

Can the UK Achieve Net-zero Greenhouse Gas Emissions by 2050?

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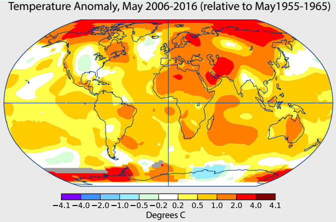
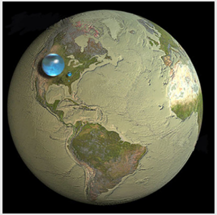
Climate Econometrics, Nuffield College, University of Oxford

Climate Econometrics Seminar, 15 March, 2022





(1) **Climate change and its implications**

(2) **Historical background and summary**

(3) **Non-GHG ‘green’ electricity generation**

(4) **Decarbonize ground transport**

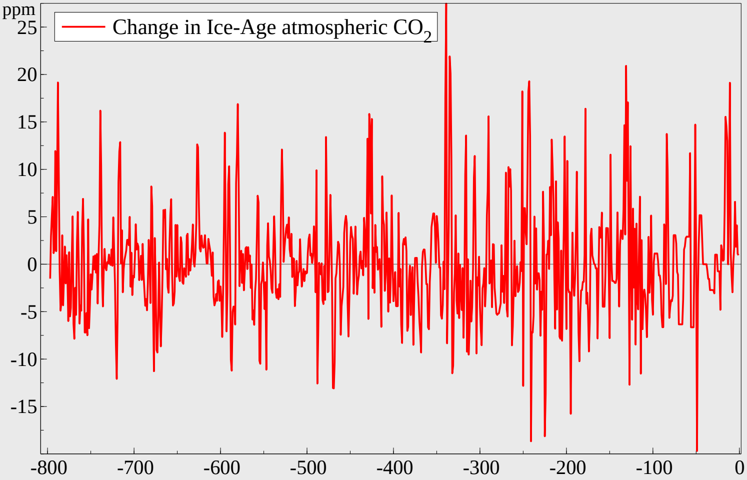
(5) **Decarbonize households and construction**

(6) **Decarbonize industry, chemical manufacturing and waste**

(7) **Reduce GHG emissions from agriculture**

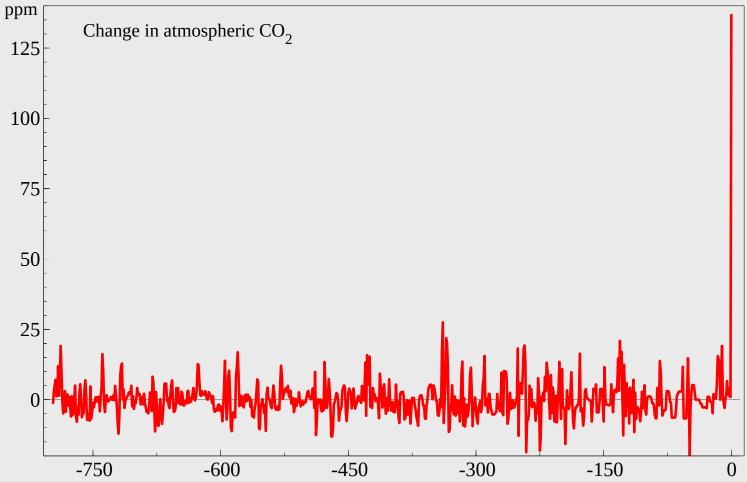
(8) **Conclusions**

Climate change and CO_2 emissions

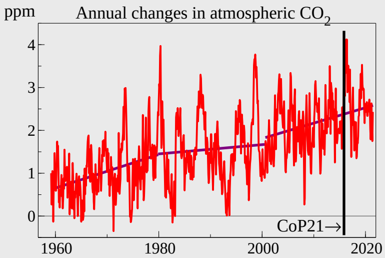


Thousand-year changes of $\pm$ 25 parts per million (ppm) in atmospheric CO_2 over 800,000 years of 8 major Ice Ages coming & going.

Climate change and CO_2 emissions

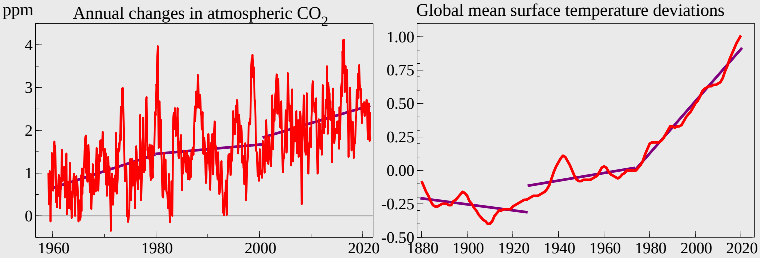


Last 250 years of $+$130ppm CO_2 where 1ppm = 7800 billion kg of CO_2.
Humans are altering the atmosphere–and hence the climate.



Atmospheric CO_2 increases still increasing–despite CoP21

Increases in atmospheric CO_2 accelerating since 2000, increasing planet's temperature and sea level.



https://climate.nasa.gov/vital-signs/global-temperature/

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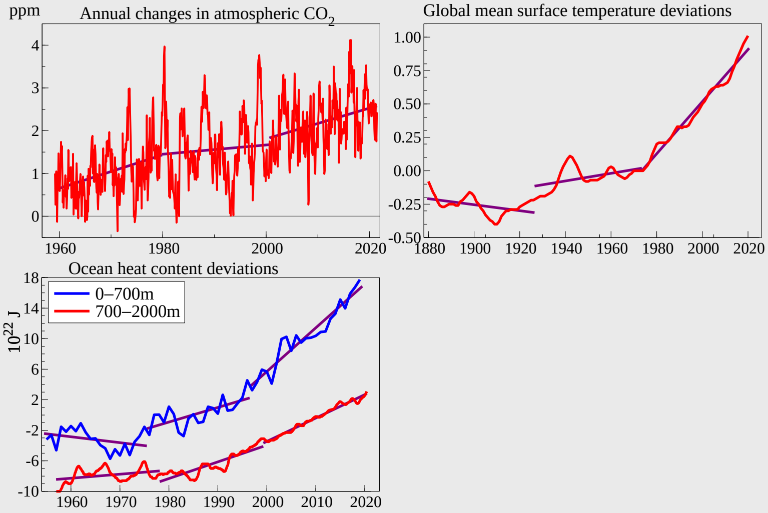

http://159.226.119.60/cheng/images_files/IAP_OHC_estimate_update.txt

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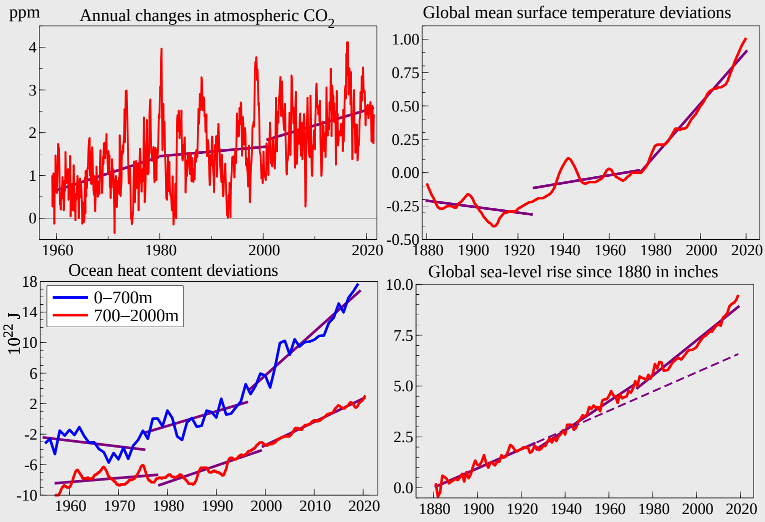
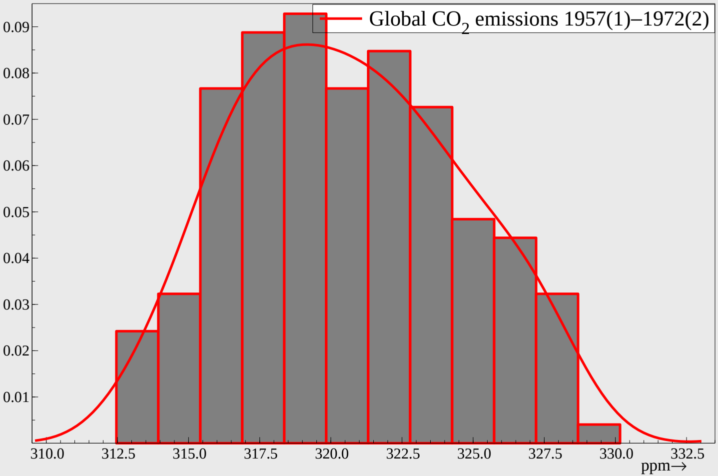


Rise now 0.14in p.a. versus 0.05in p.a. over 1850-1992

https://www.epa.gov/climate-indicators/climate-change-indicators-sea-level

Distributional shifts in monthly global atmospheric CO_2



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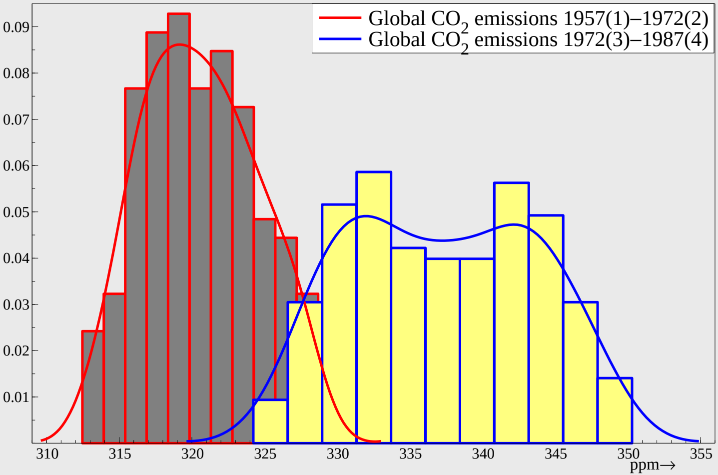

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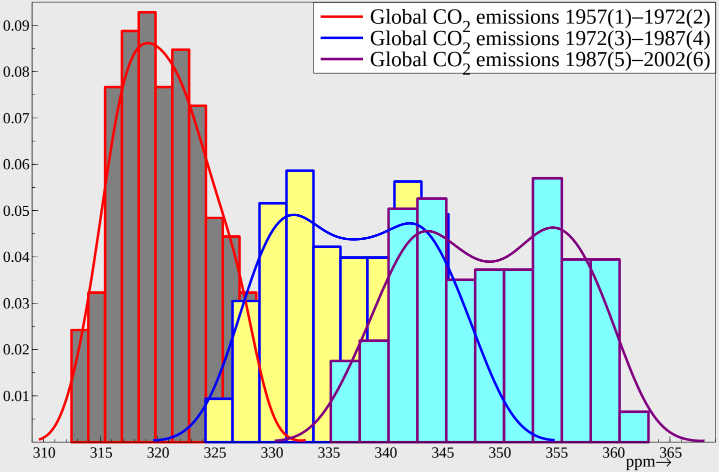

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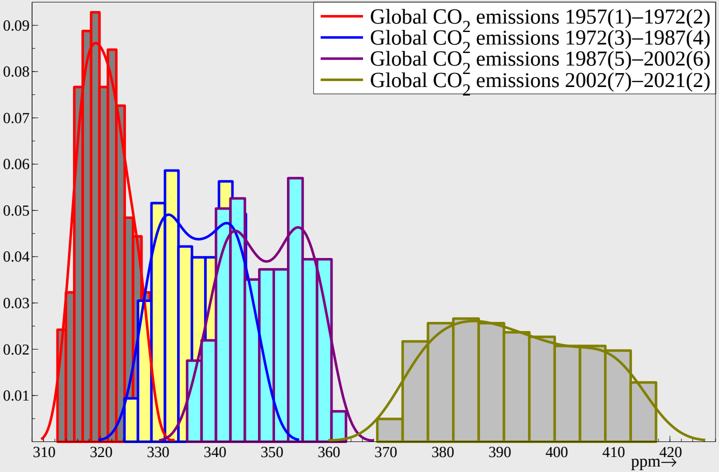

Anthropogenic greenhouse gas emissions from energy generation, artificial fertilizers, deforestation, animal husbandry & waste.

Past mass extinctions of life on Earth due to climate change:

albeit 'natural' not anthropogenic—but now may be us by emitting excessive GHGs

Extreme weather events: more powerful cyclones and tornadoes;
increased land flooding—'rivers in the sky' can hold more water than Mississippi River, causing great damage recently in Europe and China & lead to loss of soil;
but also longer & more intense droughts & dust storms, with loss of crops;
high temperatures dangerous to life from 'heat domes' as in North America last summer, and more generally from high 'wet bulb' heat; overly acidic oceans;

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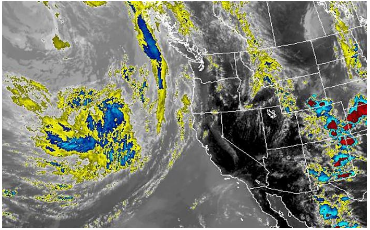
wild fires from Australia, Amazon, & California to Siberia; potential tipping point from tundra melting releasing vast volumes of methane (see Vaks *et al.*, 2019).

Sea level rises cause coastal flooding & worse storm surges reducing usable land.

Food insecurity, political conflicts over resources, increased flows of refugees.

Ideal conditions for creating and spreading infectious diseases (like COVID-19).

Rivers-in-the-sky; dust-storm; wild fires; coastal flooding



https://www.psl.noaa.gov/arportal

https://public.wmo.int/en/our-mandate/focus-areas/environment/SDS

https://earthobservatory.nasa.gov/images/81919/rim-fire-california

https://en.wikipedia.org/wiki/Coastal_flooding

Physical dangers inflict economic losses of varying magnitudes.
Falling property values in worst affected areas could lead to widespread mortgage defaults (which led to the Financial Crisis).

Commercial banks have lent $trillions to key fossil fuel producers and users. Many aspects of financial systems threatened if sudden large reductions mandated in use of fossil fuels by major economies. Capital assets and the millions employed in affected industries could become 'stranded', reducing consumers' expenditure, and investors claims on those assets could inflict large financial losses.

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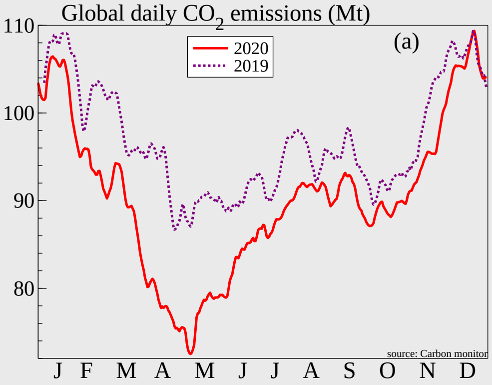
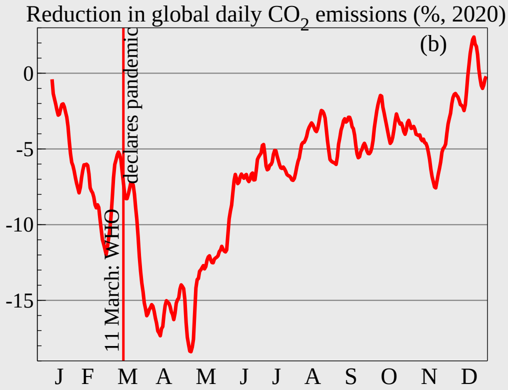
Physical risks and transition risks also face huge uncertainty about policy responses & behavioural adjustments, as well as technological developments, increasing geo-climate volatility (Campos-Martins and Hendry, 2020).

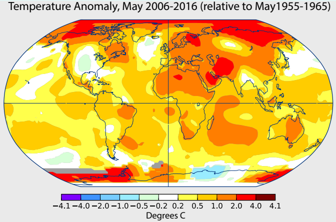
Many central banks and financial regulators are therefore reacting now to monitor and adopt strategies to make financial systems more resilient: Bank of England stress tests of commercial banks include coping with climate change.

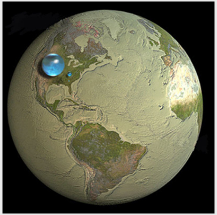
Little impact on global CO_2 emissions from pandemic lockdowns: just reducing GDP growth not a solution





(a) Global daily CO_2 emissions during 2019 & 2020 (Mt);
(b) percentage reductions in daily global CO_2 emissions during 2020:
largest fall in April was 25Mt relative to 24,000Mt emissions p.a.





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Industrial Revolution began in the UK in the mid-18th Century.
Antecedents lay two centuries earlier in scientific, technological and medical knowledge revolutions.

UK was first country to industrialize on a large scale.

Industrial Revolution and its successors have since been adopted worldwide.

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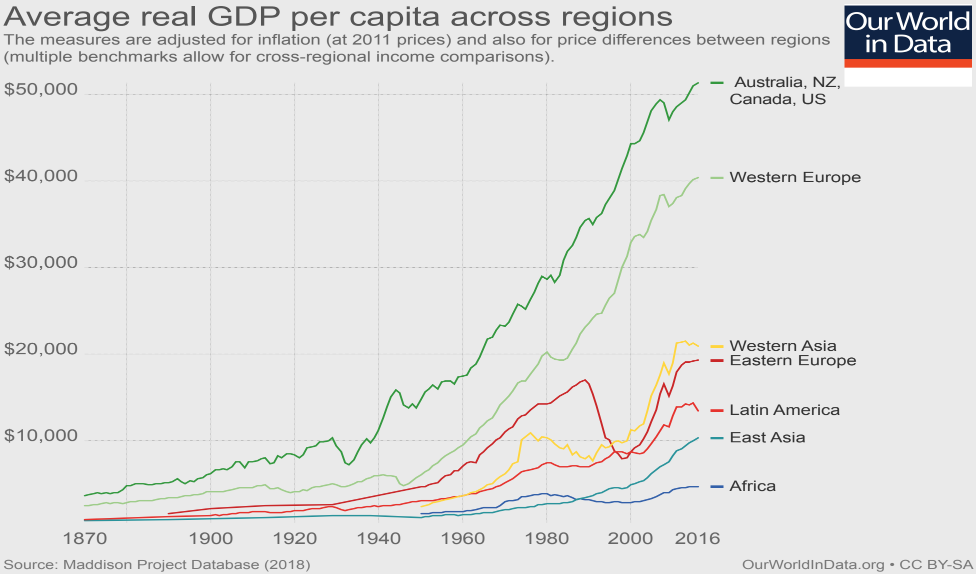
Startling consequences 250 years later:

real income levels are 7–10 fold higher per capita,
many killer diseases have been tamed, & longevity has approximately doubled.

Evidence in https://ourworldindata.org/economic-growth shows even greater improvements in many other countries.

GHG emissions an unintended consequence of economic development.

Industrial Revolution of huge benefit to humanity



So close to all electric societies 120 years ago—and yet so far

1838 first fuel cell invented by Sir William Grove;
1839 first photovoltaic cell created by Edmond Becquerel;
1856 a flask of CO_2 heated greatly in the sun, dry air did not, shown by Eunice Foote;
1859 that finding confirmed in independent experimental evidence by John Tyndall;
1864 Yosemite placed under federal protection by Abraham Lincoln
1868 first UK electricity hydro generated by Sir William Armstrong;
1883 first commercial photovoltaic solar panel by Charles Fritts;
1887 first wind turbine to generate electricity by James Blyth;
1880s electric car with high-capacity rechargeable battery by Thomas Parker;
1896 atmospheric temperature change proportional to $\Delta(\log \mathrm{CO}_2)$: Svante Arrhenius.

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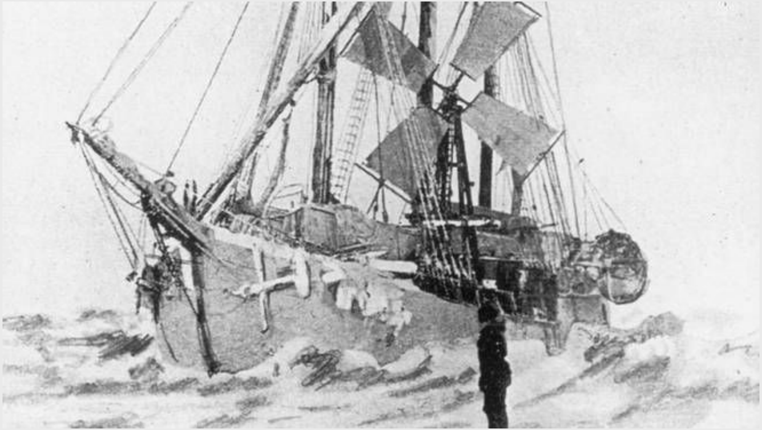
But US buyers and motor manufacturers switched to internal-combustion vehicles which soon outcompeted electric cars in both total cost and distances travelled.

Back to an all-electric future where humanity might have been 120 years ago?

Bersey Electrical Cab, 1897

Source: https://collection.sciencemuseumgroup.org.uk/objects/co24902/bersey-electric-taxi-cab-taxis.

Nansen's ship Fram in Arctic 1893–6 had a windmill to generate electricity for lighting



Source: https://www.treehugger.com/happy-birthday-fridtjof-nansen-pioneer-passive-house-4851082

Five sensitive intervention points (SIPs) linked by non-GHG generated electricity

A SIP is when a system is near a critical (or tipping) point so a small change triggers a much larger change that becomes essentially irreversible (see Farmer *et al.*, 2019).

SIPs can lever policy actions (e.g., legally-binding 2008 UK Climate Change Act, CCA08) and technology developments (e.g., solar PV & wind cheaper sources of energy than fossil fuels).

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Five SIPs to reduce GHG emissions are:

1] Expand green electricity: *Earth* (thermal, bio), *Air* (wind), *Fire* (solar, nuclear) & *Water* (hydro, tides, waves): ≈20 fold increase.
2] Electric-powered vehicles connected to a smart grid (V2G) for short-run backup storage to balance variable renewable supply.
3] Low-cost hydrogen from intermittent 'surplus' renewables;
4] Liquid hydrogen as medium-term storage & high-heat source;
5] Electricity-based agriculture (e.g., grind basalt; underground 'farms'; plasma waves to reduce ammonia pollution).

Recent published proposals for getting to net-zero emissions

Detailed analyses in MacKay (2009);
well-known IPCC reports such as IPCC (2021);
Larson, Greig, and Jenkins (2020) Princeton report for the USA;
UK Climate Change Committee https://www.theccc.org.uk/publication/sixth-carbon-budget/
UK Government's (2021) *Net zero strategy: Build back greener*
IEA (2021) *Net zero by 2050*
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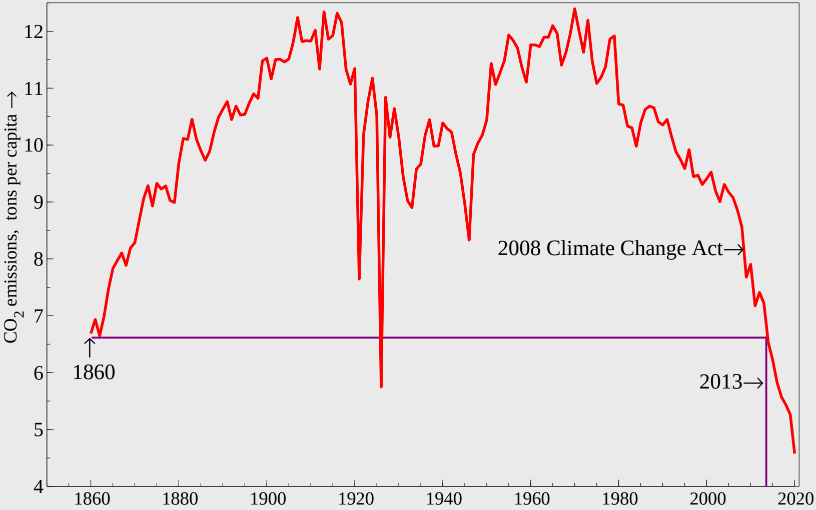
Agreement that technically can decarbonize electricity generation by 2050;
less agreement on doing so reliably at scale, decarbonizing ground transport & V2G, and on roles for bioenergy with carbon capture and storage (BECCS).

Differences in tackling storage for variable renewable electricity;
in decarbonising housing, construction, industry and agriculture.

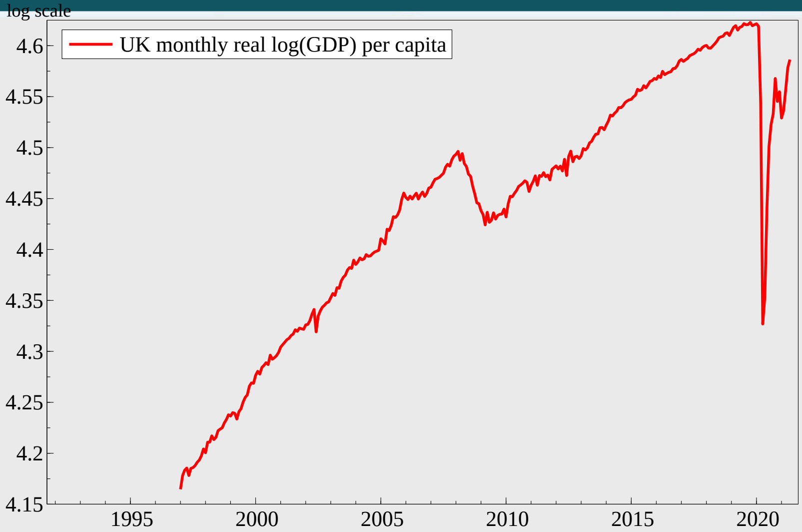
But important gaps in latest UK Government report compared to our *Evidence to Forty-Sixth Report of Session 2019–21, UK House of Commons Public Accounts Committee, https://committees.parliament.uk/writtenevidence/21638/html/*

Where is the UK now in controlling its GHG emissions?
UK territorial per capita CO_2 emissions (tons p.a.) till 2020

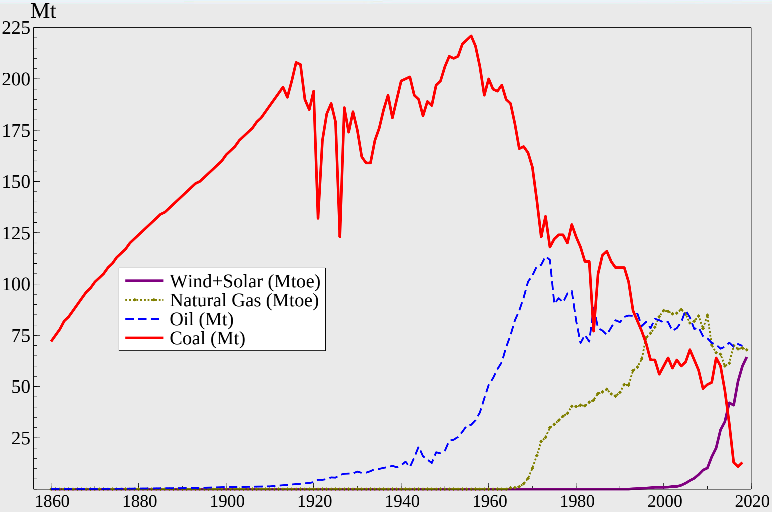


In 2013, fell below 1860 levels when UK was 'workshop of the world'.

Monthly UK real GDP per capita

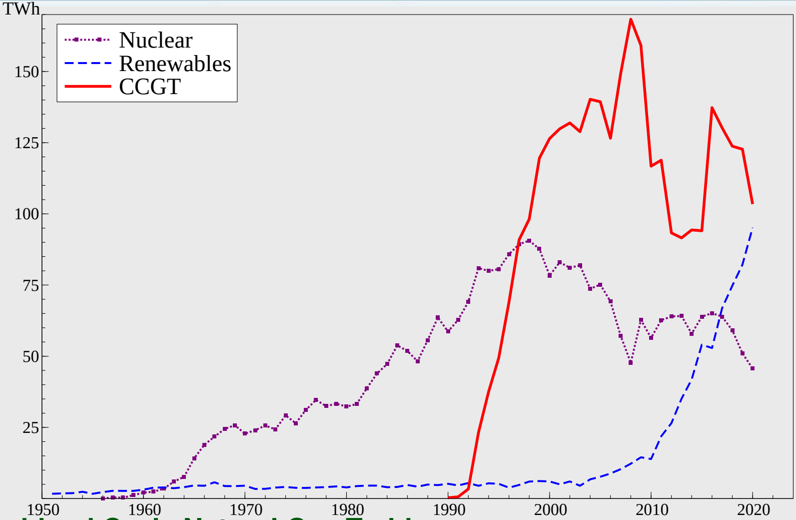


UK real GDP per capita rose by 58% between 1997 and 2019, approximately 2% p.a., despite 'great recession'.



Coal (millions of tonnes, Mt), oil (Mt), natural gas (millions of tonnes of oil equivalent, Mtoe) and wind+solar (Mtoe), all to 2019.

Main non-coal sources of UK domestically generated electricity

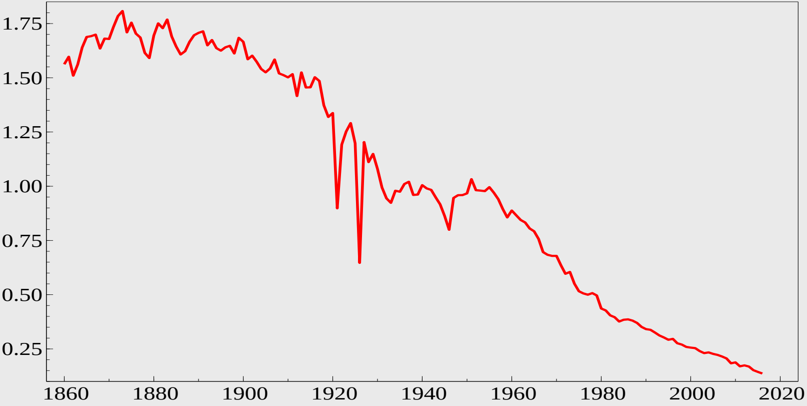


CCGT: Combined Cycle Natural Gas Turbine.

More than 20TWh of electricity imported via interconnectors in 2019

UK CO2 emissions and capital stock

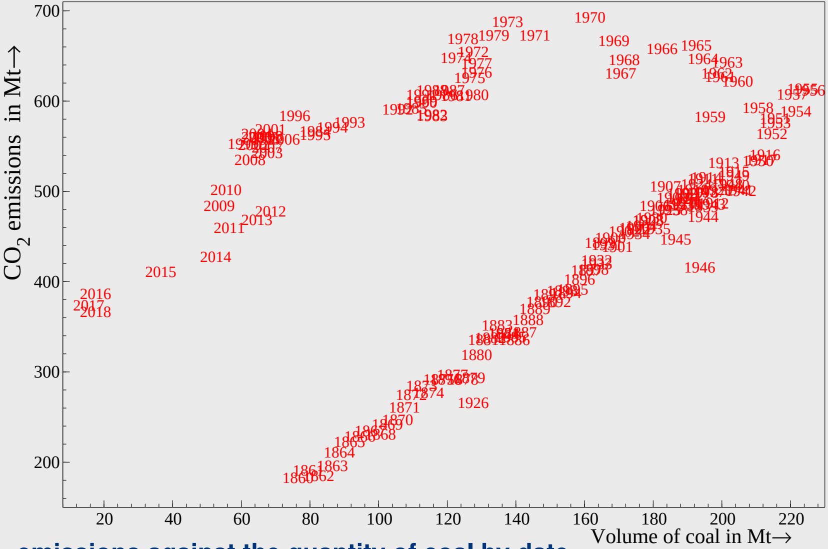
CO_2 emissions strongly affected by existing capital stock: Pfeiffer *et al.* (2016).



Ratio of CO_2 emissions to capital stock, 1860–2015, fell by 92%.

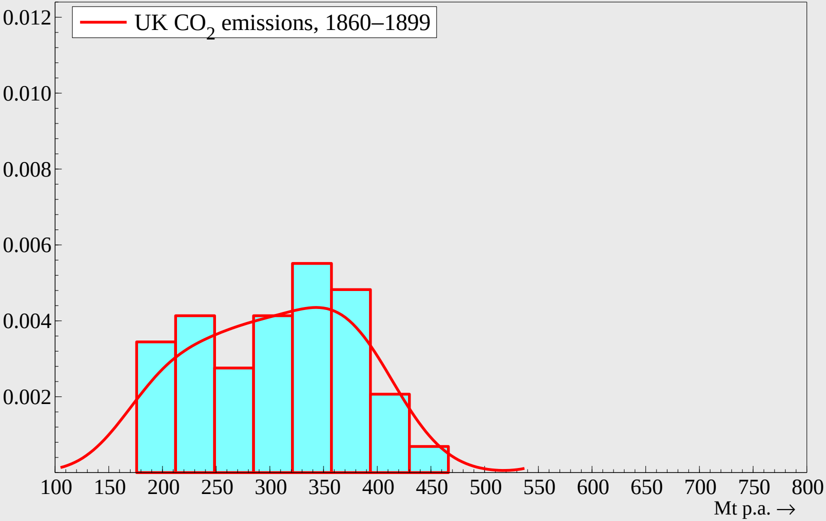
'Stranded assets' problematic if legislation lowers CO_2 targets and financial markets not adjusted.

Massive changes in relationships over time



Plot of CO_2 emissions against the quantity of coal by date.

Distributional shifts of total UK CO2 emissions in Mt p.a.



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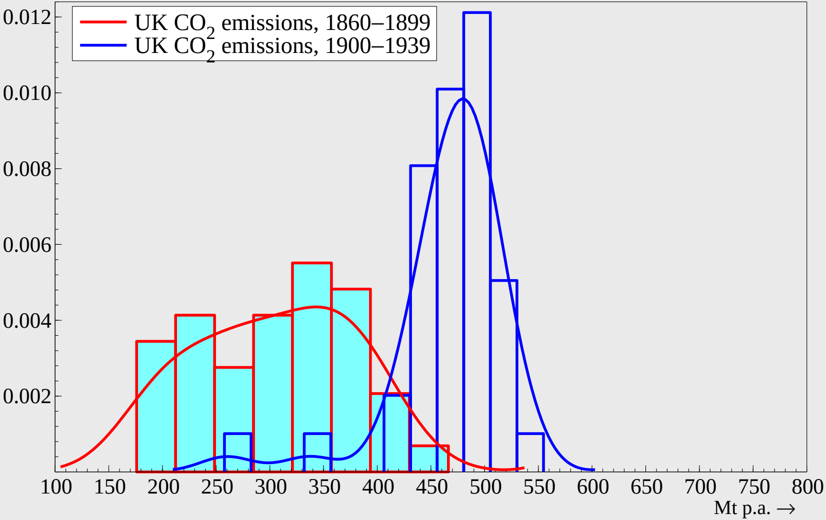

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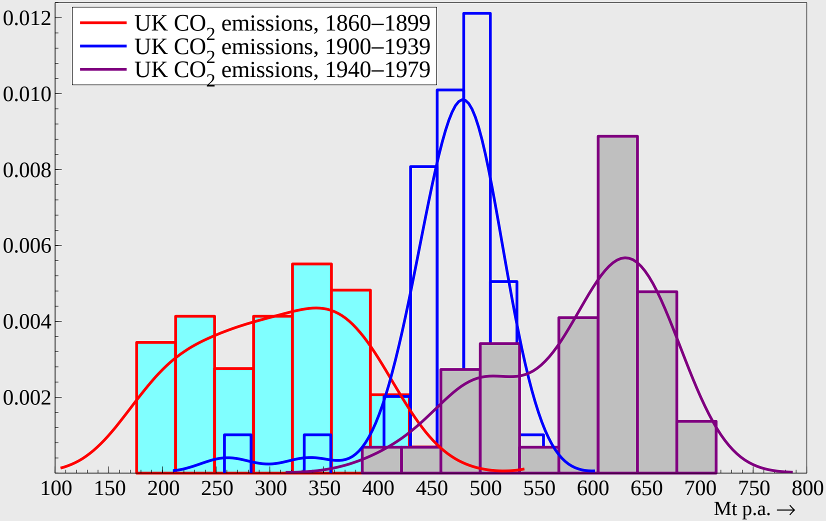

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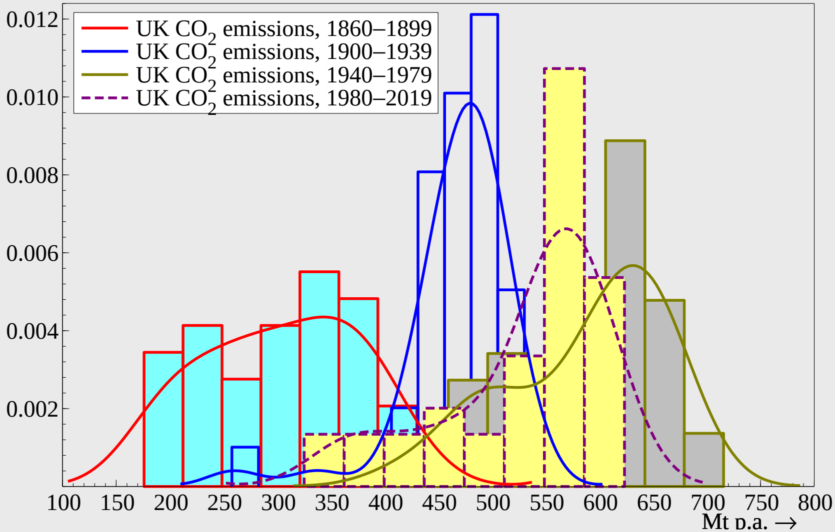
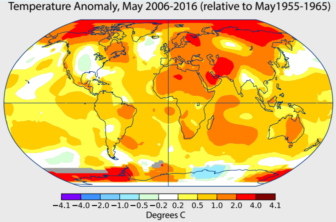
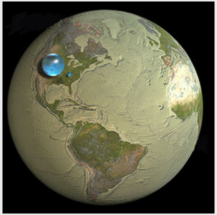


Route Map





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Non-GHG ‘green’ electricity generation

Could eliminate coal, oil & natural gas from electricity generation: needs **massive increase, linked grids & storage** to balance supply facing greater variability in renewables (V2G), & for still, cloudy periods (hydro pump & store, batteries, supercapacitors, liquid hydrogen, flywheels, etc.).

As oil produces 30% more CO_2 per kwh than methane, expand non-GHG electricity for electric vehicles before replacing natural gas in electricity generation.

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Back up renewable electricity generation by safe small modular nuclear reactors (SMRs) based on well-developed nuclear engines in submarines, as well as large 'conventional' nuclear reactors.

Castle and Hendry (2020) econometric model shows **UK climate policy has been effective**: big reductions in territorial CO_2 emissions at little aggregate cost as renewable-electricity now fully competitive.

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Technical issues to research: storage systems; economies of scale making SMRs, & their use of transuranic waste & thorium; potential from fusion.

Non-GHG energy

Wind turbines & solar photovoltaics fallen in cost and increased in efficiency so rapidly over last two decades that, for the UK, they offer lowest cost alternatives if carbon capture and storage (CCS) is enforced.

Easier to install & dismantle offshore wind turbines given 100 meter-long blades.

Hywind Scotland trial of floating wind turbines has demonstrated their viability.

However, evidence that wind speeds falling due to reduced temperature differentials between tropics and poles.

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Energy generated using waves near Orkney and tides off Shetland: tidal movements of twice daily ebb and flow predictable, so is energy from underwater turbines.

Nuclear power is successful safe low-cost electricity producer in France, about 70%.

Nuclear accidents have cast a pall over that technology, but has one of lowest death rates of energy sources. As most nuclear power plants are coastal and off-shore wind turbines little affected by ‘tsunamis’ & resilient to eathquakes, could maintain power for cooling & help avoid accidents like Fukushima Daiichi.

Will just ‘green’ electricity be possible?

UK total energy use in 2018 was ≈2250 terawatt hours (TWh): 70Mtoe petroleum, 70Mtoe natural gas & 60Mtoe non-GHG. Electricity production was 350TWh, 120TWh from renewables, so a 20-fold expansion in renewables just to replace GHG emitters.

Need staged approach integrated across all sectors: will take several decades given scale of transition, requiring major infrastructure expansions to install and ensure continuous electricity provision (compound annual growth rate $>$10%), extensive skills training for building, servicing and maintaining a green economy, and some substantial technological advances, albeit not science-fiction: 3 decades looks fast.

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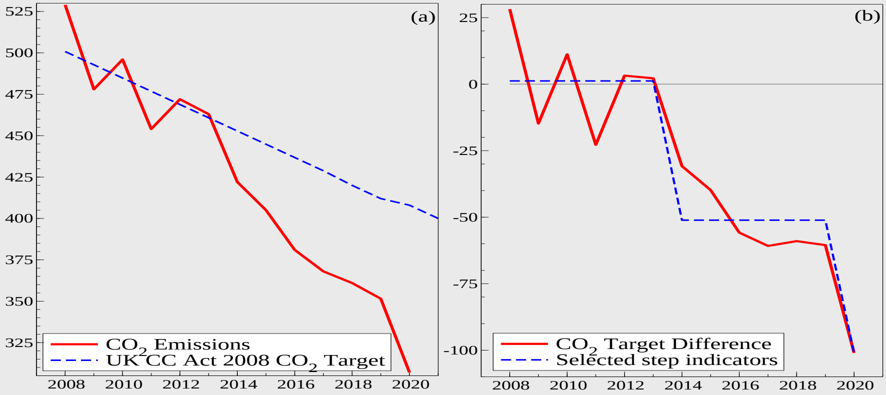
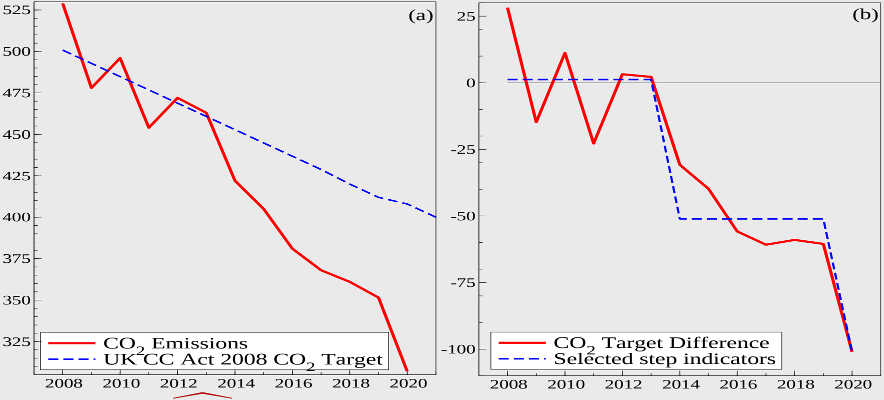
Time horizon of 2050 may be too late to keep global temperatures below 2°C, but lowers costs of switching to non-GHG alternatives: most vehicles, domestic appliances and industrial equipment need replacing anyway over 30 years, so net costs may be negative if rapid technical progress & volume cost reductions.

But if large increases in extreme weather events, public may demand far faster adjustment leading to disorderly energy markets and potential financial instability.

Testing the UK's achievement of its 2008 Climate Change Act targets



Testing the UK's achievement of its 2008 Climate Change Act targets

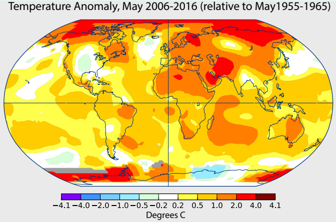


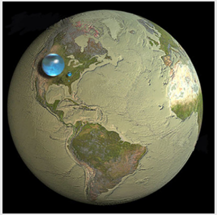
$$\widehat{\mathsf{TargDiff}}_t = \underset{(9.1)}{52.3}\, S_{2013} + \underset{(17)}{49.9}\, S_{2019} - \underset{(16)}{101} \qquad (1)$$

$$\widehat{\sigma} = 15.7 \quad R^2 = 0.85 \quad F_{ar}(1,9) = 0.38 \quad \chi^2_{nd}(2) = 0.48$$

$$F_{arch}(1,11) = 0.02 \quad F_{Reset}(2,8) = 0.00 \quad T = 2008 - 2020$$

Emissions ≈ 52Mt below target after 2013 & 50Mt more after 2019, partly from lockdowns.





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Decarbonize ground transport cutting both CO_2 and nitrous oxide

Harder, but possible by steady natural replacement of internal-combustion cars (UK average life $<$9 years) with electric: UK sales of new gasoline and diesel cars will end by law in 2030; fuel cells & hydrogen drive-trains for large trucks & UK railways.

To sustain 100% electric, research modular graphene-based carbon nanotube units (CNTs) as electrode supercapacitors for storing electricity & in vehicles for recharging batteries. Solid-state and blade batteries rapidly improving.

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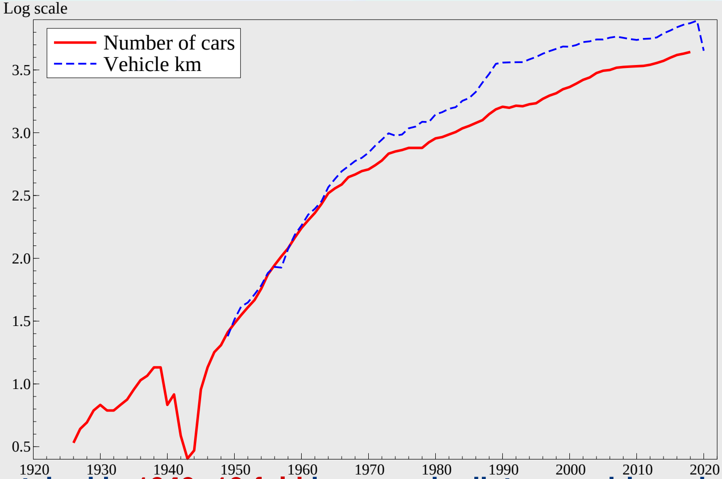
Vehicle-to-grid (V2G) could provide low-cost-investment short-term electric storage system. Vehicles plugged into intelligent grid when parked paid peak prices if discharged.

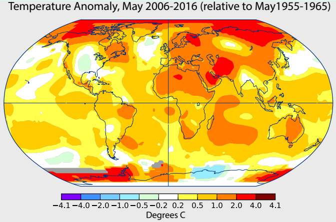
If viable, CNTs offer sufficiently light electric power to advance developments in electric aircraft.

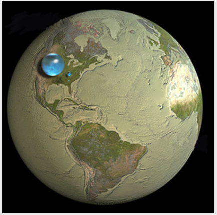
Technical issues to research: supercapacitors and batteries; intelligent standardised infrastructure for charging-discharging points and two-way payments.

Number of cars (millions) & kilometers driven p.a. (billions) in UK



Log scales, matched in 1949. 10-fold increase in distances driven despite more than doubling in real petrol prices: not very effective carbon tax–but has tilted balance to EVs being lifetime cheaper





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Decarbonize households and construction

Retrofit old buildings by improved insulation

Then heat pumps are effective. Triple glazing from ‘surplus’ electricity. Replace some household natural gas by hydrogen once all electricity non-GHG. Produce by methane pyrolosis + electrolysis when ‘surplus’ electricity: also store as liquid hydrogen. Pyrolosis by-product of black carbon for graphene.

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New buildings need zero GHG materials like glulam

Laminated wood to replace some steel. Concrete 30% stronger if add graphene, & magnesium oxide for carbon-eating cement. Install heat pumps, solar photovoltaics & evacuated-tube solar collectors on roofs or switch to hydrogen boilers.

Needs major improvements in infrastructure to pipe hydrogen, preceded by better CCS in its manufacture, and better designed, greener, cities.

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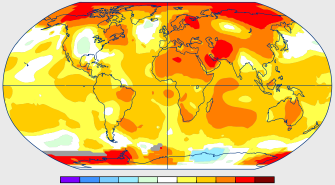
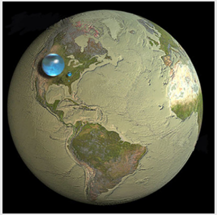
Technical issues to research: perovskite-based solar windows to generate electricity; lower GHG refrigerants & non-GHG building materials.

UK has just over 3 million hectares of woodland at roughly 1000 trees per ha. Aim is for 30,000 ha p.a. additional planting. But vast majority of UK timber imported.

Route Map

Temperature Anomaly, May 2006-2016 (relative to May1955-1965)





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Liquid hydrogen as high heat source for industry

Also electric arc methods. Both require non-GHG electricity generation: self-defeating to use natural gas based electricity to make hydrogen.

CCS and CO_2 extraction will remain essential as chemical manufacturing uses some coal, oil and natural gas.

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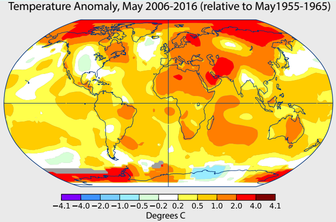
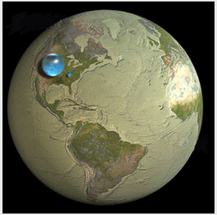
New four Rs are repair, reuse, recycle, reduce: 5 pence charge per plastic bag in 2015 led to 13 billion fewer bags (an 80% fall) after 2 years.
Try similar charges for other non-recyclable items like disposable coffee cups.

Technical issues to research: Efficient liquid hydrogen production; reformable plastics; CCS methods; CO_2 absorbers; CO_2 extraction with efficient separation & collection of useful gasses, & convert CO_2 to a useful fuel https://doi.org/10.1016/j.xcrp.2020.100210

Fund research by prizes–successful historical route: Hendry (2011).

Route Map





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(8) Conclusions

Essential to reduce GHG emissions from agriculture: get down to *Earth* for a lower 'foodprint' with less food waste!

Reduce CO_2 emissions: stop deforestation, peat use; restore wetlands & mangroves

Plant appropriate trees and vegetation to re-absorb CO_2.

Reduce nitrous oxide emissions by less artificial fertiliser: basalt + biochar

Land round volcanoes very fertile so use basalt dust ($+$ absorbs CO_2); cut cropland & environmental damage by more efficient crop production, zero-tillage, biochar, bury slurry; vertical & underground farms cost effective with LED lighting.

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Improve aquaculture production by marine protection areas

Seaweed farming (kelp, seagrass, asparagopsis) also cuts NoX pollution; off-shore wind farms can act as marine reserves and mix ocean layers.

Technical issues to research: breed low methane ruminants; biochar production; seaweed farming; high protein meat substitutes & changes to human diets.

Reduce methane from ruminants by dietary changes, selective breeding

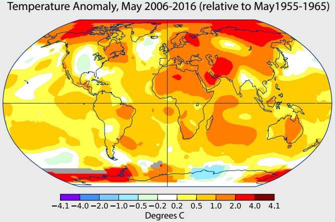
Fumaric acid; *asparagopsis taxiformis*, seaweed as on North Ronaldsay

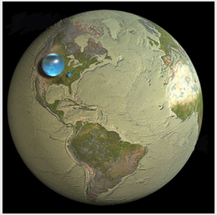
Sheep on the island of North Ronaldsay in the Orkneys

Reduce methane from ruminants by dietary changes, selective breeding

Fumaric acid; *asparagopsis taxiformis*, seaweed as on North Ronaldsay

Ancient breed of local sheep forced to live off seaweed on the beach by a dry stone dyke round the island: controls methanogenic bacterial activity, so they belch far less methane than grass-fed ones. High grass diet dangerous from copper intake.





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Five key sensitive intervention points (SIPs) given green electricity

1] First vastly expand non-GHG electricity so no coal $\rightarrow$ much less CO_2

2] Decarbonize ground transport so no oil, plus electricity storage in V2G

3] Decarbonize households & construction so no natural gas

4] Decarbonize industry so less of all fossil fuels

5] Reduce agriculture GHG 'foodprint' so less CO_2, nitrous oxide & methane

UK's total CO_2 higher as some embodied in net imports. To reduce, impose import tariffs on countries not reducing their GHG emissions (Nordhaus, 2020) or deforesting, threatening species extinctions (https://www.nicfi.no/).

Cap and trade like the EU Emissions Trading System could help facilitate GHG reductions where coal still widely used.

Also increase taxes on oil and gas as prices fall to maintain shift to all electric.

Conclusions on reducing CO_2 emissions

Having been first into the Industrial Revolution that has transformed the world's wealth at the cost of climate change, the United Kingdom is one of the first out in terms of its CO_2 emissions.

Per capita UK CO_2 emissions now below their level in 1860—when the UK was the 'workshop of the world'—yet per capita real incomes are more than 7-fold higher.

UK climate policy has been effective so far:
large reductions in CO_2 emissions have had only a small aggregate cost,
but local losses were not addressed and must be in future for a 'just transition'.
'Stranded people' must not be abandoned.

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The UK's reductions of 240 Mt since 1990 (40%) are the more impressive against global increases of about 23,000Mt annually. But much more difficult to get near net-zero GHG emissions–which is necessary, not sufficient.

At a global level, total accumulation of atmospheric GHGs determines temperature increases and climate change, so the trajectory of getting to net-zero matters greatly–the faster emissions are reduced the less damaging.

Policy implications: creating virtuous circles using SIPs

Integrated GHG reduction strategy and its timing essential for net-zero target.

Replacing oil by non-GHG electricity entails huge expansion:
hence vast storage requirement to balance instant and long-term supply and demand (so V2G & liquid hydrogen from 'surplus' electricity).

Further large non-GHG increase needed to remove natural gas from electricity generation, then make hydrogen when 'surplus', and replace household use.

Liquid hydrogen then also available for industrial use.
Green electricity facilitates basalt grinding, plasma waves, etc. in agriculture, as well as vertical and underground farms.

'Stranded assets' problematic if greatly lower CO_2 emissions targets suddenly required & financial markets not adjusted.
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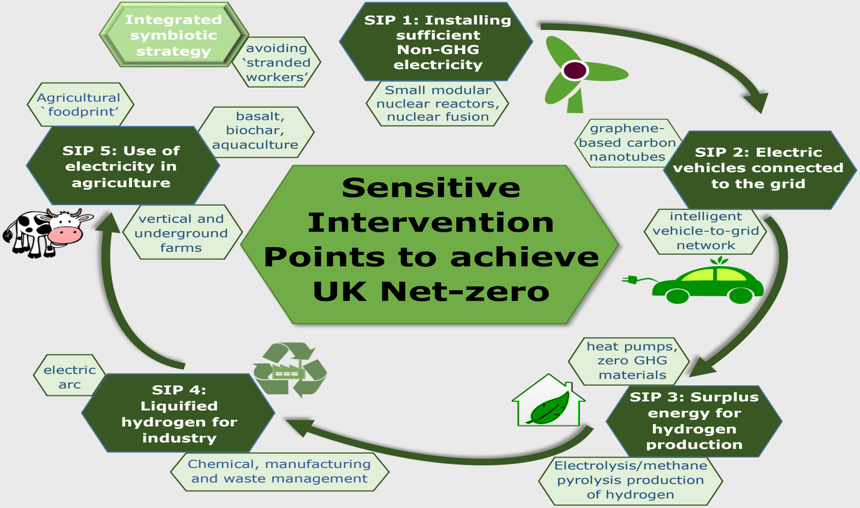
Achieving net zero can be done at relatively low cost, but unclear the UK will do it.

SIPs linked by non-GHG electricity



Thank you! https://www.climateeconometrics.org/

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Expected levelised costs for power generation technologies in £/MWh

Technology | year	2015	2025	2040	2050
Solar Large-scale PV (Photovoltaic)	80	**44**	**33**	**41**
Onshore Wind	**62**	46	44	-
Offshore Wind	102	57	40	51
Biomass	87	87	98	125
Nuclear PWR (Pressurized Water Reactor)	93	93	93	98
Natural Gas Combined Cycle Gas Turbine	66	85	125	-
CCGT with CCS	110	85	82	79

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Lowest cost for each year in **bold**. MWh = megawatt hour Source 2015–2040: Table 4.18 central case, *Electricity Generation Costs* 2020, UK Department for Business, Energy and Industrial Strategy (BEIS). BEIS rankings assume increasing carbon taxes and falling CCS costs over time. Source 2050: Table 7.2 in on Climate Change (2019). Levelised (life-cycle) cost is the discounted lifetime cost of building and operating in £/MWh: the different expected costs are determined by various differences in assumptions. The price of £92.50/MWh from 2023 for nuclear power was guaranteed for the output from Hinkley Point C.

Simulating CCA08's aim of 80% reduction by 2050 from 1990 base of 590Mt

CO_2 emissions must drop by 120 Mt pa.

Simulated a scenario with no coal and 70% fall in oil use to around 20 Mt p.a.

Must reduce natural gas to 35 Mtoe p.a. (75% reduction) & at least halve CO_2 emissions from agriculture, construction and waste (currently c 100 Mt p.a.).

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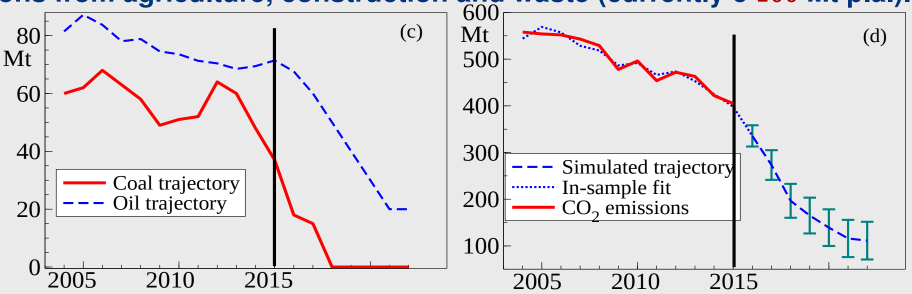

(c) Scenario reductions required in coal and oil use; (d) resulting reductions in CO_2 emissions from the model, compressed to 5-year intervals after 2015.

Need to add other GHG & CO_2 embedded in net imports for full appraisal.

Relative emissions of fuel sources

Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (sub-bituminous)	214.3
Diesel fuel & heating oil	161.3
Gasoline	157.2
Propane	139.0
Natural gas	117.0

Pounds of CO_2 emitted per 293 kWh of energy produced.
Source: US Department of Energy https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.