

# The Kaya Identity: Energy Use, Conservation and Efficiency

EES 2110

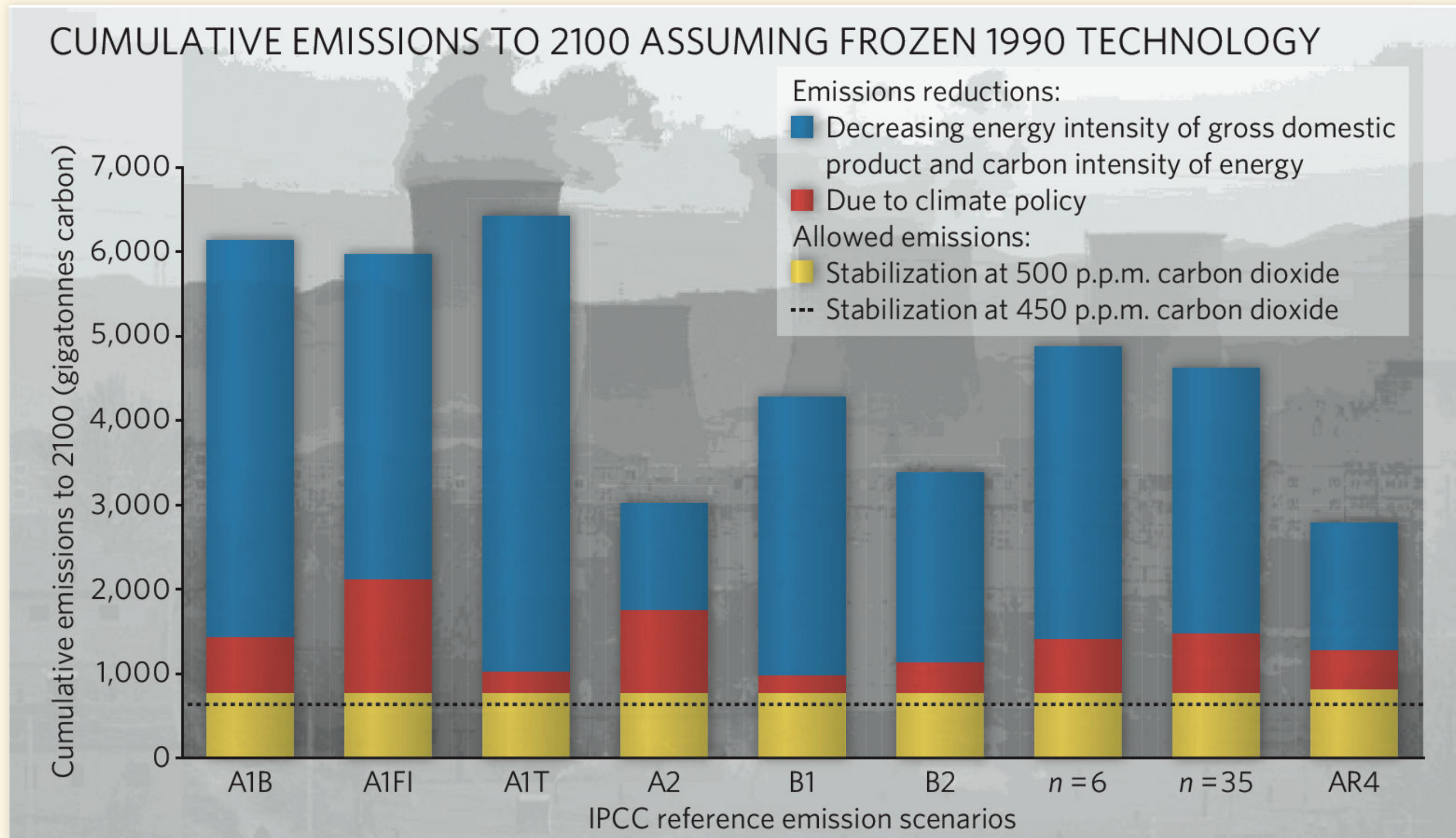
Introduction to Climate Change

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Class #30: Monday, March 27 2023

Myth 3:  
We have all  
the technology we need.

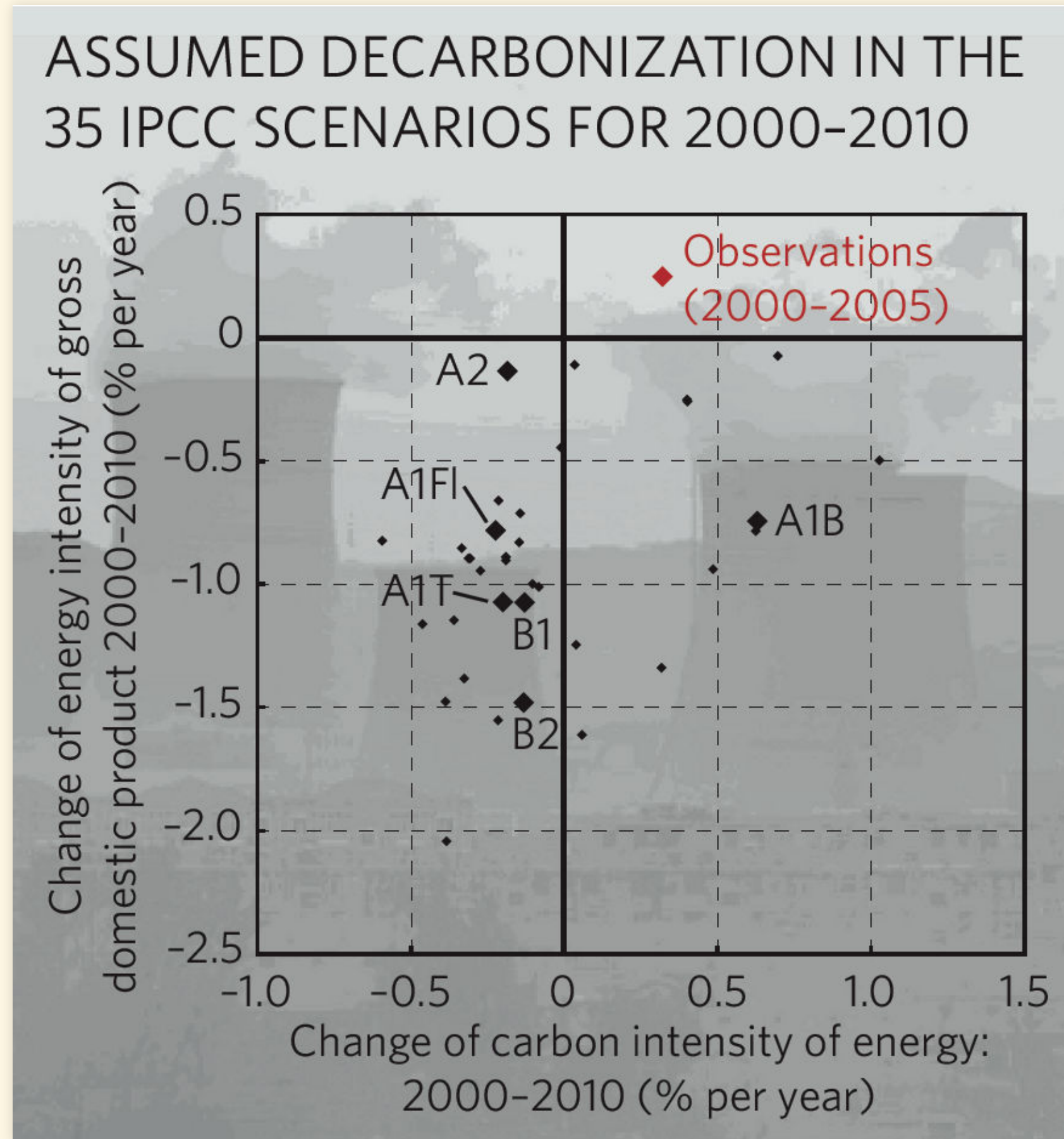
# Do we have the technology?



R.A. Pielke, Jr. et al., Nature **452**, 531 (2008). doi: 10.1038/452531a

- Blue = Assumed spontaneous emissions reduction
- Brown = Regulations
- Yellow = Allowed emissions to stabilize CO<sub>2</sub> at 550 ppm.

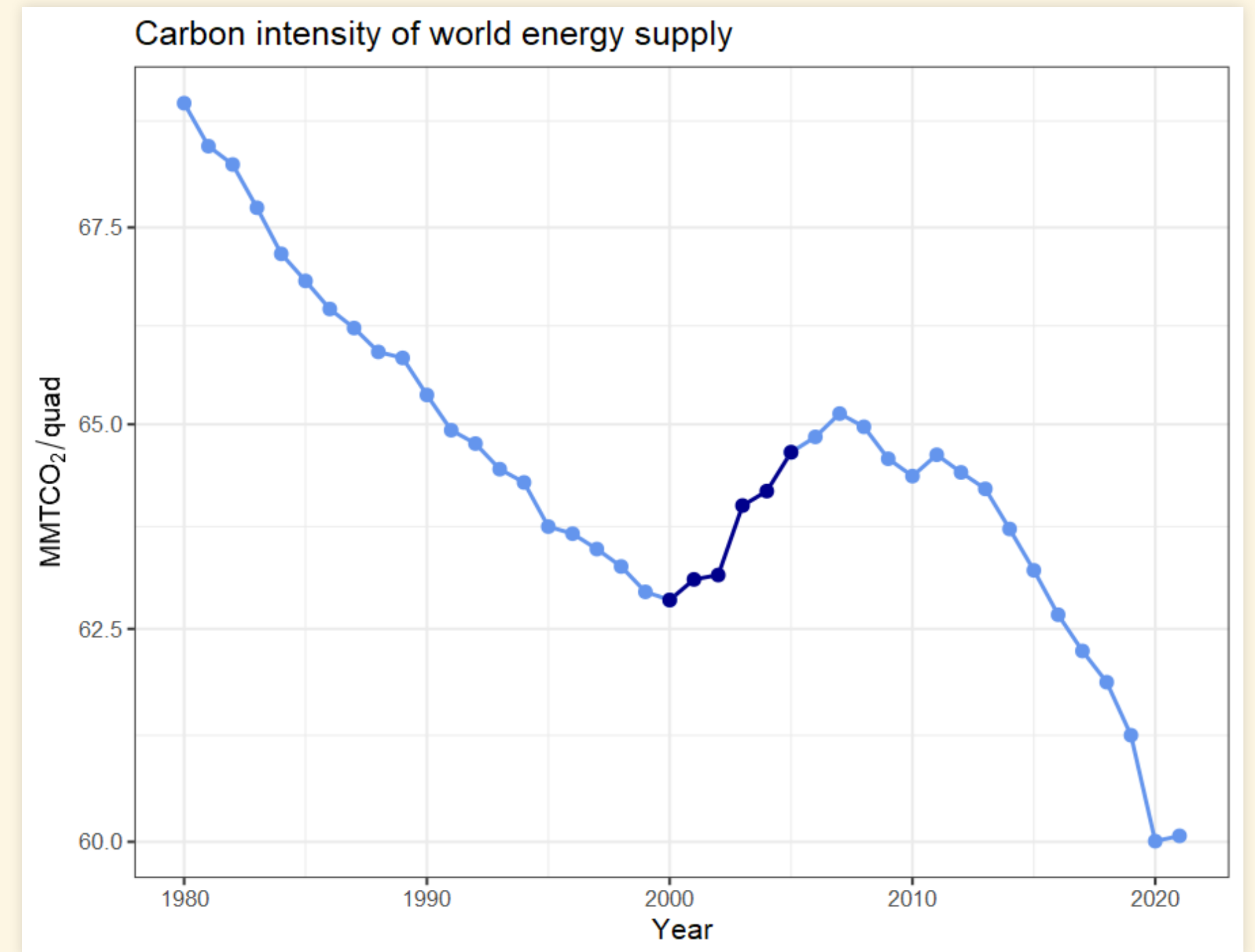
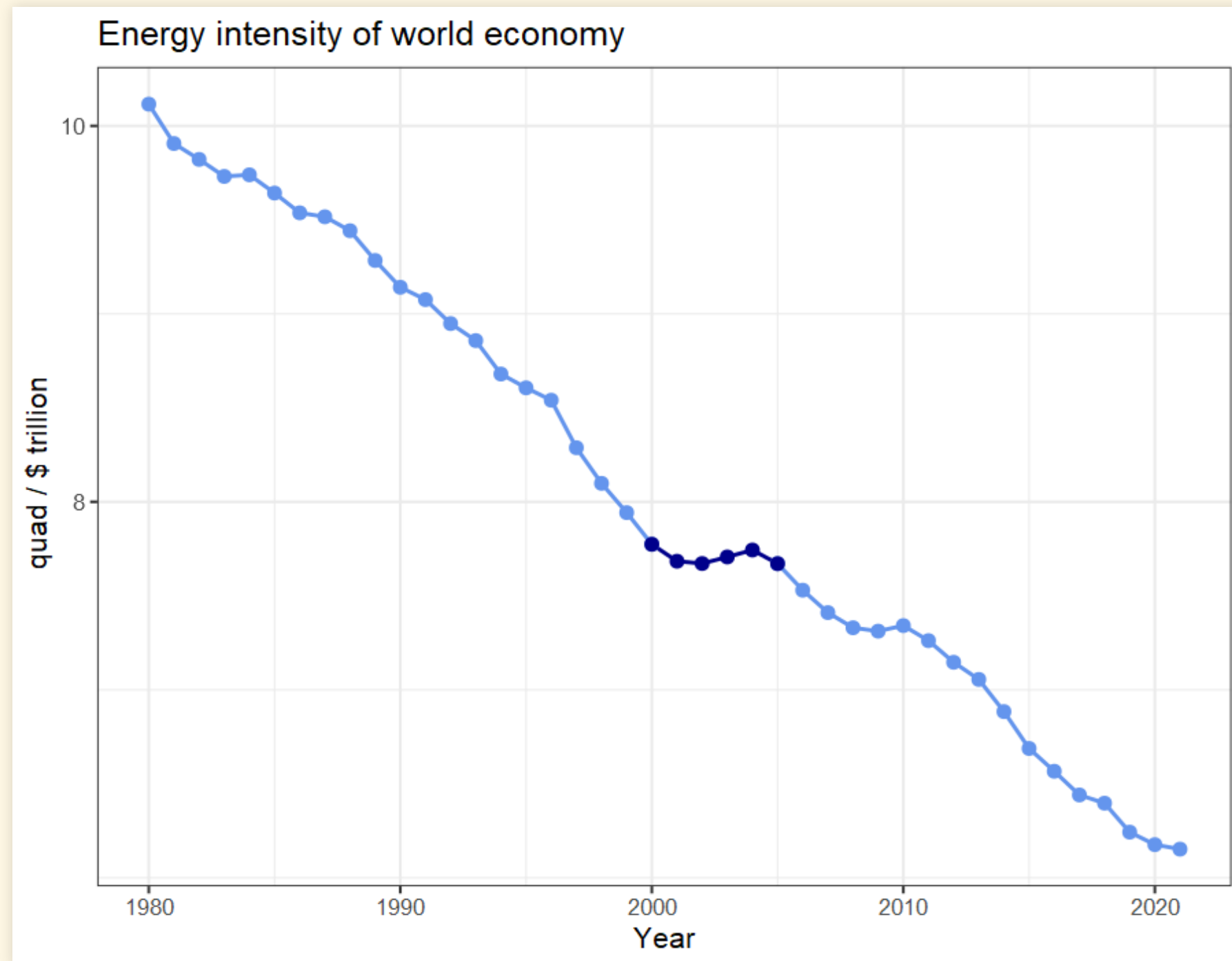
# Optimism on energy efficiency



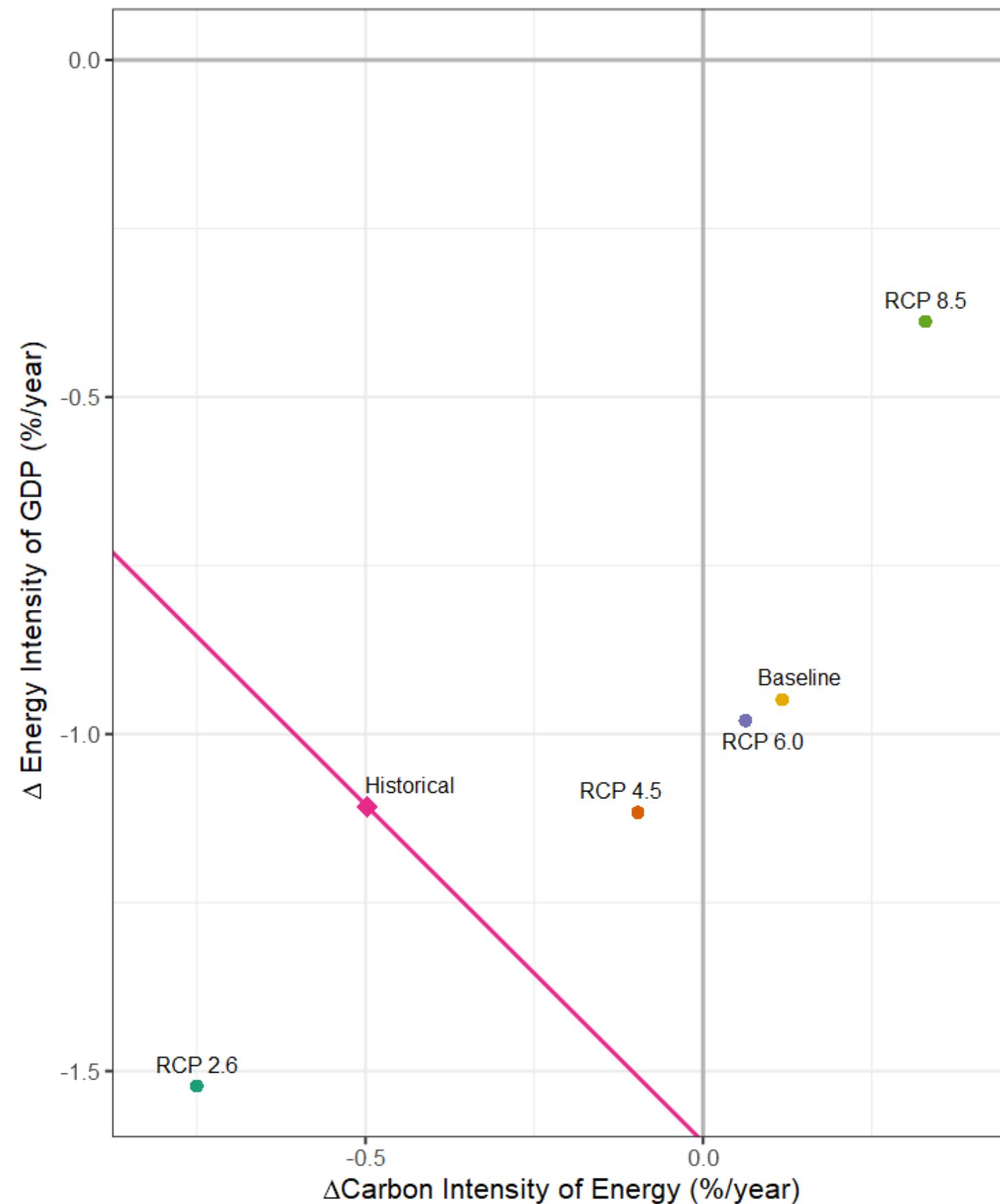


# The View from 2023:

- Pielke's numbers focus on 2000–2005
  - The years when China's economy began really rapid growth
- After 2005, things changed:



# Current Emissions Pathways



- Comparing actual trends for 2005–2021 to trends for 2005–2020 in 5 emissions scenarios:
  - Points **above & right** of the magenta line have **higher** emission trends than historical
  - Points **below & left** of the magenta line have **lower** emission trends than historical
- The historical trend from 2005–2021 is doing **better** (lower emissions) than several scenarios including baseline (no policies) and RCP 6.0 (business as usual with current policies).

# Summary

- Pielke and others were very pessimistic around 2010
- Ten years later:
  - Some reasons for greater optimism
  - But still cause for concern

# 2021 UN Report



*“Current levels of climate ambition are very far from putting us on a pathway that will meet our Paris agreement goals,” said Patricia Espinosa, executive secretary of the U.N. Framework Convention on Climate Change.*

*Even if countries follow through, [they] would put the world on a path to achieve only a 1 percent reduction in global emissions by 2030....*

*By contrast, scientists have said that emissions must fall by nearly 50 percent this decade for the world to realistically have a shot at avoiding devastating temperature rise.*



# Decarbonizing Global Economy

# Decarbonizing Global Economy

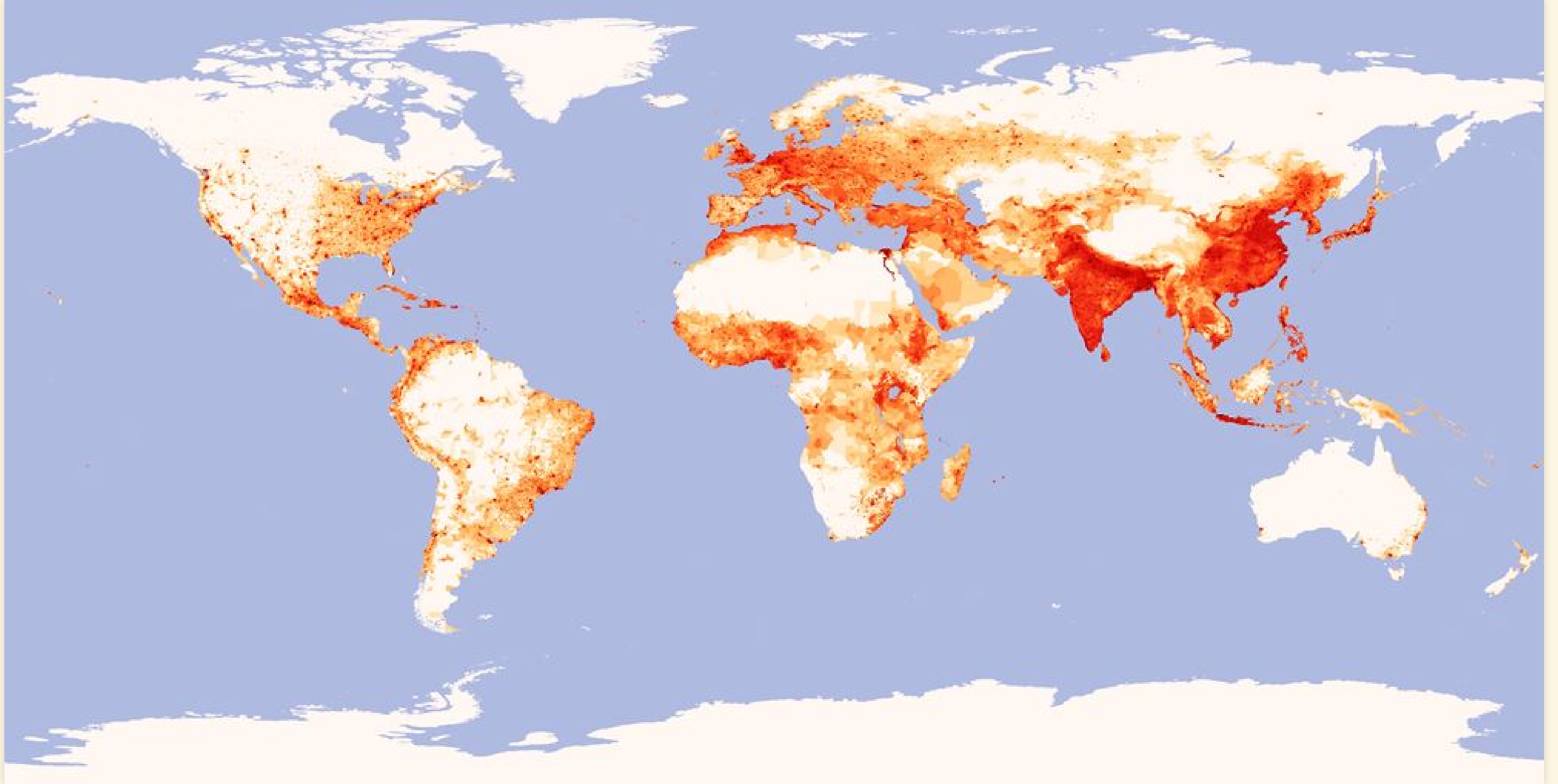
- World needs lots more energy
  - National/industrial energy poverty:
    - Energy consumption for economic growth
  - Household energy poverty:
    - Energy consumption for quality of life

# Energy



Image credit: NASA

# Population Density





# Energy Poverty



Photo: Rebecca Blackwell, Associated Press, June 2007.



# Household Energy Poverty

- Roughly 1.2 billion people do not have access to electricity.
  - Down from 1.5 billion in 2008
- Benefits of providing even a little electricity:
  - Children study 30% more with just one light bulb in home.
  - Women have more say in household decisions
  - Allows economically productive activity in evening
- Role of refrigeration in preventing disease
- Electricity and gas reduce exposure to indoor air pollution
  - Indoor air pollution from cooking, lighting kills around 4.3 million/year
- Home solar typically provides light, but insufficient for refrigeration, cooking



# Measuring Energy and Environmental Impact

# Measuring Energy

- Heat:
  - BTU (British Thermal Unit) = quantity of heat
  - Quad = quadrillion BTU
  - Kilowatt Hour (kWh): measure of electricity
- Conversions:
  - 1 quad is about 300 billion kWh
  - 1 quad per year is about 11 billion watts
    - Typical large power plant (coal or nuclear) produces an average of around 750 million watts
    - 1 quad per year is about 15 big power plants
- Magnitudes
  - World uses about 560 quads per year of primary energy
  - U.S. uses about 90 quads per year of primary energy
    - 4% of population, 16% of energy consumption

# Some Definitions:

- Primary vs. Secondary
  - Primary energy consumption = heat generated
  - Secondary energy consumption = useful energy consumed
    - Coal generation is about 33% efficient
    - Gas generation is about 45% efficient
    - A car engine is about 33% efficient
  - More efficient generation can produce more secondary energy with less primary energy.
- Nameplate vs. Average Power Output:
  - Nameplate = power when operating at 100% capacity
  - Capacity factor = average fraction of maximum capacity achieved over a year
  - Actual energy produced = nameplate power  $\times$  capacity factor  $\times$  1 year

# Kaya Identity

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$$\textcolor{firebrick}{F} = \textcolor{darkgreen}{P} \times \textcolor{blue}{g} \times \textcolor{mediumorchid}{e} \times \textcolor{crimson}{f}$$

- $\textcolor{firebrick}{F}$  = emissions (million tonnes carbon per year)
- $\textcolor{darkgreen}{P}$  = population (billions)
- $\textcolor{blue}{g}$  = per-capita GDP (\$1000 per person)
- $\textcolor{mediumorchid}{e}$  = energy intensity of economy (quads / trillion dollars)
- $\textcolor{crimson}{f}$  = carbon intensity of energy supply (million tonnes carbon / quad)

## Policy

- We can't directly control  $\textcolor{darkgreen}{P}$
- We want  $\textcolor{blue}{g}$  to grow
- Therefore, decrease  $\textcolor{mediumorchid}{e}$  and  $\textcolor{crimson}{f}$





# Economic and Energy Trends

# Interactive Tool

<https://ees2110.jgilligan.org/decarbonization/>

## Decarbonization Explorer

Country/Region

Target year

2050

Emissions reduction (%)

80

Reference year for emissions reduction

1990

Calculate trends starting in

1980

Trends

Calculations

Implied Decarbonization

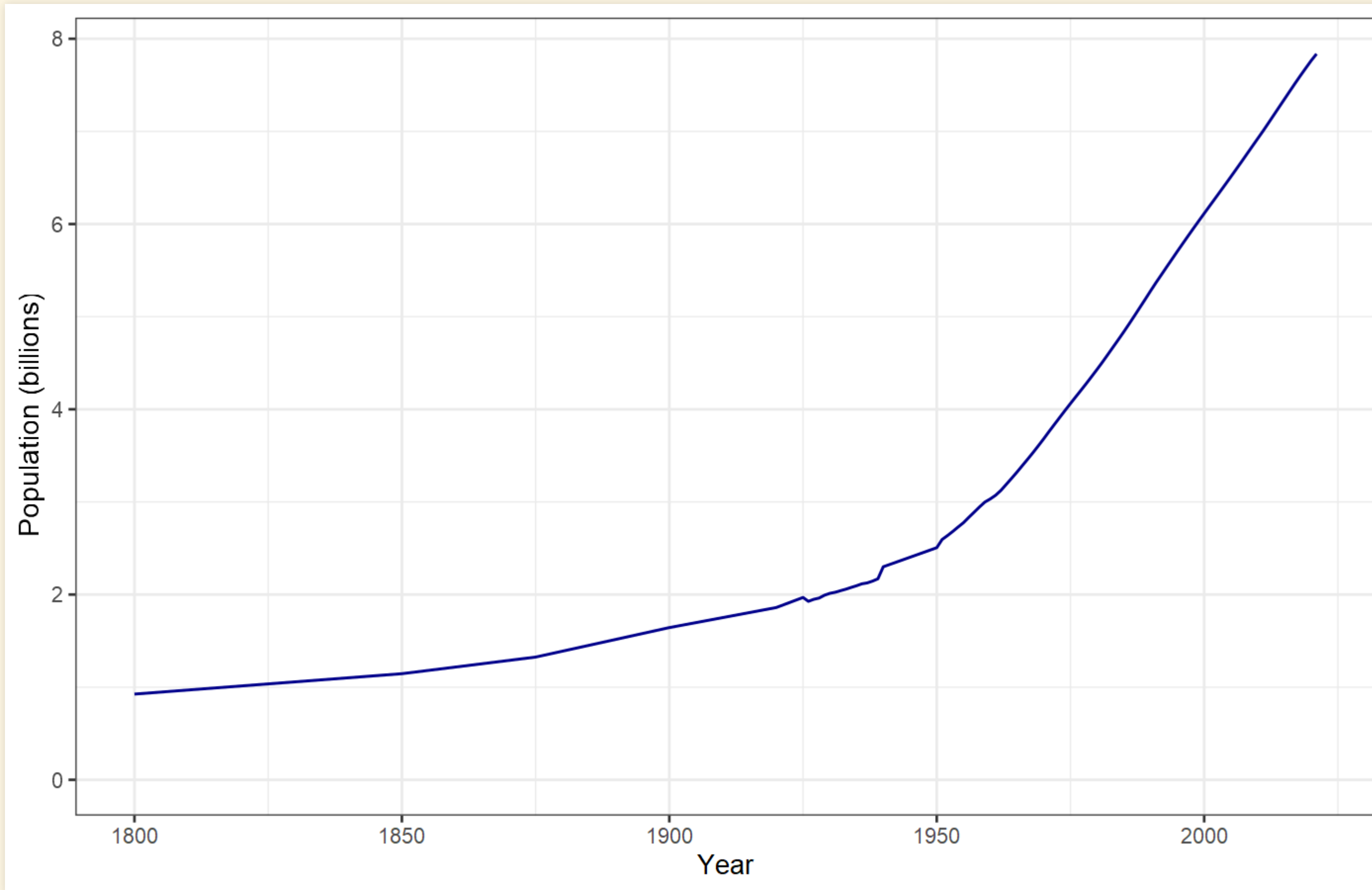
Energy Mix

Historical

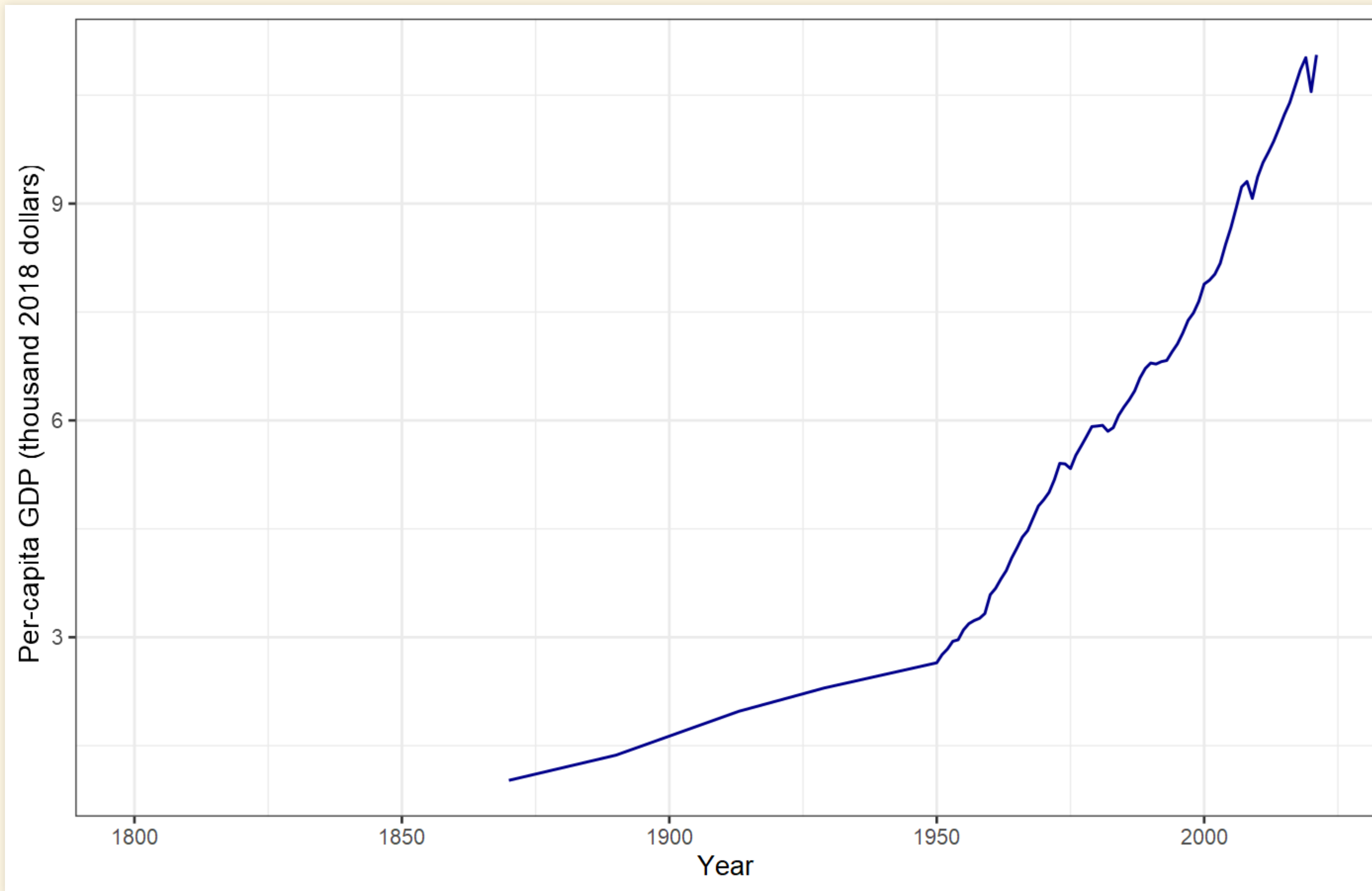
Variable

P

# Global Population ( $P$ )



# Global Economy (per-capita GDP $g$ )



# Global Income Distribution

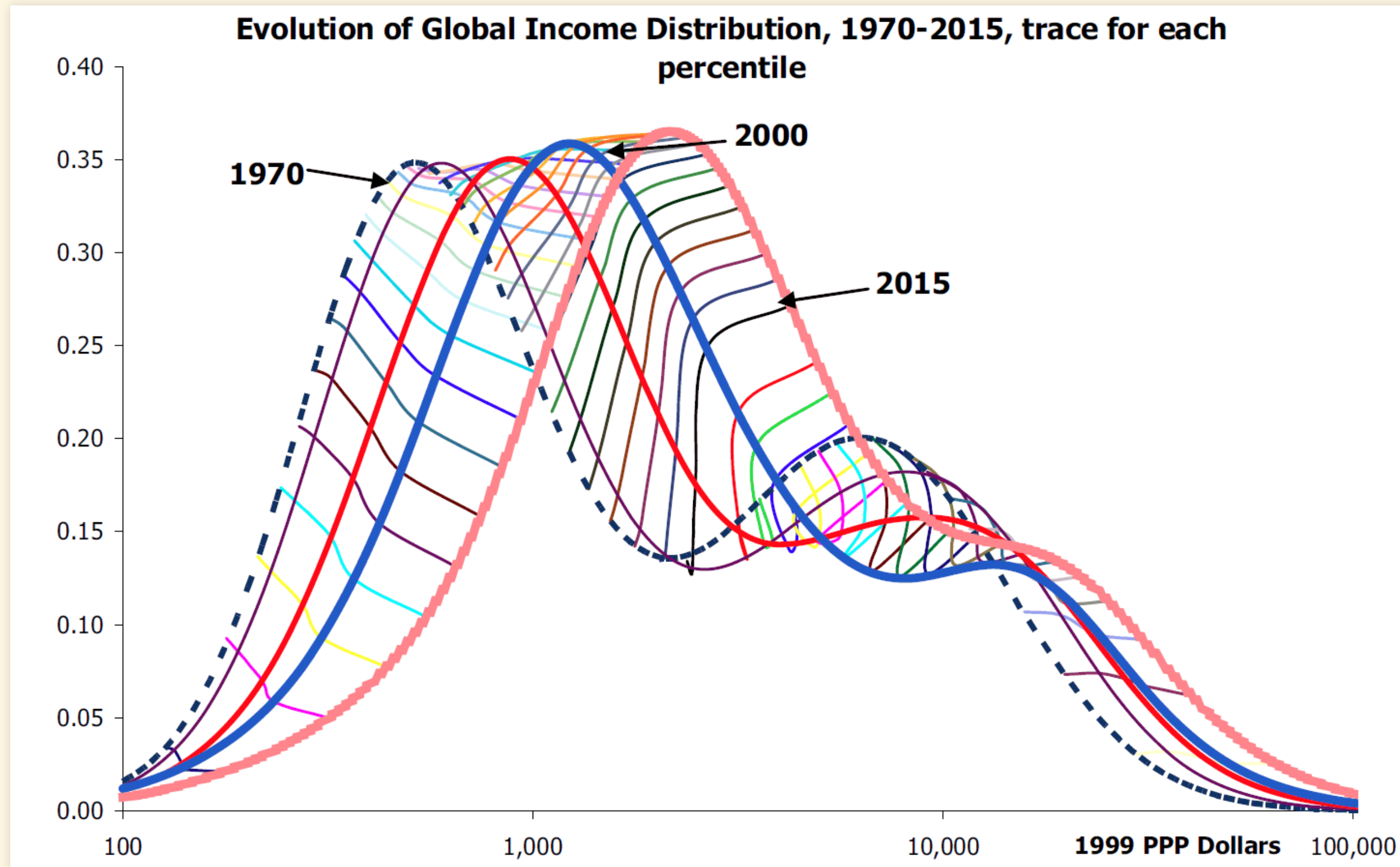


Image credit: Y. Dikhanov & M. Ward, "Evolution of the Global Distribution of Income in 1970-99" (2001).

- Big drop in "desperate poverty"
- Growth of global middle-class

# Global Income Distribution

Figure 5: Global distribution of income (using top-heavy adjustment)  
compared with standard income from surveys alone, logarithmic scale, population-weighted

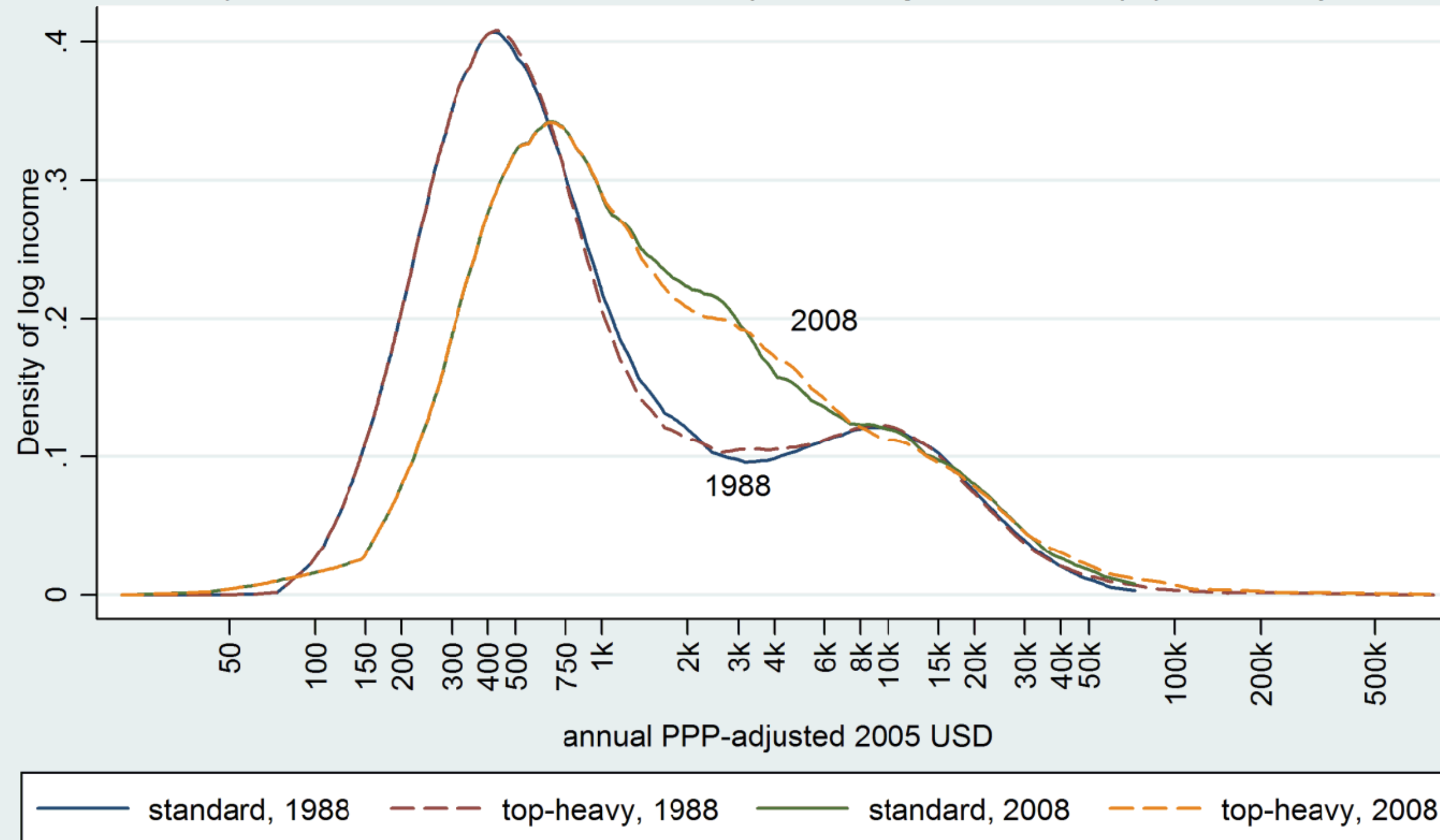


Image credit: B. Milanovic, *Global Inequality* (Harvard, 2016).

- Rightward movement of lower end: Big drop in poverty
- Growing lump in middle: Rise of global middle-class



# Global Income Growth over Time

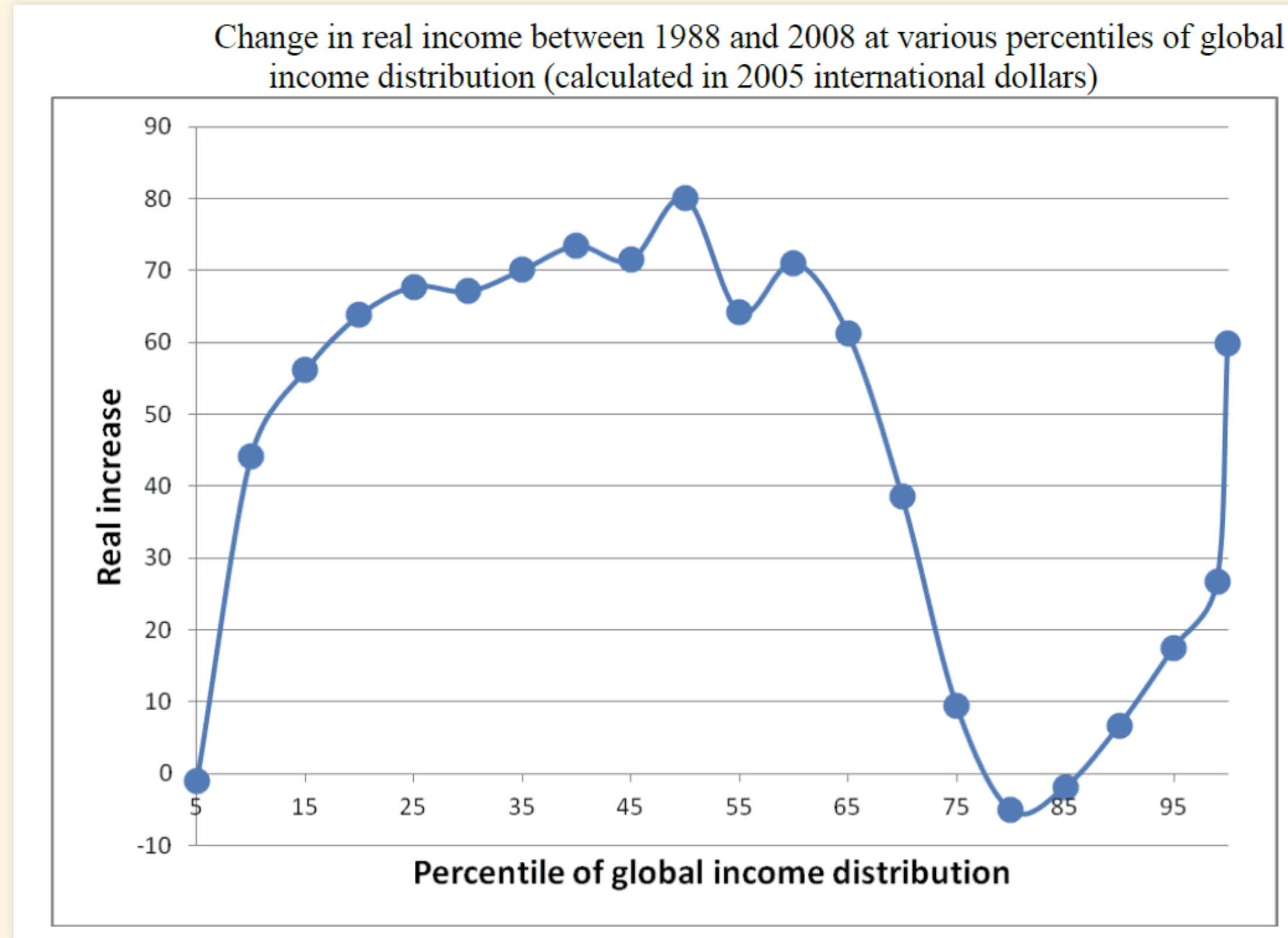
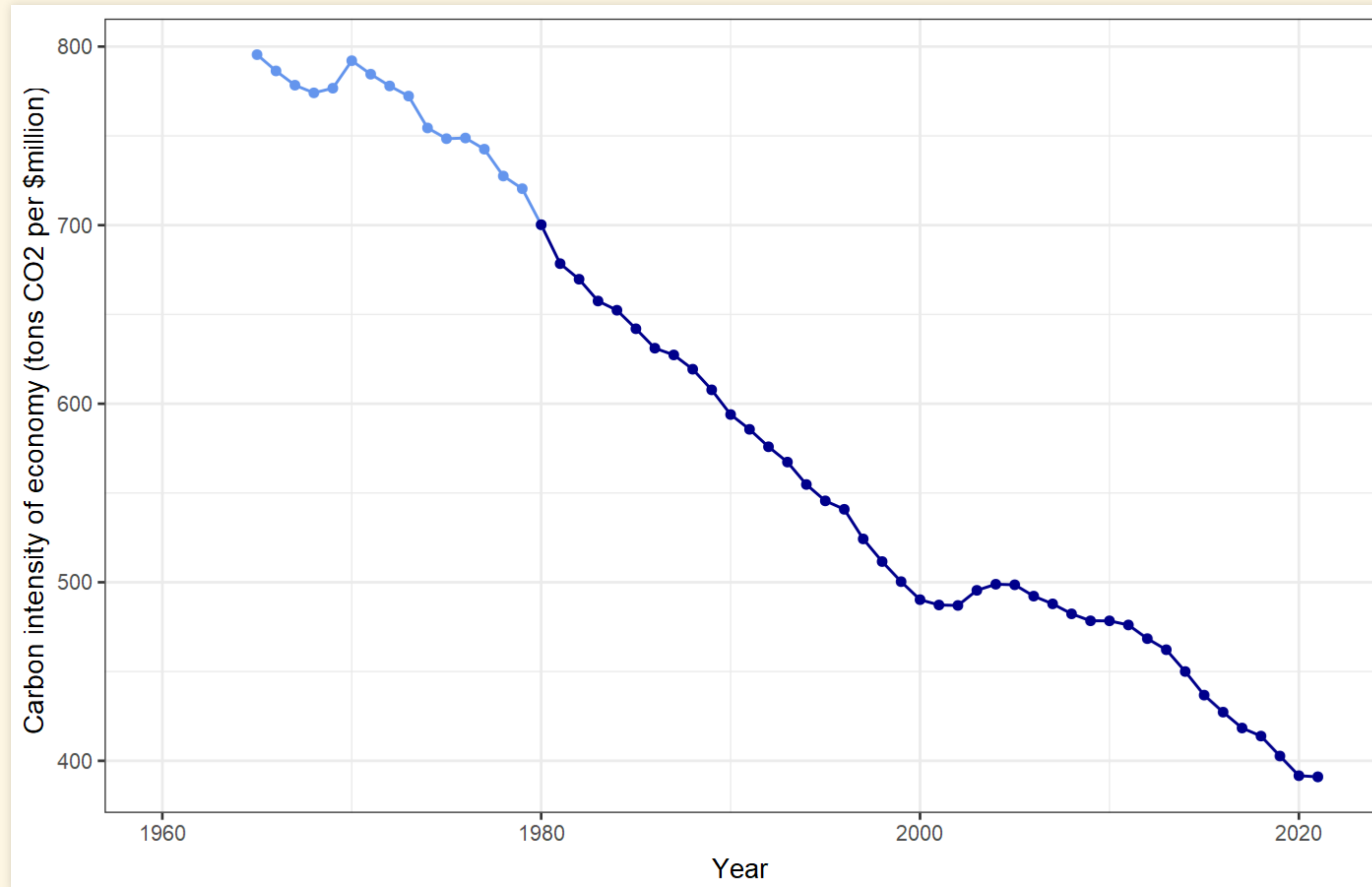


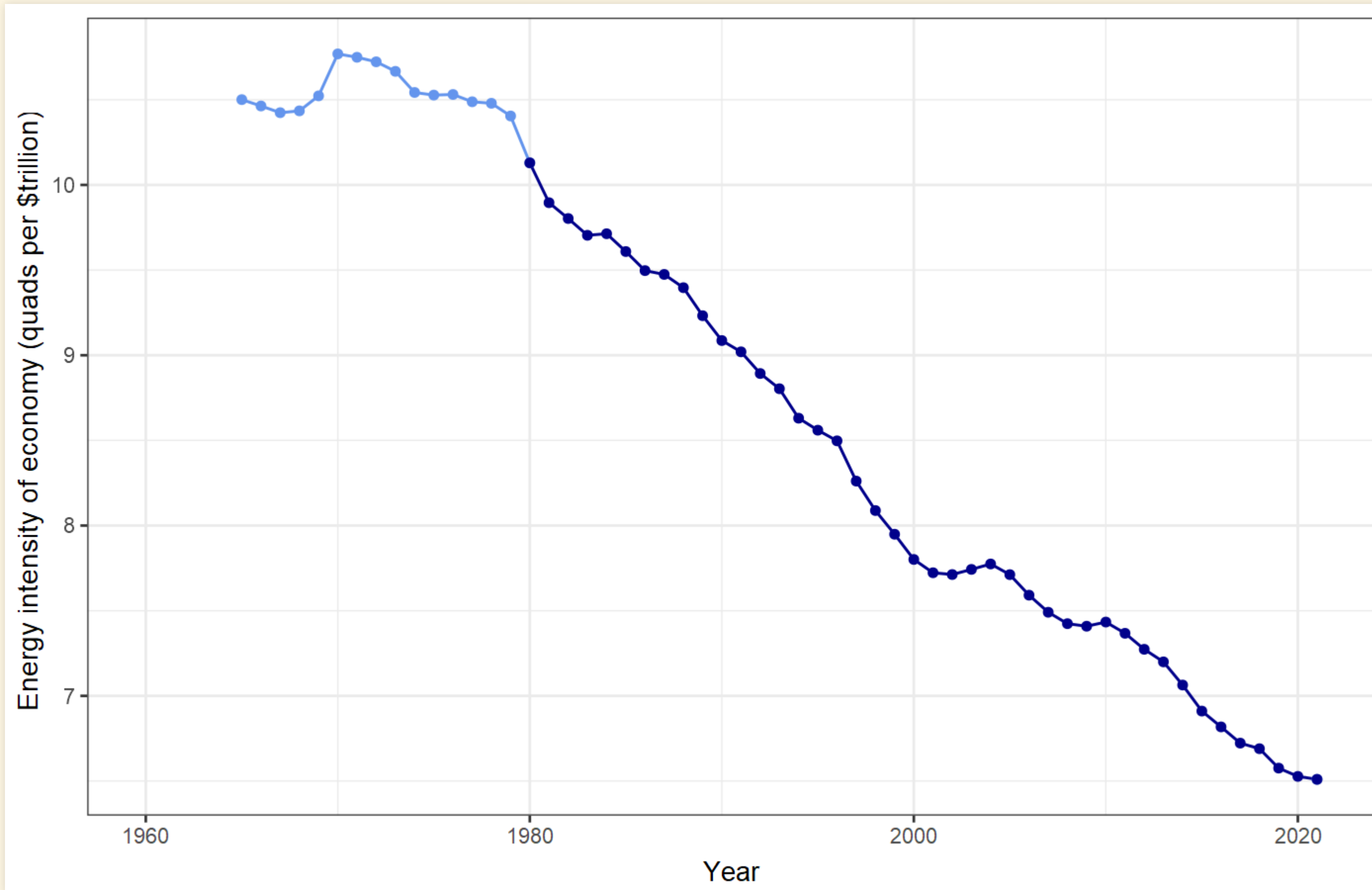
Image credit: B. Milanovic, *Global Inequality* (Harvard, 2016).

- Biggest gains for 10<sup>th</sup>–65<sup>th</sup> percentile (poor and middle class)
- Losses for 80<sup>th</sup>–85<sup>th</sup> percentile (middle class of rich nations)
- Big gains for richest 5% (> \$75,000 US)

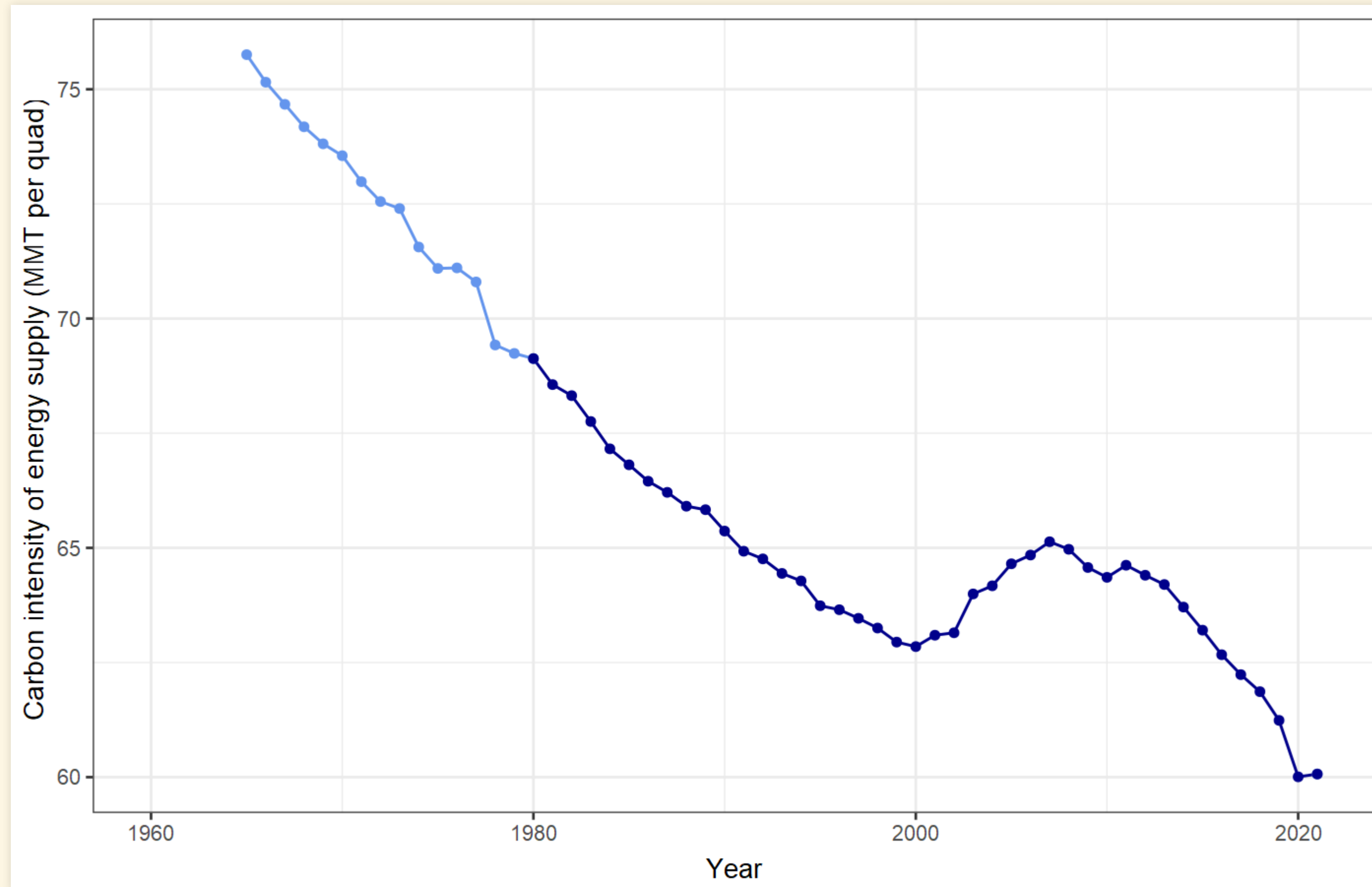
# Emissions Intensity of Global Economy ( $ef$ )



# Energy Intensity of Global Economy ( $e$ )



# Carbon Intensity of Global Energy Supply ( $f$ )



# Implied Decarbonization

# Implied Decarbonization

- Specify emissions for 2050, compared to 2010
- Assume global GDP  $(G)$  grows at rate  $(r)$  (5%  $\rightarrow r = 0.05$ )

$$\begin{aligned} \text{emissions: } F &= P \cdot g \\ e \cdot f &= G \cdot \text{times} \\ F(2050) &= G(2050) \cdot \text{times} \\ e \cdot f(2050) \end{aligned}$$

## Growth:

$$\begin{aligned} y(\text{5 years from now}) &= y(\text{today}) \cdot \exp(r \cdot 5) \\ &\approx y(\text{today}) \cdot (1 + r)^5 \end{aligned}$$

- $\exp$  = exponential function  $(e^x)$ .
- Call it “exp” to avoid confusing  $e$  in Kaya formula with  $e$ , base of natural logarithm.

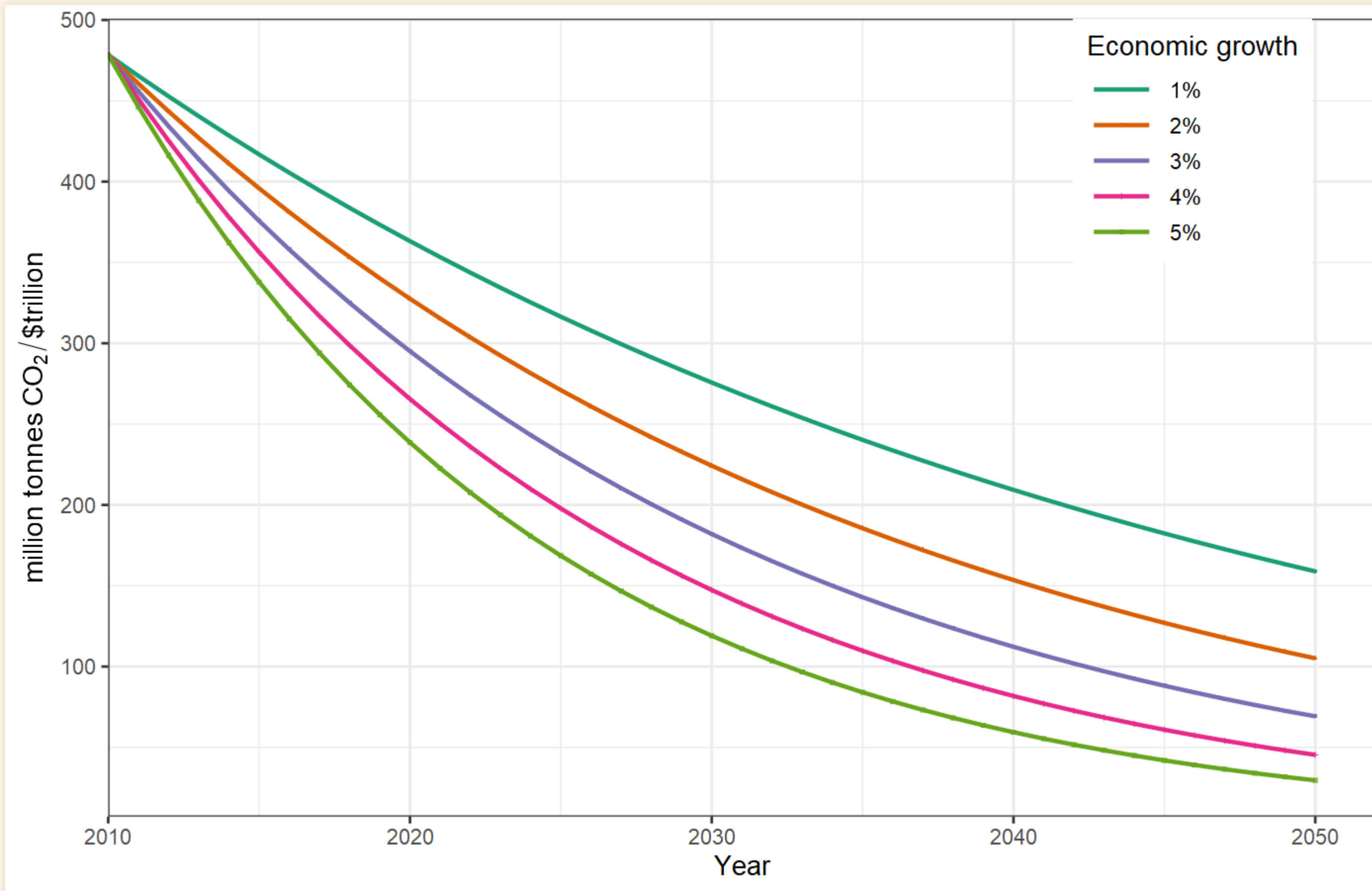


# Implied Decarbonization

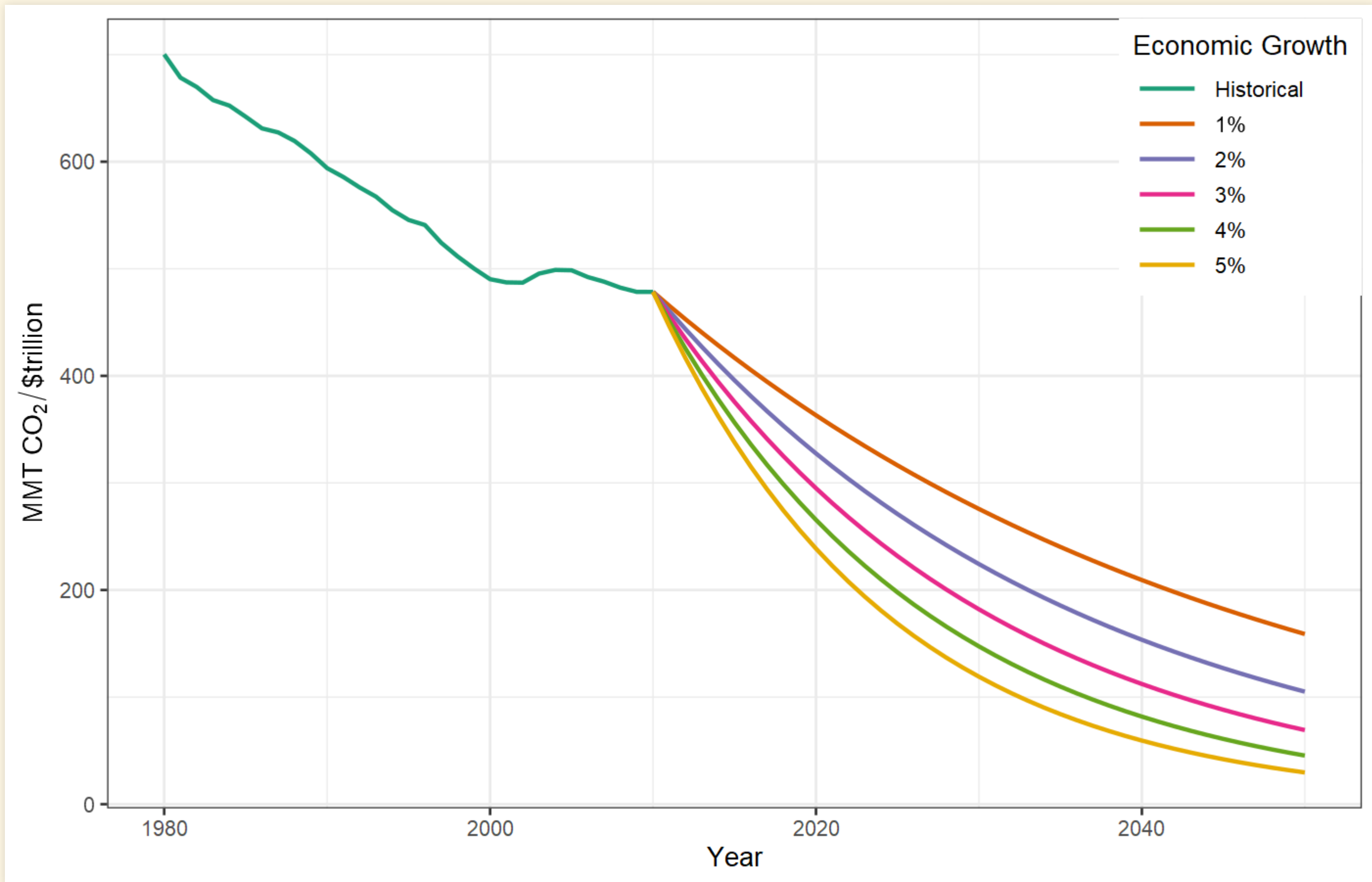
- Specify emissions for 2050, compared to 2010
- Assume global GDP  $\{\color{darkcyan}G\}$  grows at rate  $\{r\}$  (5%  $\rightarrow \{r = 0.05\}$ )

$$\begin{aligned} \text{emissions: } \{\color{firebrick}F\} &= \{\color{darkgreen}P\} \{\color{blue}g\} \{\color{mediumorchid}e\} \{\color{crimson}f\} = \{\color{darkcyan}G\} \times \{\color{mediumorchid}e\} \{\color{crimson}f\} \\ \{\color{firebrick}F\}(2050) &= \{\color{darkcyan}G\}(2050) \times \{\color{mediumorchid}e\} \{\color{crimson}f\}(2050) \\ \{\color{mediumorchid}e\} \{\color{crimson}f\}(2050) &= \{\color{darkcyan}G\}(2050) \times \{\color{mediumorchid}e\} \{\color{crimson}f\}(2010) \times \exp(r \times (2050 - 2010)) \\ \{\color{crimson}f\}(2050) &= \frac{\{\color{firebrick}F\}(2050)}{\{\color{darkcyan}G\}(2050)} = \frac{\{\color{firebrick}F\}(2050)}{\{\color{darkcyan}G\}(2010) \times \exp(r \times 40)} \approx \frac{\{\color{firebrick}F\}(2050)}{\{\color{darkcyan}G\}(2010) \times (1 + r)^{40}} \end{aligned}$$

# Reduce emissions 50% by 2050:



# Actual and Implied Decarbonization



# Pielke's Policy Criteria

1. Policies should flow with public opinion
2. Public will not tolerate significant short-term costs, even for big long-term benefits
3. Policy must center on clean energy innovation

