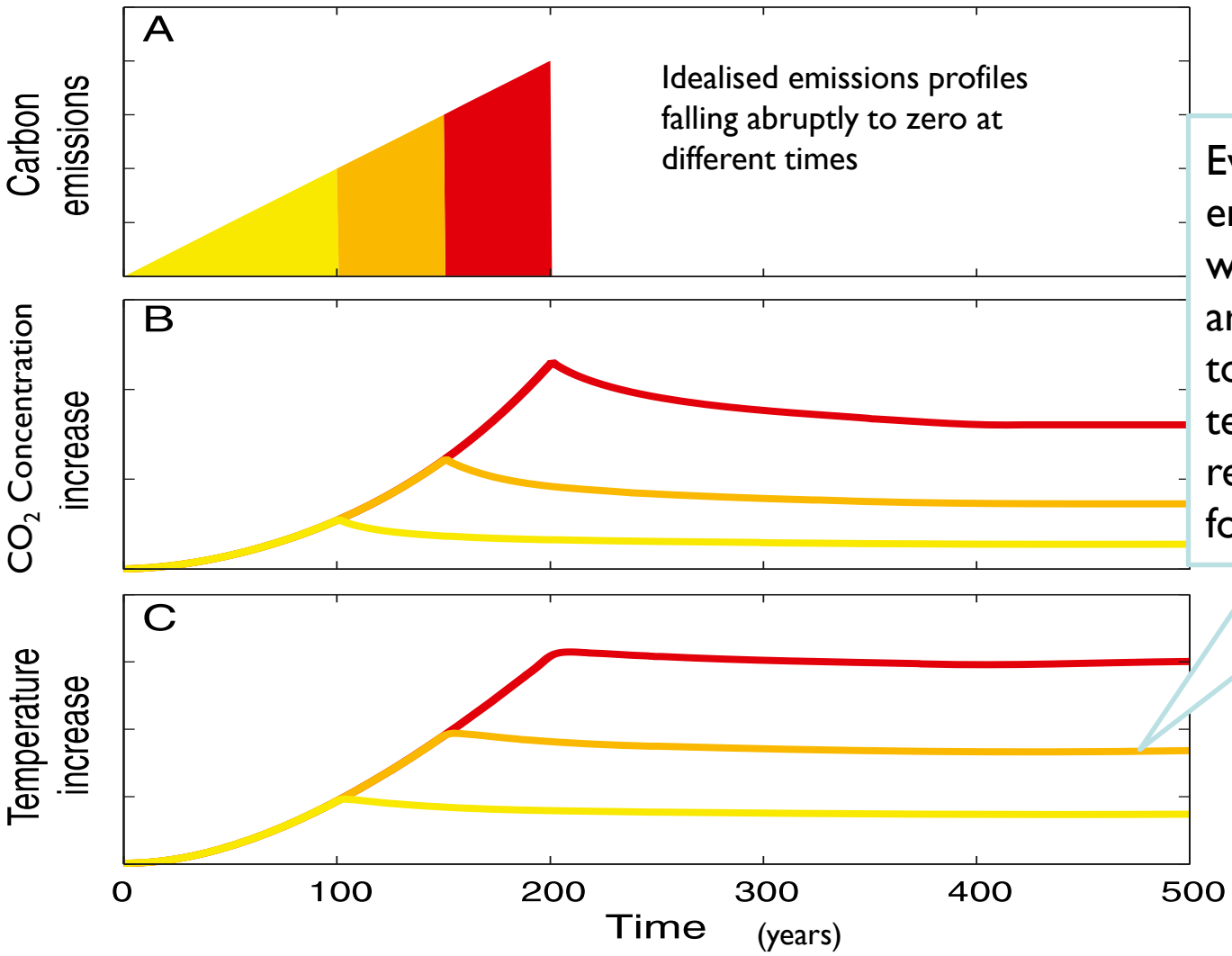
Economists typically think at the margin, which has drawbacks for a challenge like climate change



The key result from science is that temperatures only stabilise with total decarbonisation



Even in idealised emissions scenarios in which emissions of CO_2 are completely stopped tomorrow, temperatures will remain flat and not fall for hundreds of years

Source: Knutti & Rogelj (2015)

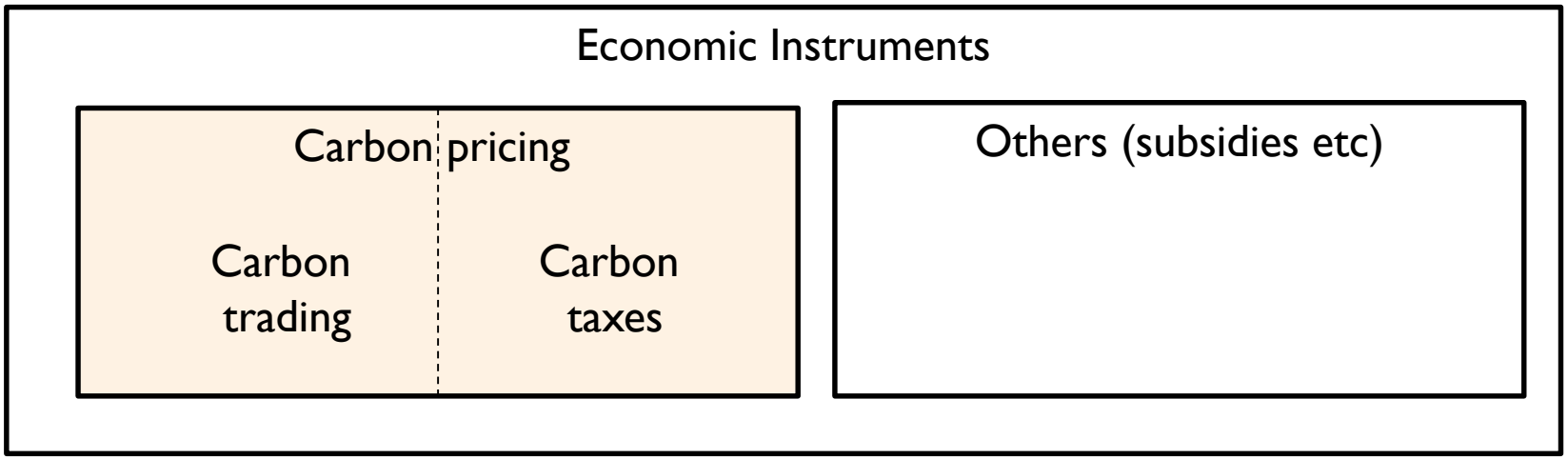
G7 declared support for full decarbonisation of the global economy before 2100, and then so did Paris

- **US**
- **EU (Germany, France, UK, Italy)**
- **Japan**
- **Canada**

"deep cuts in global greenhouse gas emissions are required, with a decarbonisation of the global economy over the course of this century."

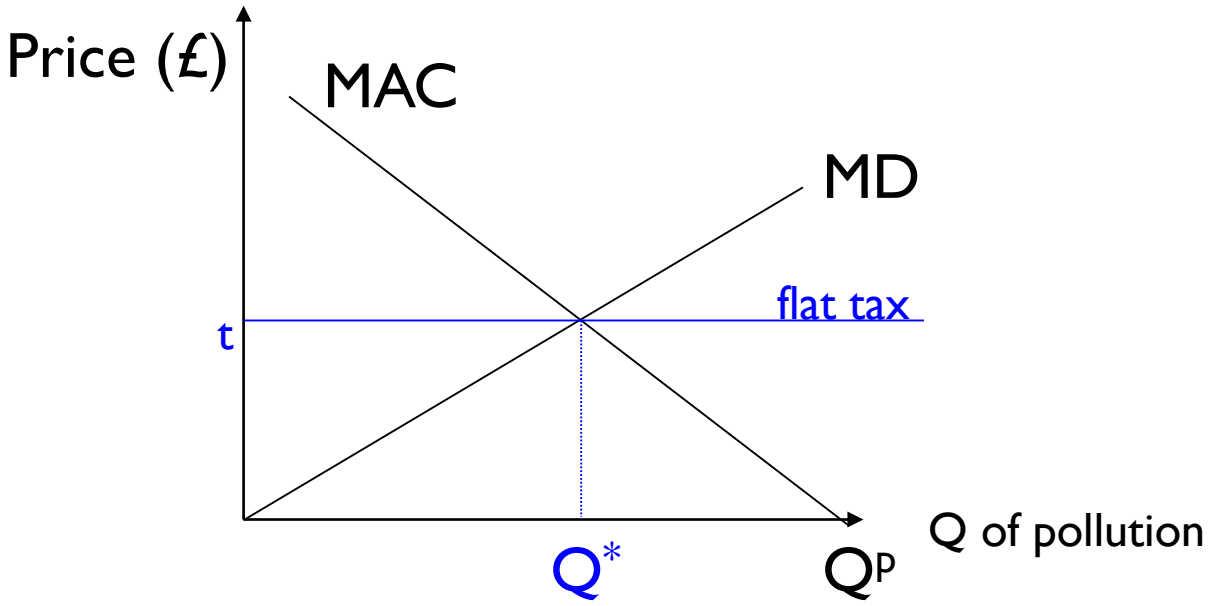
How do we get there? Every economist wants to price carbon…the most obvious is a pollution tax

- Note, however, that economists also recognise carbon pricing will not be enough, for various reasons
- A carbon tax is a **price** instrument
- Also called Pigouvian tax or fee
- Fairly well used in environmental policy:
  - Water pollution charges
  - Aggregates levy, waste taxes
- With uncertainty, taxes cannot guarantee a specific quantity of pollution



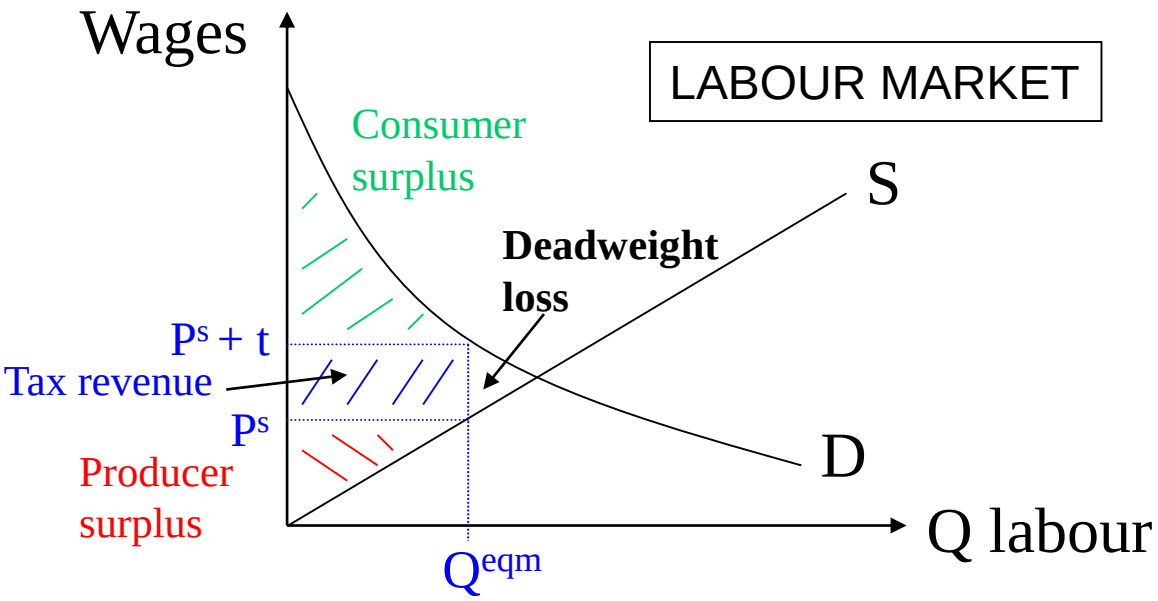
Economics of carbon taxes

- Aim to force firms to internalise MD curve
- With flat tax as shown, firms will pollute up to Q*



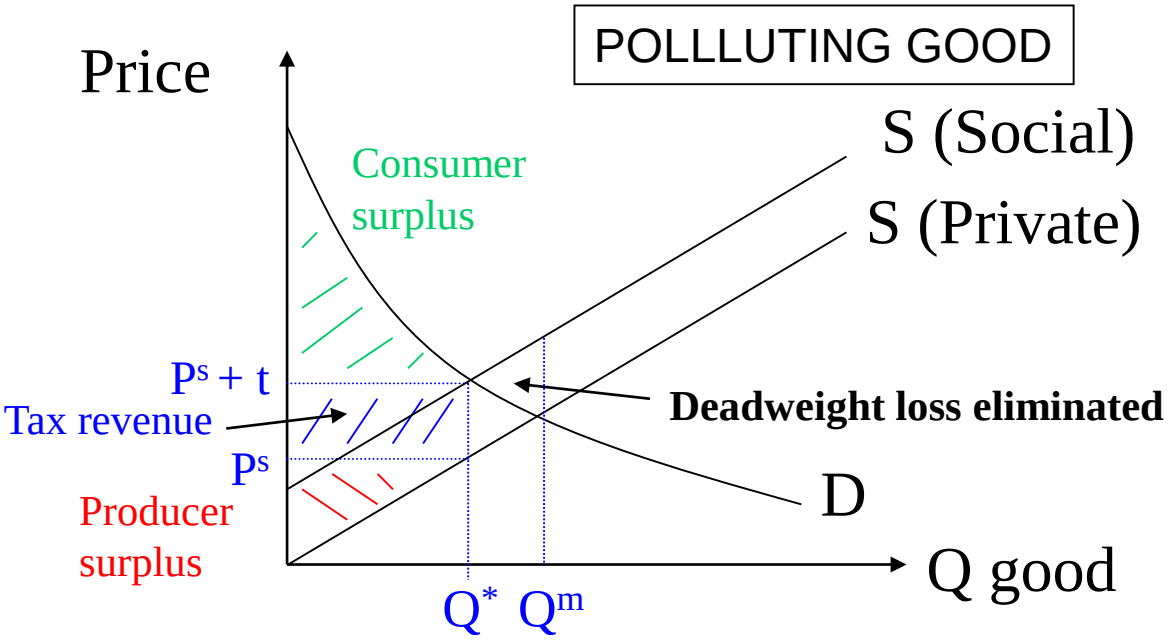
Why would we want a carbon tax? Don't taxes produce deadweight losses?

- Income taxes, VAT etc, drive a wedge between the producer price and the consumer price
- Results in 'deadweight loss', not Pareto efficient



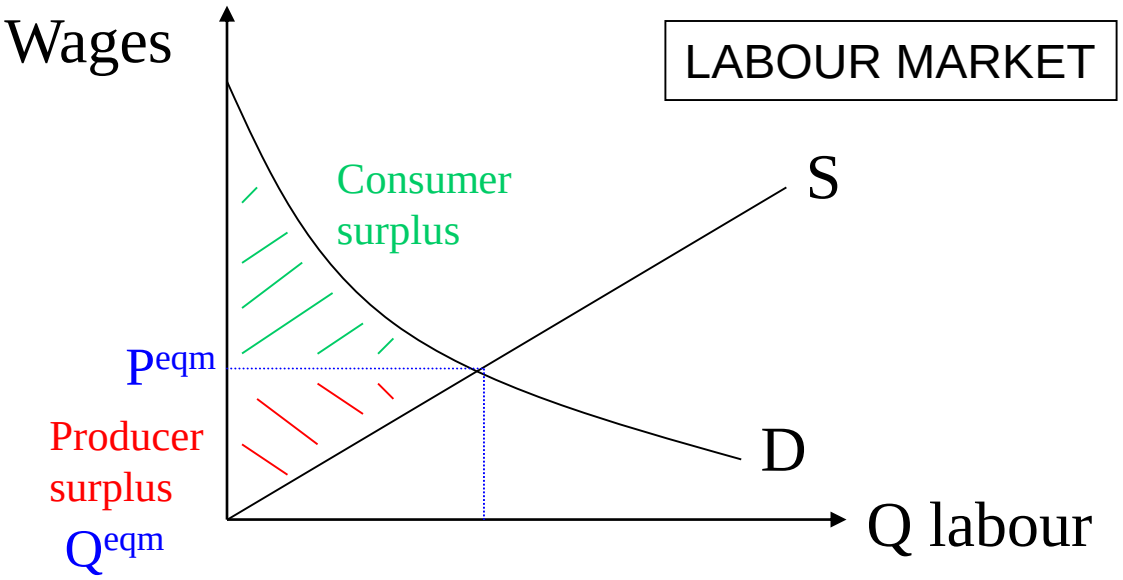
But taxes on an externality can eliminate a deadweight loss

- Taxes create a loss if previously at the optimum
- Taxes can eliminate a loss if not at the optimum



Revenue can in principle give a double dividend

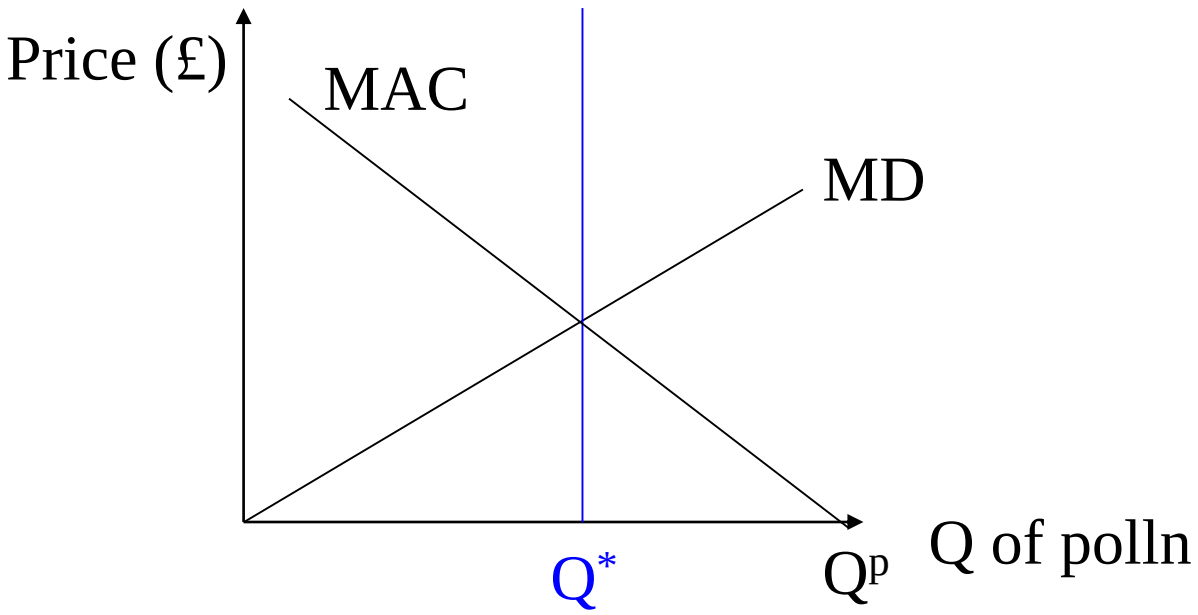
- If the revenue is used to reduce (or eliminate) other distortionary taxes
- However, the literature on this is rich, long and complex



Emissions trading

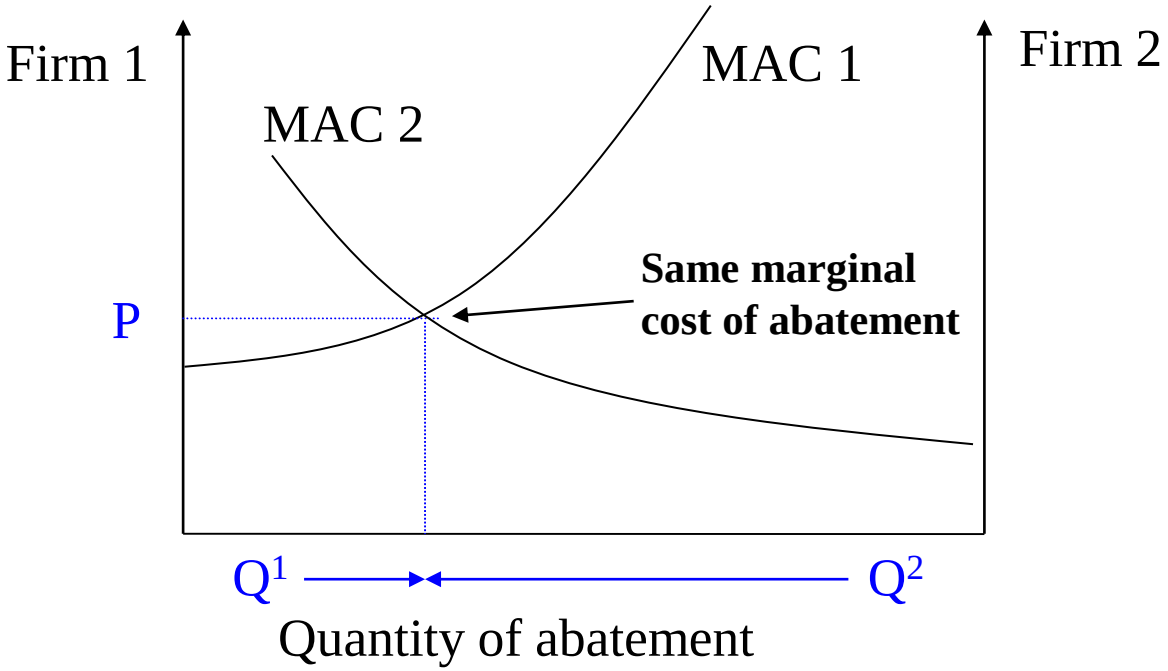
- Carbon trading is a "**quantity**" instrument
- Guarantees that quantity of pollution is optimal (unlike pollution taxes)
- But does not cap the costs of achieving that target, like taxes do
- Different options for initial allocation
- EU ETS Phase I runs 2005-2007
- EU ETS Phase II runs 2008-2012
- EU ETS Phase II runs 2013-2020
- China's national ETS is getting going this year and next

- Set number of permits to the optimum level of pollution



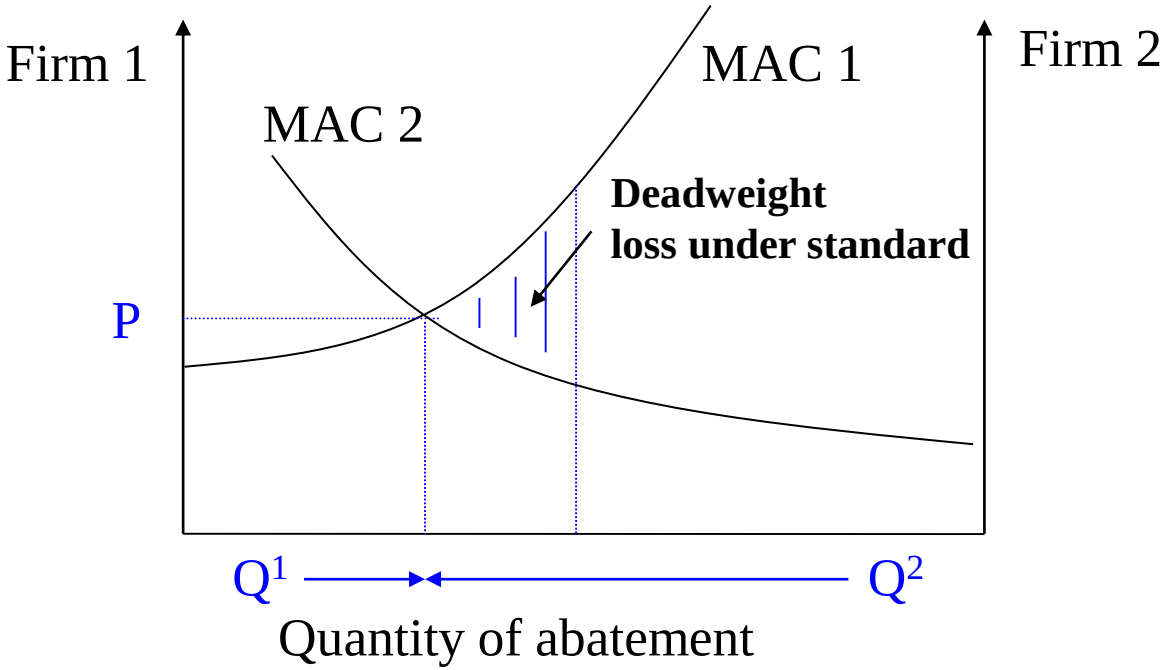
Advantage of trading

- Efficiency gains occur when firms have different abatement costs
- Firm 2 abates more, sells permits to 1



Equimarginal principle

- *Equimarginal* principle applies: abate until marginal costs of abatement are equalised



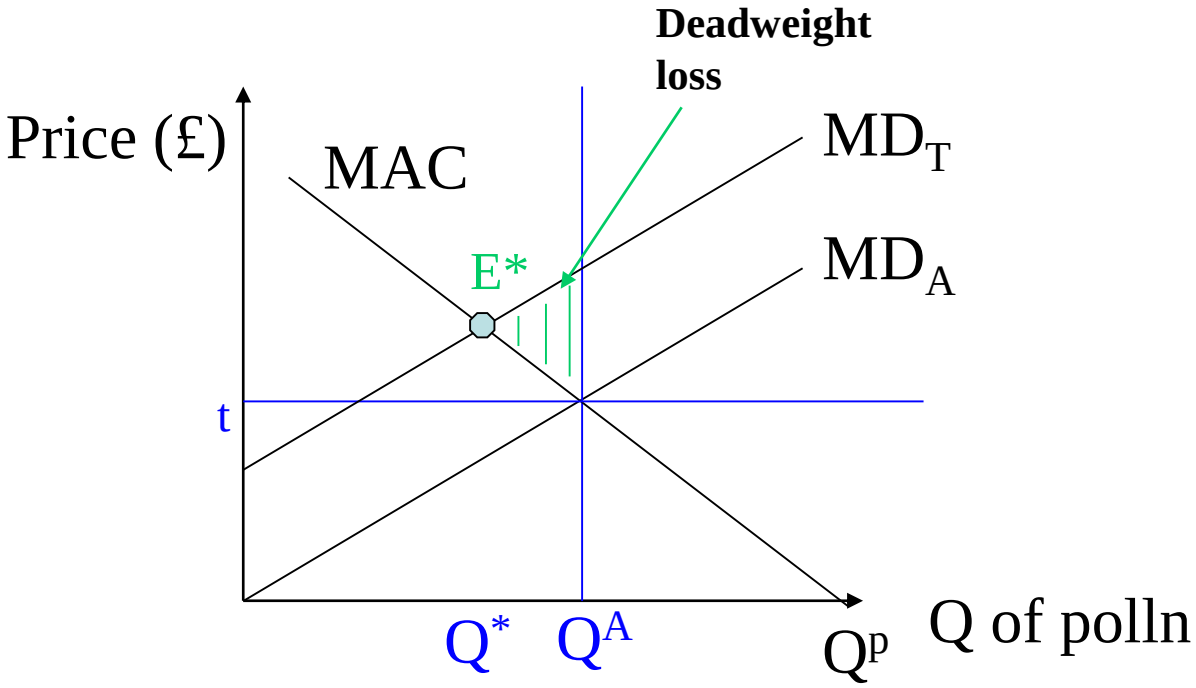
Is trading / taxes more efficient?

- Depends on the situation
  - What is important?
  - Ensure threshold not exceeded?
  - Ensure reasonable cost?
- Uncertainty
  - Do we know MD with certainty?
  - Do we know MAC with certainty?

  → Weitzman (1974, RES) following Hepburn (2006)

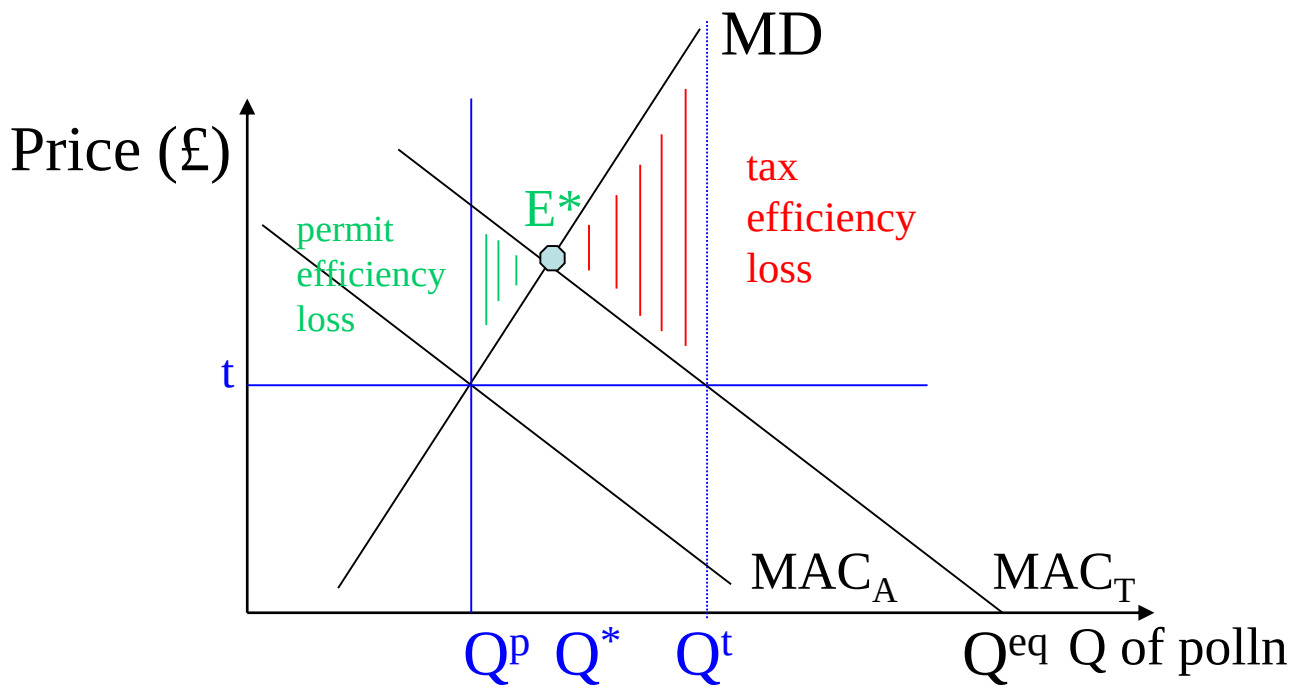
No difference if MAC certain

- Weitzman (1974, RES)
- No difference if the MAC curve is certain
- Even if wrong, efficiency loss will be the same



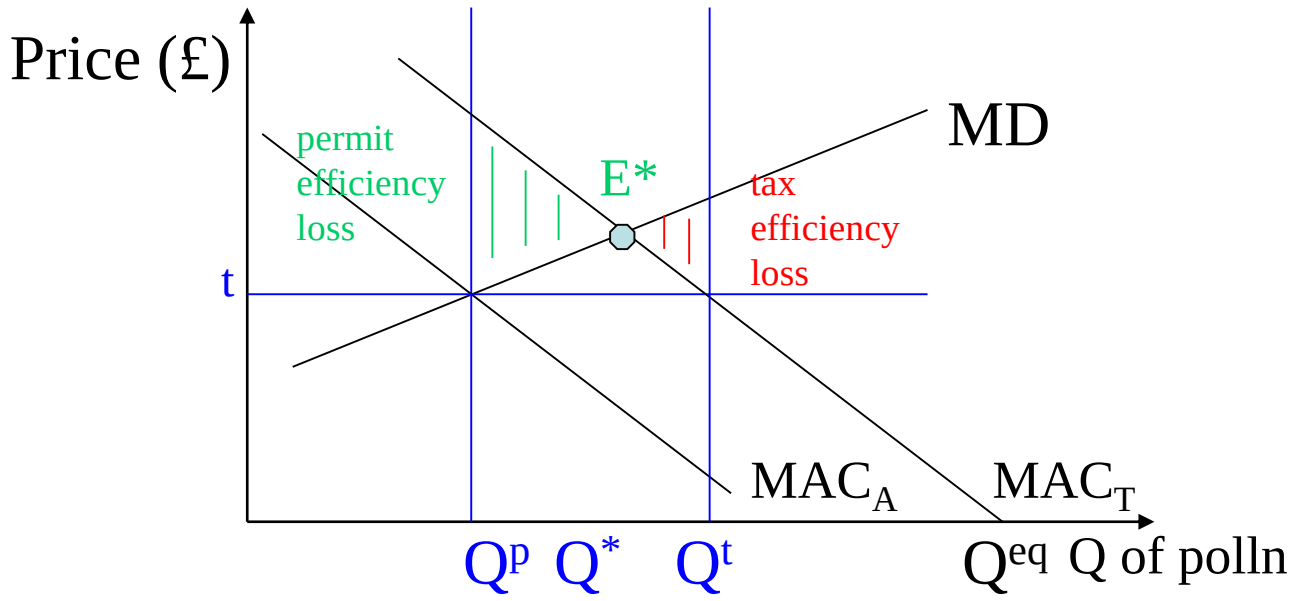
MAC uncertain (MD steep)

- Trading efficiency loss smaller when MD is steep (Permit line is like MD curve)



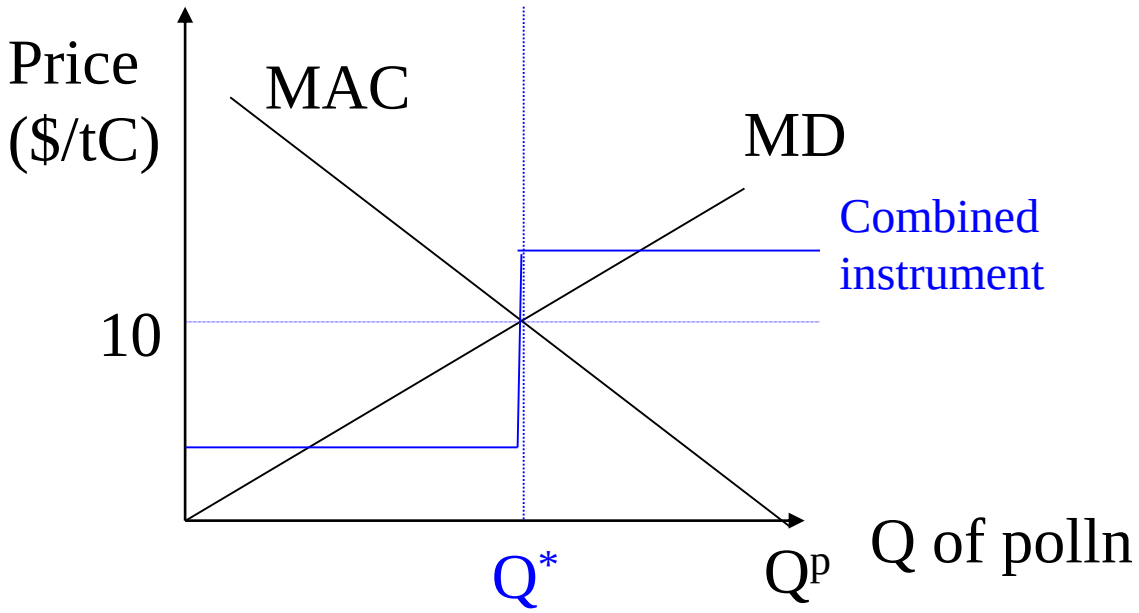
MAC uncertain (MD flat)

- Tax efficiency loss smaller when MD is flat (tax line is like MD curve)

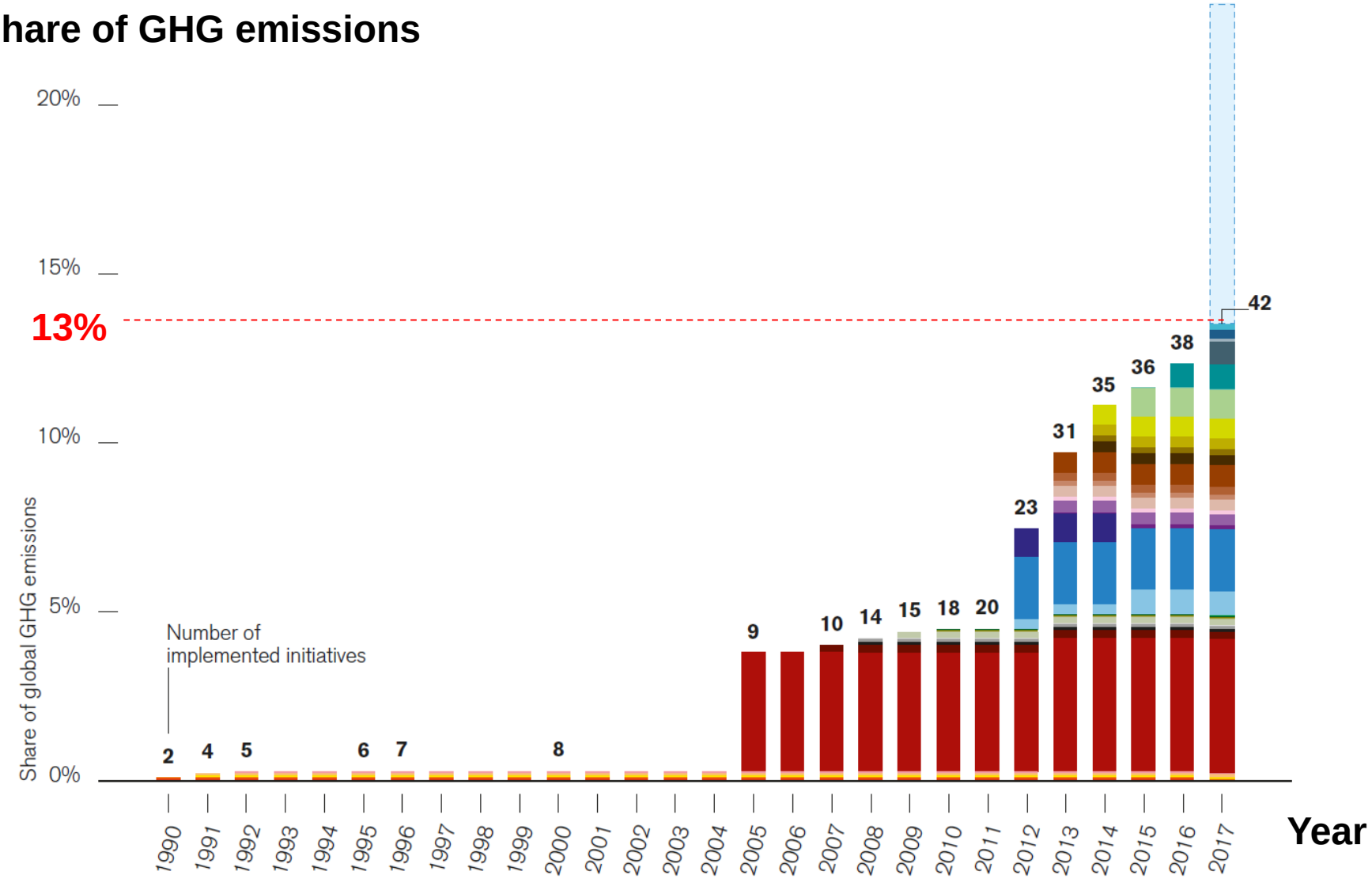


Economics of hybrids

- Set number of permits to the optimum level of pollution
- Ceiling on permit price (tax level)



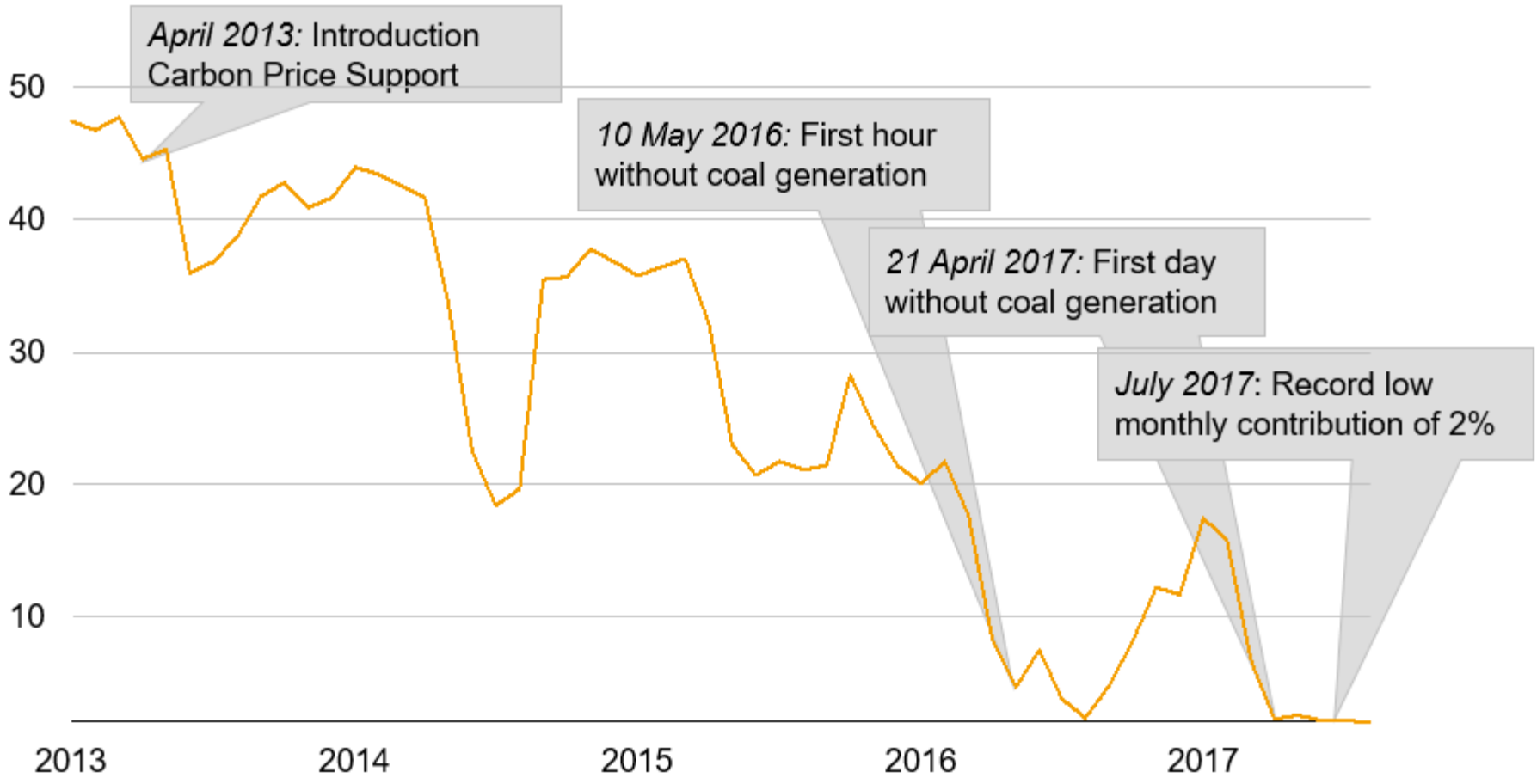
There is much more potential – carbon pricing only covers 13% of emissions (still < 25% with China)



Source: World Bank (2016) State and Trends of Carbon Pricing

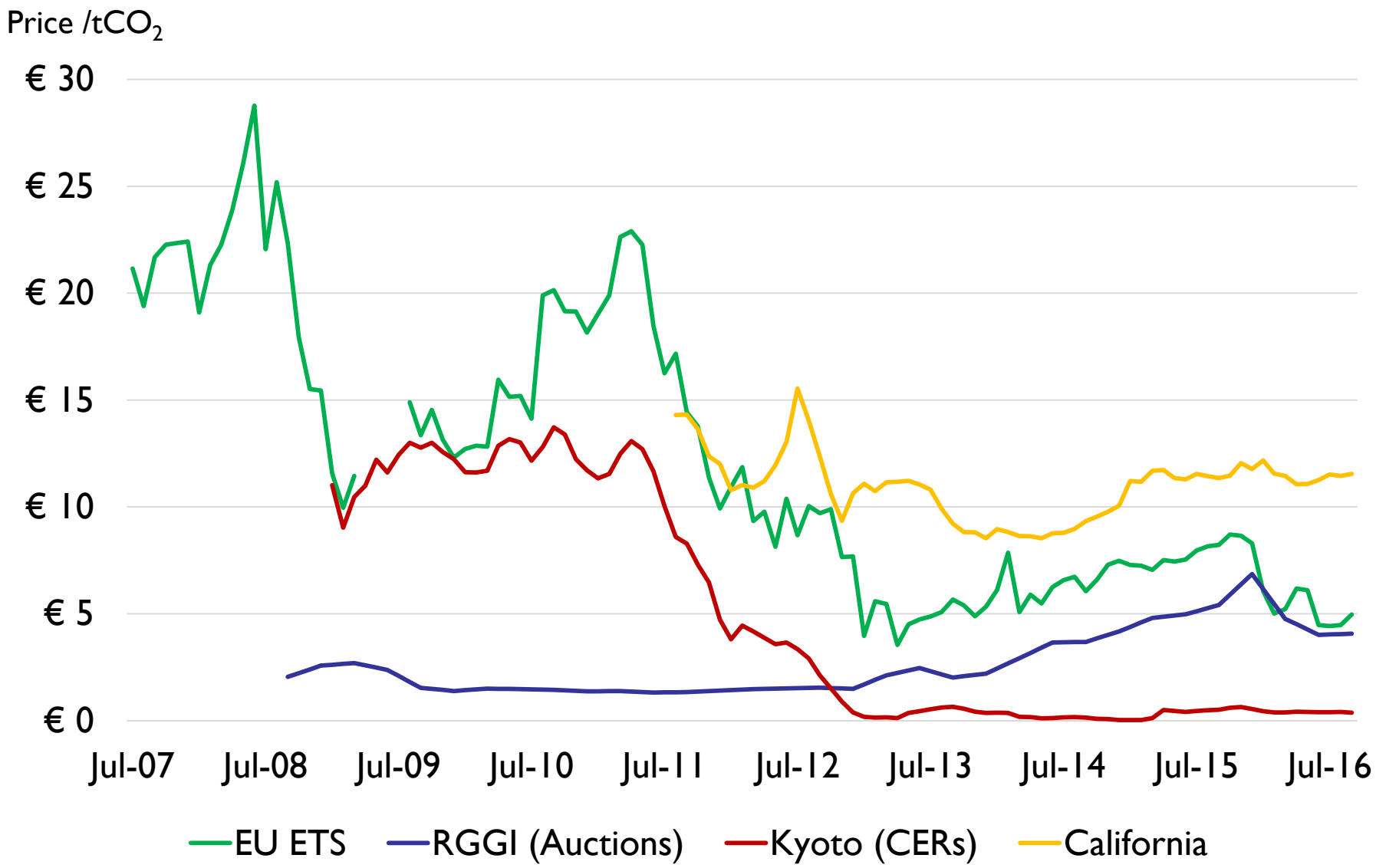
Do carbon prices work? The Carbon Price Floor in the UK has gradually wiped out coal

Coal share of total generation,
% total generation, monthly figures

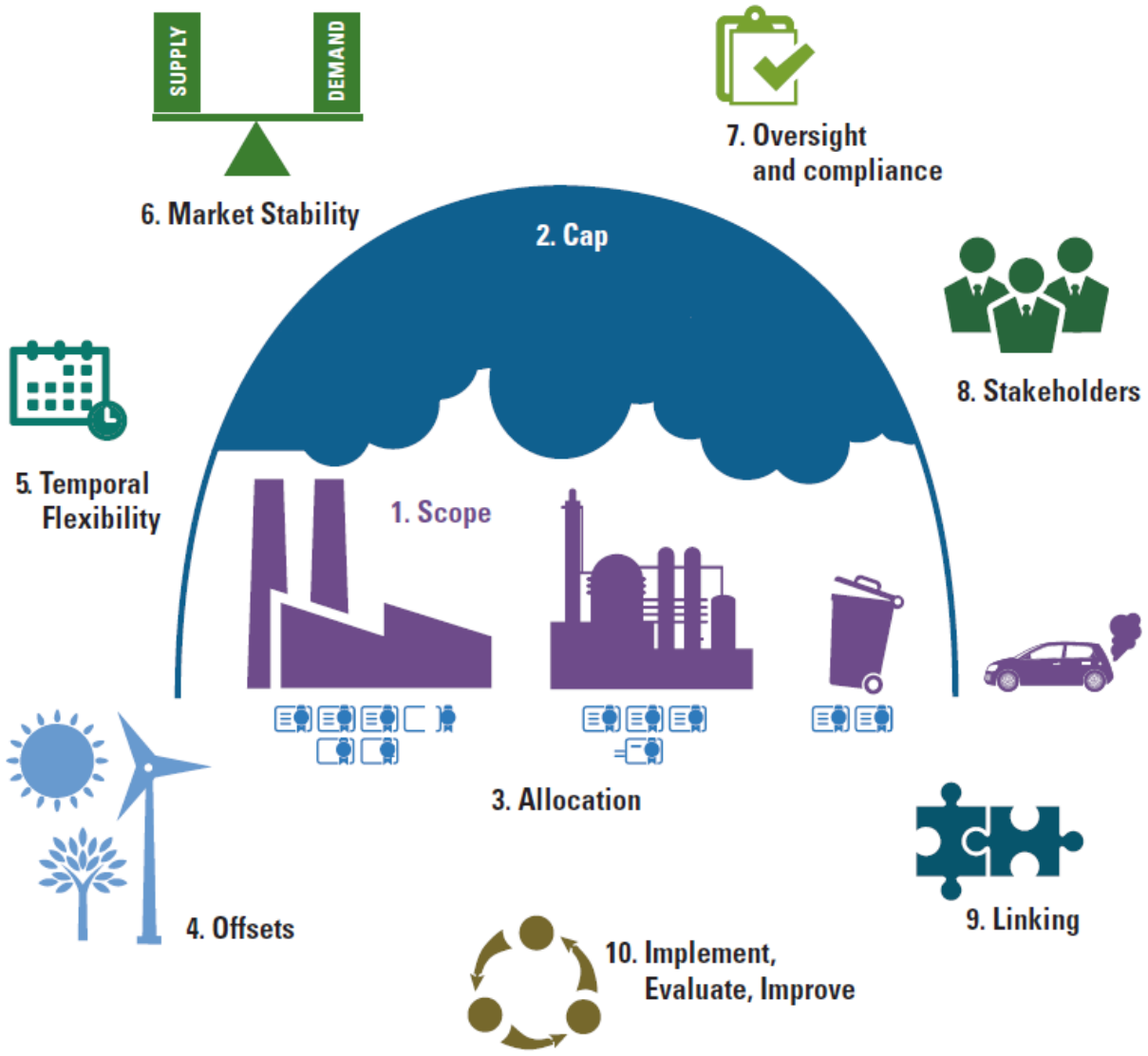


Source: Aurora analysis

As noted earlier, carbon trading often leads to lower prices than taxes

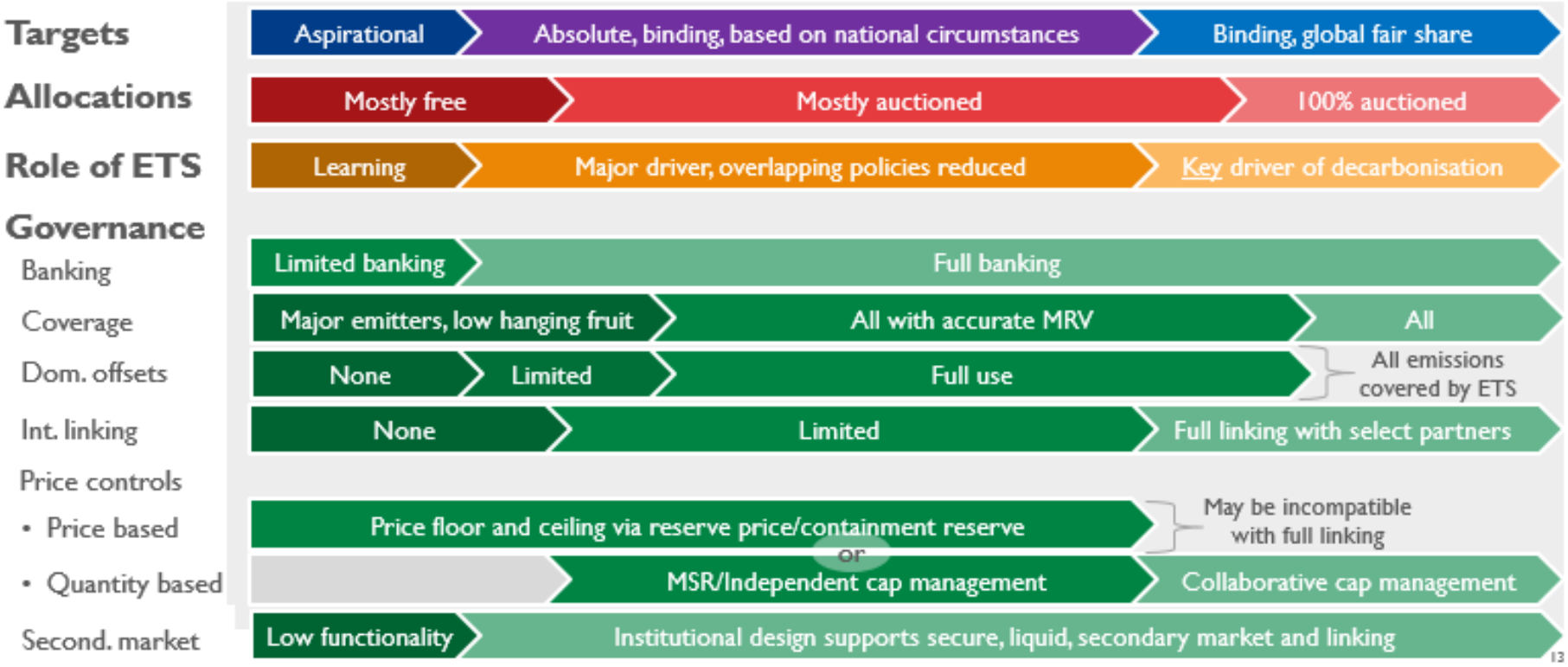


Actually putting a carbon trading scheme into practice is a non-trivial exercise



Source: PMR (2016) Emissions Trading in Practice: A handbook of design and implementation

A large number of features need to be thought through in designing a carbon market



Source: Vivid Economics analysis

The main alternative to economic instruments (markets, taxes) is direct "command and control"

- Direct intervention by government does have some advantages:
  - Can be extremely simple
  - Lower transactions costs
  - Government less likely to fail, long experience
  - Appropriate for pollutants with an optimal quantity of zero
  - Can convey a moral message; directors of companies are (in rare cases) liable under criminal law

There are many examples

- CFD FITS
- IED
- Licencing requirements
- Portfolio standards
- Grants
- Tax breaks

But such direct regulation has some serious drawbacks

- Generally less *efficient* than market instruments
  - Generally each firm has to achieve the same standard, regardless of the differences in clean up costs
  - Market instruments ensure (in theory) that pollution is eliminated in the cheapest manner
- Firms have no incentive to emit less than Q*
- And **have** to do Q*, irrespective of costs
- Tends to trigger vast array of complex "picking winners"

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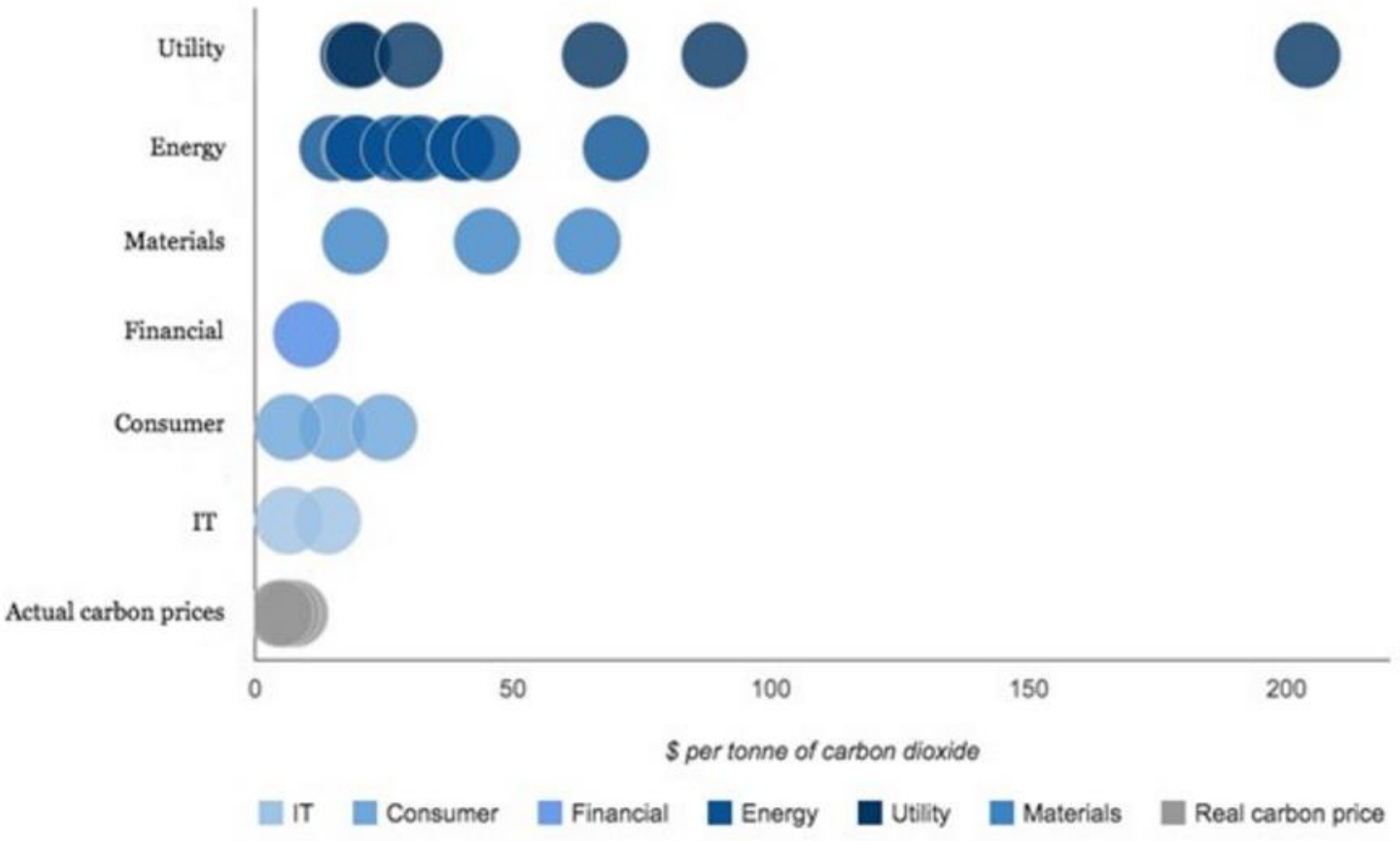
How far could we get with voluntary behaviour by corporates?

The business of business is business

Some large companies are managing risk with carbon prices that are above official market prices



The G20 FSB TCFD framework covers governance, strategy, risks and metrics

Governance
The organization's governance around climate-related risks and opportunities

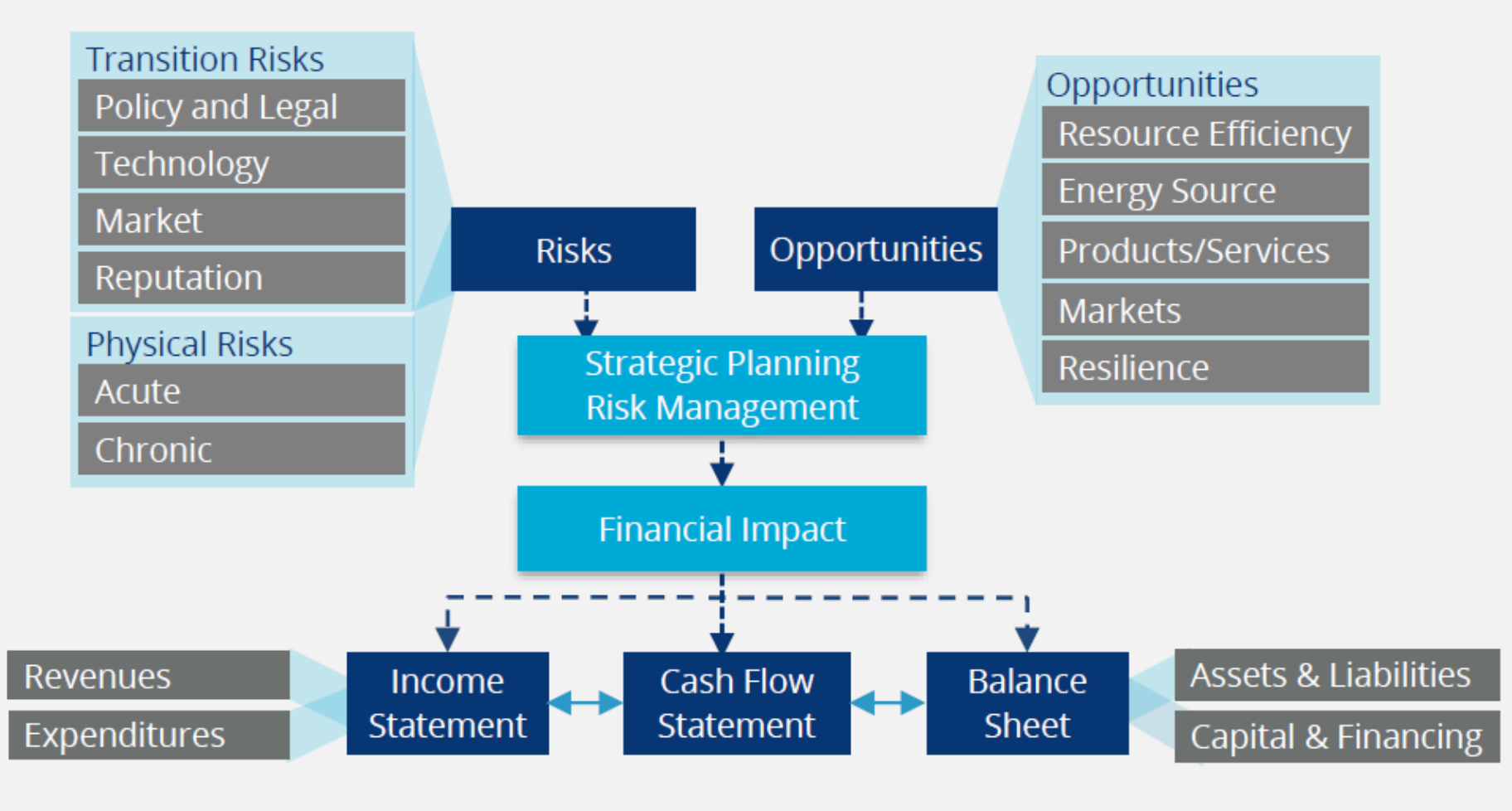
Strategy
The actual and potential impacts of climate-related risks and opportunities on the organization's businesses, strategy, and financial planning

Risk Management
The processes used by the organization to identify, assess, and manage climate-related risks

Metrics and Targets
The metrics and targets used to assess and manage relevant climate-related risks and opportunities

Sources:, fsb-tcfd.org

Disclosures are to be forward looking and address risks and opportunities on P&L and balance sheet



Sources:, fsb-tcfd.org

Wrap up for this session: we covered

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2. Policy responses thus far
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Next session

1. Technological progress and the energy transition
2. Will we get there in time?

Thank you

Climate Science and Economics as Q&A

1. Climate change is not happening
2. Humans are not causing it
3. Any warming will be very modest
4. There are benefits from climate change
5. Any damages are small or uncertain
6. Humans will be able to adapt
7. The cost of reducing emissions are very high
8. Other countries are not playing their part

Climate Science and Economics as Q&A

"It is warm / cold today, therefore climate change is / is not happening."

- Climate is the thirty-year average of the weather. The weather on any particular day is not an indicator of relevance to climate change trends.
- However, scientists are 95% confident that human emissions of greenhouse gases have increased the frequency (Schaller et al, 2015) or doubled the risk of the occurrence (National Academies, 2016) of some extreme events.

"There has been a 15 year pause in temperature increases – Earth has stopped warming."

- Warming appeared to slow between 1998 and 2012.
- However, warming increased again in 2013-6 (see Figure 1) driven partly by the large 2015-2016 natural El Niño cycle.
- Debate is now about whether there was a "pause" at all. Updated ocean temperature measurements (Karl et al, 2015) suggested there was no pause, which was recently corroborated by another study (Hausfather et al, 2017).

Climate Science and Economics as Q&A

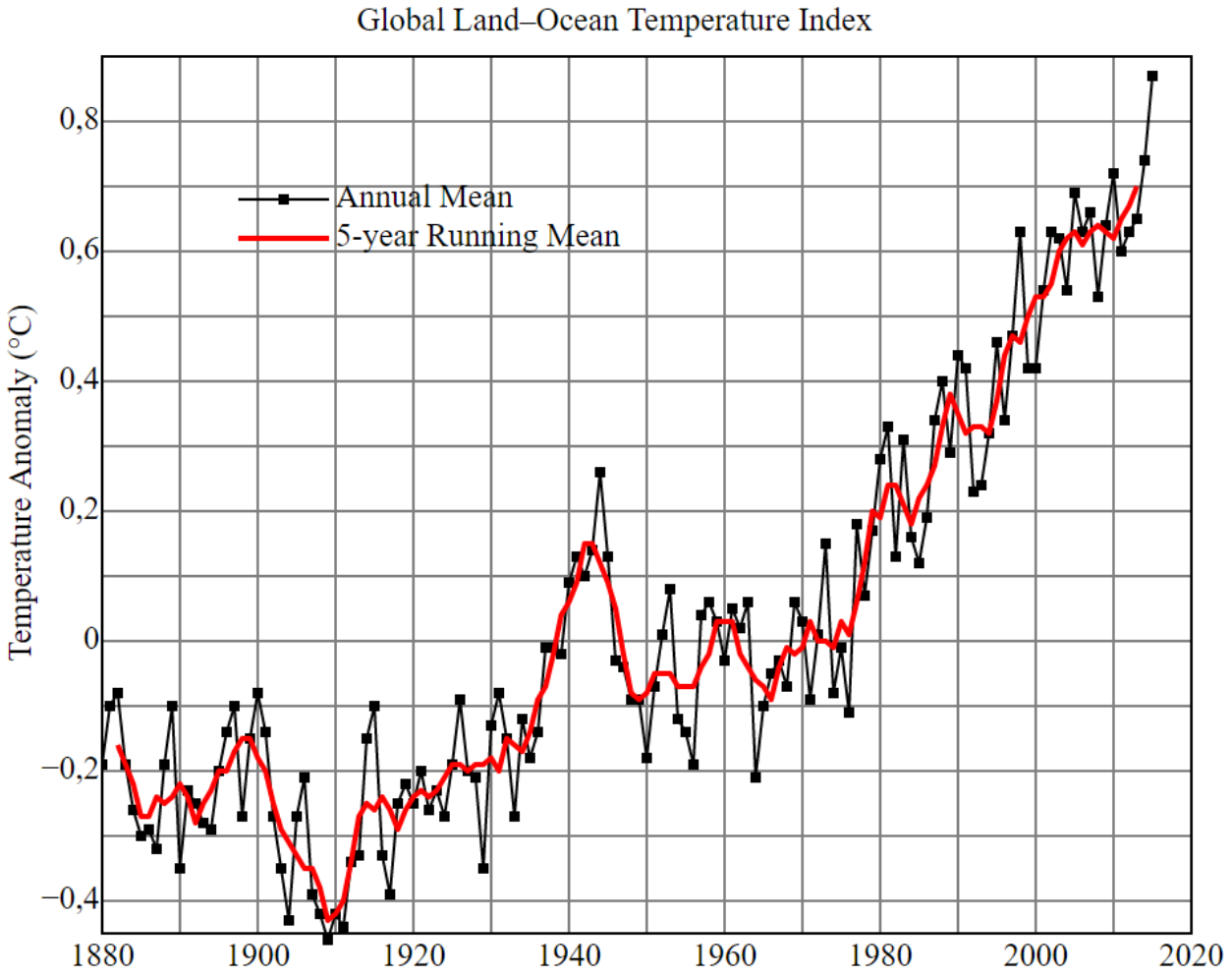

Figure 1. Source: NASA Goddard Institute for Space Studies (2017)

Climate Science and Economics as Q&A

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7. The cost of reducing emissions are very high
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"We don't know how emissions are affecting temperatures?"

- It is 100% certain that CO_2 traps infra-red radiation, such as emitted from the surface of the Earth. This can be demonstrably measured in a lab.
- It is true that the precise relationship between cumulative emissions of greenhouse gases is uncertain. The uncertainty is shown by the coloured plume in Figure 2.
- The emissions of every 1000 billion tonnes of carbon is expected to increase peak surface air warming by between 1.3 to 3.1°C within a decade (IPCC, 2013).
- As Figure 2 shows, we have now emitted around 500 billion tonnes of CO_2 (measured as carbon), and warming is just above 0.9°C since 1861-1880.
- The uncertainty arises from various feedbacks, including how clouds respond.

Climate Science and Economics as Q&A

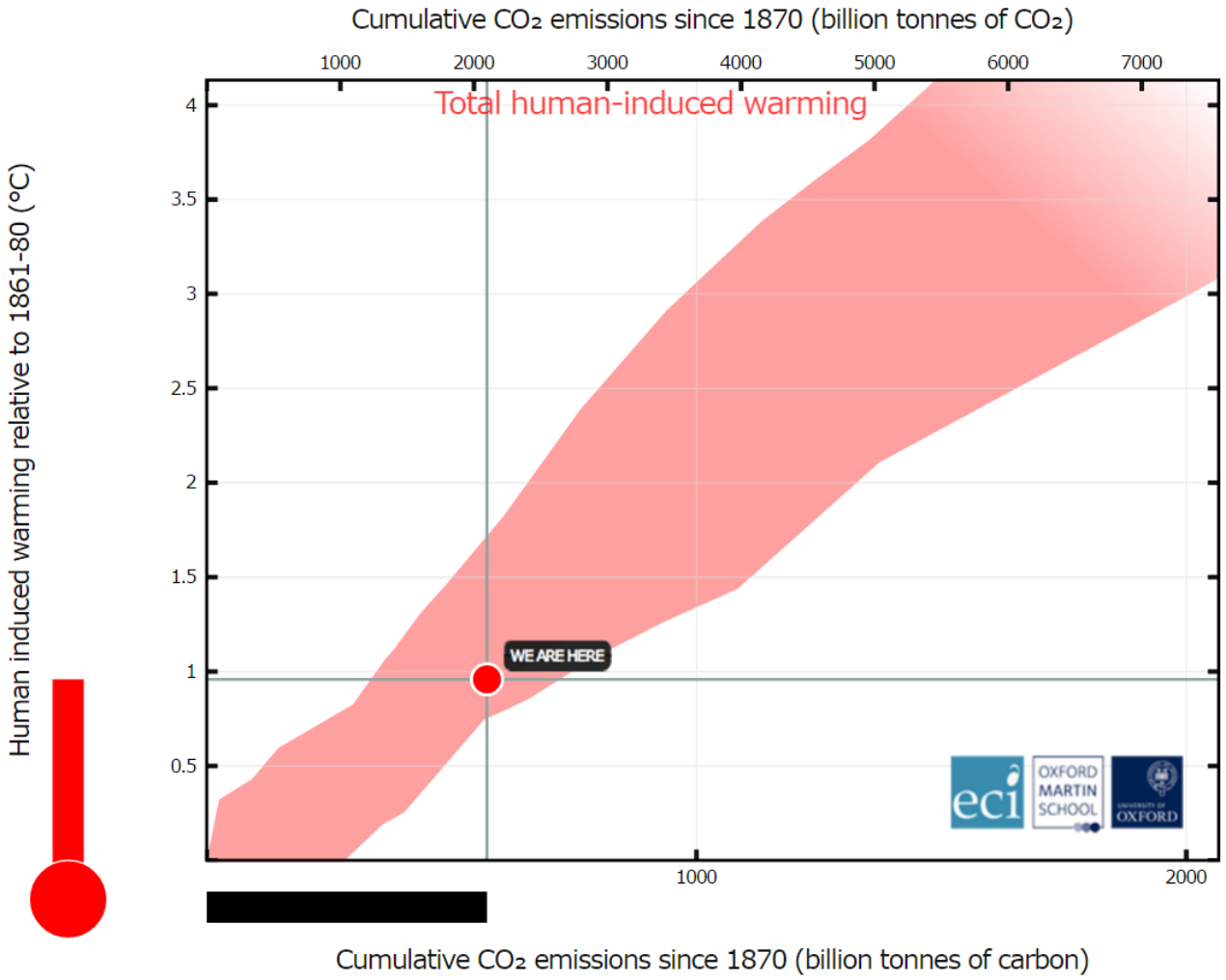

Figure 2. Source: www.safecarbon.org based on IPCC (2013)

"The climate has always been changing, and well before humans were around"

- Yes, it is absolutely correct that Earth's climate has changed continuously.
- Over the last 400,000 years Earth has been both 8°C cooler and over 2°C warmer than today (Petit et al, 1999).
- However, the rate of change is unprecedented in earth history since the industrial revolution began (Clark et al, 2016).

"Increase in temperature causes increases in CO_2, not the other way around"

- There is a marked correlation between temperature and CO_2.
- Causation is actively researched. The current status is that there is evidence of dual causality – an increase in CO_2 can increase temperature and vice versa.
- However, from analysis making use of the different ratio of ^{13}C to ^{12}C in atmospheric and fossil carbon, we know that almost all of the observed increase in CO_2 in the atmosphere is old fossil carbon, coming from human activities, and not driven by increases in observed global temperatures. (See references at Real Climate.)

"Any warming is due to the sun and other natural drivers, not due to human CO_2"

- It is true that natural factors, also called natural "forcings", affect the climate.
- But natural factors have contributed relatively little to the warming since 1951.
- Figure 3 shows most of the warming since 1951 is due to greenhouse gases.
- Bloomberg and NASA provide a more exciting interactive version of this figure.

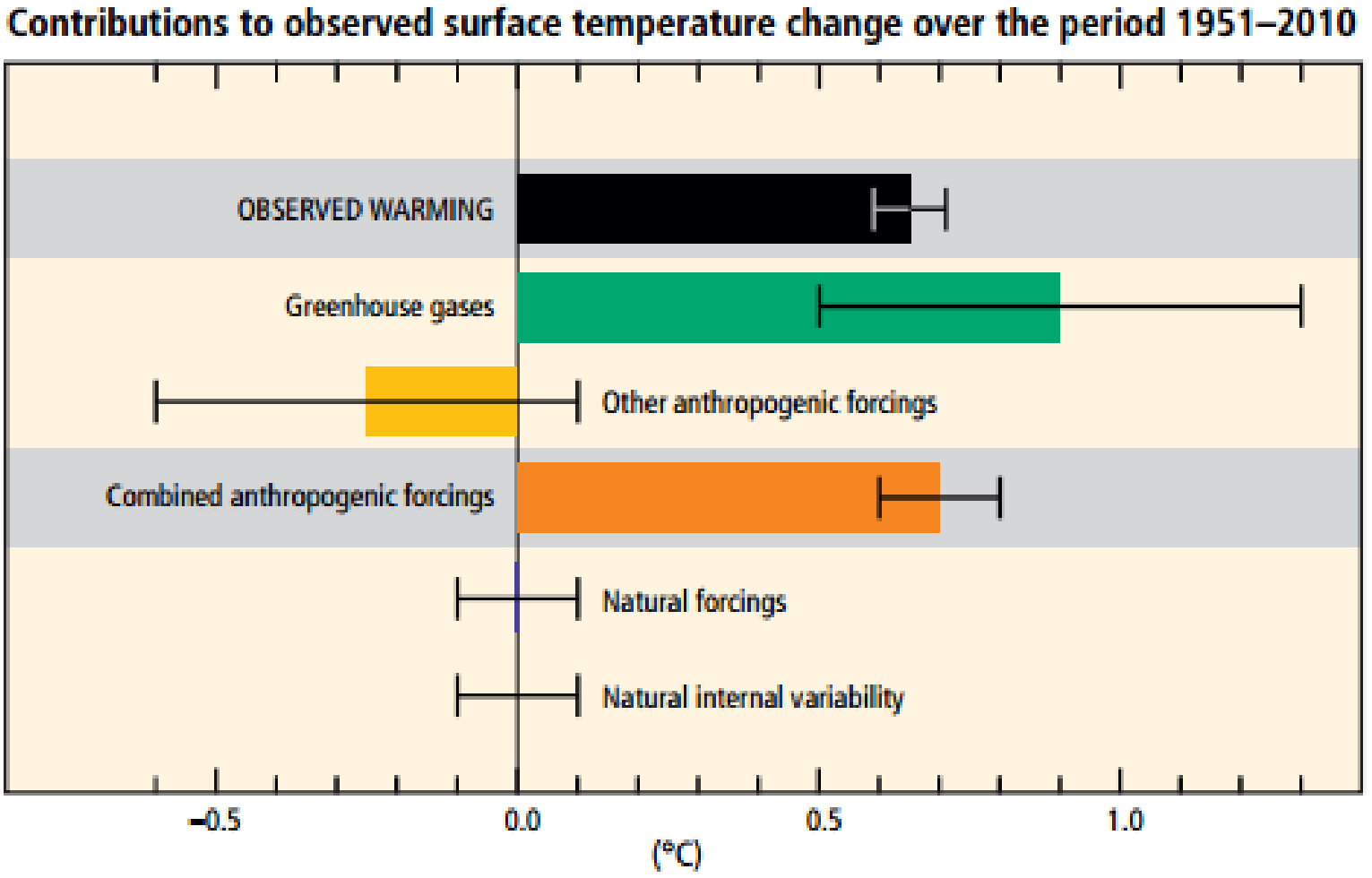

Figure 3. Source: Intergovernmental Panel on Climate Change (2014)

Climate Science and Economics as Q&A

1. Climate change is not happening
2. Humans are not causing it
3. Any warming will be very modest
4. There are benefits from climate change
5. Any damages are small or uncertain
6. Humans will be able to adapt
7. The cost of reducing emissions are very high
8. Other countries are not playing their part

"Serious scientists say that warming might only be 1.5°C (without geoengineering)"

- Perhaps, but human-induced warming since 1861-1880 is already likely above 0.9°C (Otto et al, 2015). This leaves less than 0.6°C until 1.5°C.
- The remaining emissions budget this 0.6°C is less than 300 billion tonnes of carbon (Allen et al, 2009; also Rogelj et al 2016) depending on action on non-CO_2 gases.
- We are currently emitting over 10 billion tonnes of carbon a year ((IPCC, 2013).
- So for roughly even odds of keeping to 1.5°C we could emit at current levels for at most 30 years and then (unrealistically) suddenly stop, or equivalently start reducing emissions now and continue rapidly to zero in a straight line over the next 60 years.
- So keeping warming to less than 1.5°C is not physically impossible but is unlikely.

Climate Science and Economics as Q&A

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Climate Science and Economics as Q&A

"More CO_2 will help trees grow and will green the Earth"

- Yes, higher CO_2 concentrations increases plant growth, other things equal
- But current science on agricultural impacts shows that climate change has already had a more negative than positive impact on crop yields (IPCC WG2, 2014), in part due to increased heat and water stresses.

"Opportunities will open up in Northern latitudes"

- Yes, as Arctic ice is melting, the Northwest passage is opening up, cutting shipping distance from Asia to Europe by 7,000 km.
- Yes, new fossil reserves may be recoverable in the Arctic as the ice retreats, but these are relatively expensive and may not be recoverable at scale (Lloyds, 2012).
- More arable land is likely in Russia, Canada and Northern USA (Zabel et al., 2014)

Climate Science and Economics as Q&A

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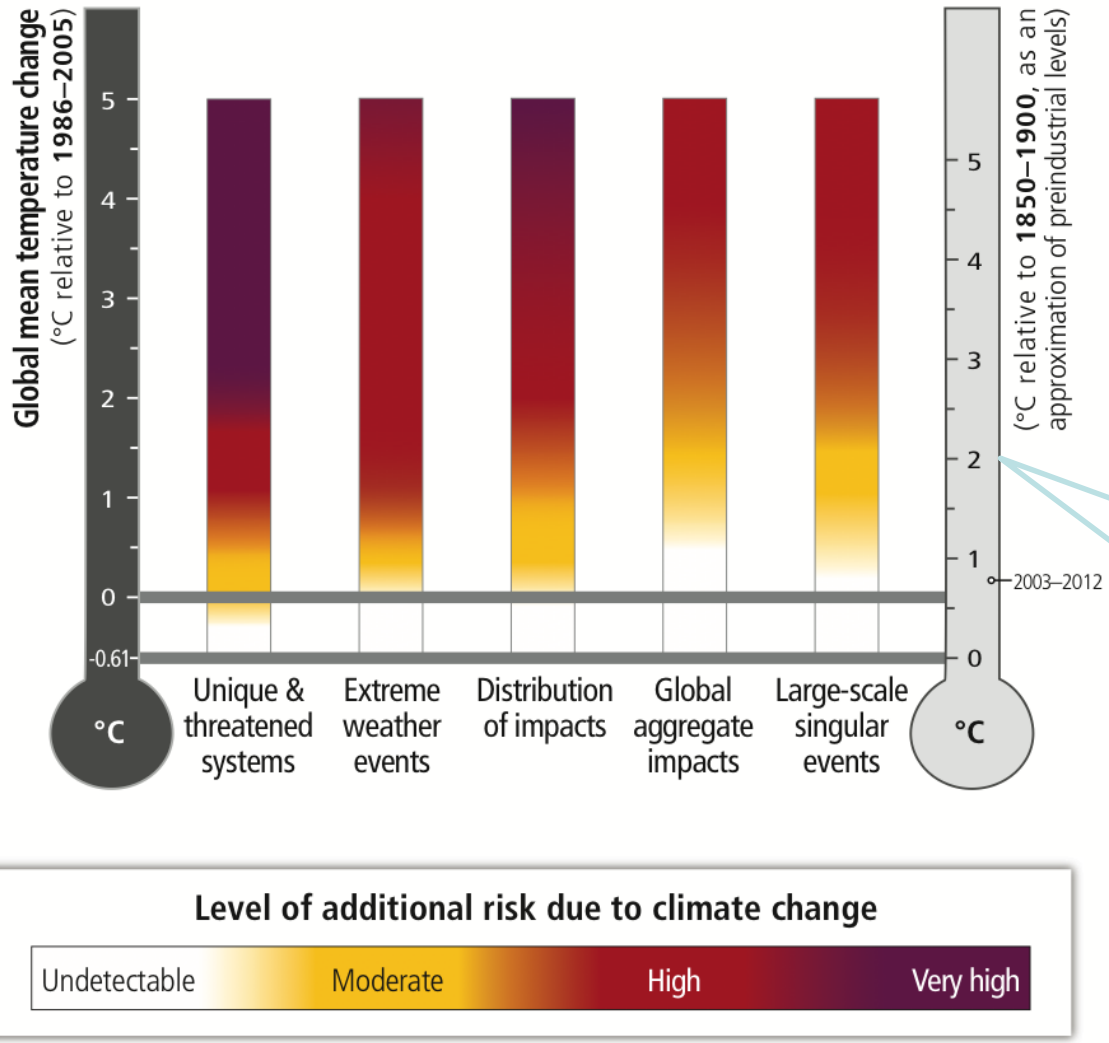
Climate change related risks are a function of '**peak warming**'



Restricting global temperature changes to **less than 2°C** above pre-industrial reduces many climate related risks to moderate levels

Source: IPCC AR5 WG2 (2014)

"The impacts are small"

- It is possible that we will be lucky and the economic impacts will be minor, but it is also possible that the economic impacts will be catastrophic.
- Given the risk of catastrophic impacts, economists from the left and right of politics conclude that hedging those risks is optimal (Litterman, 2013).
- For instance, it is "very likely" (90-100% confidence) that heat waves will occur more often, storms will increase in frequency and severity, the ocean will warm and acidify, and global mean sea levels will rise (IPCC, 2014).
- There is "high confidence" that climate change will contribute to undermining food security and that a large fraction of species face extinction (IPCC, 2014).
- The human body and human civilisation has adapted to current climate and geography. Optimal productivity of the human body is at around 20°C (Heal and Park, 2016), our cities have been built on the current location of coastline for reasons of transportation and logistics.

Climate Science and Economics as Q&A

"Models of economic damage are hopelessly uncertain and don't tell us anything"

- Yes, economic models of climate change are weak (Farmer et al, 2015)
- They often leave out impacts that are too hard to model, thus *underestimating* risk
- They also can't easily model the massive transformation involved in moving off fossil fuels. This could be more expensive, but also potentially significantly cheaper and more valuable (e.g. horse to car), than currently believed.
- In short, the weaknesses of economic models are a cause of concern

Climate Science and Economics as Q&A

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"We have adapted to much greater challenges"

- Humans will indeed be able to adapt to some degree, using simple technologies like dykes, improved flood management, storm-proofed buildings, and air conditioning
- Our ability to adapt is shown by the result that hot days have a lower economic impact in areas where heat stress is common (e.g. Houston) compared to those where it is not (e.g. Boston) suggesting long-run adaptation (Heal and Park, 2016).
- But our ability to adapt is limited; adaptation cannot eliminate the negative effects, and up to around 2°C prevention is cheaper than adaptation (IPCC, 2014).

Climate Science and Economics as Q&A

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Climate Science and Economics as Q&A

"Vast sums are spent on renewables and they are still more expensive than fossil"

- Larger subsidies for fossil fuels have dwarfed those to renewables (IEA, 2014).
- After 5 years of rapid cost declines, new renewables are now often cheaper than new fossil fuels (depending on location and system)
- The costs of renewables continue to fall quickly, whereas the cost of fossil fuel has been stationary in real terms for around 100 years (Farmer and Lafond, 2016)
- Large investments are needed in low-carbon infrastructure, which is expensive if forced as a retrofit. But the overall cost of new low-carbon infrastructure is roughly the same as new high-carbon infrastructure (see New Climate Economy, 2016).
- Air pollution, often from fossil fuels, kills 5.5 million people p.a. (Global Burden of Disease, 2016), yet this is often not factored into the costs of clean vs dirty energy.
- In the USA, over 200,000 people die p.a., which economists have monetized as being equivalent to losses of $250 billion p.a.

Climate Science and Economics as Q&A

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Climate Science and Economics as Q&A

"China is the worst polluter and they not doing anything"

- China is indeed the largest current polluter in total. However, per capita, China emits less than half that of America. Since the industrial revolution, America has the highest cumulative emissions (Matthews, 2015).
- China has the largest solar, wind, nuclear and hydro deployment programme in the world (IRENA, 2016) and will introduce a CO_2 trading scheme in 2017

"Other countries are not on board"

- 196 countries unanimously signed the Paris Agreement committing to keep temperatures "well below 2°C" and they will "pursue efforts" to 1.5°C.

"Countries are making pledges but not doing anything"

- It is true that at present not enough is being done; Earth is on track to warm 3-4°C (Climate Action Tracker)
- But action is happening in every country on Earth (Climate Action Tracker).
- **China** announced in January 2017 that it will cancel 120 GW of coal-fired power (compared to the USA capacity of just over 300 GW).
- Chinese, Asian and global coal consumption is now falling (BP, 2016).
- The **USA** and **China** have decoupled emissions from economic growth (IEA, 2016).
- The **United Kingdom** has reduced emissions from around 800MtCO_2e in 1990 to around 500MtCO_2e, with a legal requirement to reduce emissions by 80% by 2050, shown in Figure 4.
- The UK Secretary of State announced in 2015 that coal-fired power will be phased out and closed entirely by 2025.

Climate Science and Economics as Q&A

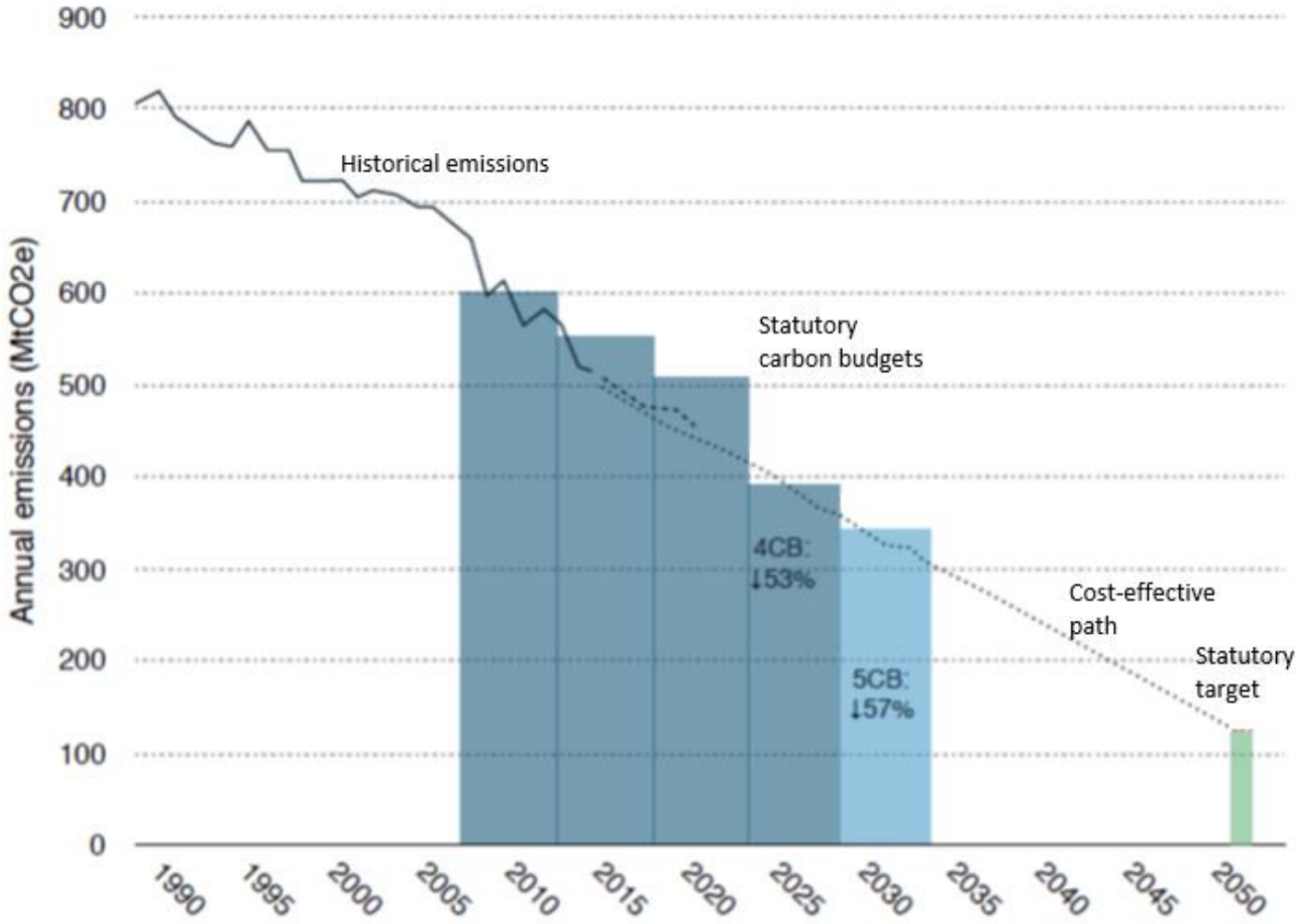


Figure 4. Source: Adapted from United Kingdom Committee on Climate Change (2015)

"Countries are making pledges but not doing anything"

- Carbon prices are now in place in 40 countries and 24 subnational regions, raising $26 billion of revenue in 2015, see Figure 5. (World Bank, 2016).
- In 2016, more was invested in renewable energy than in fossil fuels. Mission Innovation will double clean energy R&D to $30 billion in 22 countries & the EU.

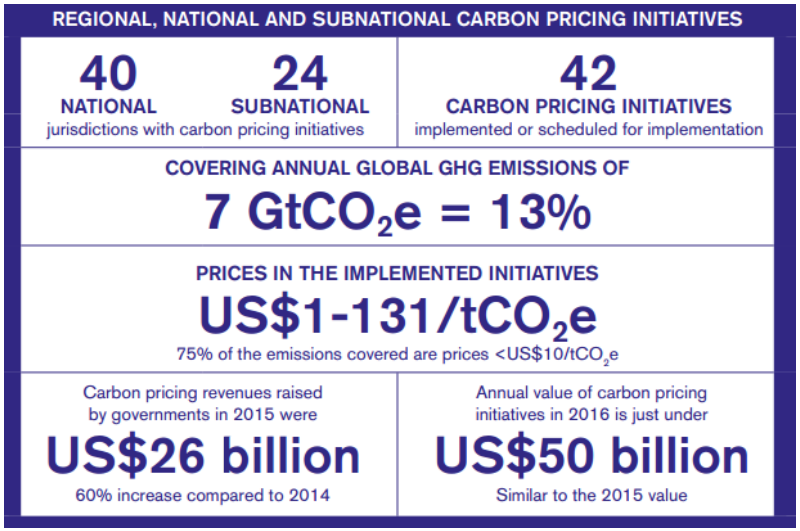


Figure 5. Source: World Bank (2016)

Importance of the atmosphere:

Total energy radiated by the sun = constant x $(T_{sun})^4$

with T in degrees K = ^{0}C + 273

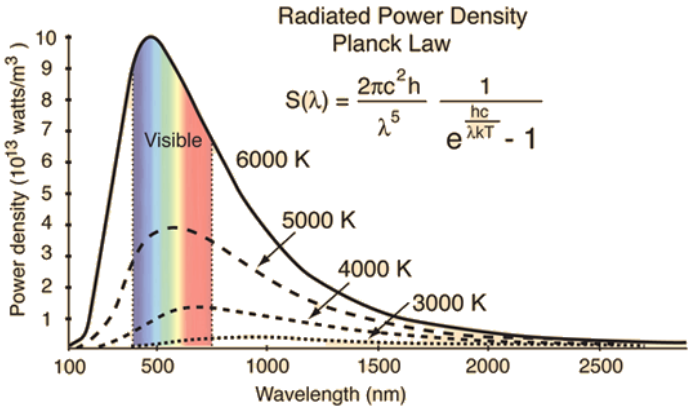
If earth had no atmosphere:

Total energy radiated by the earth = constant x $(T_{earth})^4$

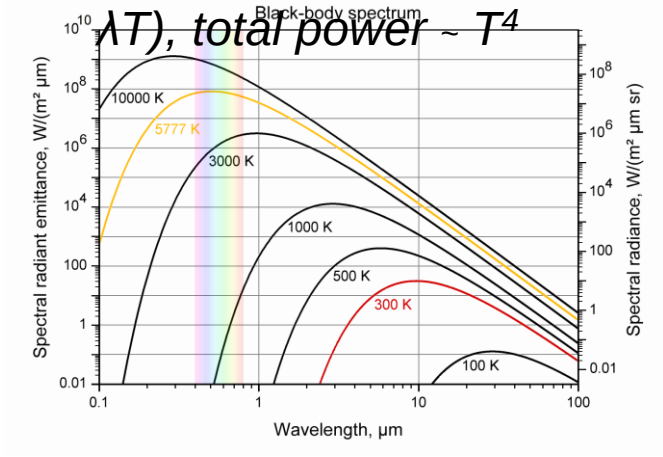
Energy balance T_{earth} = geometrical factor x $\eta^{1/4}$ x T_{sun}

where η = (1 – fraction of sun's energy reflected by the earth) ≤ 1

→ **T_{earth} ≤ 6 ^{0}C** – observed value is 15 ^{0}C



Integrating over λ (changing variable to $x = \lambda T$), total power ~ T^4



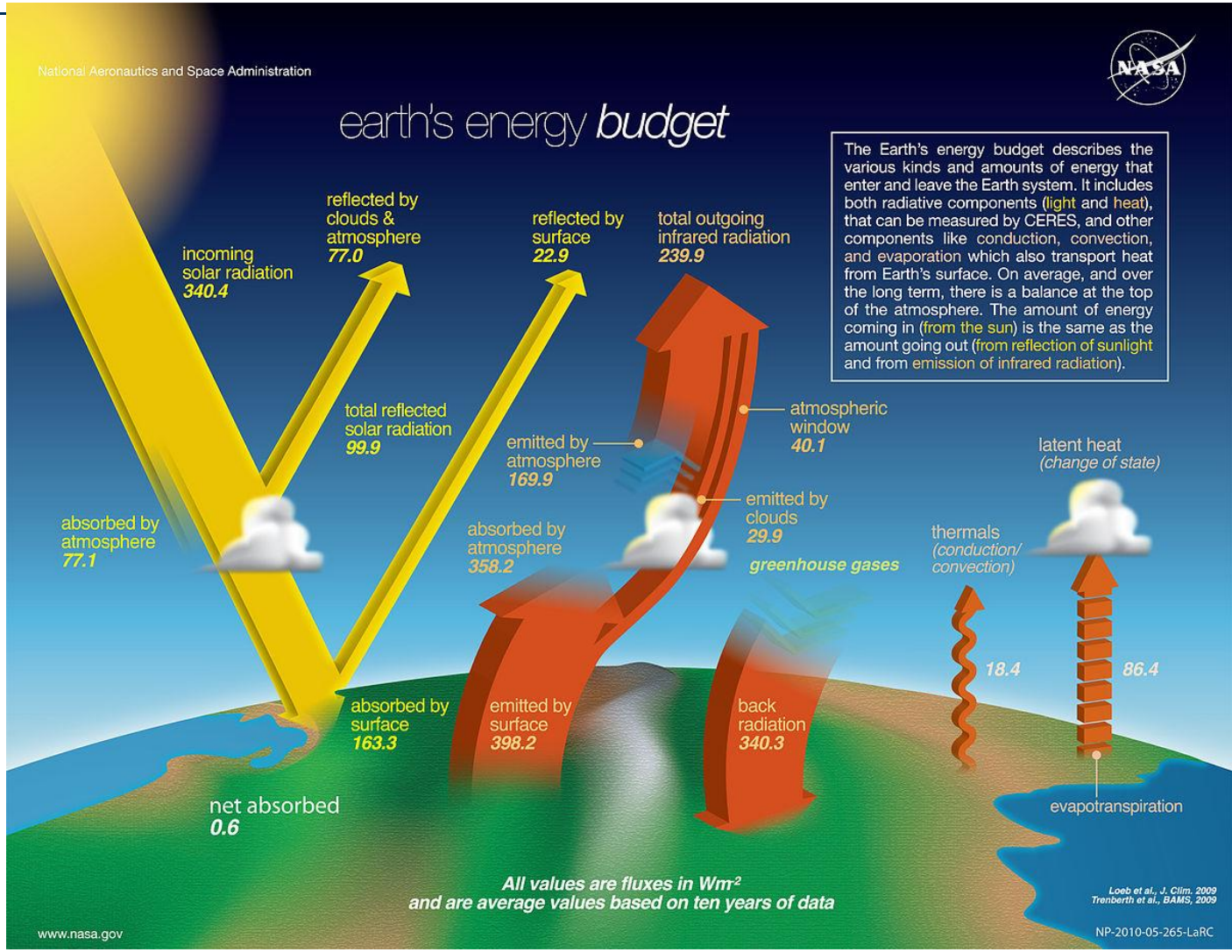
Simple description of global warming:

Atmosphere is essentially transparent to energy from sun (at 5778 K) which peaks (see curves) at wavelengths around 500 nm, but water vapour (and other greenhouse gases) absorbs much of the outgoing energy, which peaks at around 10 μm

Energy Balance:

Very hard to measure, but it seems there is a net radiation balance of 0.6 Wm^{-2} (maybe now bigger)

- driving warming



Clear that i) an increase in CO2 will generate a temperature rise (note: absorption already saturated at the peak of absorption by CO2 - effect is in the tail), which in turn

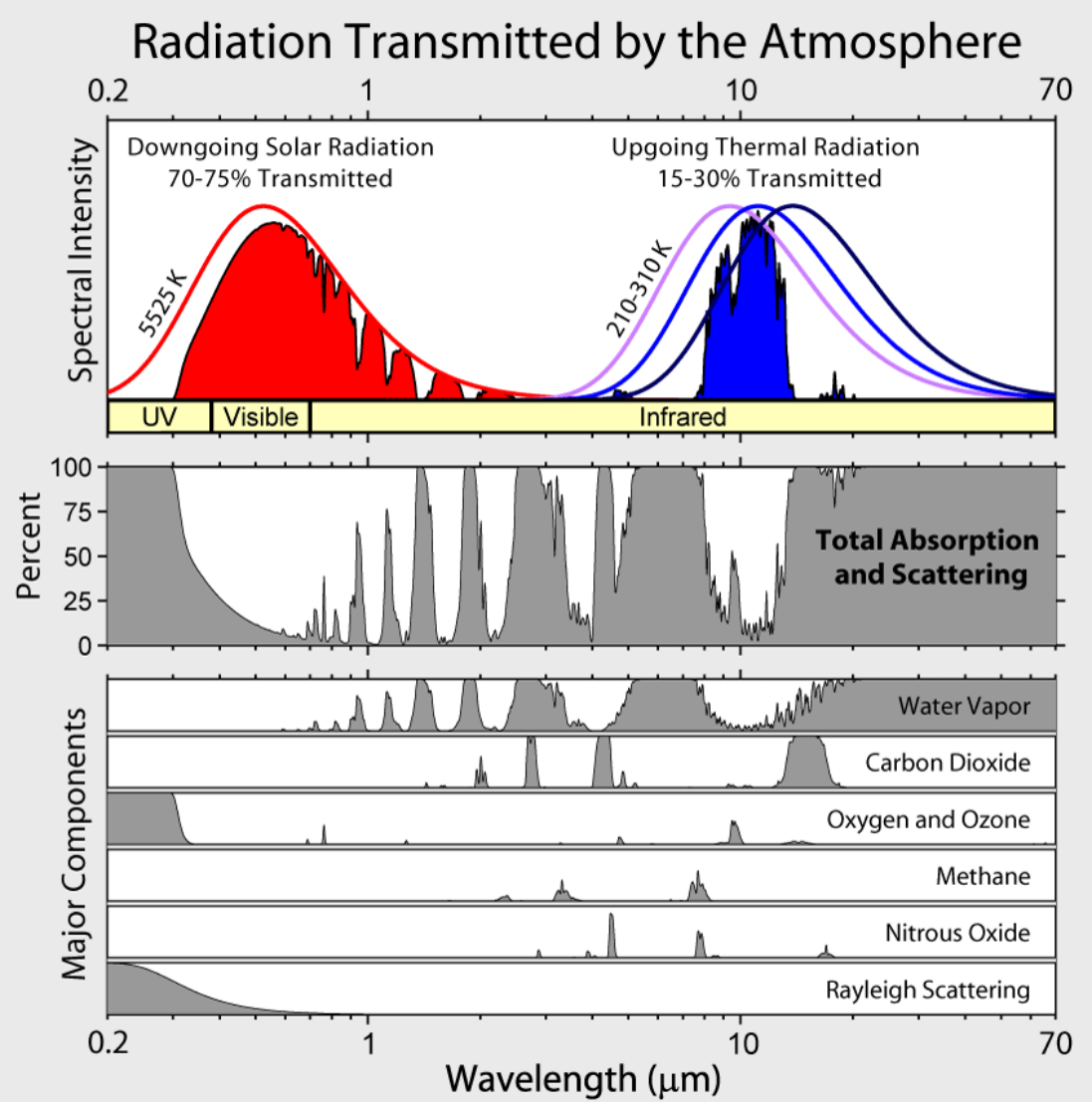
will ii) lead to an increase in water vapour, and a further increase in temperature

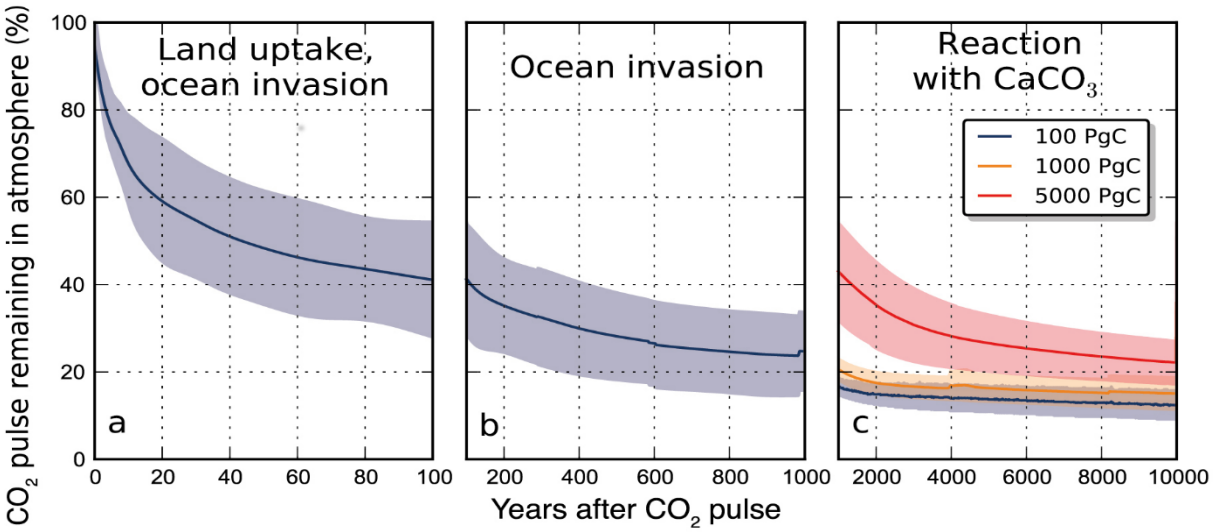
Relatively simple analytic calculations show that that these effects are similar in magnitude

Computer models are needed to work out all details. They confirm the simple calculations, although adding methane* and other feedbacks (from changes in cloud cover, albedo,…) → somewhat larger warming.

My conclusion: given also that the calculations fit the data - worry a lot about global warming

*methane: relatively big effect but only stays in the atmosphere for a decade, while *CO2 accumulates and stays in the atmosphere for a very long time – see next*

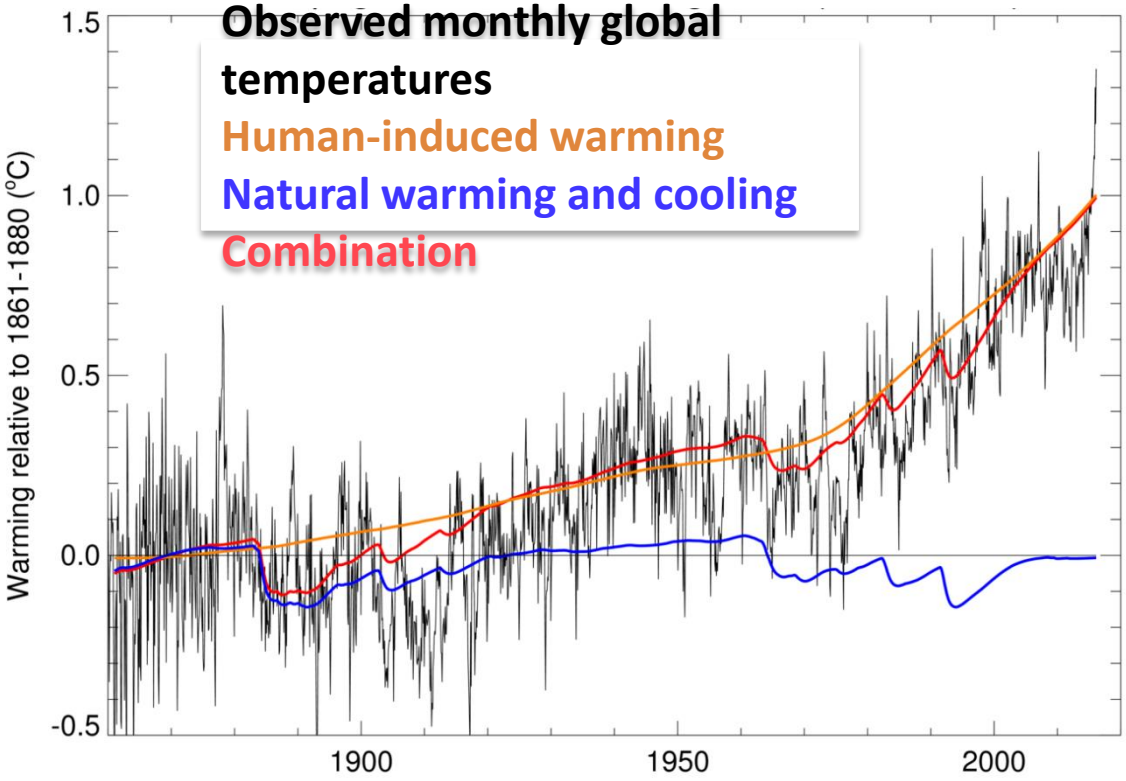




Percentage of CO2 remaining in the atmosphere following a 100 GtC (367 GtCO2) injection as a function of time, for a wide range of models of varying degrees of complexity: grey bands contain 90% of the model results (third figure includes responses to 1000 and 5000 GtC injections)
From IPCC AR5

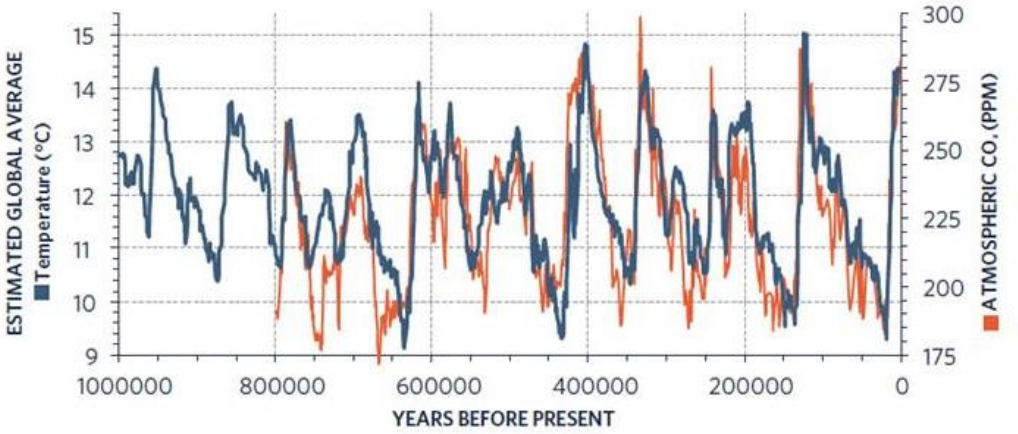
Human-induced warming: now at about 1°C

+0.5°C since the 1980s. Oxford Modelling:



Looking backwards

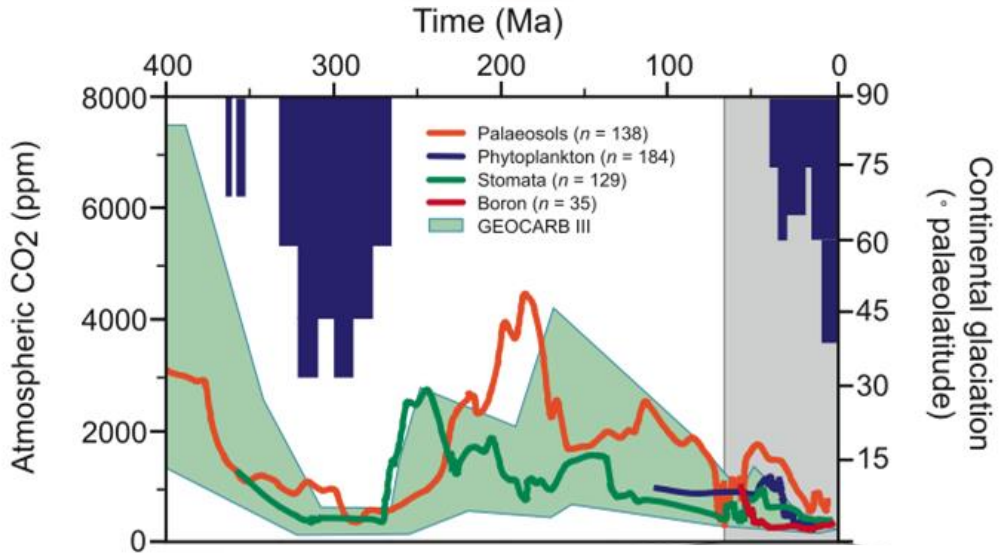
Atmospheric CO2 and temperature are correlated, although correlation does not prove causation:



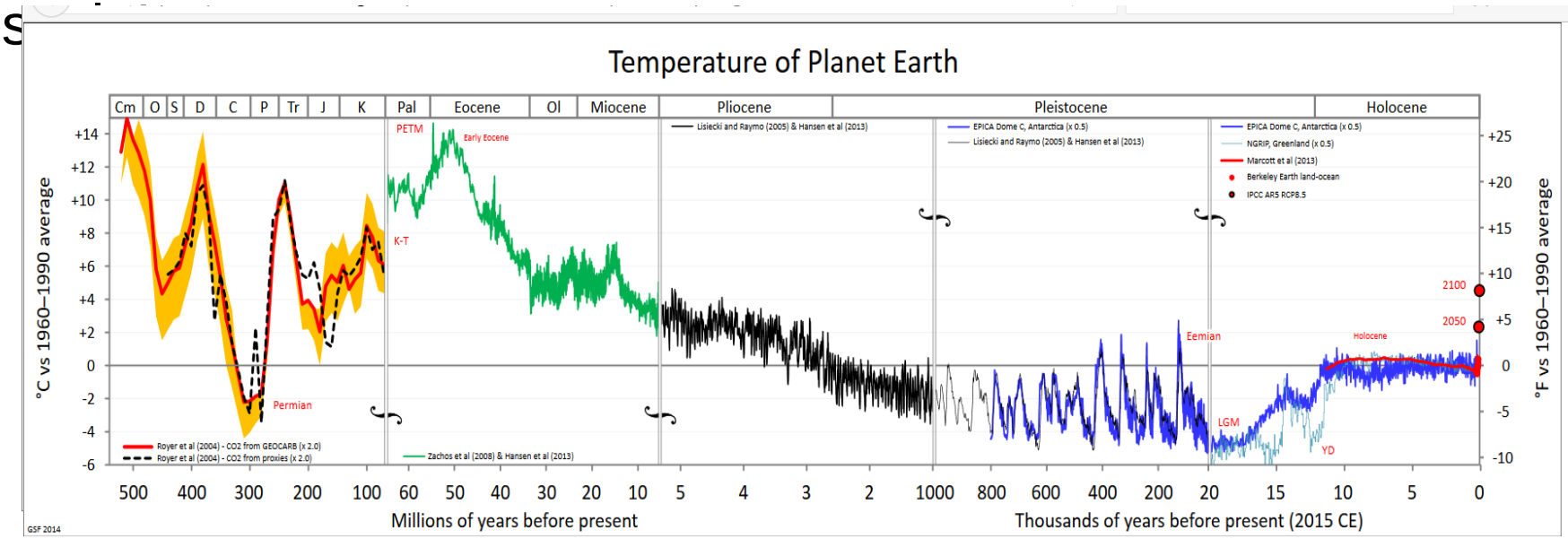
Looking further back

Ice ages have only occurred at times of relatively low CO2:

Vertical blue bars mark the timing and palaeolatitudinal extent of ice sheets. Plotted CO_2 records represent five-point running averages from each of the four major proxies. Also plotted are the plausible ranges of CO_2 from the geochemical carbon cycle model GEOCARB III.

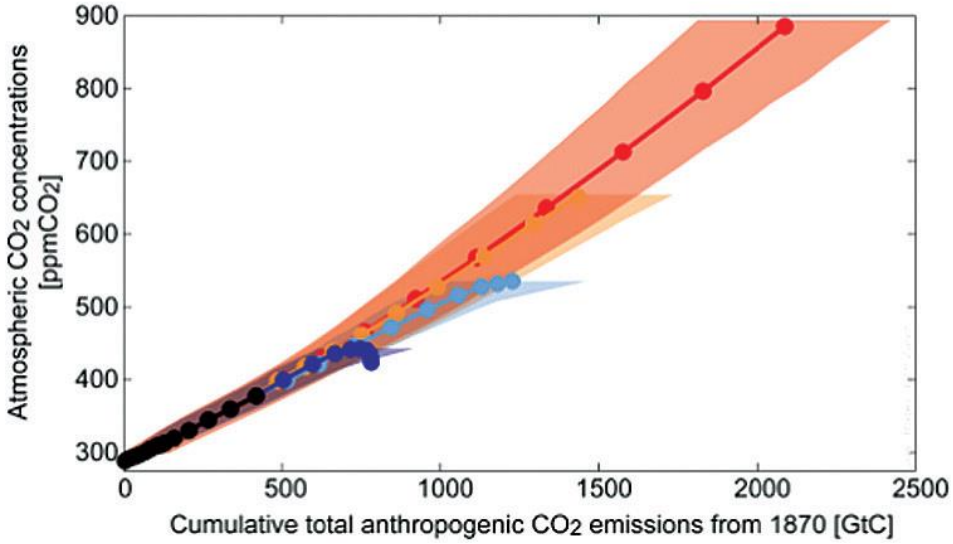


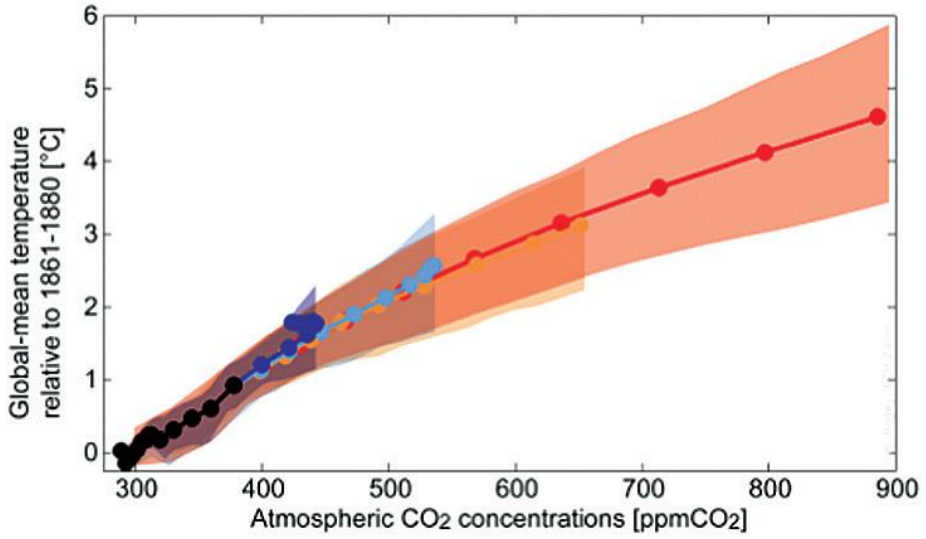
The recent temperature rise shows even on a 500 million year s



From Wiki, which comments *Direct combination of these interpreted geological temperature records is not necessarily valid, nor is their combination with other more recent temperature records, which may use different definitions. Nevertheless, an overall perspective is useful even when imprecise. Temperatures in the left-hand panel are very approximate, and best viewed as a qualitative indication only.* Here the present is taken to be 2015. Note different scales in different segments.

Looking Forward:





Note that:

1) The atmosphere and the temperature do not respond to additions of CO2 instantaneously. The concentration of CO2 as a function of cumulative emissions, and temperature rise as a function of concentration, depend on how you got there – different lines correspond to different pathways

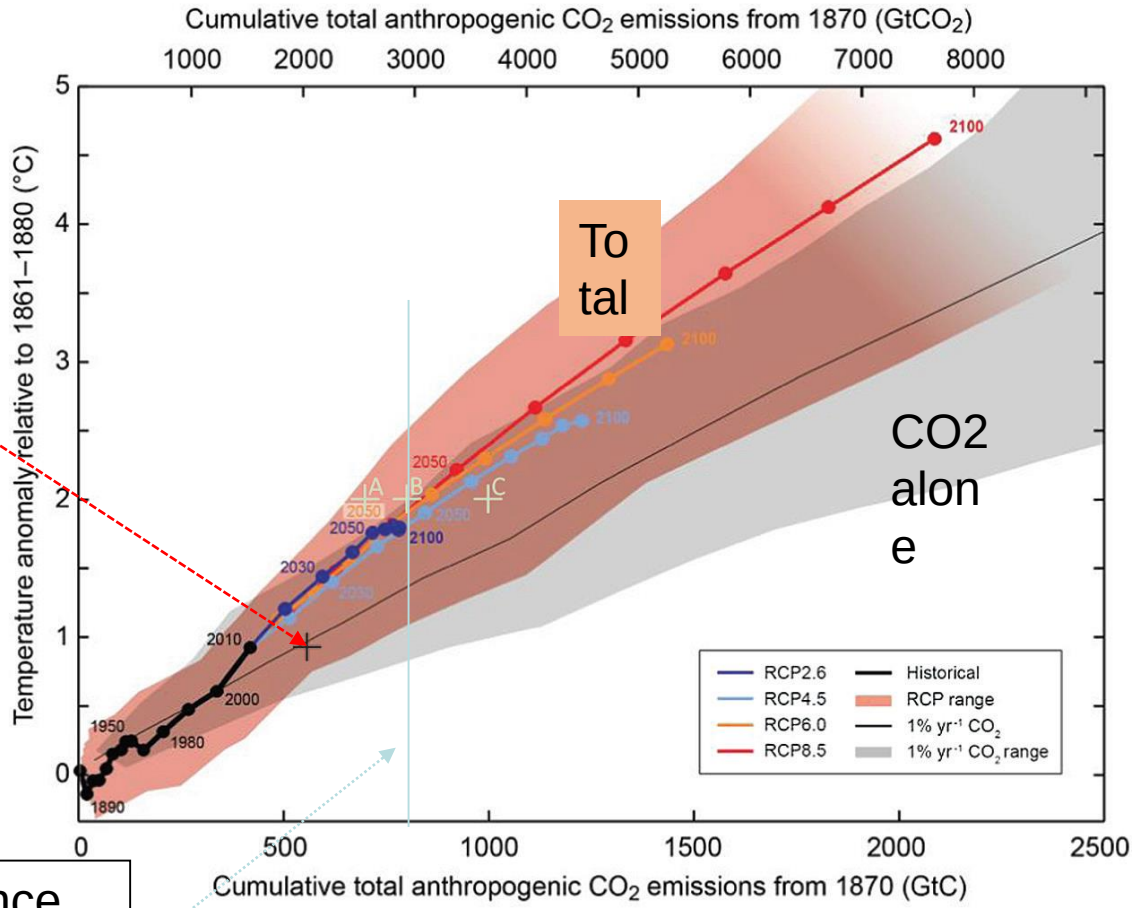
2) There is uncertainty in the climate models – 90% of models studied give results inside the bands below (5% above, 5% below)

Note:

2015 data point within the uncertainty band, but

suggests that there could be some leeway

e.g. could keep below + 1.5 C if emissions decrease linearly to zero in next 40 years



To tal

CO2 alon e

800 GtC – 66% chance of + T < 2 C according to IPCC

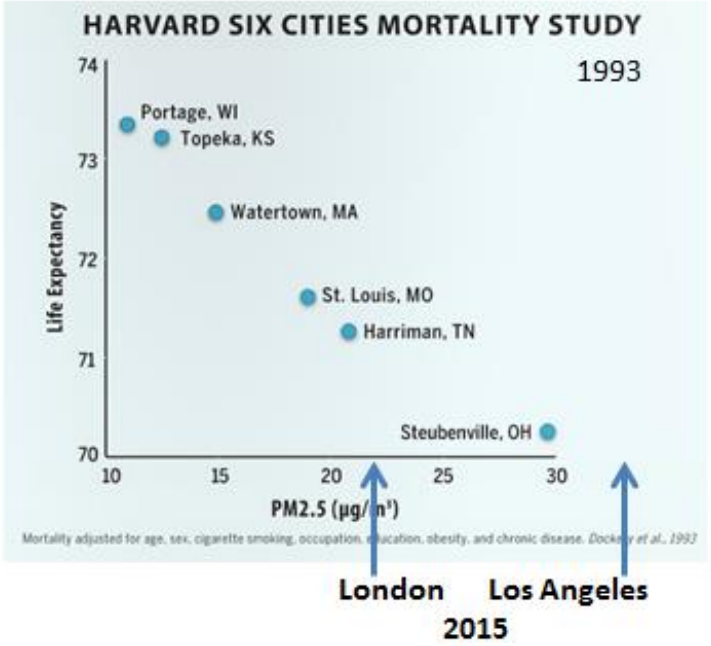
Air Pollution

- **Globally** (WHO 2014) 7 million premature (typically 10 years loss of useful life) deaths p.a. (out of 56 million p.a. total) – 4.3 million for indoor pollution, 3 m outdoor (some double counting)

- **US** (2013 MIT study) 210 k p.a. from burning fossil fuels (out of 2.5 million total) of which 200 k from particulates including : 58 k road transport,

  54 k power generation, 43 k industry – main culprit is coal

Numbers very uncertain but undoubtedly a single large coal power station is far more lethal than Chernobyl



EU [US] limit 25 [12] μgm^{-3}

New Harvard Study of 60 million people aged over 65 in the USA - published on 28 June

- Effects of PM2.5 persist at very low concentrations
- Even below the US limit, a rise of 10 μgm^{-3} increases risk of death by 14%
- 1 μgm^{-3} reduction would save 12,000 [2,400] lives in the US [UK]

Coal is the largest environmental problem

- Comparison of fossil fuels using IEA numbers for world averages (in detail depends on quality of coal…):

	Coal	Oil	Gas
CO2/thermal energy	1	0.7	0.6
Efficiency of power generation*	33%	32%	37%
CO2/electrical energy	1	0.7	0.54
* Japan	42%	44%	47%

- Should move away from coal (CO2, pollution, mining deaths) and improve efficiency of power generation
- Replacing all coal with gas would reduce CO2 emissions from energy by over 20%

We should be Decarbonising, **but there's a long way to go:**

Thermal equivalent primary energy

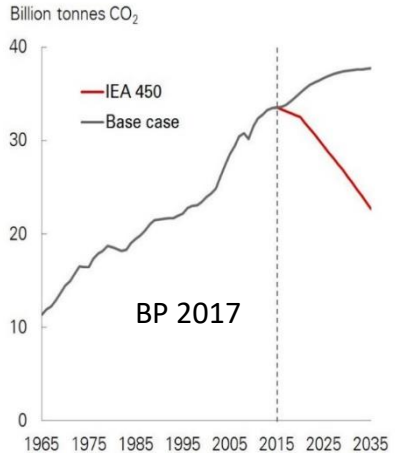
2015: Fossil - 78.4%, Bio + Wast[illegible]%,
Hydro - 6.2%, Nuclear - 4.0%,
Wind - 1.3%, Solar - 0.4%, Geo - 0.1%

Moving target - energy use expected to grow 30% by 2035 (fossils 20%). Non-oecd* + 50% (+ 25% per capita) *where 1.2 bn/2.7 bn lack electricity/clean cooking facilities

~~Climate Change~~

IEA 450 scenario - atmospheric CO2 stays below 450 ppm; thought → 66% chance of keeping the temperature rise below 2 C

CO2 accumulates in the atmosphere – it's the area under the curve that matters



Pfeiffer, Miller, Hepburn & Beinhocker: even if all other sectors comply, can only meet 450 ppm target if no emitting electricity infrastructure is built after 2017, or existing infrastructure is retired early or retrofitted with CCS

Air pollution: numbers very uncertain, but Didcot power station probably killed some 100 times more people tha[illegible]ernobyl
Coming on to the public agenda (VW has drawn attention to the problem)