

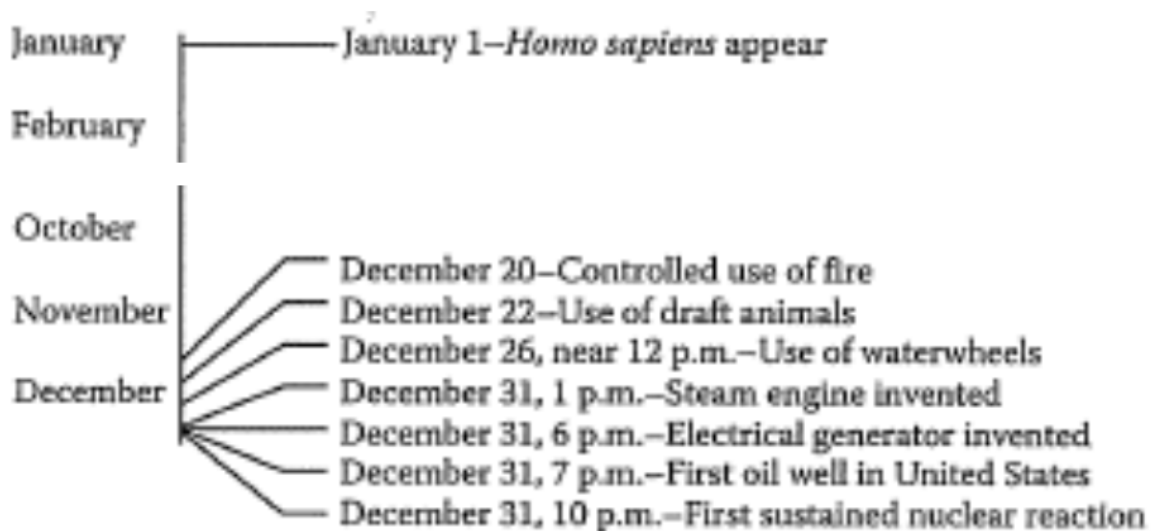
Climate Change Facts

Consists of ME 531 slides and 2018 IPCC Report

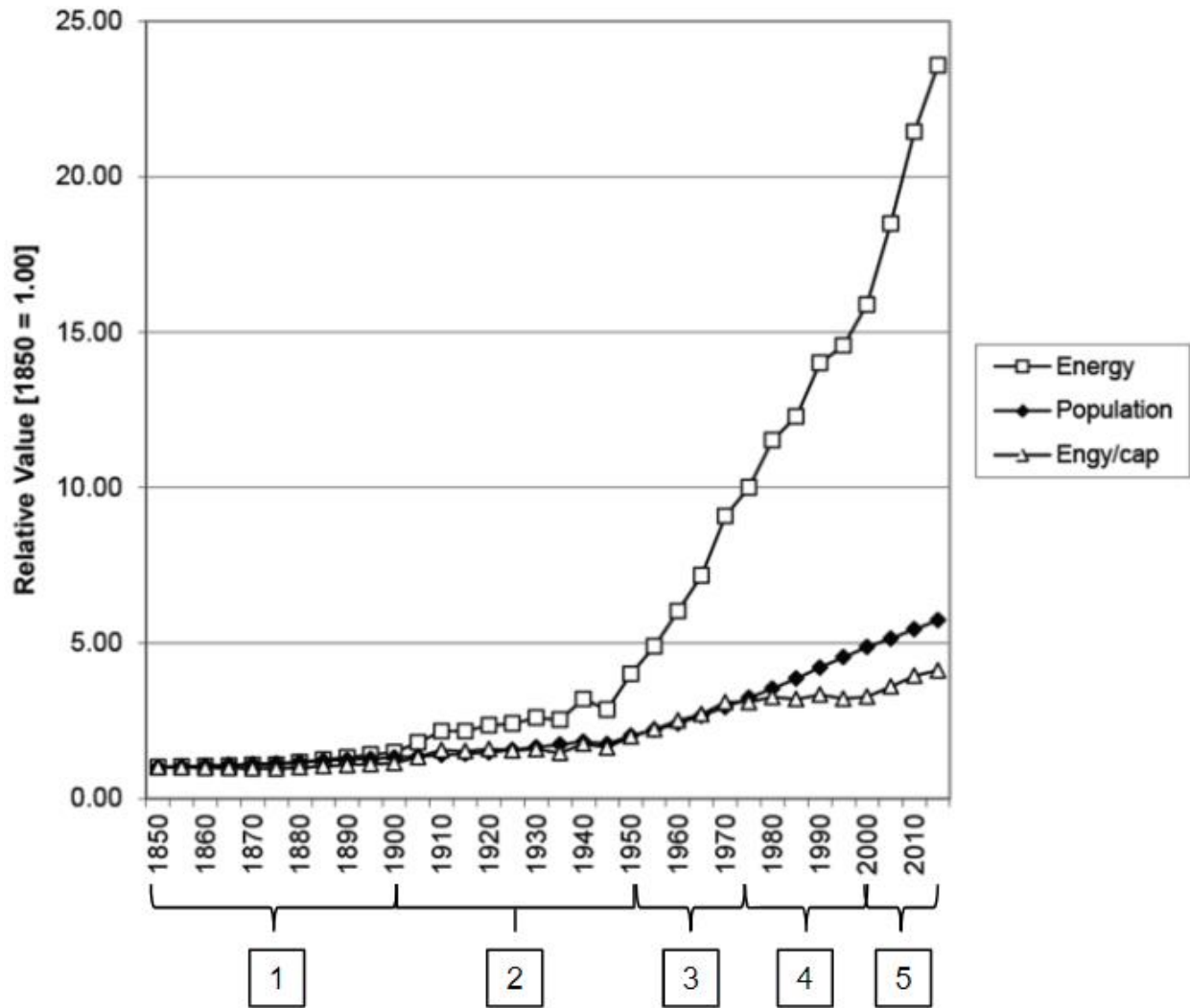
1. Background: Energy Growth

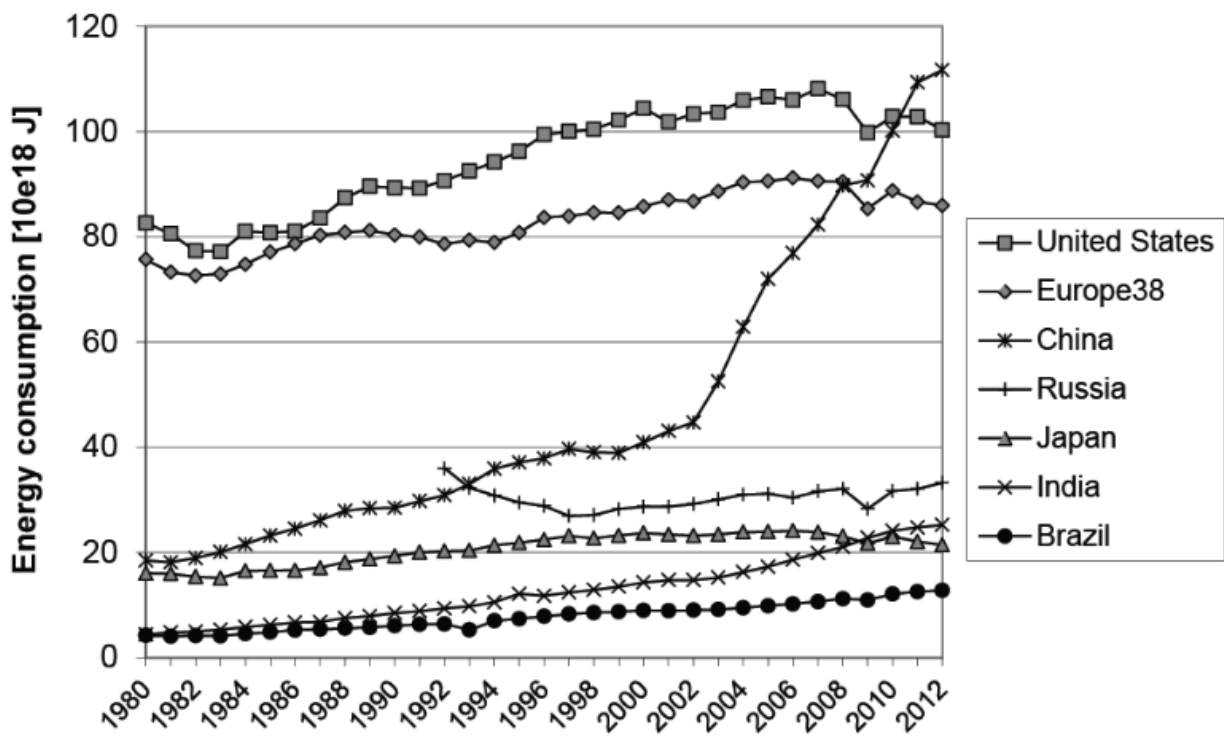
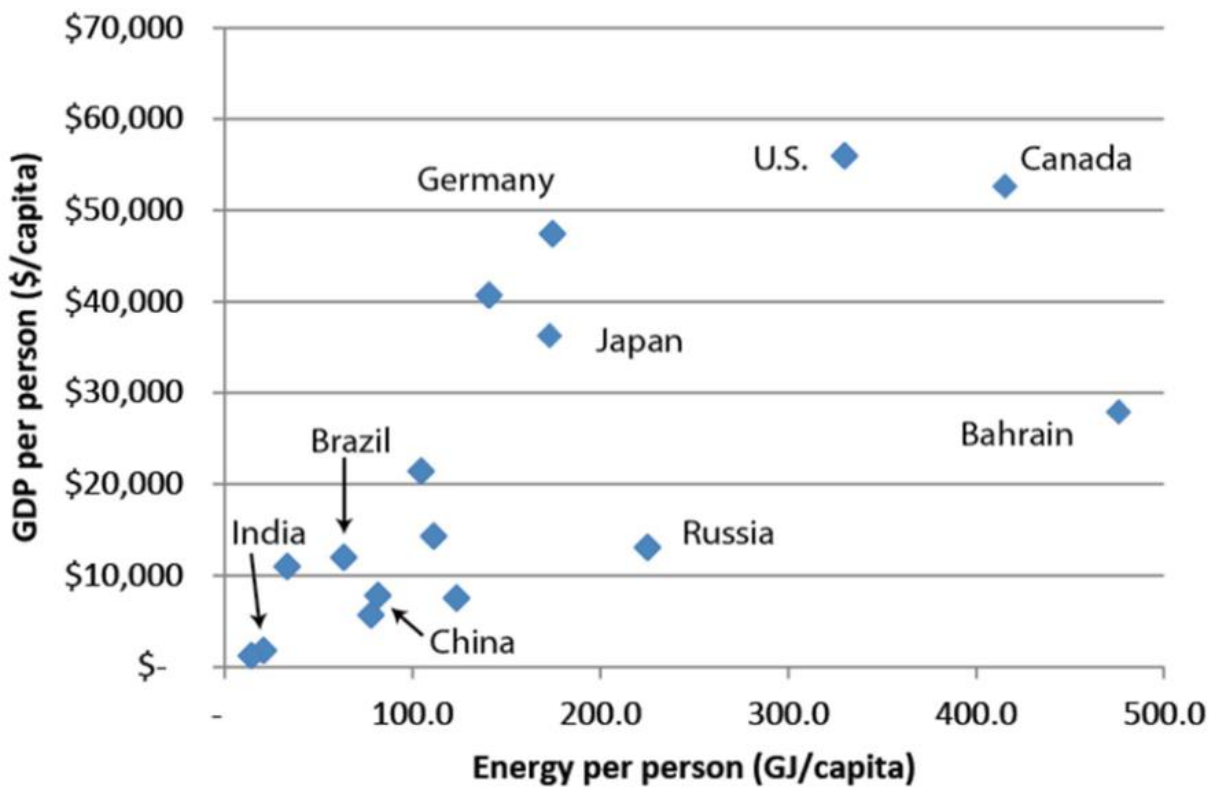
1.1. History of Human Energy Use

- If all of human history were compressed into a single year, the use of energy sources by humans would not have begun until December 20, when the controlled use of fire was harnessed.

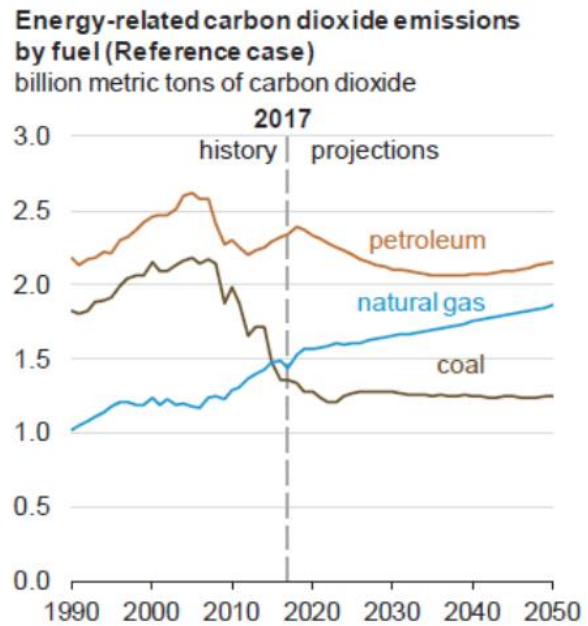
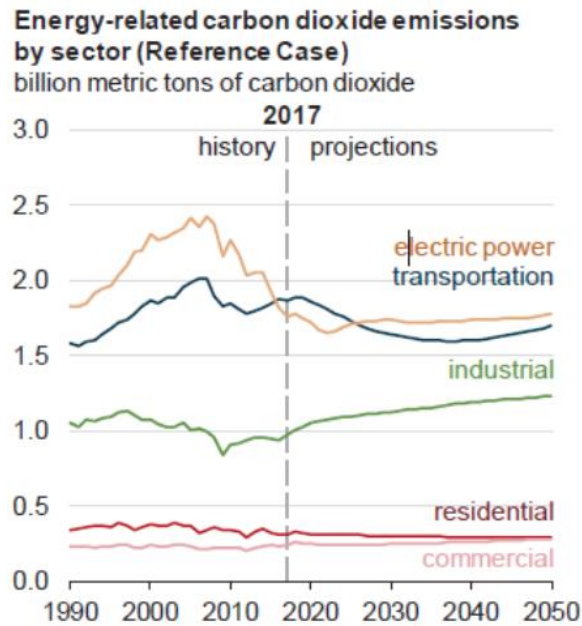
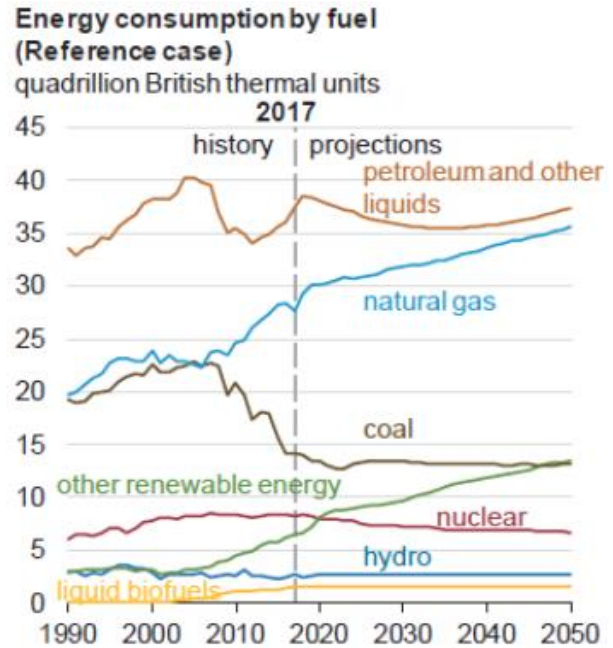
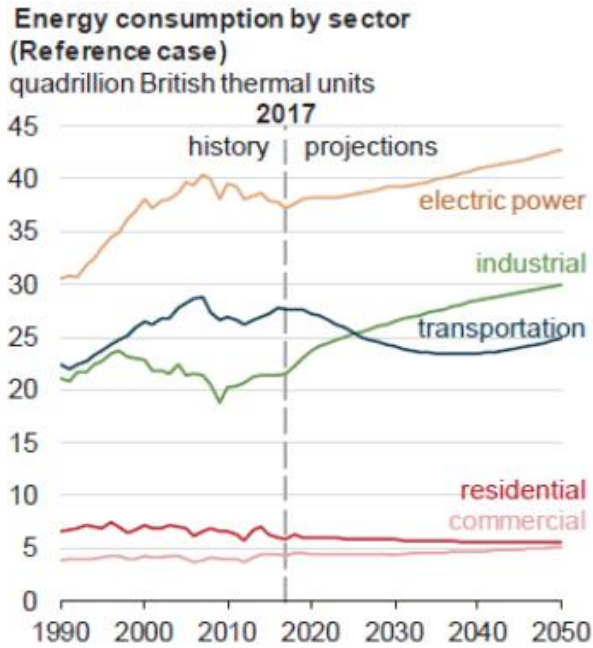


1.2. Relationship between Energy and Country GDP/Wealth

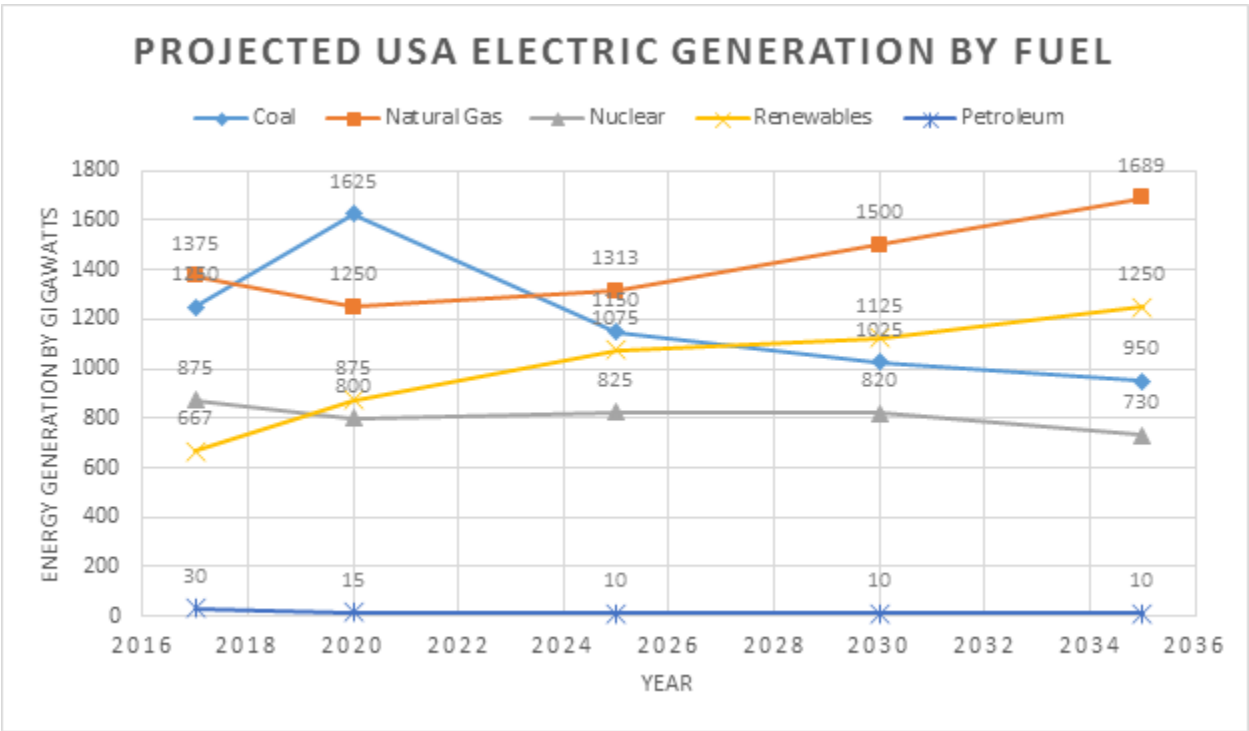
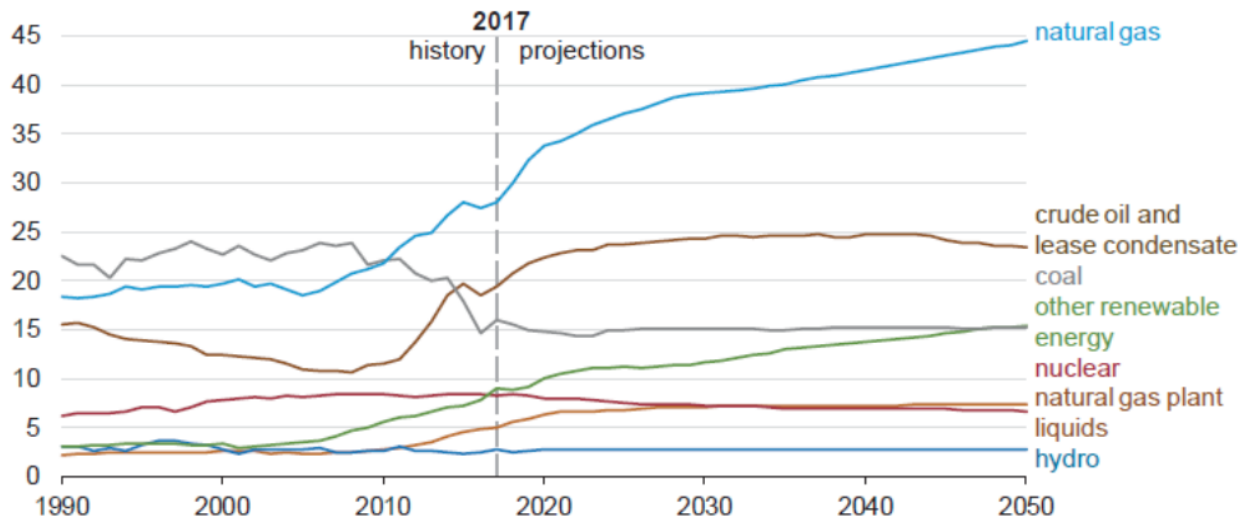




1.3. Projected World Energy Consumption

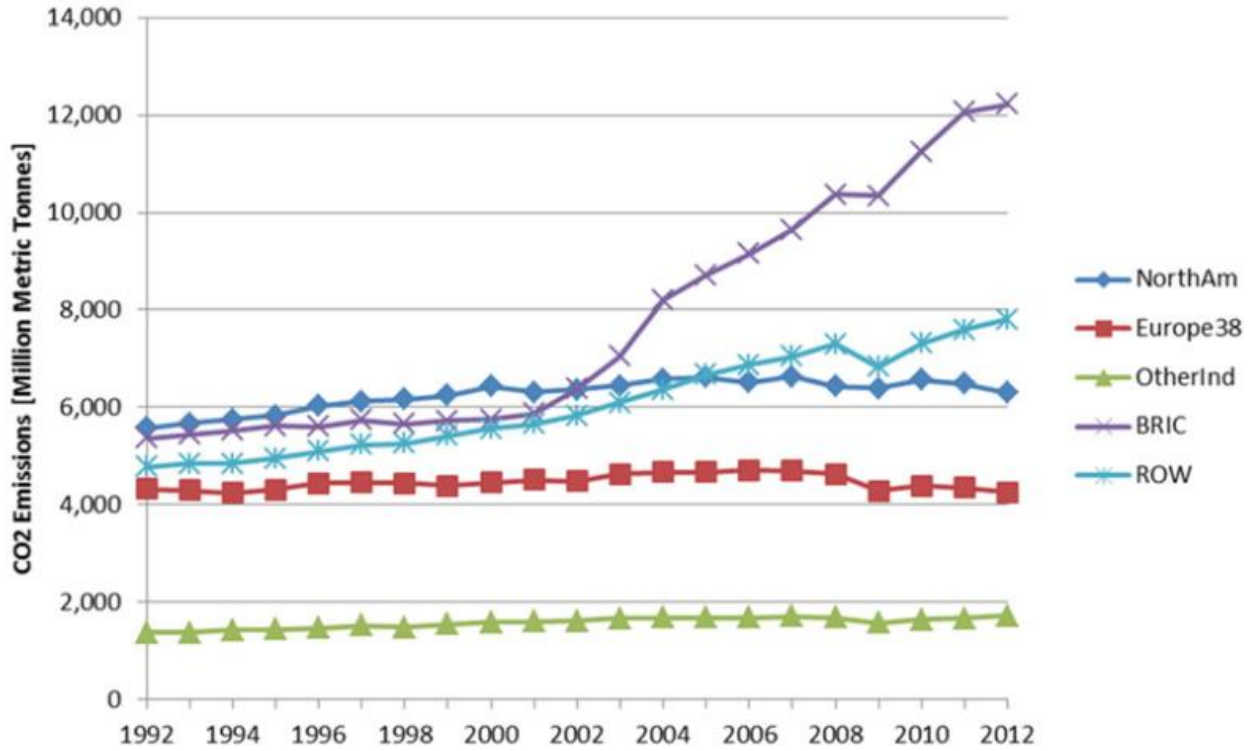


Energy production (Reference case)
quadrillion British thermal units



^ my graph of the same above that ... By 2035, renewables is projected to have a growth of 50%

1.4. Impact of Increased Energy Use

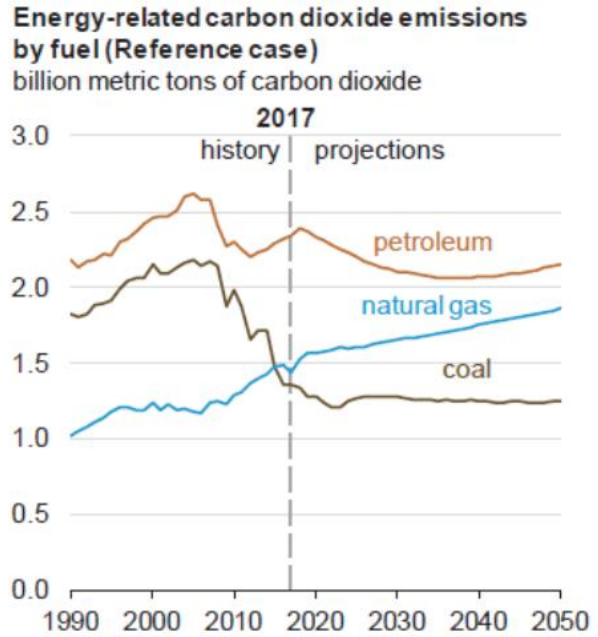
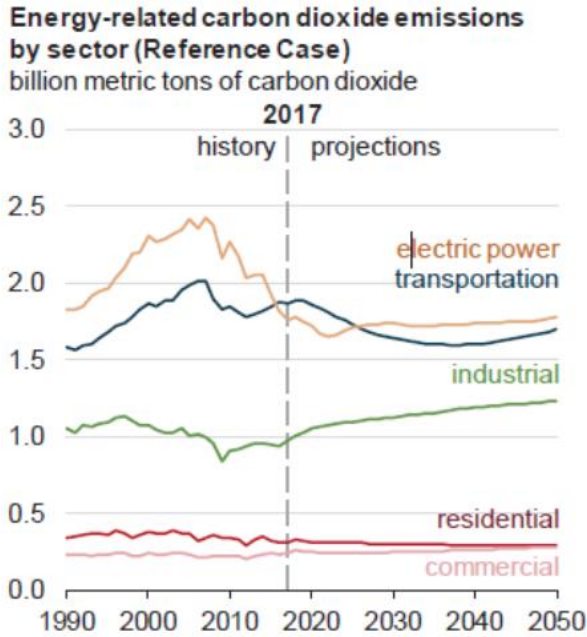


BRIC = Brazil, Russia, India, China

ROW = Rest Of World

OtherInd = Other Industrial Countries

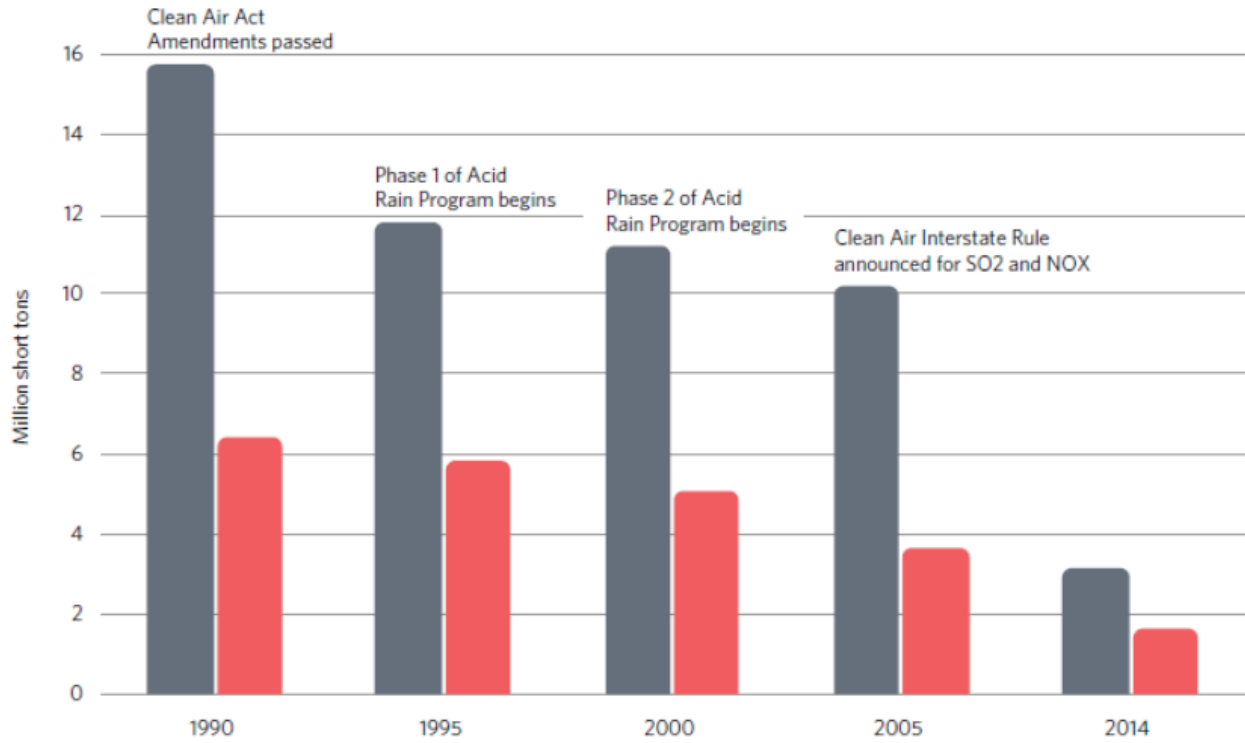
1.5. Projected US Emissions



1.6. The Importance of Legislation

The Clean Air Act Has Resulted in a More Than 70% Decline in Key Emissions

Electricity sector sulfur dioxide and nitrogen oxide emissions, 1990-2014, in million short tons



1.7. US Renewable Energy Potential and Projections

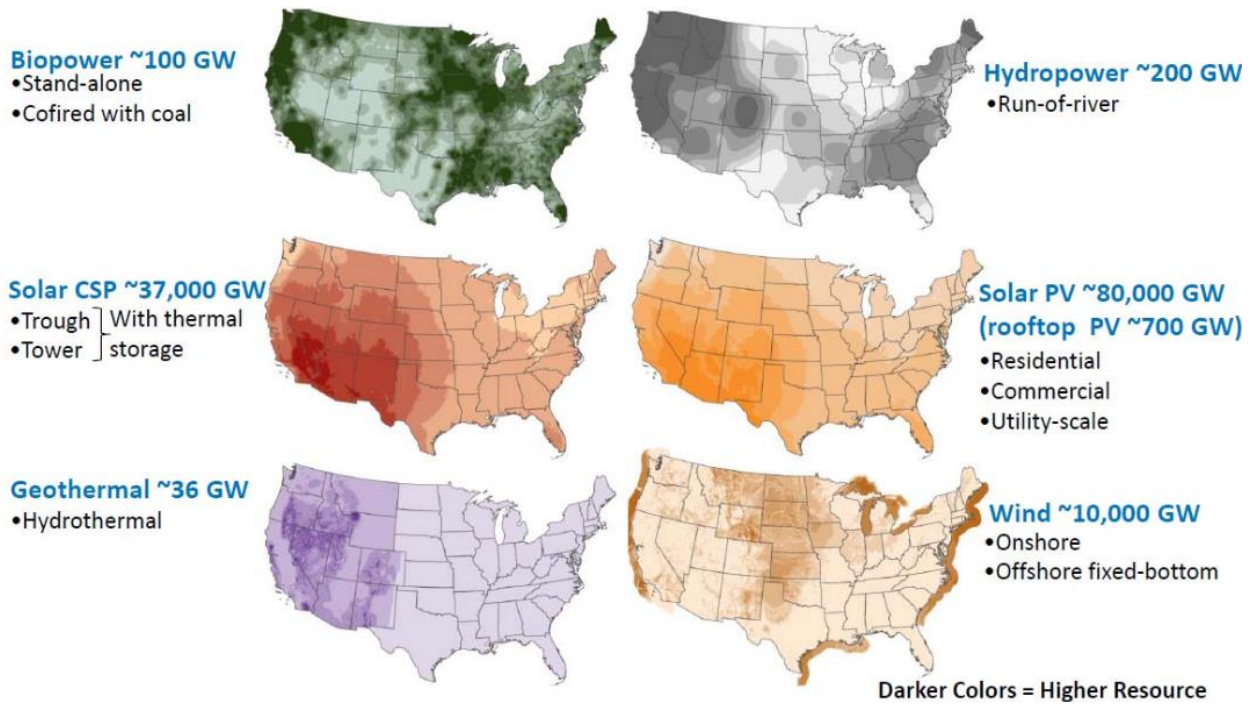
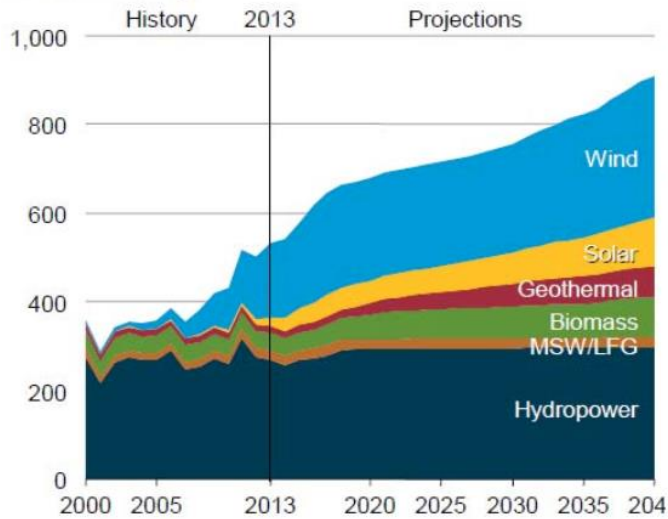
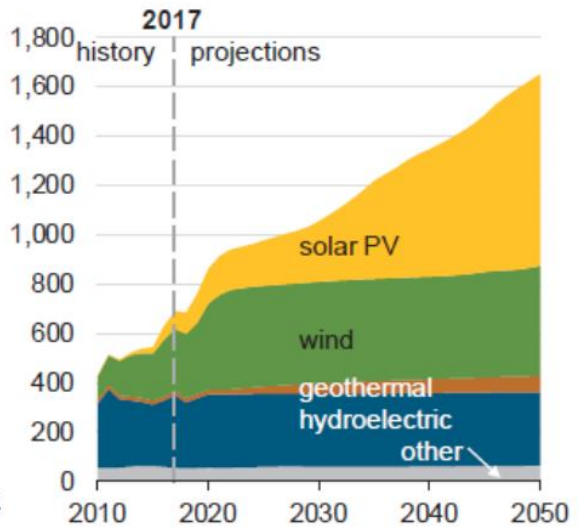


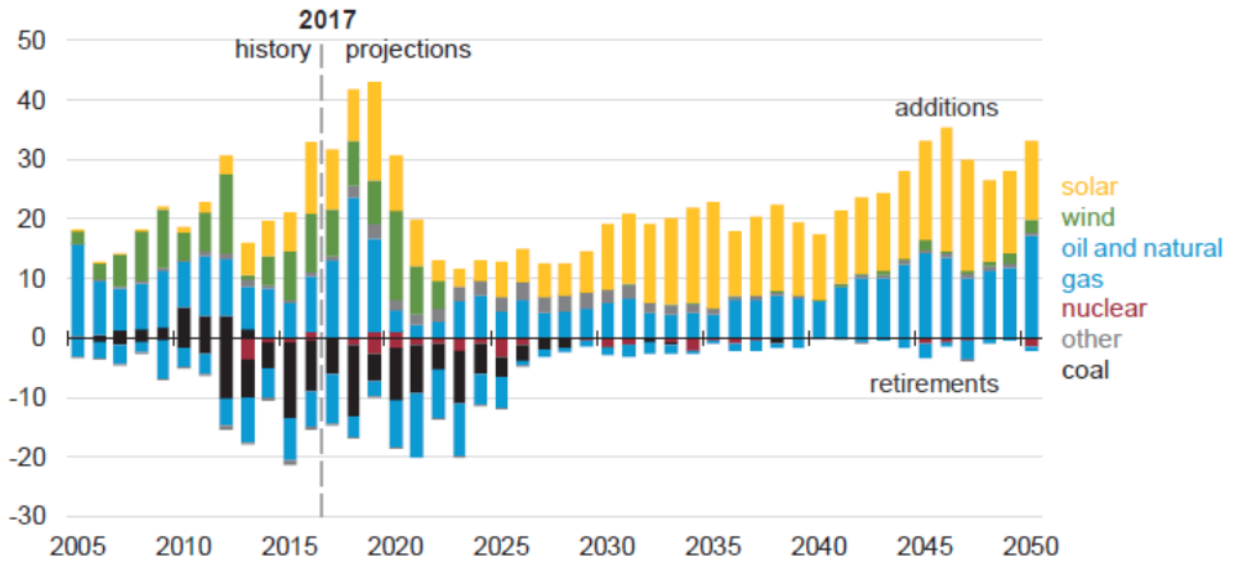
Figure 34. Renewable electricity generation by fuel type in the Reference case, 2000-2040 (billion kilowatthours)



Renewable electricity generation, including end-use generation (Reference case billion kilowatthours)



Annual electricity generating capacity additions and retirements (Reference case)
gigawatts

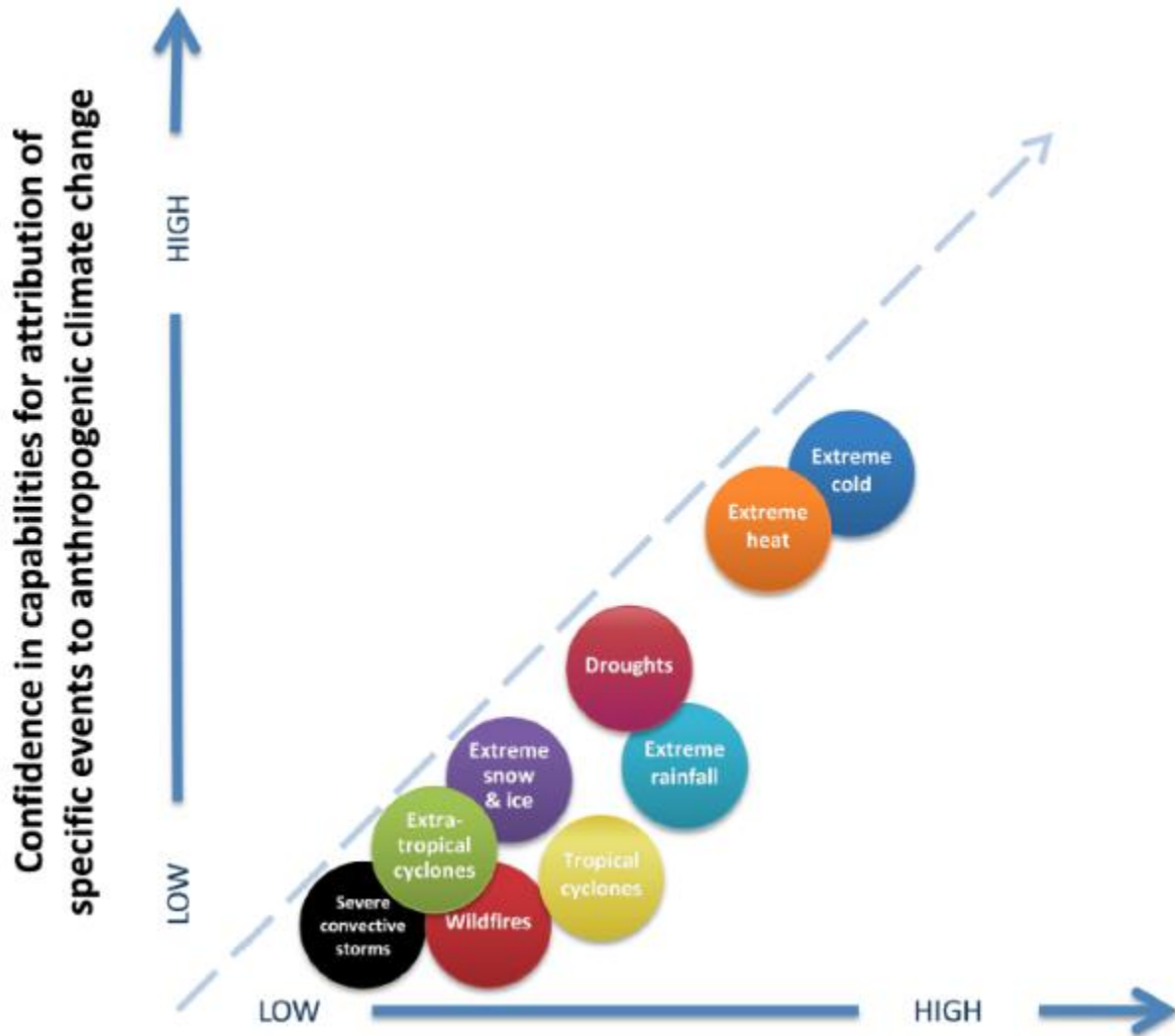


Wind and coal boom: 2005-2025

Solar boom: 2025-2045

2. Background: Climate Change Science

2.1. Newer Science Brings More Uncertainty

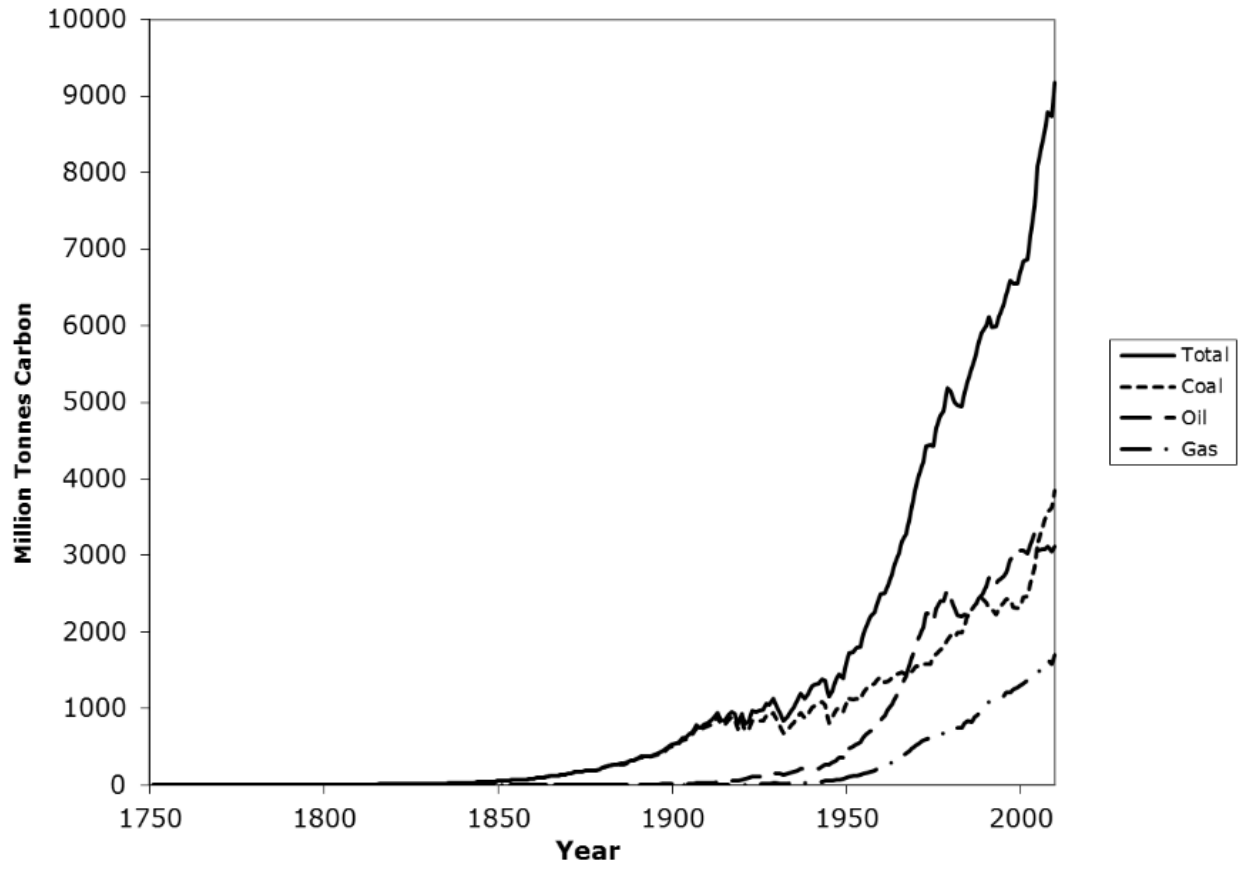


	Capabilities of Climate Models to Simulate Event Type	Quality/Length of the Observational Record	Understanding of Physical Mechanisms That Lead to Changes in Extremes as a Result of Climate Change
● = high			
◐ = medium			
○ = low			
Extreme cold events	●	●	●
Extreme heat events	●	●	●
Droughts	◐	◐	◐
Extreme rainfall	◐	◐	◐
Extreme snow and ice storms	◐	○	◐
Tropical cyclones	○	○	◐
Extratropical cyclones	◐	○	○
Wildfires	○	◐	○
Severe convective storms	○	○	○

2.2. Greenhouse Gas (GHG)

- Greenhouse gases:
 - Water vapor
 - CO₂, methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs)
 - Biogenic GHGs – resulting from interactions in the natural world (water vapor from evaporation)
 - Anthropogenic GHGs – resulting from human activity other than respiration

2.3. History of Increasing CO2



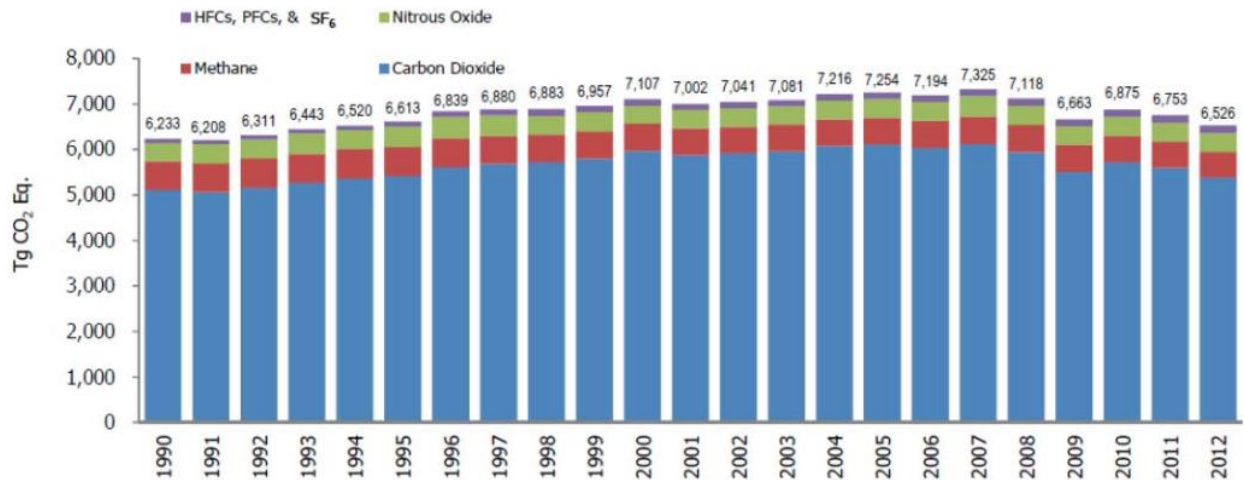
2.4. Global Warming Potential (GWP)

Gas	Atmospheric Lifetime	GWP ^a
CO ₂	*	1
CH ₄ ^b	12±3	21
N ₂ O	120	310
HFC-23	264	11,700
HFC-32	5.6	650
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF ₄	50,000	6,500
C ₂ F ₆	10,000	9,200
C ₄ F ₁₀	2,600	7,000
C ₆ F ₁₄	3,200	7,400
SF ₆	3,200	23,900

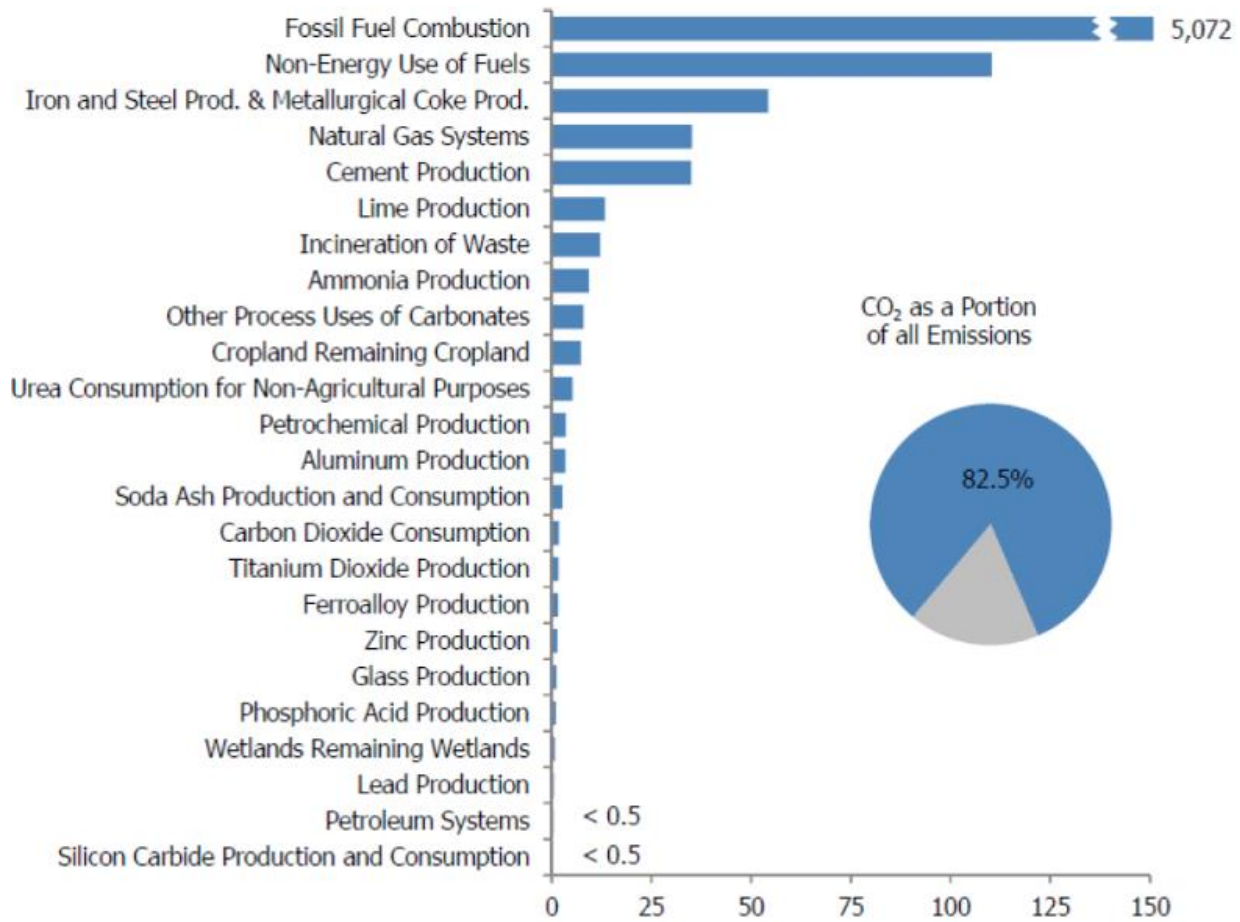
1 GWP = 1 CO₂-Equivalent Potency

1 Atmospheric Lifetime = 1 Year

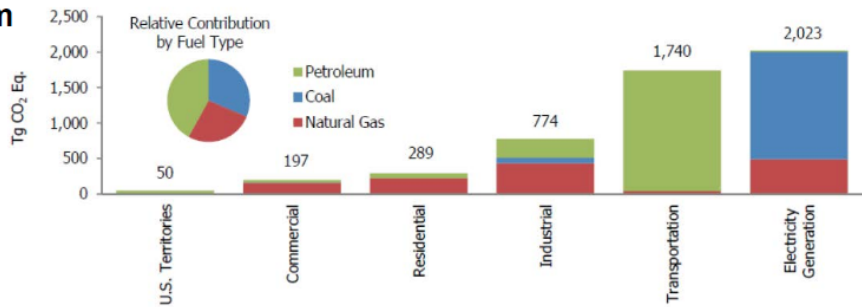
2.5. US's GHG Emission Types



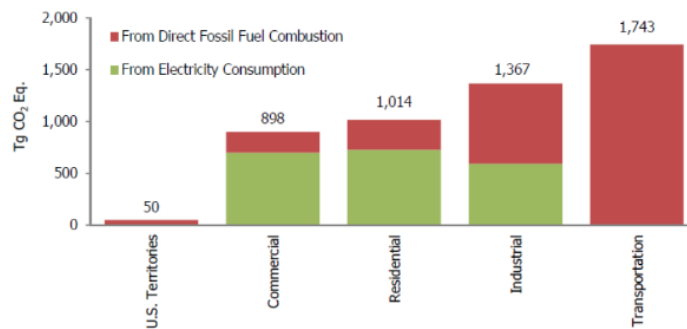
2.6. Leading Causes of Emissions (2012 Data)

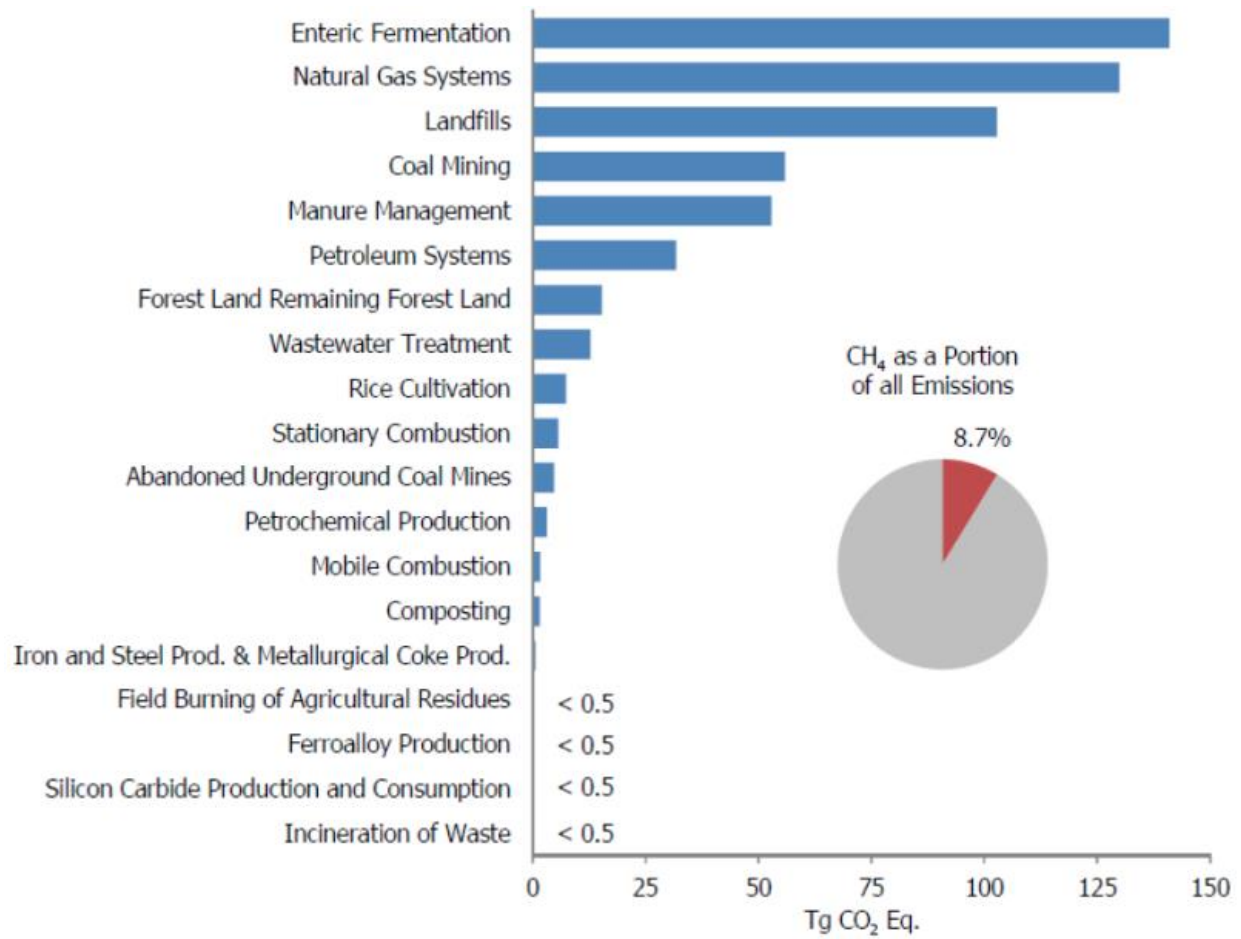


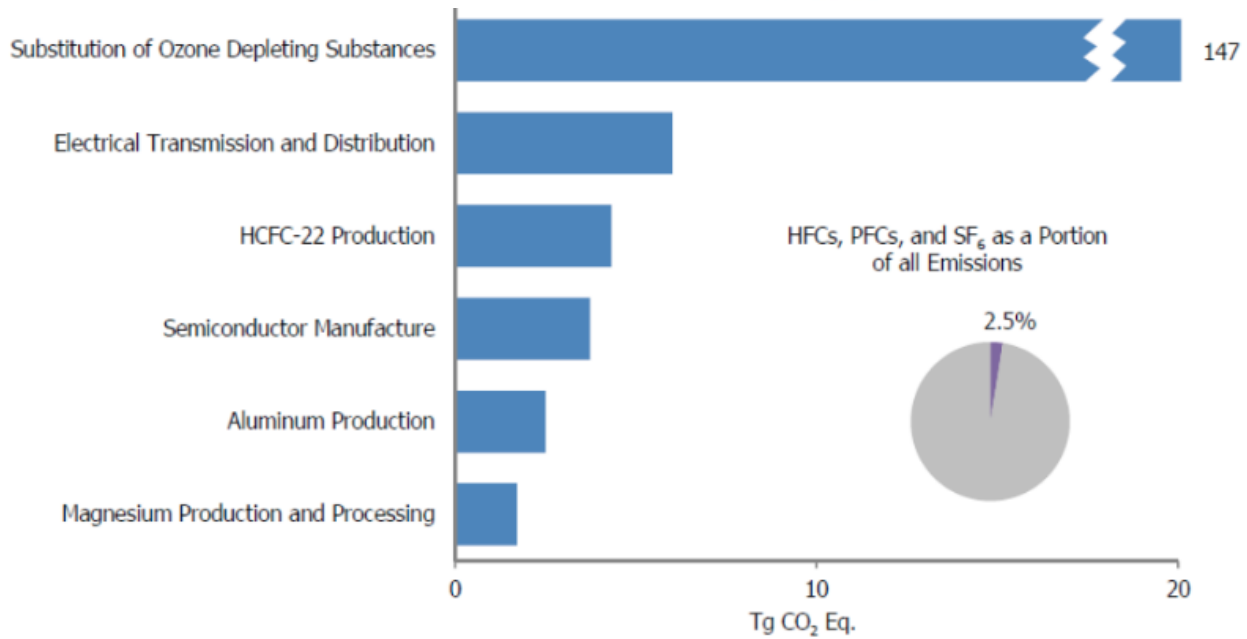
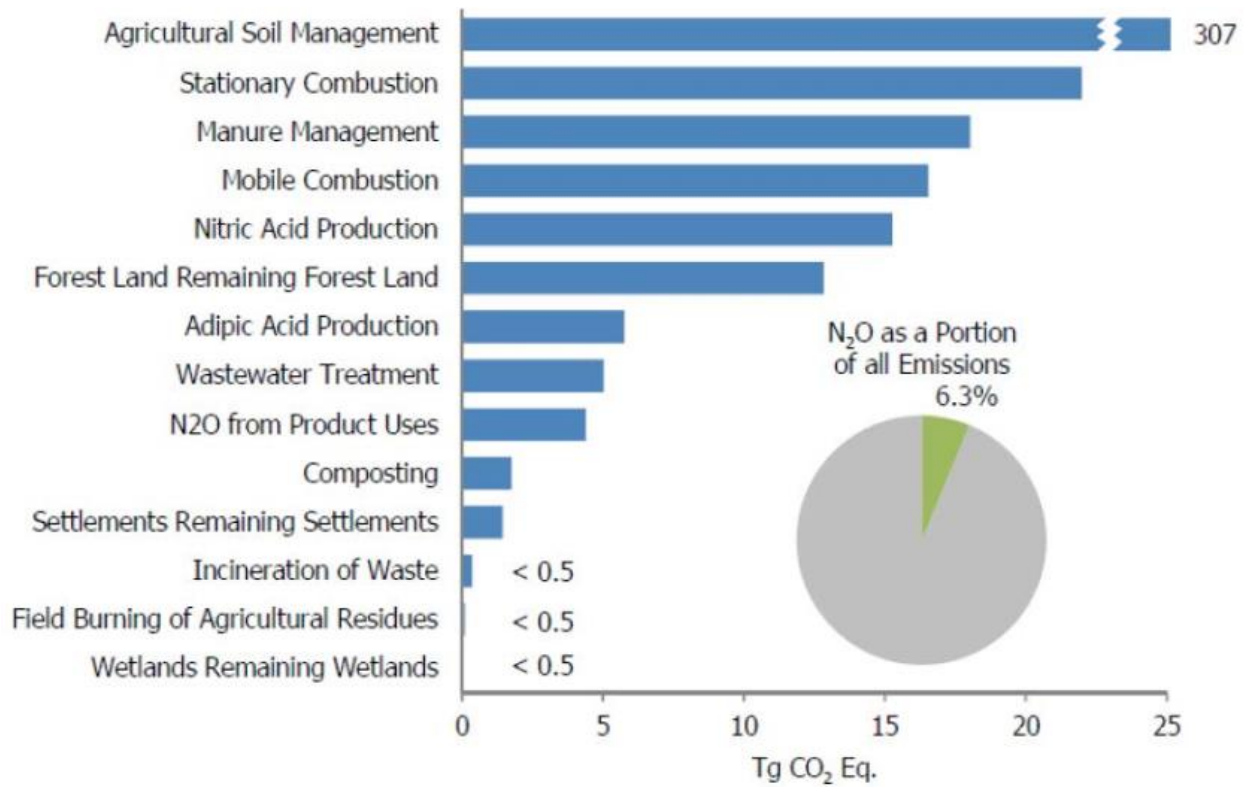
2012 CO₂ Emissions from Fossil Fuel Combustion by Sector and Fuel Type

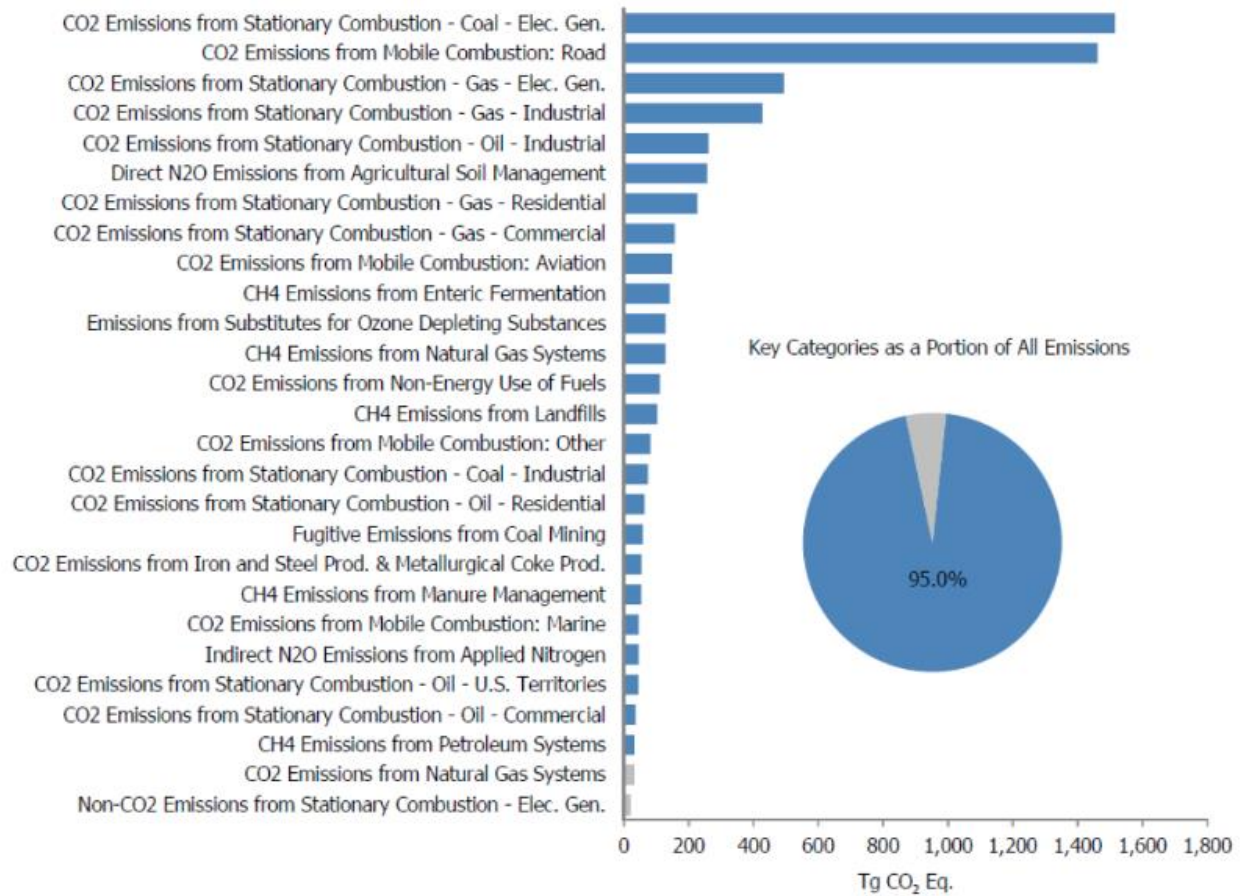


2012 End-Use Sector Emissions of CO₂ from Fossil Fuel Combustion

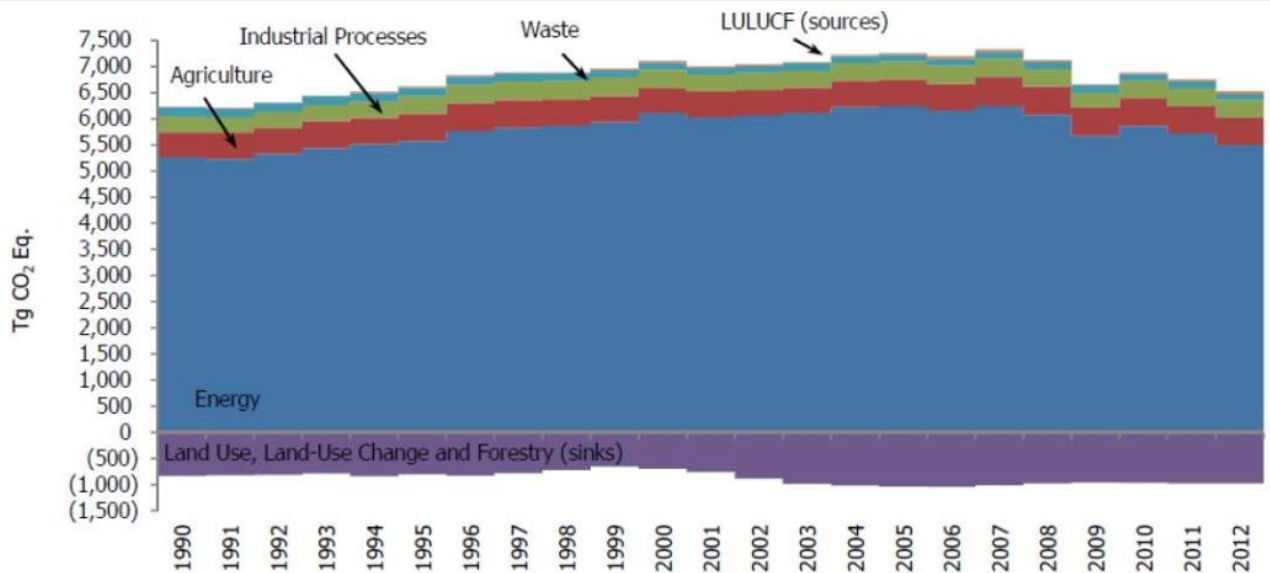


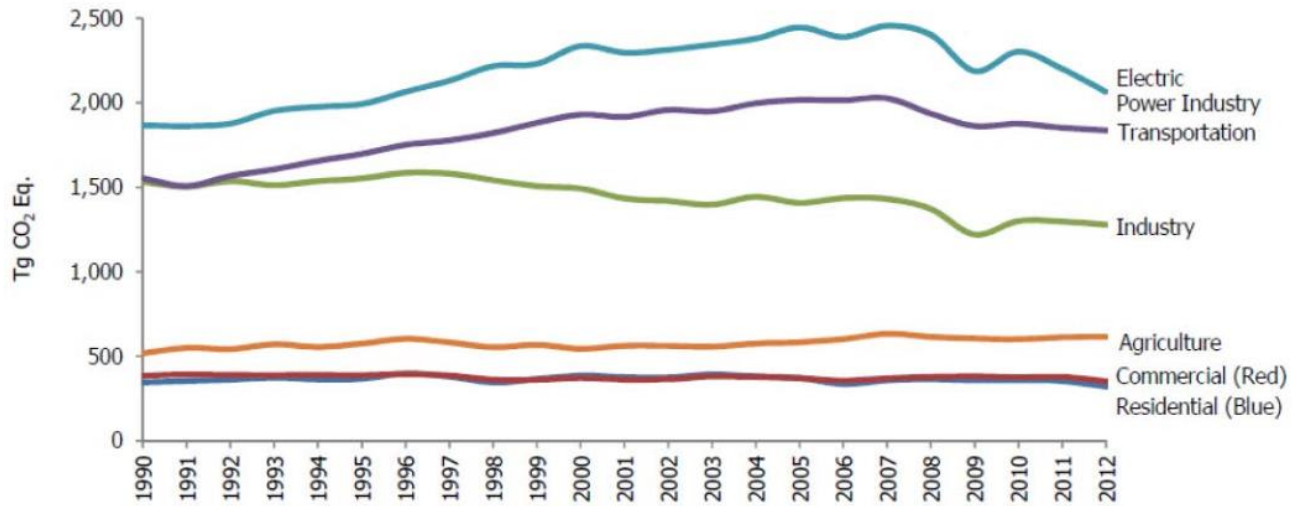






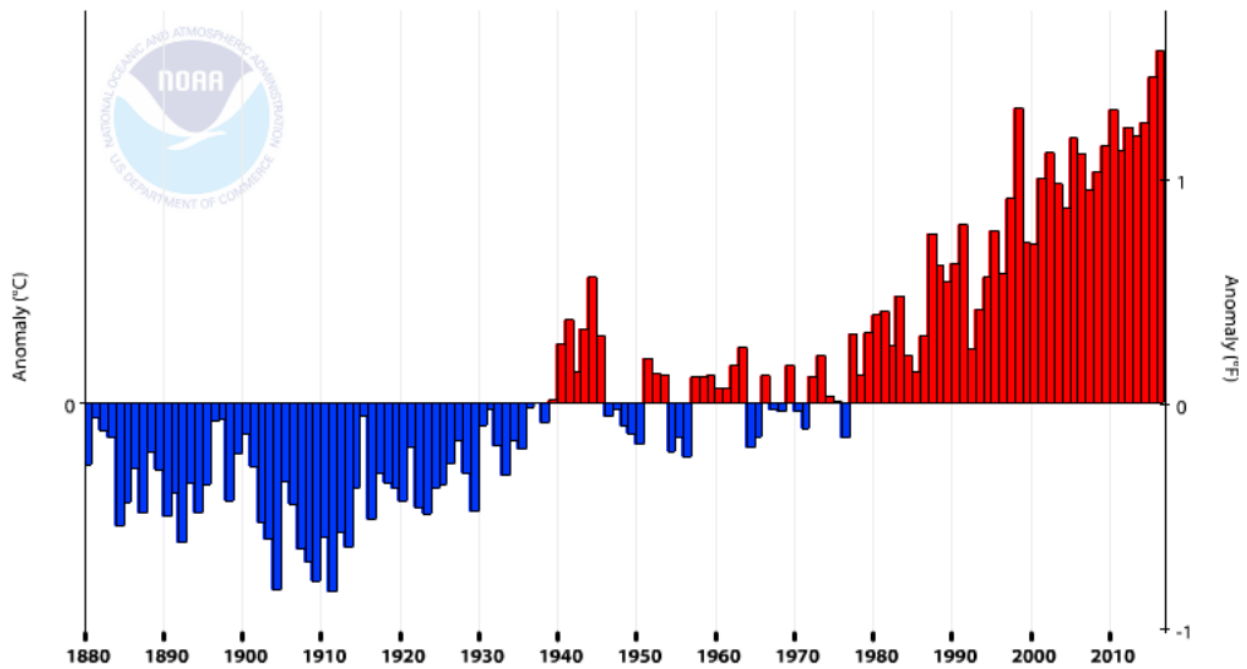
2.7. US Emissions by Sector



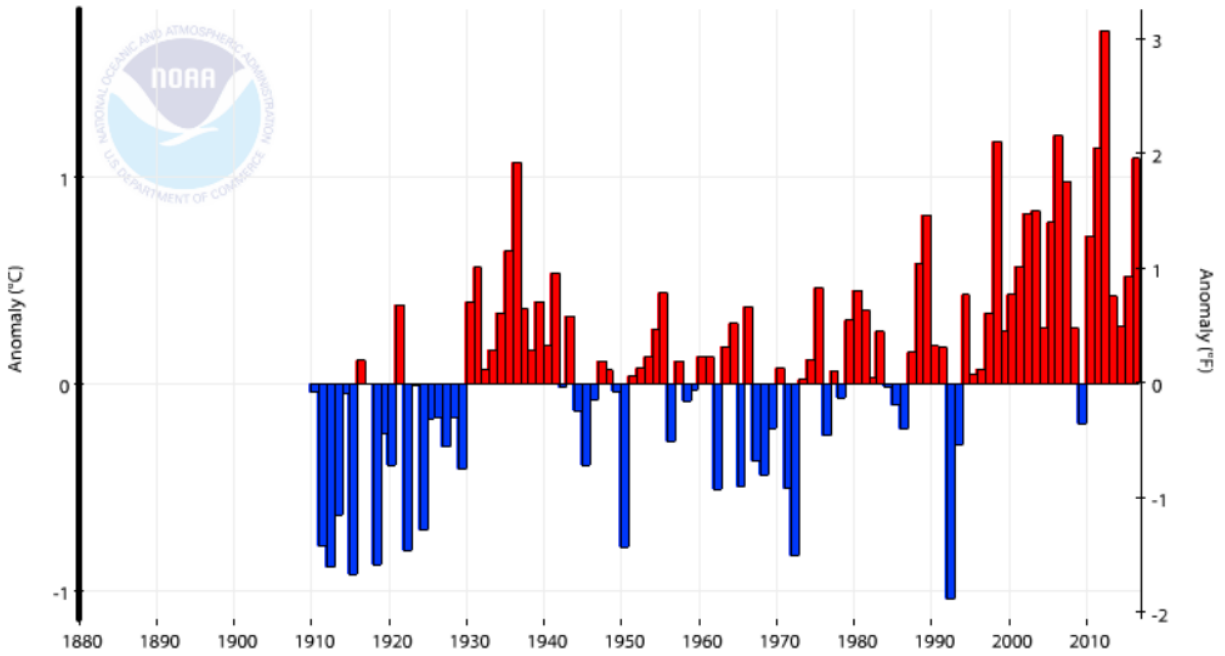


2.8. GHG Emissions are Proportional to Temperature

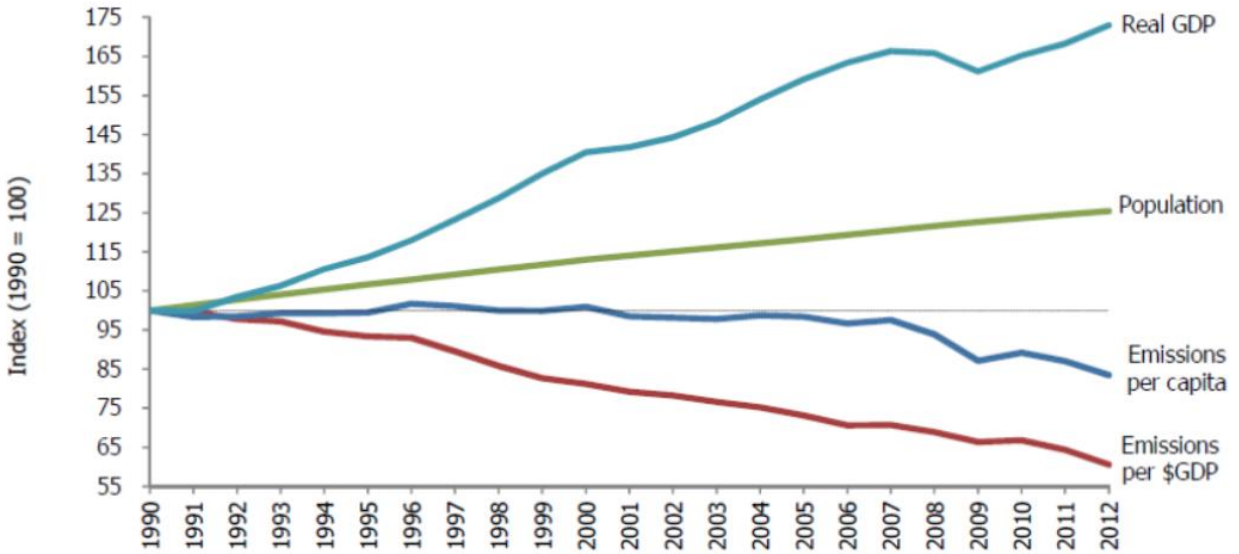
Global Land and Ocean Temperature Anomalies, July



North America Land Temperature Anomalies, July

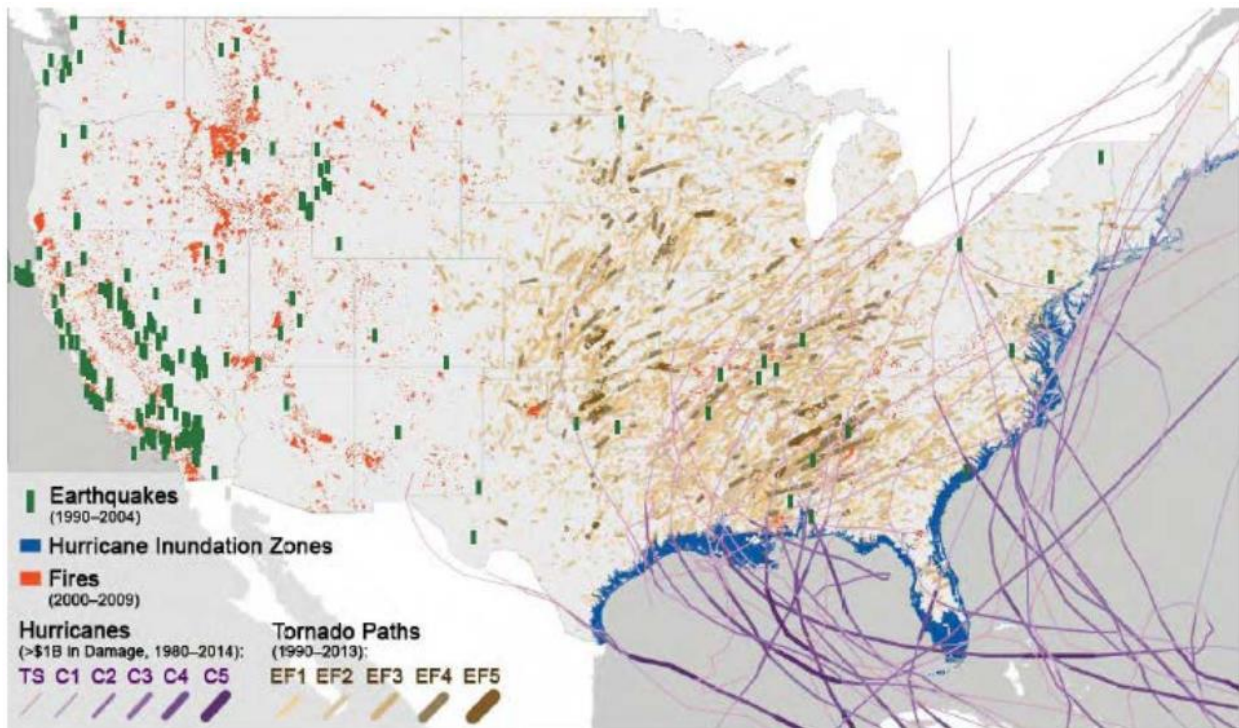


2.9. US GHG Emissions per Capita and GDP



2.10. US Climate Change Impact

Key climate impacts projected by region	
Climate impact	Regions with energy systems that are most affected
Increasing temperatures and heat waves	All regions
Increasing heavy downpours	Northern regions
Decreasing water availability	Western and southern regions
Increasing wildfire	Western regions
Increasing sea level rise and storm surge	Nearly all coastal regions
Increasing frequency of intense hurricanes	Gulf and Atlantic regions, including Puerto Rico
Permafrost thaw	Alaska



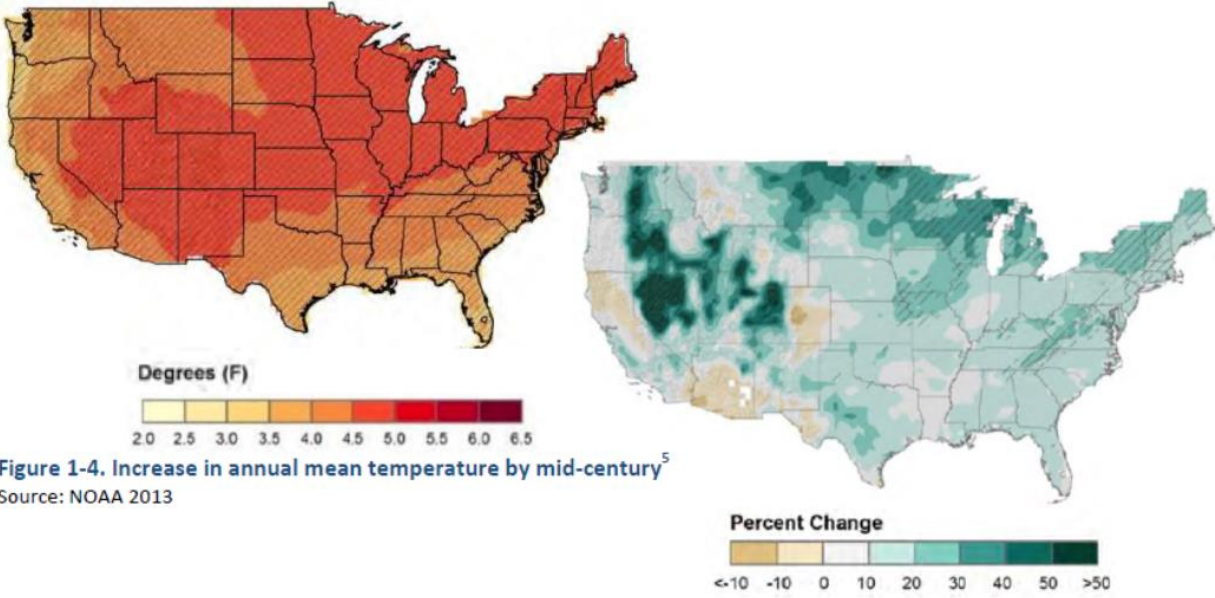


Figure 1-4. Increase in annual mean temperature by mid-century⁵
 Source: NOAA 2013

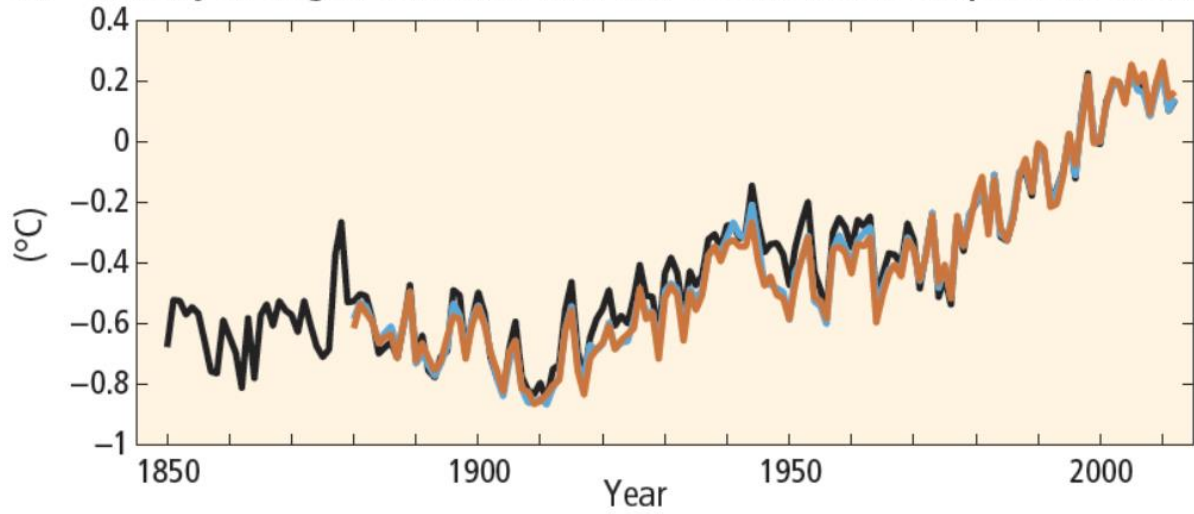
Figure 1-5. Change in annual heavy precipitation events by mid-century⁶
 Source: NOAA 2013

3. 2014 IPCC Report Summary [Global]

- Many reports available
- Oreskes (2004) sampled 928 peer-reviewed papers between 1993 and 2003 that included “climate change” in their keywords
 - 75% concluded climate change is connected to human activity
 - 25% took no position
 - None disagreed
- Intergovernmental Panel on Climate Change (IPCC):
 - The leading international body for the assessment of climate change.
 - Established by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) in 1988
 - See <http://www.ipcc.ch/index.htm#.Ui8iP8co670>
 - *Climate Change 2007: Synthesis Report* (IPCC 2007)
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf
 - Climate Change 2014: IPCC Fifth Assessment Synthesis report
http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf
 - Report web site: <http://ar5-syr.ipcc.ch/>

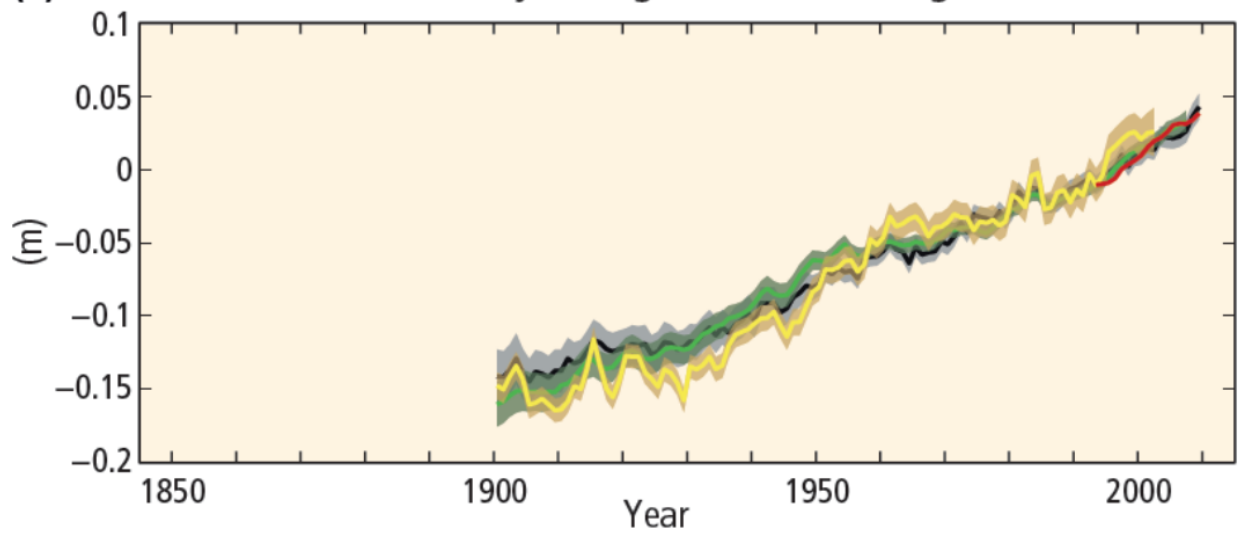
3.1. Land and Ocean Surface Temperature Anomaly

(a) Globally averaged combined land and ocean surface temperature anomaly

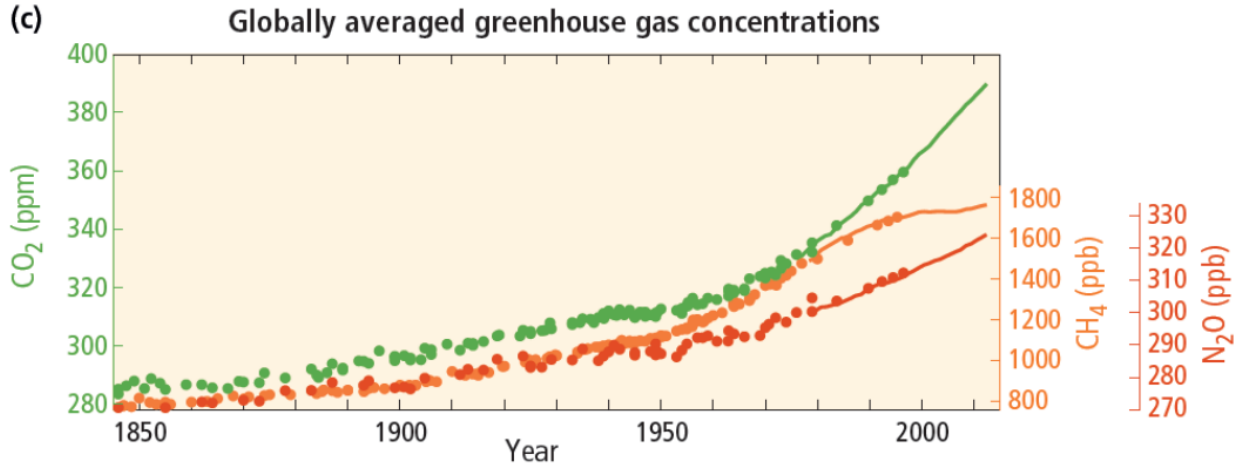


3.2. Sea Level Change

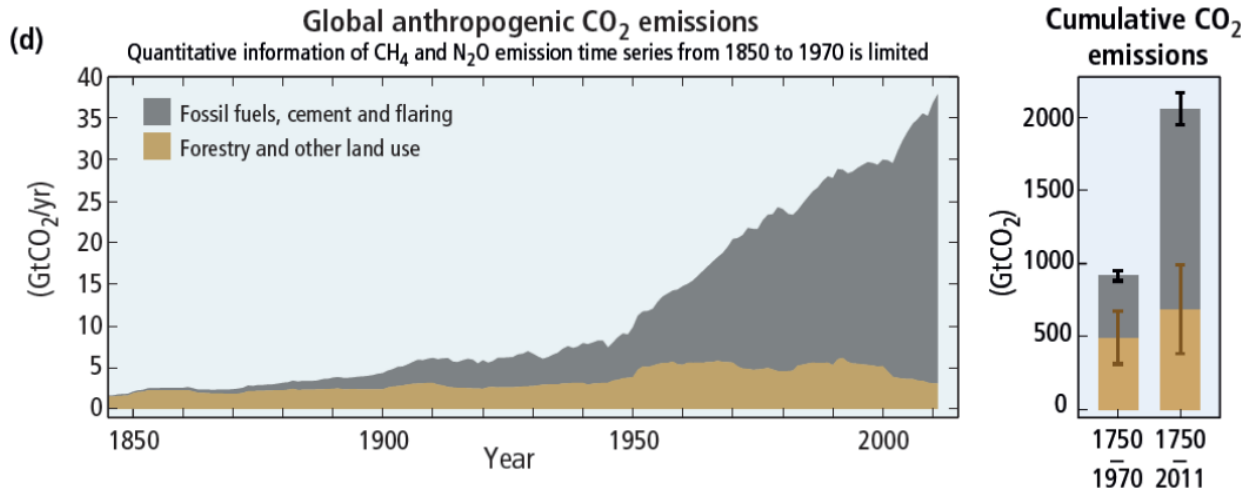
(b) Globally averaged sea level change



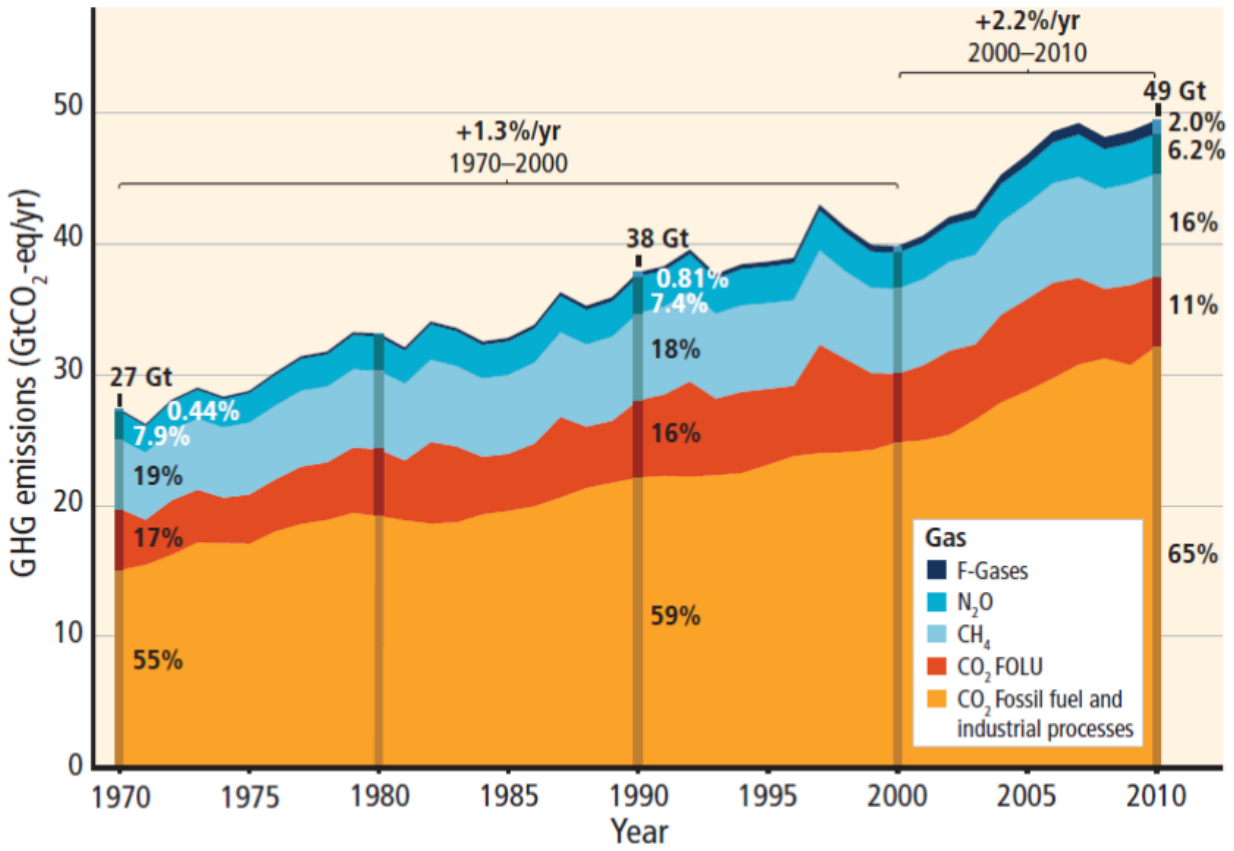
3.3. GHG Concentrations



3.4. Anthropogenic CO₂ Emissions

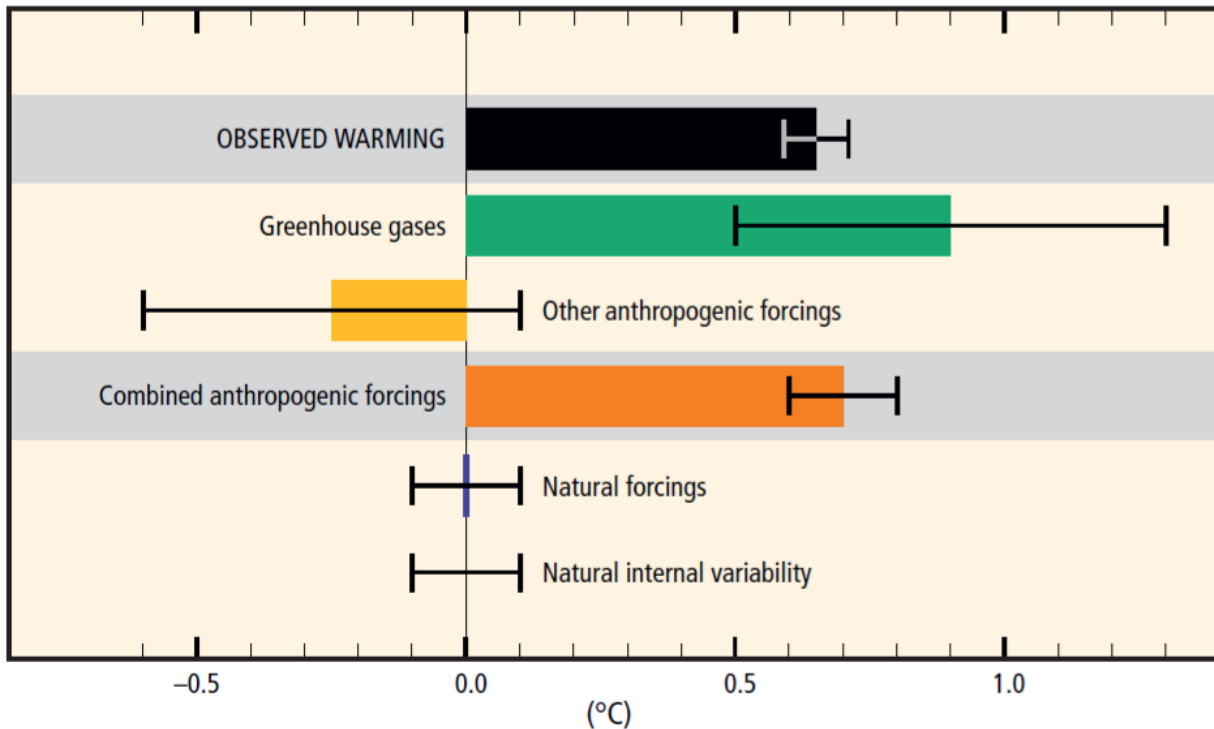


Total annual anthropogenic GHG emissions by gases 1970–2010



3.5. Contributions to Observed Temperature Change

Contributions to observed surface temperature change over the period 1951–2010

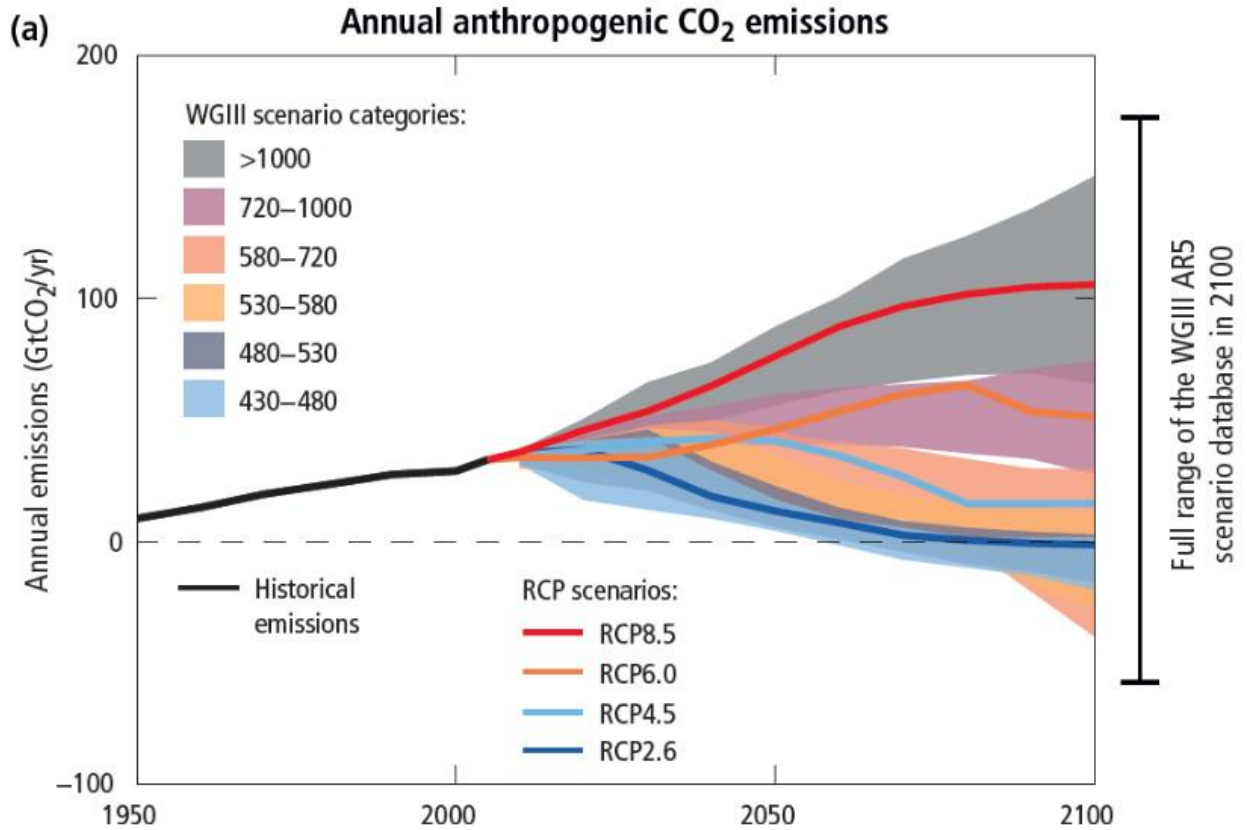


3.6. Climate Change Impact: Summary

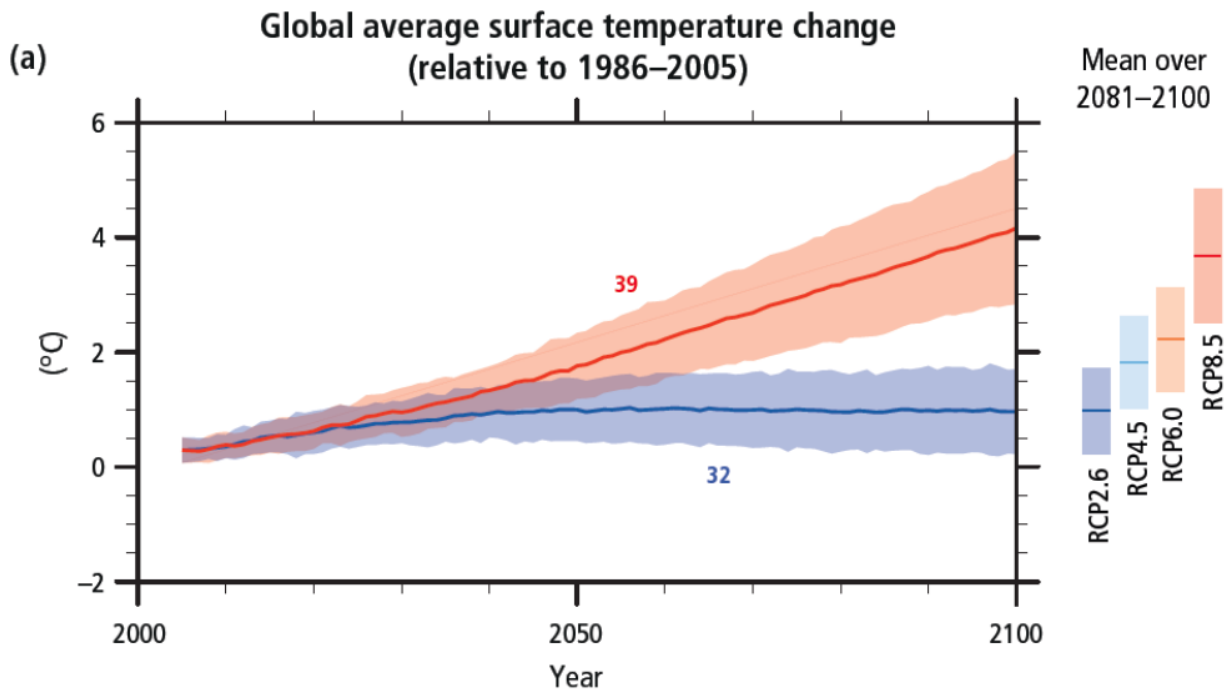
- Impacts of climate change:
 - Evidence of observed climate change impacts is strongest and most comprehensive for natural systems.
 - In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality.
 - Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change.
 - Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts.
 - Some impacts of ocean acidification on marine organisms have been attributed to human influence.

- Impact on extreme events:
 - Changes in many extreme weather and climate events have been observed since about 1950.
 - Some of these changes have been linked to human influences, including:
 - a decrease in cold temperature extremes
 - an increase in warm temperature extremes
 - an increase in extreme high sea levels
 - an increase in the number of heavy precipitation events in a number of regions.

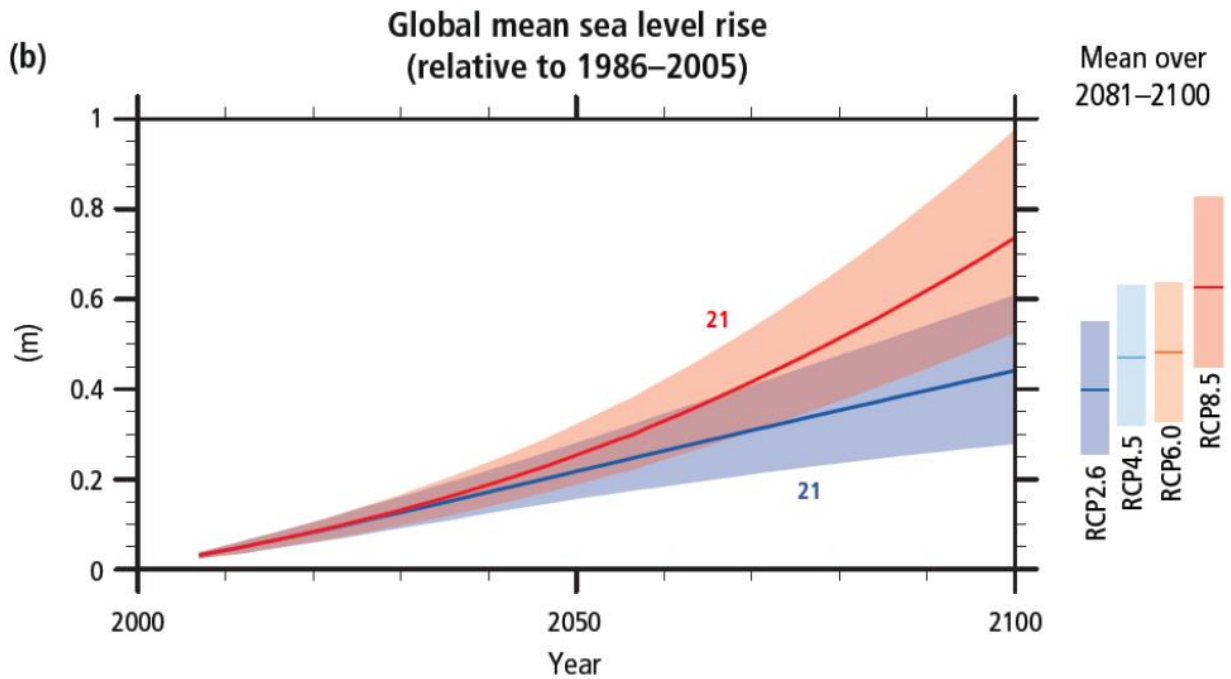
3.7. Predicting CO₂ Emissions



3.8. Predicting Temperature Change



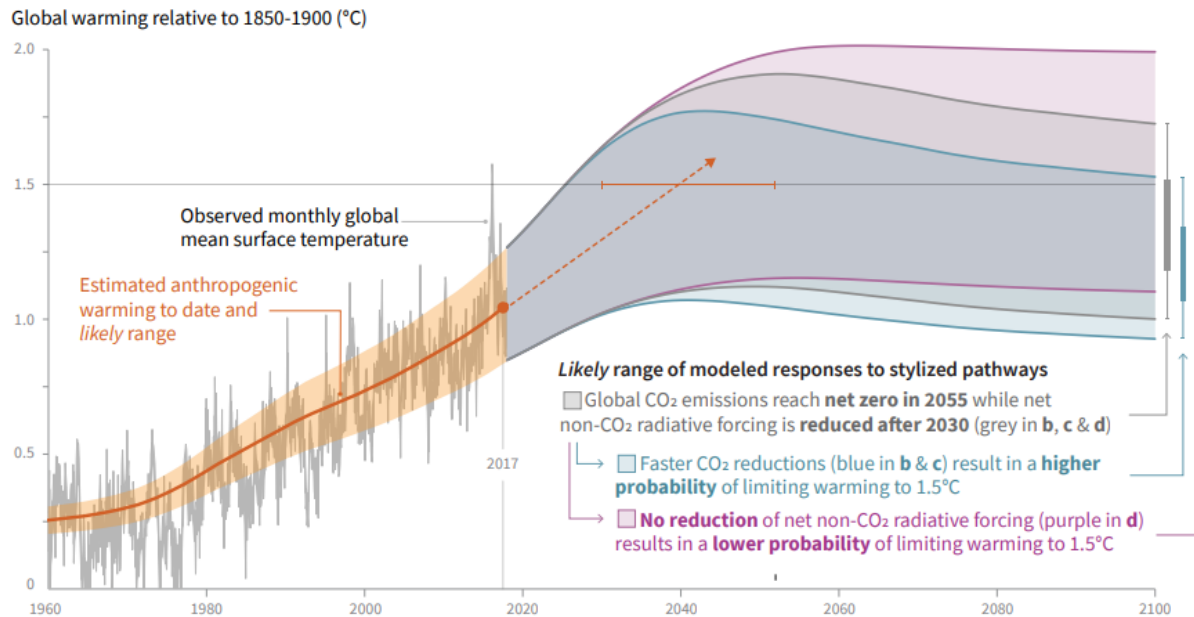
3.9. Predicting Sea Level Change



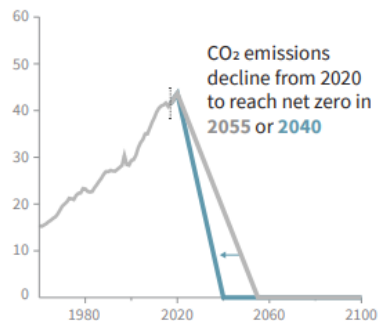
4. 2018 IPCC Report Summary [Global] [Quotes]

Cumulative emissions of CO₂ and future non-CO₂ radiative forcing determine the probability of limiting warming to 1.5°C

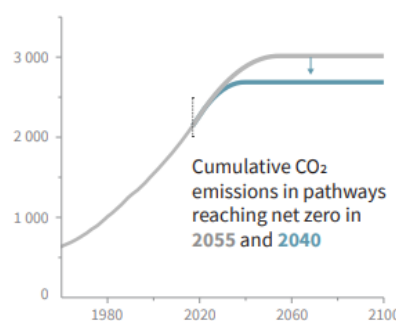
a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways



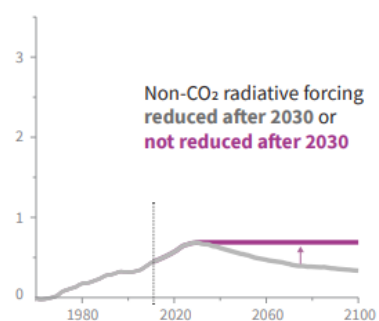
b) Stylized net global CO₂ emission pathways
Billion tonnes CO₂ per year (GtCO₂/yr)



c) Cumulative net CO₂ emissions
Billion tonnes CO₂ (GtCO₂)



d) Non-CO₂ radiative forcing pathways
Watts per square metre (W/m²)



Faster immediate CO₂ emission reductions limit cumulative CO₂ emissions shown in panel (c).

Maximum temperature rise is determined by cumulative net CO₂ emissions and net non-CO₂ radiative forcing due to methane, nitrous oxide, aerosols and other anthropogenic forcing agents.

4.1. General Numbers

- Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C.
- Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (high confidence)

- Estimated anthropogenic global warming is currently increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (high confidence).

4.2. General Trends and Risks

- Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (medium confidence). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950.
- Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (high confidence), but these emissions alone are unlikely to cause global warming of 1.5°C (medium confidence)
- Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (high confidence)

4.3. Higher Land Temperature

- Temperature extremes on land are projected to warm more than GMST (high confidence): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (high confidence). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (high confidence)

4.4. Sea Level Rise / Higher Sea Temperature

- By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (medium confidence). Sea level will continue to rise well beyond 2100 (high confidence), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (medium confidence).
- Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (high confidence). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered around 1.5°C to 2°C of global warming (medium confidence).
- Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (high confidence).
- Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks enabling greater

opportunities for adaptation including managing and restoring natural coastal ecosystems, and infrastructure reinforcement (medium confidence).

- There is high confidence that the probability of a sea-ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming.

4.5. Increased Risk of Natural Disasters

- Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C global warming in some regions (medium confidence).
- Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (medium confidence) ... There is generally low confidence in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2.0°C than at 1.5°C of global warming (medium confidence).
- Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence).
- As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (medium confidence).
- Impacts associated with other biodiversity-related risks such as forest fires, and the spread of invasive species, are lower at 1.5°C compared to 2°C of global warming (high confidence).

4.6. Negative Impacts of Biodiversity and Ecosystems

- On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater, and coastal ecosystems and to retain more of their services to humans (high confidence).
- Of 105,000 species studied, 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (medium confidence).
- Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence).
- High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (high confidence) and will proceed with further warming. Limiting global warming to 1.5°C

rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km² (medium confidence)

- Global warming of 1.5°C is projected to shift the ranges of many marine species, to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources, and reduce the productivity of fisheries and aquaculture (especially at low latitudes).
- Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (high confidence) with larger losses (>99%) at 2°C (very high confidence). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (high confidence).
- The level of ocean acidification due to increasing CO₂ concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, e.g., from algae to fish (high confidence).

4.7. Negative Effects of our Food

- Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C.
- Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (medium confidence) but are projected to be less at 1.5°C of global warming than at 2°C. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (medium confidence).

4.8. At-Risk People

- Populations at disproportionately higher risk of adverse consequences of global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (high confidence).
- Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small-island developing states, and least developed countries (high confidence). Poverty and disadvantages are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (medium confidence).
- Any increase in global warming is projected to affect human health, with primarily negative consequences (high confidence). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (very high confidence) and for ozone-related mortality if emissions needed for ozone formation remain high (high confidence).

- Urban heat islands often amplify the impacts of heatwaves in cities (high confidence). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (high confidence).
- Limiting warming to 1.5°C, compared with 2°C, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO₂ dependent, nutritional quality of rice and wheat (high confidence).
- Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (medium confidence). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (high confidence).
- Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century (medium confidence). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2 °C (medium confidence).
- Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (high confidence). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (medium confidence).

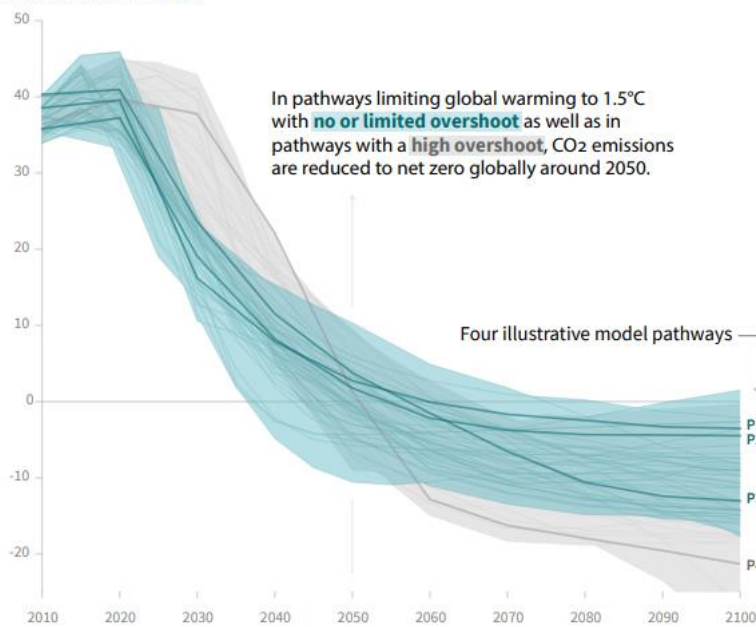
4.9. What is planned?

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO₂, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM3B.

Global total net CO₂ emissions

Billion tonnes of CO₂/yr



Timing of net zero CO₂

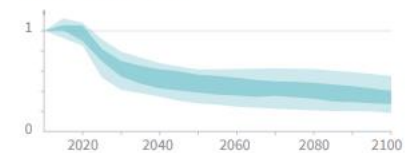
Line widths depict the 5-95th percentile and the 25-75th percentile of scenarios



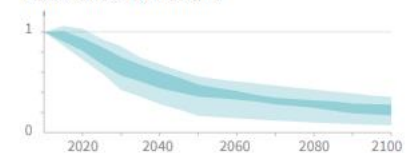
Non-CO₂ emissions relative to 2010

Emissions of non-CO₂ forcers are also reduced or limited in pathways limiting global warming to 1.5°C with **no or limited overshoot**, but they do not reach zero globally.

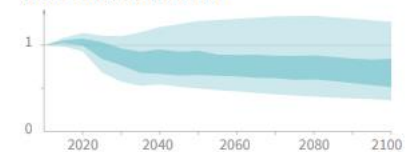
Methane emissions



Black carbon emissions



Nitrous oxide emissions



- In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO₂ emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C CO₂ emissions are projected to decline by about 20% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2075 (2065–2080 interquartile range). Non-CO₂ emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (high confidence)
- CO₂ emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation

challenges, and potential synergies and trade-offs with sustainable development. (high confidence).

- Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010).
- Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO₂ since the preindustrial period, i.e. staying within a total carbon budget (high confidence).¹³ By the end of 2017, anthropogenic CO₂ emissions since the preindustrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 GtCO₂ (medium confidence). The associated remaining budget is being depleted by current emissions of 42 ± 3 GtCO₂ per year (high confidence). The choice of the measure of global temperature affects the estimated remaining carbon budget.

4.10. What would we have to change to stay at 1.5 degrees?

- Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (medium confidence).
- In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (high confidence). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2%) of electricity (high confidence). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (high confidence). These improvements signal a potential system transition in electricity generation
- CO₂ emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 75–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (medium confidence). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In

industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (high confidence).

- In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (medium confidence). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C global warming (medium confidence). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (high confidence).
- Model pathways that limit global warming to 1.5°C with no or limited overshoot project the conversion of 0.5–8 million km² of pasture and 0–5 million km² of non-pasture agricultural land for food and feed crops into 1–7 million km² for energy crops and a 1 million km² reduction to 10 million km² increase in forests by 2050 relative to 2010 (medium confidence).¹⁶ Land use transitions of similar magnitude can be observed in modelled 2°C pathways (medium confidence). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (high confidence). Mitigation options limiting the demand for land include sustainable intensification of land use practices, ecosystem restoration and changes towards less resource-intensive diets (high confidence). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (high confidence).

4.11. Carbon Dioxide Removal

- All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO₂ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence). CDR deployment of several hundreds of GtCO₂ is subject to multiple feasibility and sustainability constraints (high confidence). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred GtCO₂ without reliance on bioenergy with carbon capture and storage (BECCS)
- In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 GtCO₂ yr⁻¹ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 GtCO₂ yr⁻¹ in these years (medium confidence).
- Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO₂ emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b). (high confidence). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability

to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (high confidence).

- Most current and potential CDR measures could have significant impacts on land, energy, water, or nutrients if deployed at large scale (high confidence). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity and other ecosystem functions and services (high confidence). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (high confidence).

4.12. Needing to Act ASAP

- Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions¹⁸ in 2030 of 52–58 GtCO₂eq yr⁻¹ (medium confidence). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (high confidence). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO₂ emissions start to decline well before 2030 (high confidence).
- Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (high confidence). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (medium confidence).
- The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (high confidence). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long-term (high confidence). These may increase uneven distributional impacts between countries at different stages of development (medium confidence).

4.13.