# Role of energy systems in meeting climate change mitigation targets

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Santa Fe Institute

# Today's agenda

- Role of energy systems in climate change mitigation
- Evaluating energy technologies against climate targets

# Lecture 1 outline: role of energy systems

- Carbon cycle and emission sources
- Mitigation scenarios
- Role of supply-side technology transformation

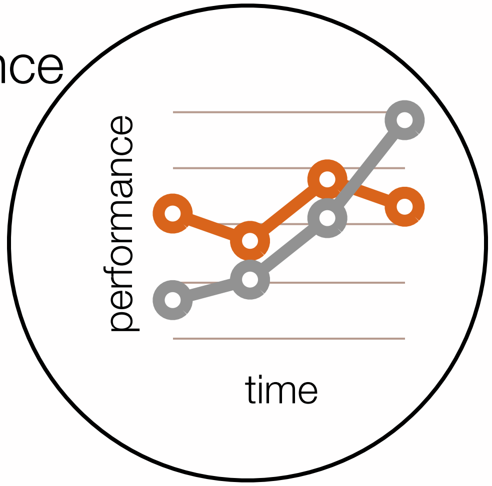
# Lecture 2 outline: evaluating energy technologies

- Technology innovation dynamics

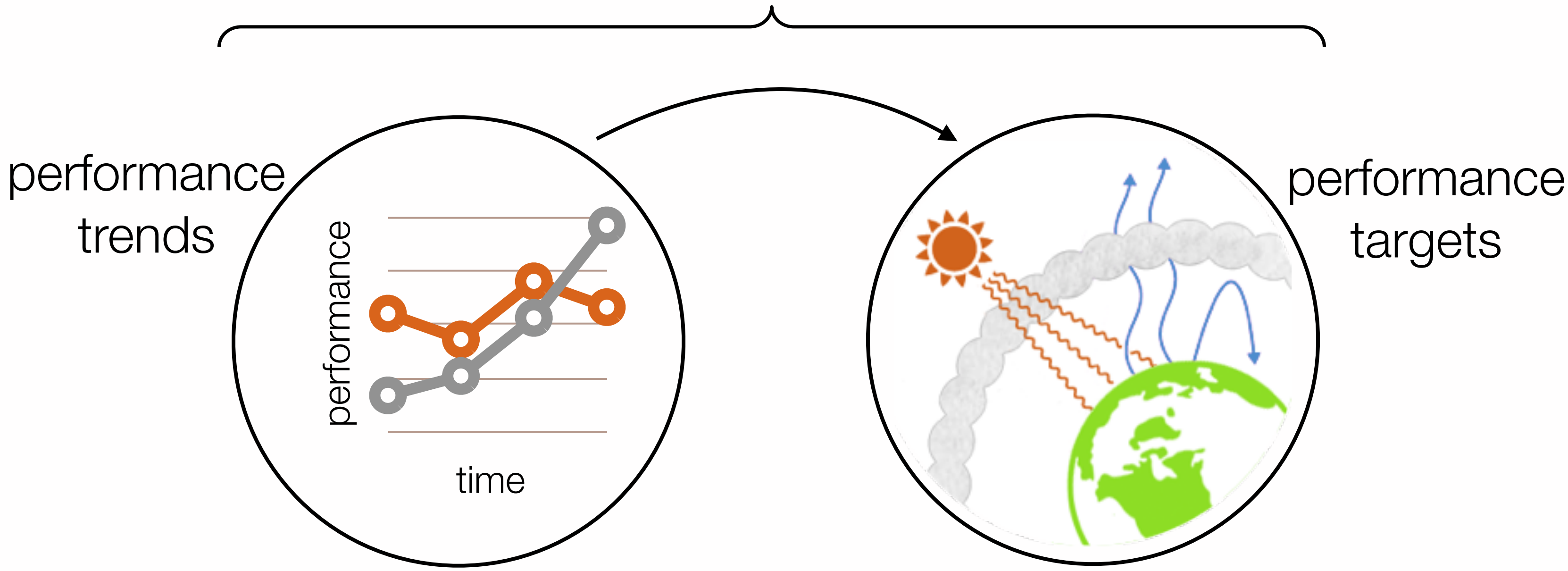
- Evaluating technologies against demand patterns

# Modeling energy systems

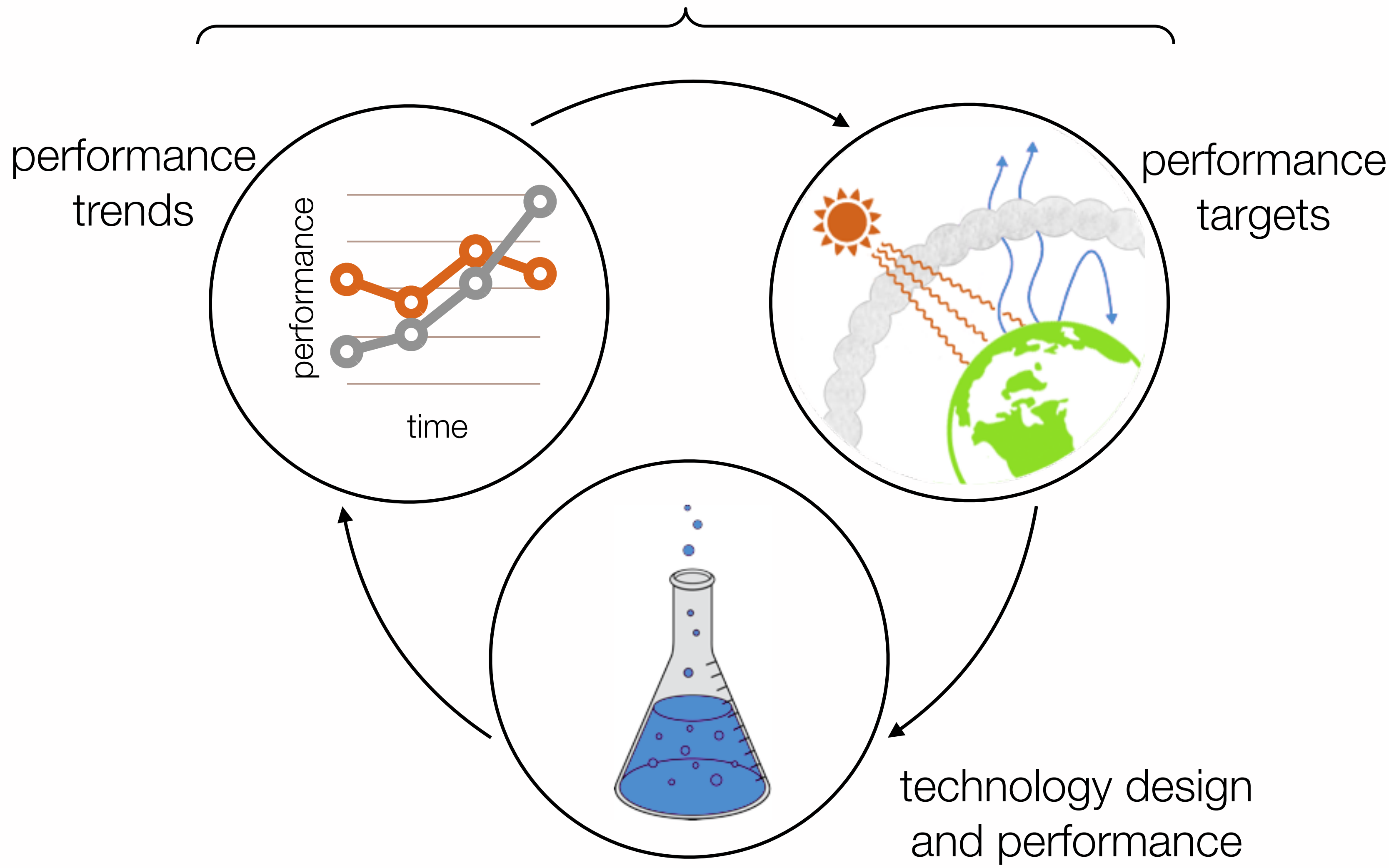
performance
trends



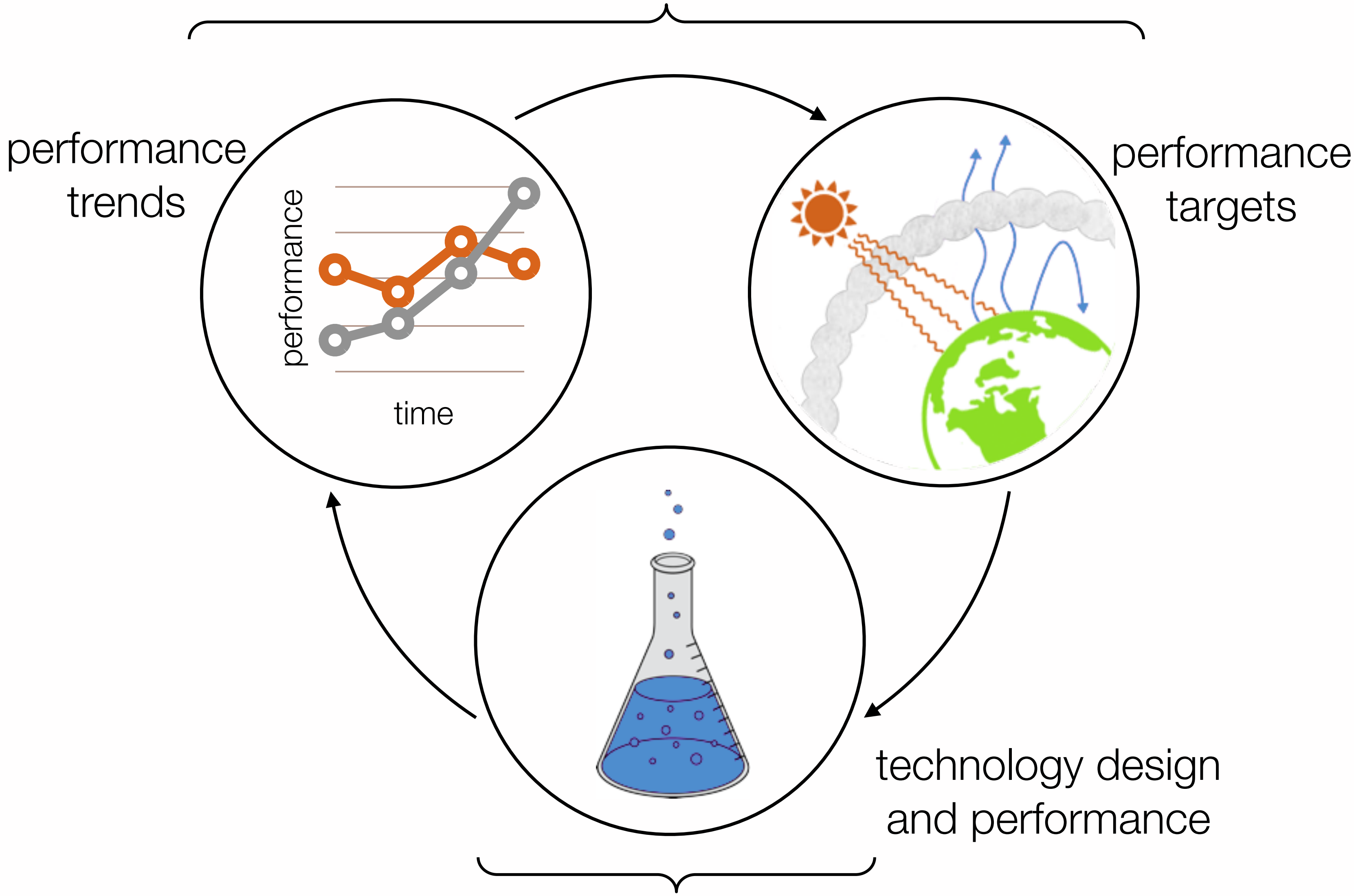
# Modeling energy systems



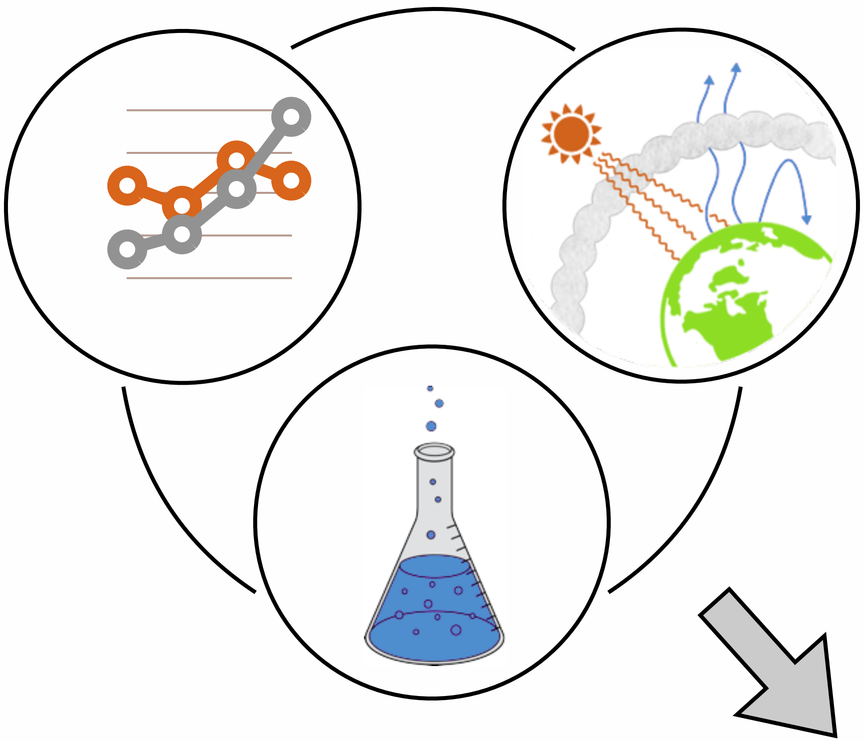
# Modeling energy systems



Modeling energy systems




to accelerate low-carbon technology development



Research results inform decisions:

- engineers
- private investors
- policy makers (R&D, regulations)

# Research examples: directed innovation

- Cost, performance trends and limits for solar, other techs
- Cost targets for stationary storage
- Battery performance targets for electric vehicles
- Methane emissions targets for natural gas as a bridge fuel

# Research examples: directed innovation

- Cost trends and limits for solar, other techs
  - Will x-Si photovoltaics costs continue to fall?

- Cost targets for stationary storage

- Battery performance targets for electric vehicles

- Methane emissions targets for natural gas as a bridge fuel

Trancik, *Nature* 2014; Kavlak, McNerney, Jaffe, Trancik, 2015; Nagy, Farmer, Bui, Trancik *PLoS One*, 2013; Bettencourt, Trancik, Kaur, *PLoS ONE* 2013; McNerney, Farmer, Trancik, *Energy Policy* 2011; McNerney, Farmer, Redner, Trancik *PNAS* 2011

# Research examples: directed innovation

- Cost trends and limits for solar, other techs
- Cost targets for stationary storage
  - Flow batteries or Li-ion for renewables integration?
- Battery performance targets for electric vehicles
- Methane emissions targets for natural gas as a bridge fuel

Braff, Mueller, Trancik, *Nature Climate Change*, 2016; Pereira, Trancik, in prep.; Mueller, Trancik, in prep.

# Research examples: directed innovation

- Cost trends and limits for solar, other techs
- Cost targets for stationary storage
- Battery performance targets for electric vehicles
  - Energy density required for widespread electrification?
- Methane emissions targets for natural gas

Needell, McNerney, Chang, Trancik, to appear in *Nature Energy*, 2016; Miotti, Supran, Kim, Trancik, to appear in *ES&T* 2016; Needell, McNerney, Chang, Miotti, Trancik, in prep.

# Research examples: directed innovation

- Cost trends and limits for solar, other techs
- Cost targets for stationary storage
- Battery performance targets for electric vehicles
- Methane emissions targets for natural gas
    - Can natural gas serve as an effective bridge fuel?

Edwards, Trancik, *Nature Climate Change* 2014; Roy, Edwards, Trancik, *Environmental Research Letters* 2015; Edwards, McNerney, Trancik, in review

# Research examples: directed innovation

- Cost trends and limits for solar, other techs
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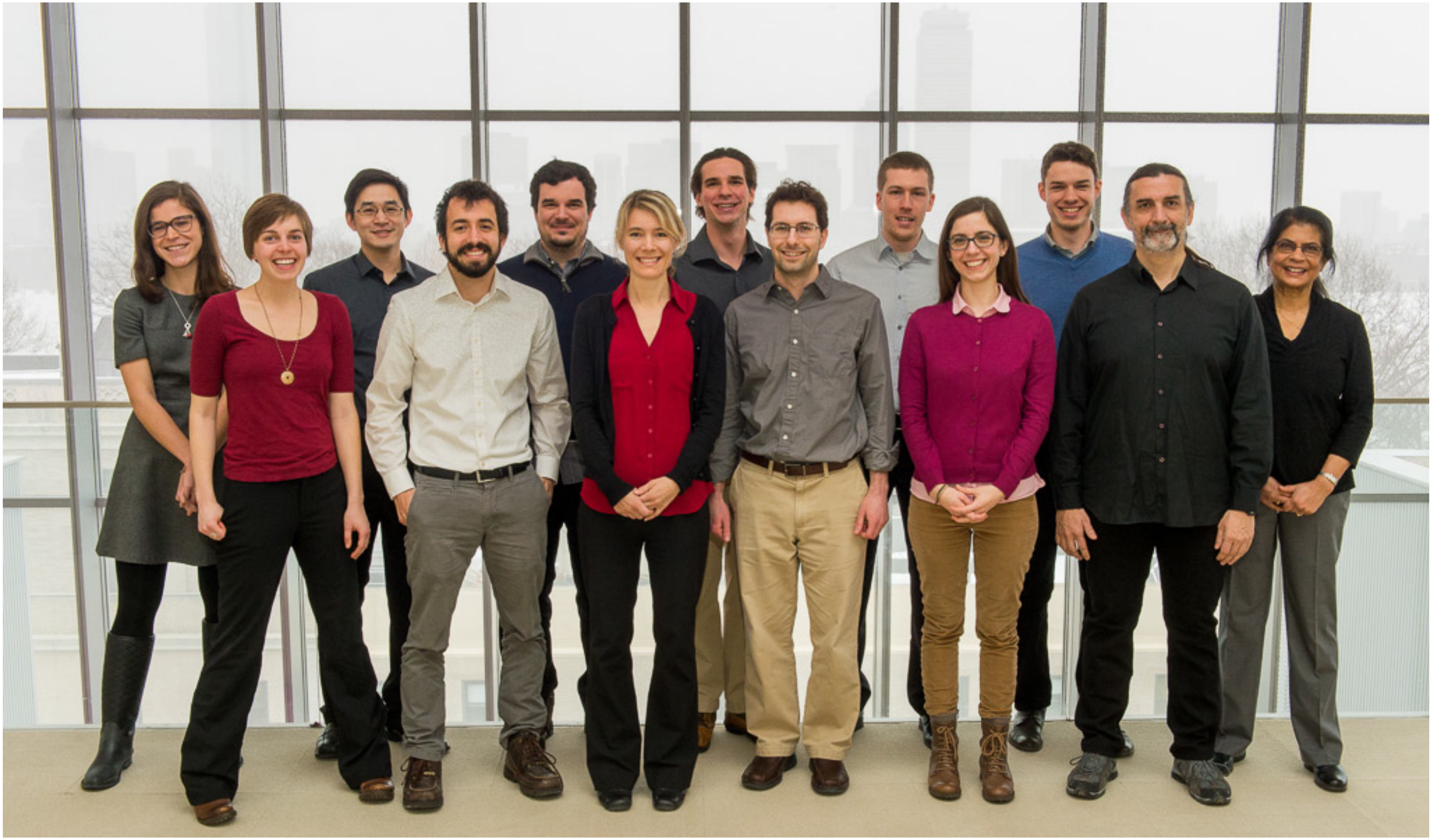
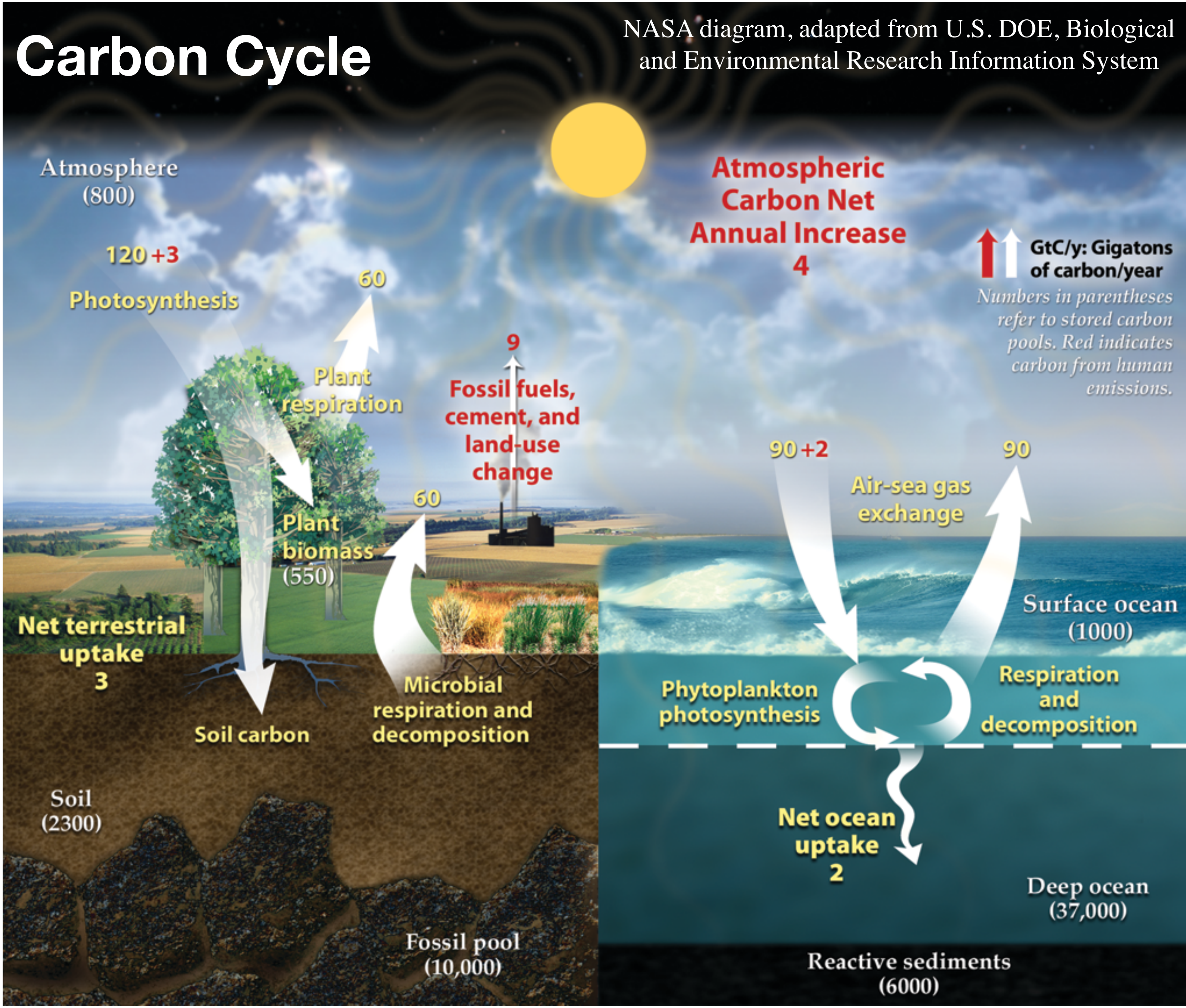
**New fundamental understanding required of:**
temporal patterns and determinants of technological improvement, energy consumption, and environmental impact.



Magdalena Klemun, Michael Chang, Gonçalo Pereira, Joshua Mueller, Fabian Riether, Marco Miotti, Mandira Roy
Morgan Edwards, Zach Needell, Jessika Trancik, James McNerney, Göksin Kavlak, Victor Ocana

# Lecture 1 outline

- Carbon cycle and emission sources
- Mitigation scenarios
- Role of supply-side technology transformation


Carbon Cycle
NASA diagram, adapted from U.S. DOE, Biological and Environmental Research Information System
Atmosphere (800)
120 +3
Photosynthesis
60
Plant respiration
9
Fossil fuels, cement, and land-use change
Atmospheric Carbon Net Annual Increase 4
GtC/y: Gigatons of carbon/year
Numbers in parentheses refer to stored carbon pools. Red indicates carbon from human emissions.
60
Plant biomass (550)
Net terrestrial uptake 3
Soil carbon
Microbial respiration and decomposition
90 +2
Air-sea gas exchange
90
Surface ocean (1000)
Phytoplankton photosynthesis
Respiration and decomposition
Net ocean uptake 2
Soil (2300)
Fossil pool (10,000)
Deep ocean (37,000)
Reactive sediments (6000)

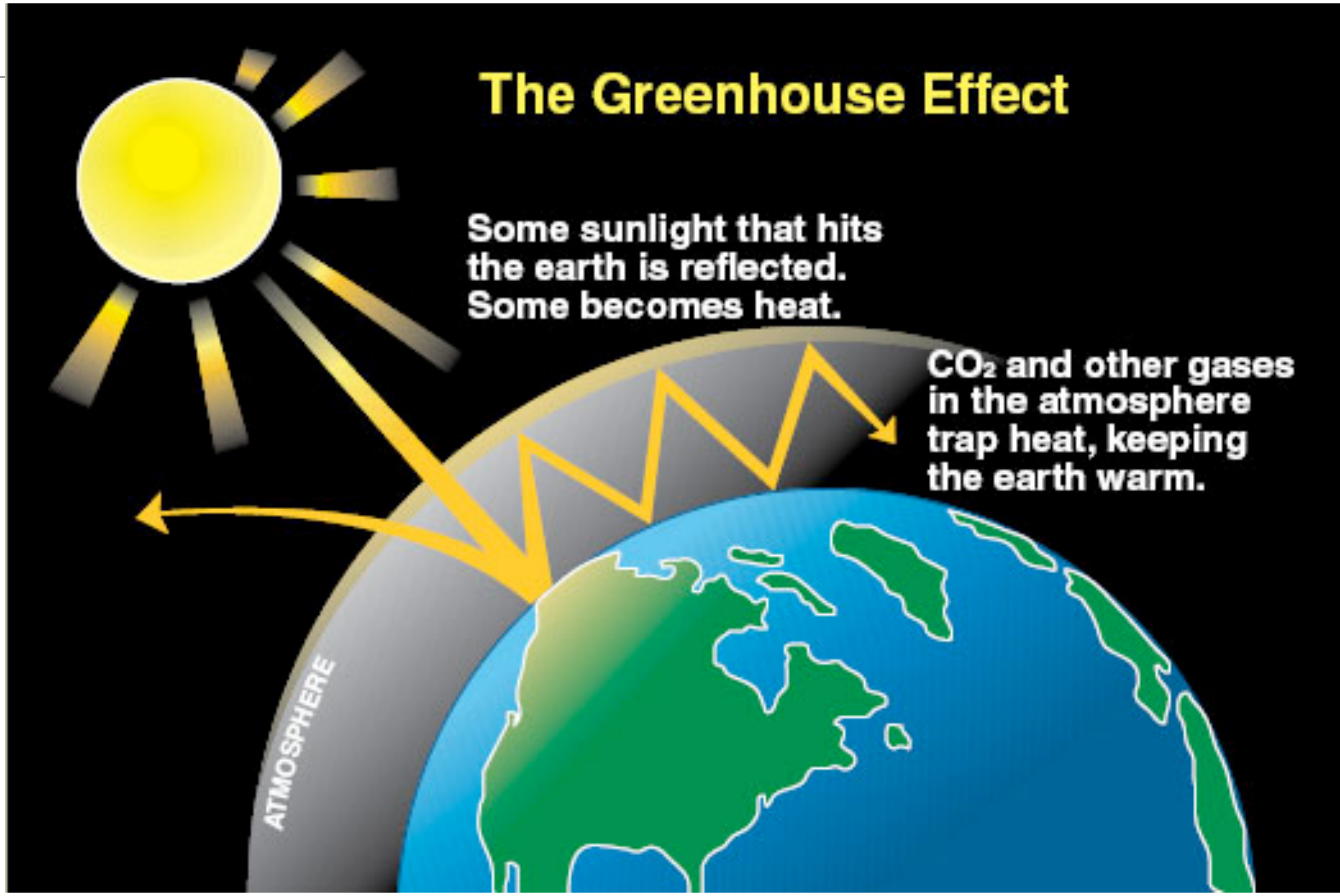
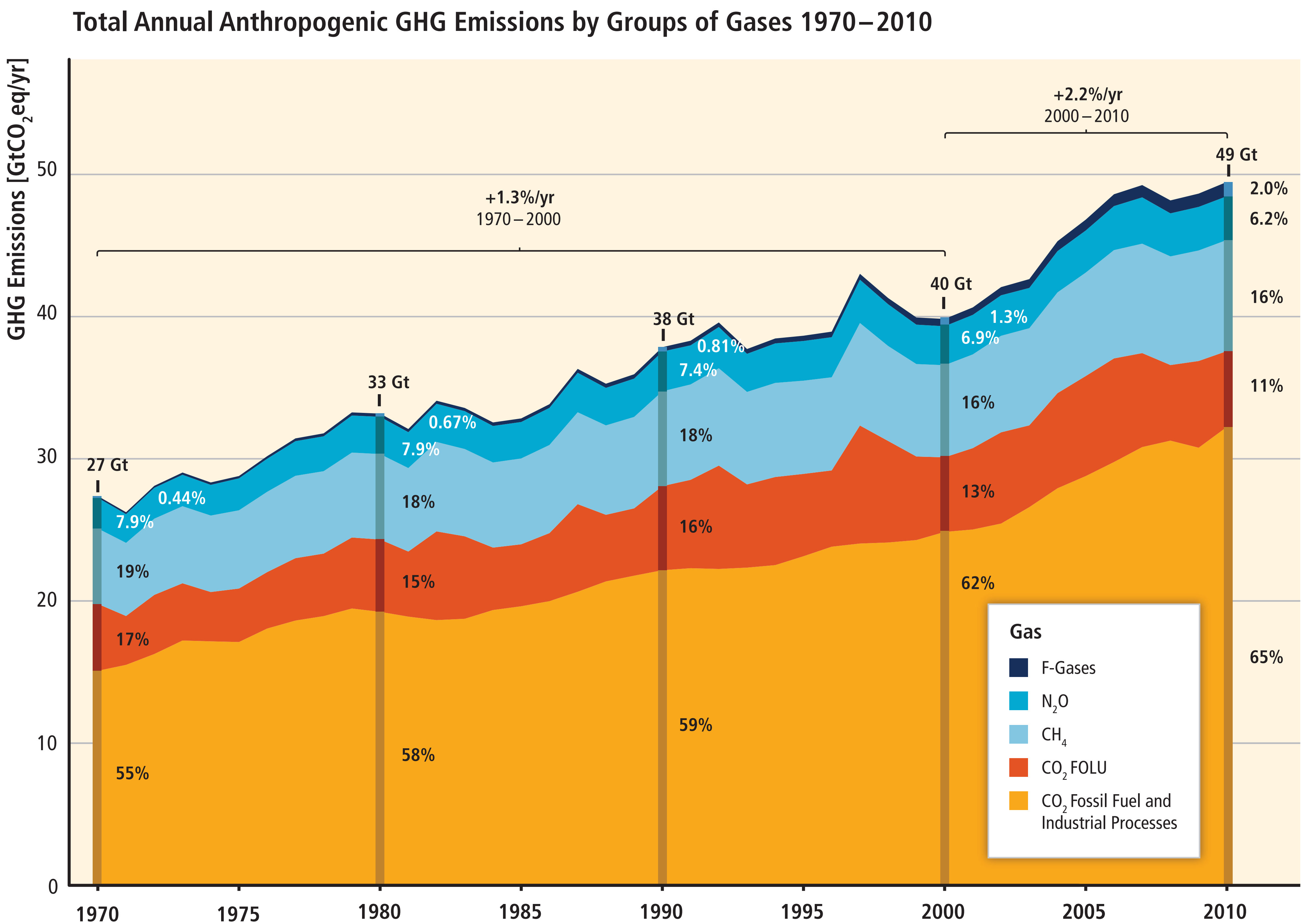
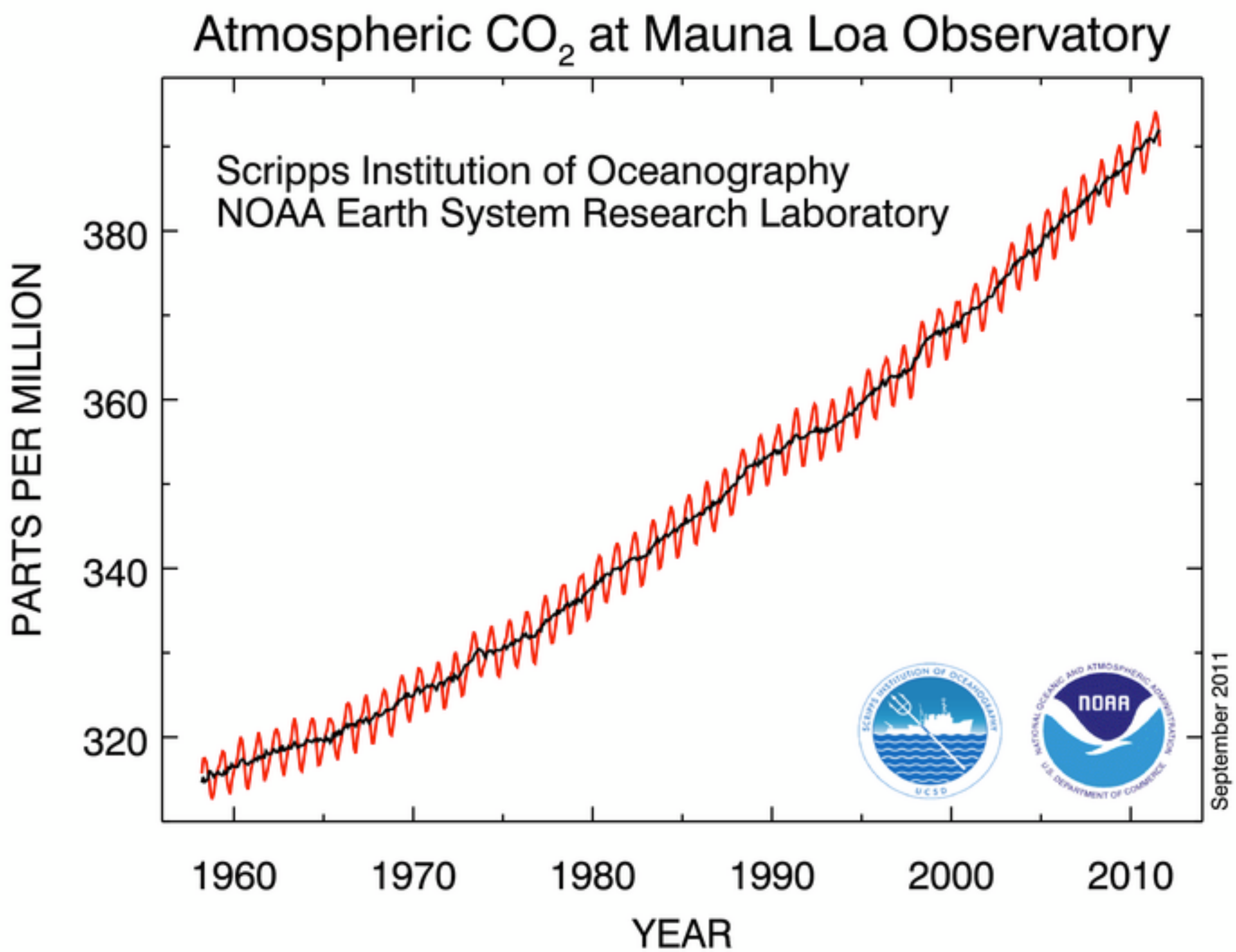



image from NOAA

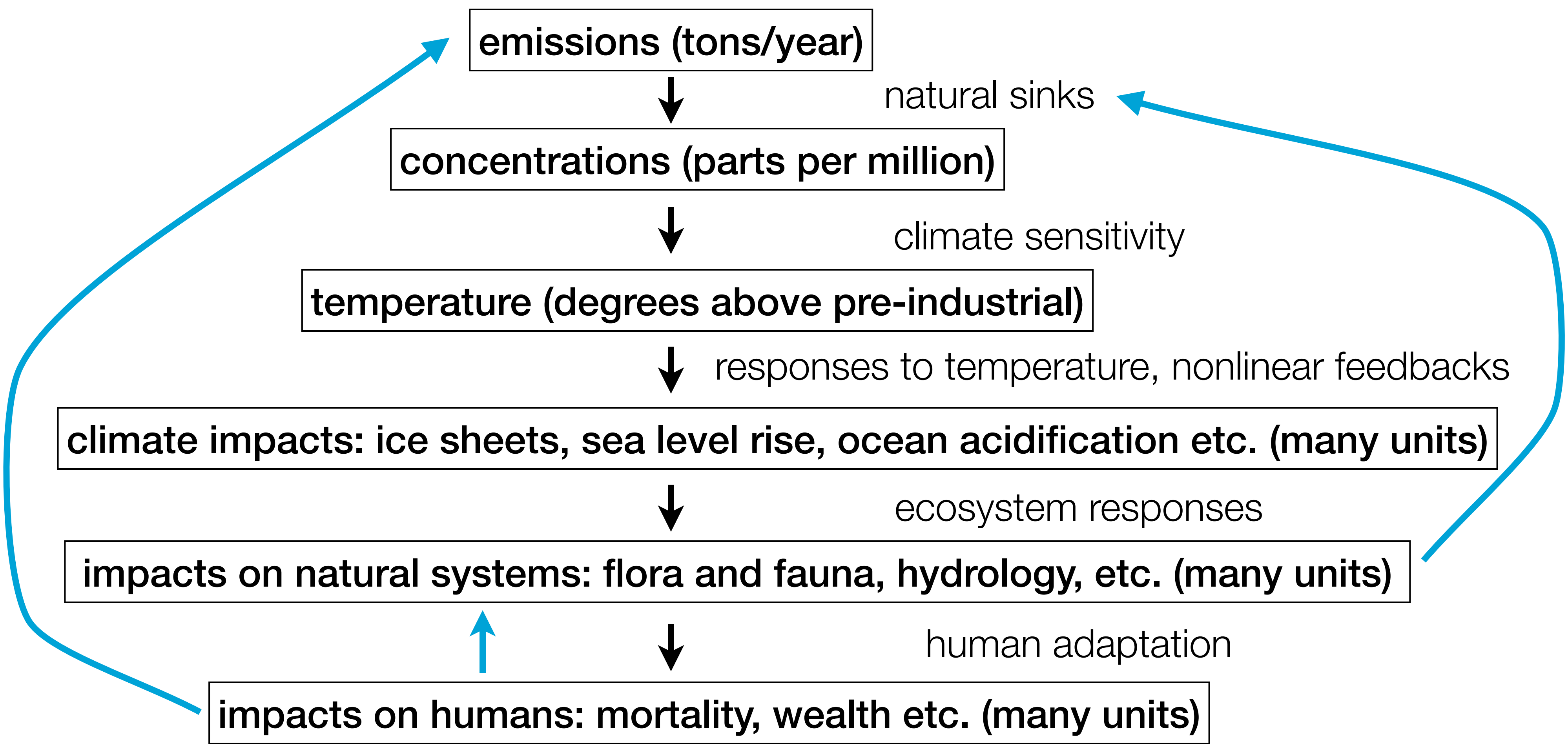

Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970−2010
GHG Emissions [$GtCO_2eq/yr$]
+1.3%/yr
1970−2000
+2.2%/yr
2000−2010
27 Gt
33 Gt
38 Gt
40 Gt
49 Gt
0.44%
7.9%
19%
17%
55%
0.67%
7.9%
18%
15%
58%
0.81%
7.4%
18%
16%
59%
1.3%
6.9%
16%
13%
62%
2.0%
6.2%
16%
11%
65%
Gas
F-Gases
$N_2O$
$CH_4$
$CO_2$ FOLU
$CO_2$ Fossil Fuel and Industrial Processes
0
10
20
30
40
50
1970
1975
1980
1985
1990
1995
2000
2005
2010

IPCC, 2014

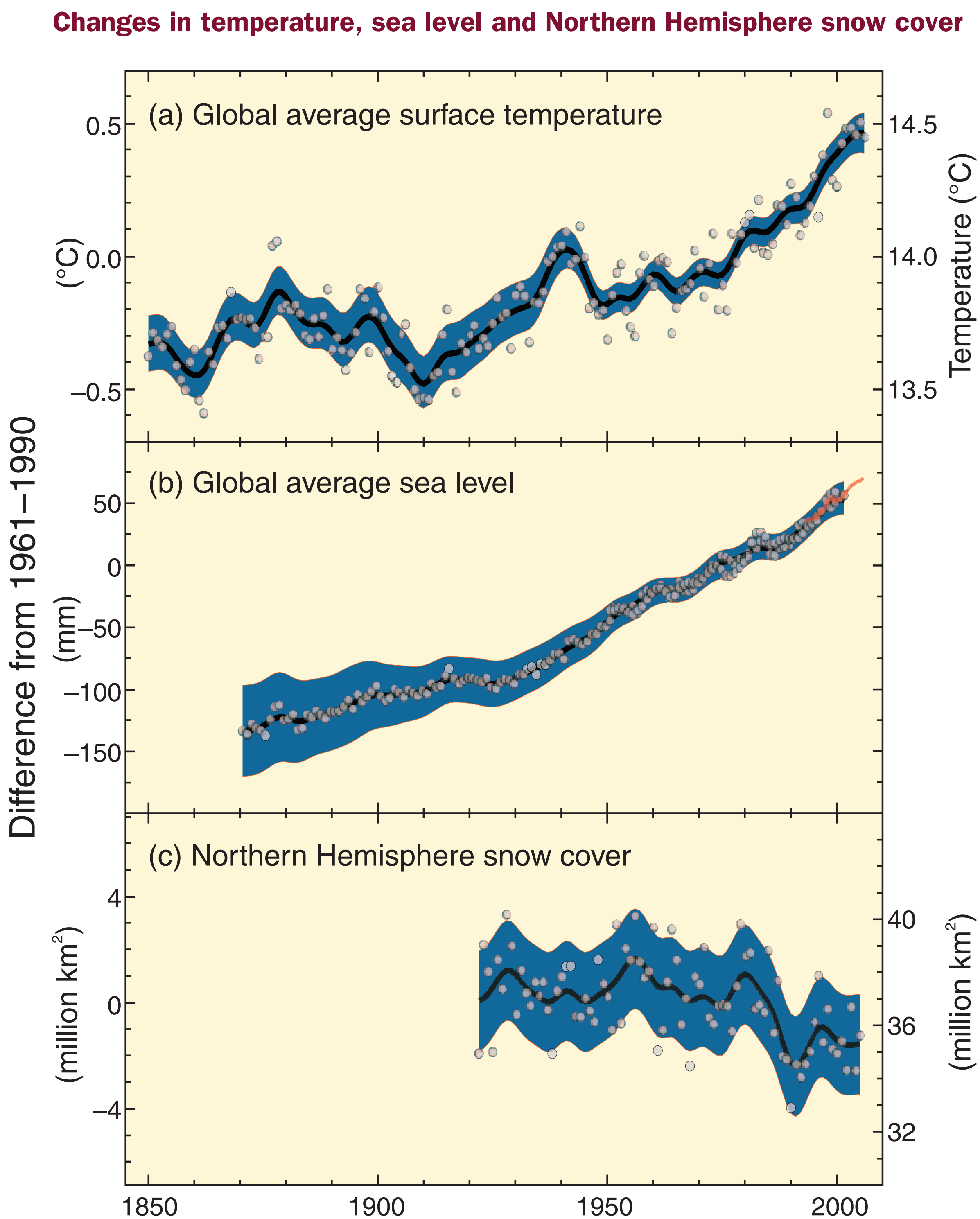
# Concentrations



# Climate change risks

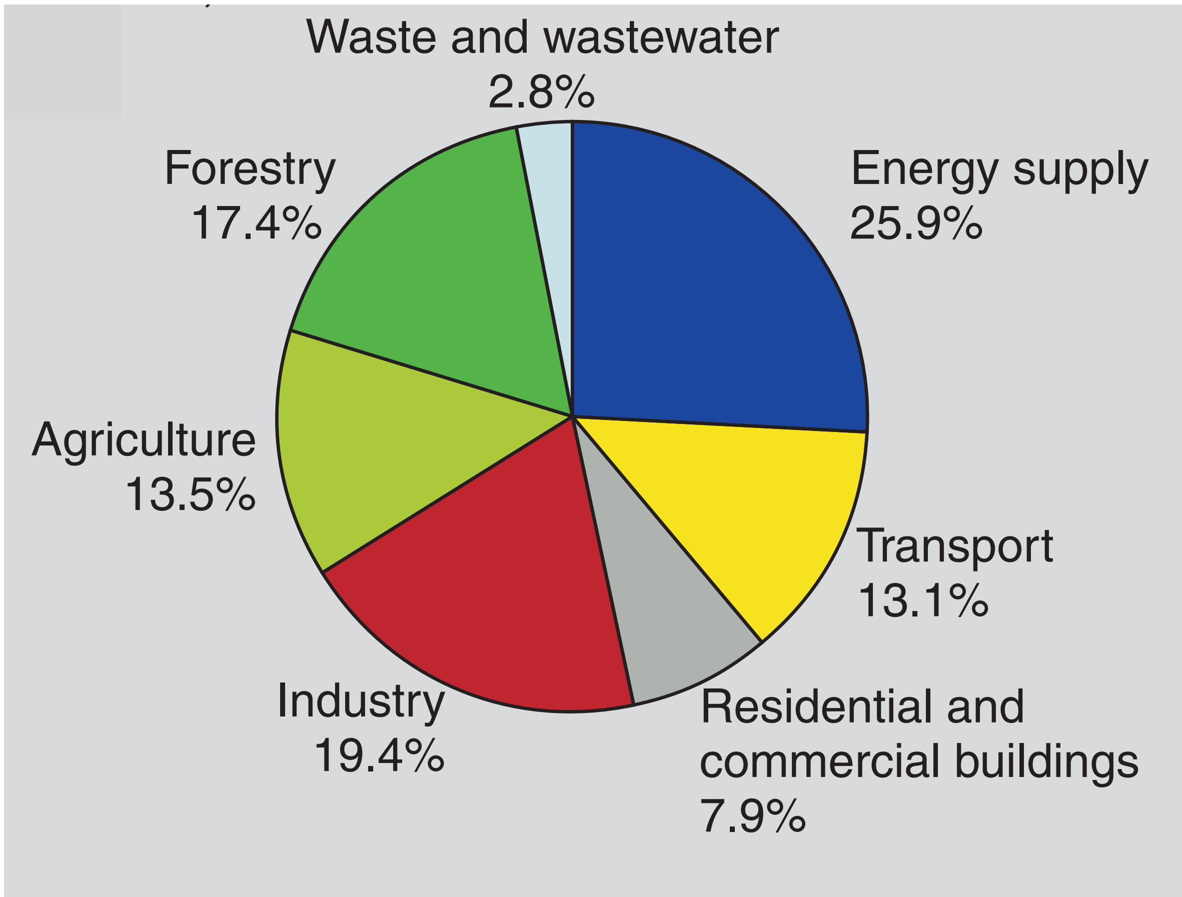


# Evidence of past climate change




IPCC, 2007

# Anthropogenic emissions - distribution across sectors

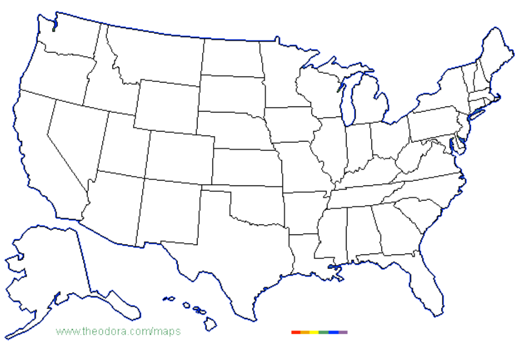



IPCC, 2007

# Power (or rate of energy usage)

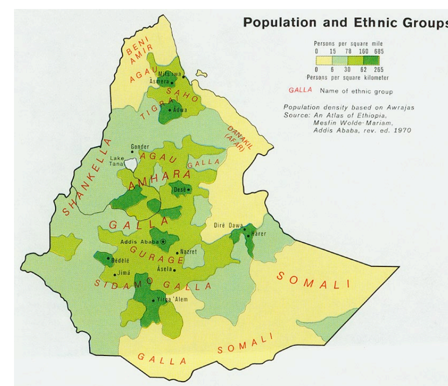
active human: ~100W

dishwasher: ~1500W



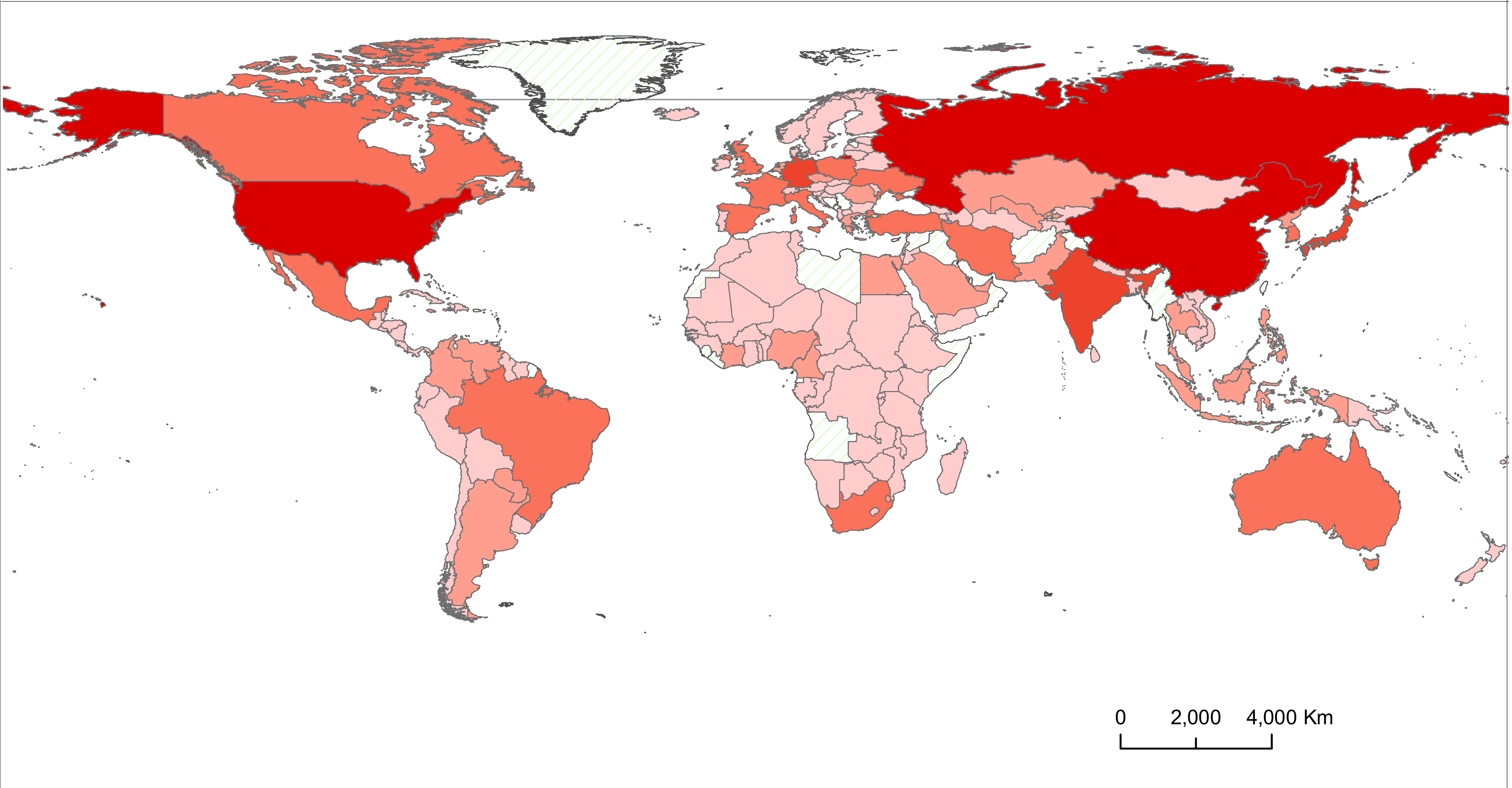

USA per capita
avg. power: ~10000W


Mexico per capita
avg. power: ~2000W




Ethiopia per capita
avg. power: ~400W

# Total Greenhouse Gas Emissions




**Units: mio. tonnes of $CO_2$ equivalent**

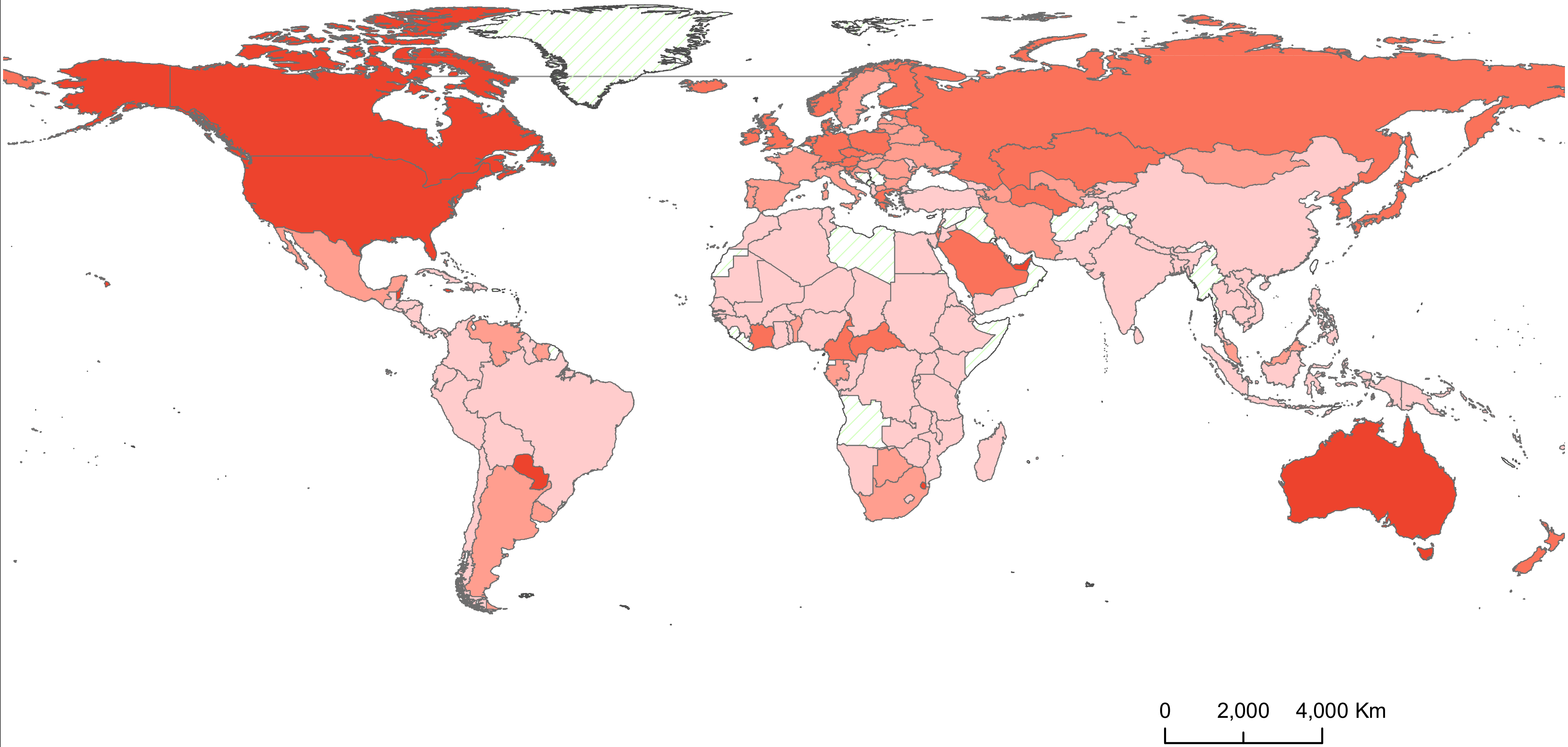
*Note that data correspond to the latest year available.

0.00- 100.00 | 100.01 - 350.00 | 350.01 - 750.00 | 750.1 - 1,500.0 | 1,500.01 - 7,000.00 | No data available

**Data Source: UNFCCC**
**Map Source: UNGIWG**

**Last Update: July 2010**
**Map available at: http://unstats.un.org/unsd/environment/qindicators**

# Greenhouse Gas Emissions per Capita




**Units: tonnes of $CO_2$ equivalent**

*Note that data correspond to the latest year available.

0.21 - 5.00 | 5.01 - 10.00 | 10.01 - 20.00 | 20.01 - 50.00 | 50.01 - 2,055.00 | No data available

**Data Source: UNFCCC**
**Map Source: UNGIWG**

**Last Update: July 2010**
**Map available at: http://unstats.un.org/unsd/environment/qindicators**

# Lecture 1 outline

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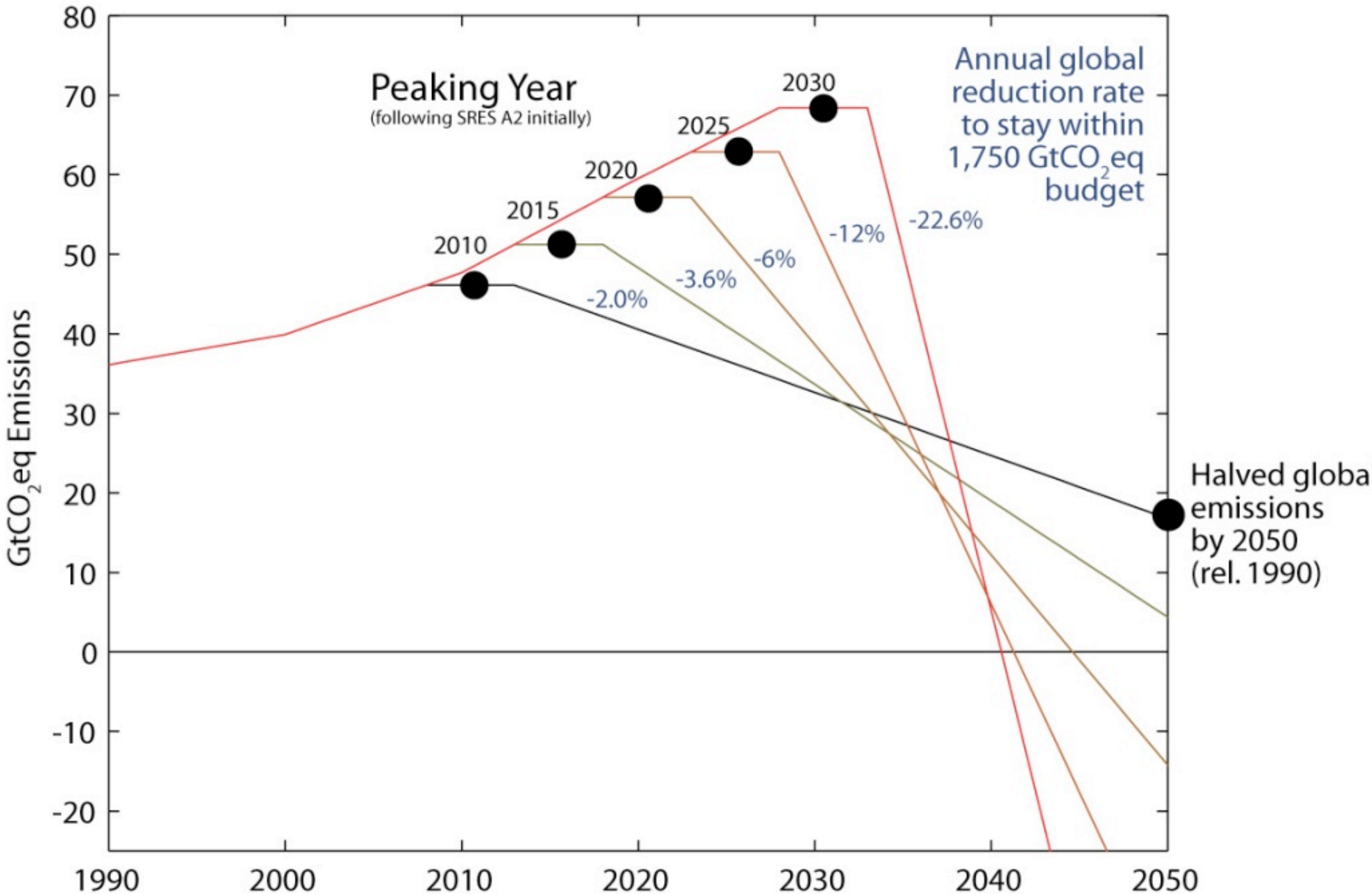
- Mitigation scenarios
- Role of supply-side technology transformation




Meinshausen, *Nature*, 2009

# “World Formula” for Climate Policy

$$C_{glob}(p) = \int_{T_1}^{T_2} E_{glob}(t)dt$$

Total global $CO_2$ budget in period $[T_1,T_2]$ that keeps global warming below 2°C with probability $p$

Integral over global profile of $CO_2$ emissions

$$C_{nat} = \int_{T_1}^{T_2} E_{nat}(t)dt = C_{glob}(p)\frac{M_{nat}(T_M)}{M_{glob}(T_M)}$$

National $CO_2$ budget in $[T_1,T_2]$

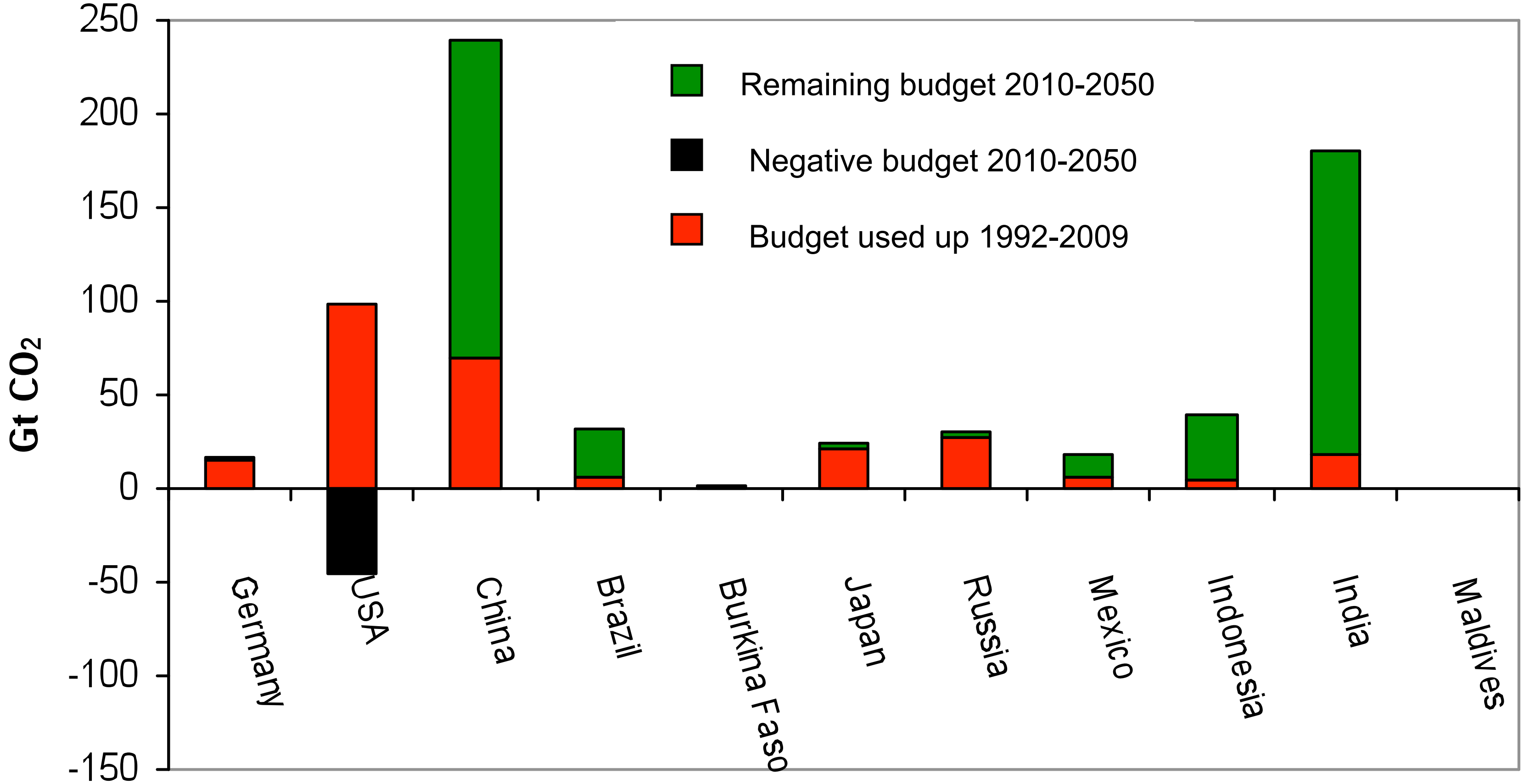
Integral over national emission profile

Fraction of global $CO_2$ budget as determined by ratio of national population $M_{nat}$ to world population $M_{glob}$ at time $T_M$

Schellnhuber, 2009

# Scenario 1: Historic Responsibility

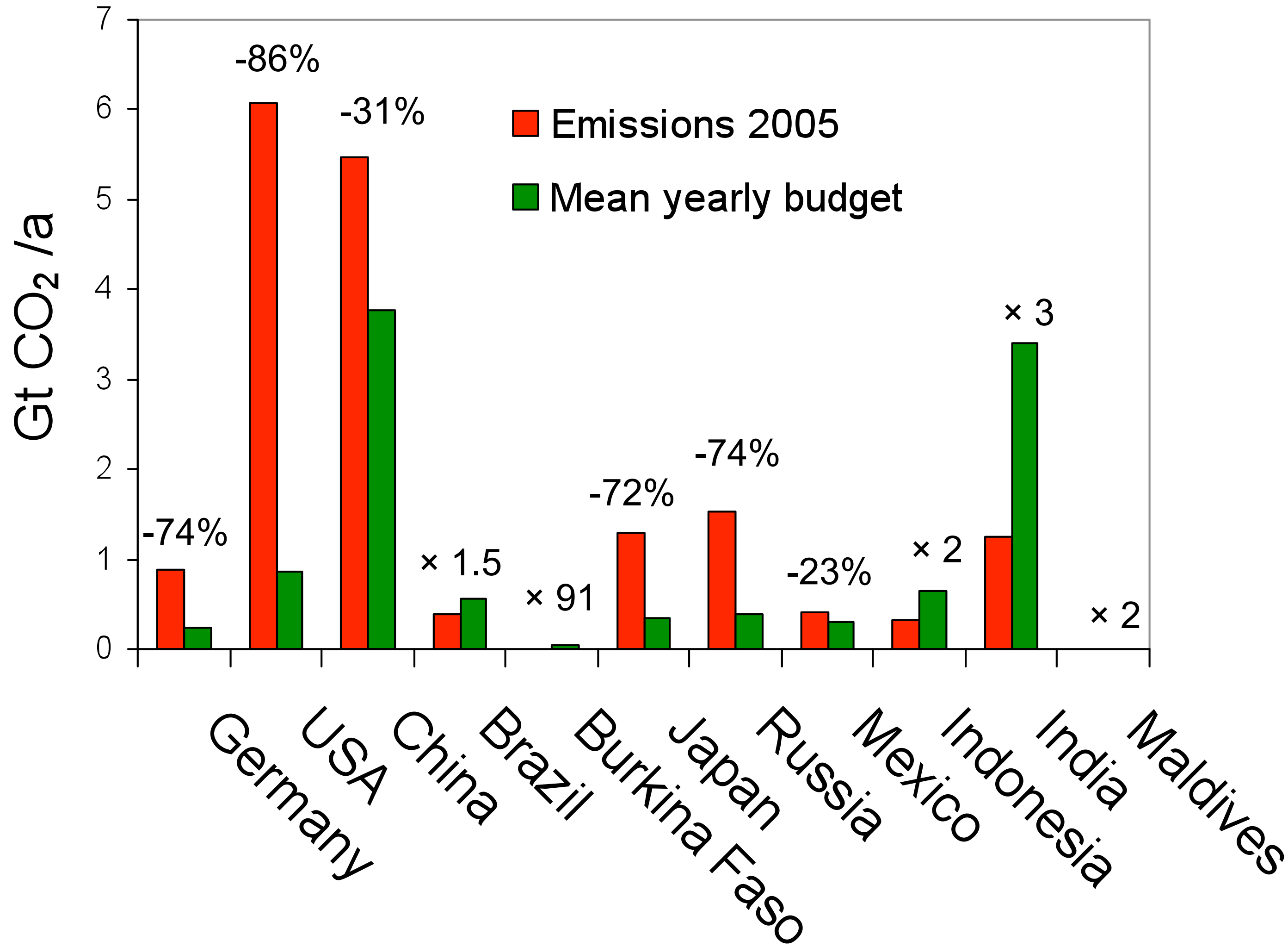
$T_1 = 1992$, $T_2 = 2050$, $T_M = 1994$, $p = 0.75$




Schellnhuber, 2009

# Scenario 2: Climate Compromise

$T_1$ = 2010, $T_2$ = 2050, $T_M$ = 2010, $p$ = 2/3




Schellnhuber, 2009


image from newclimate.org

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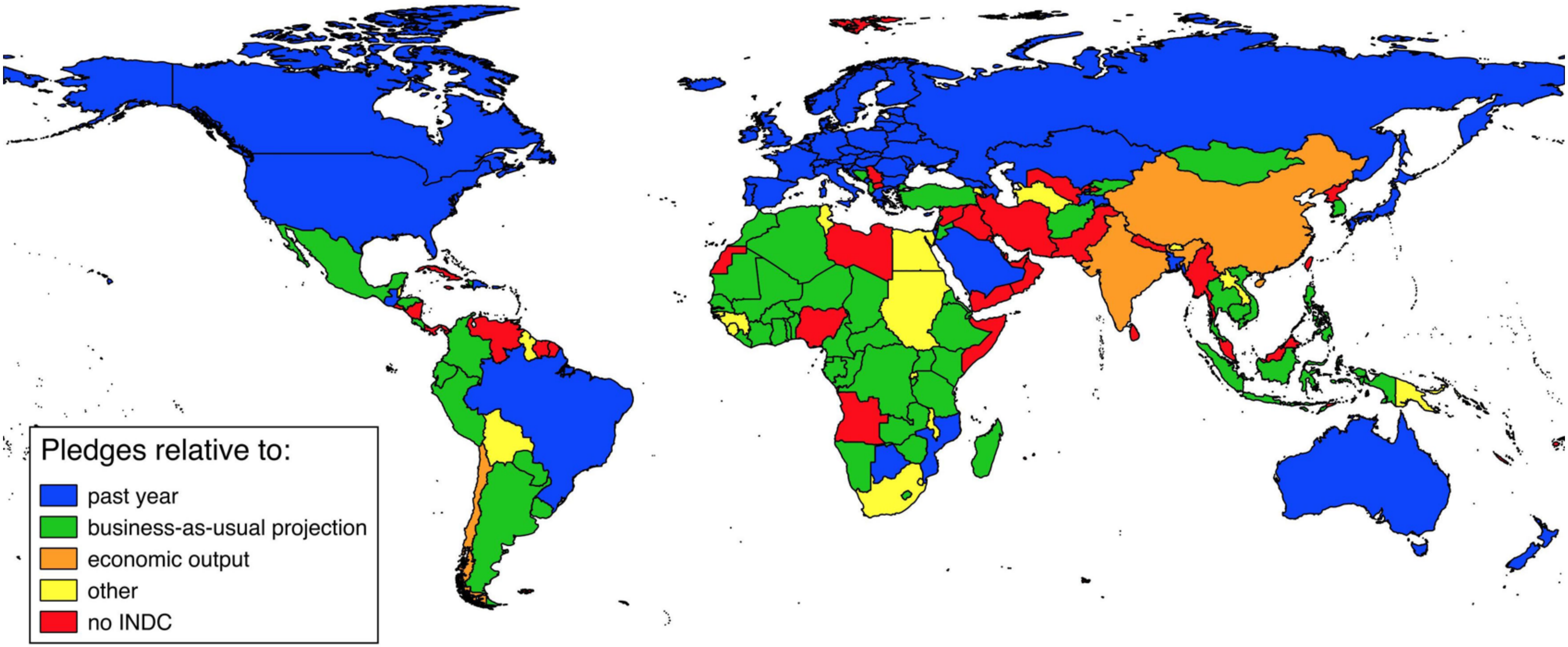
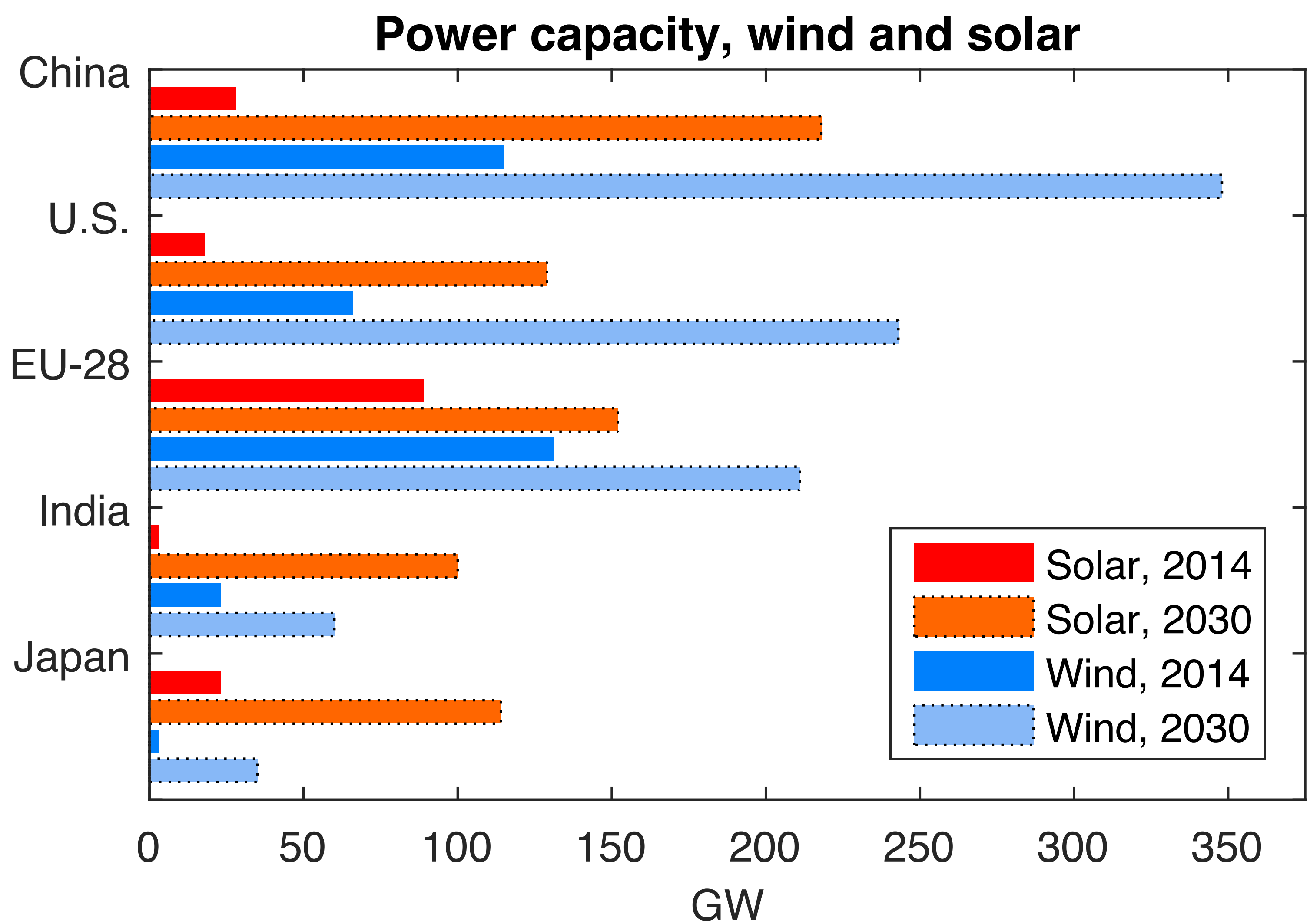



Trancik, Brown, Jean, Kavlak, Klemun et al. *tech, report*, 2015

# Renewables growth under countries' climate pledges (INDCs)




Trancik, Brown, Jean, Kavlak, Klemun, Edwards, McNerney, Miotti, Mueller, Needell, Technical Report, 2015

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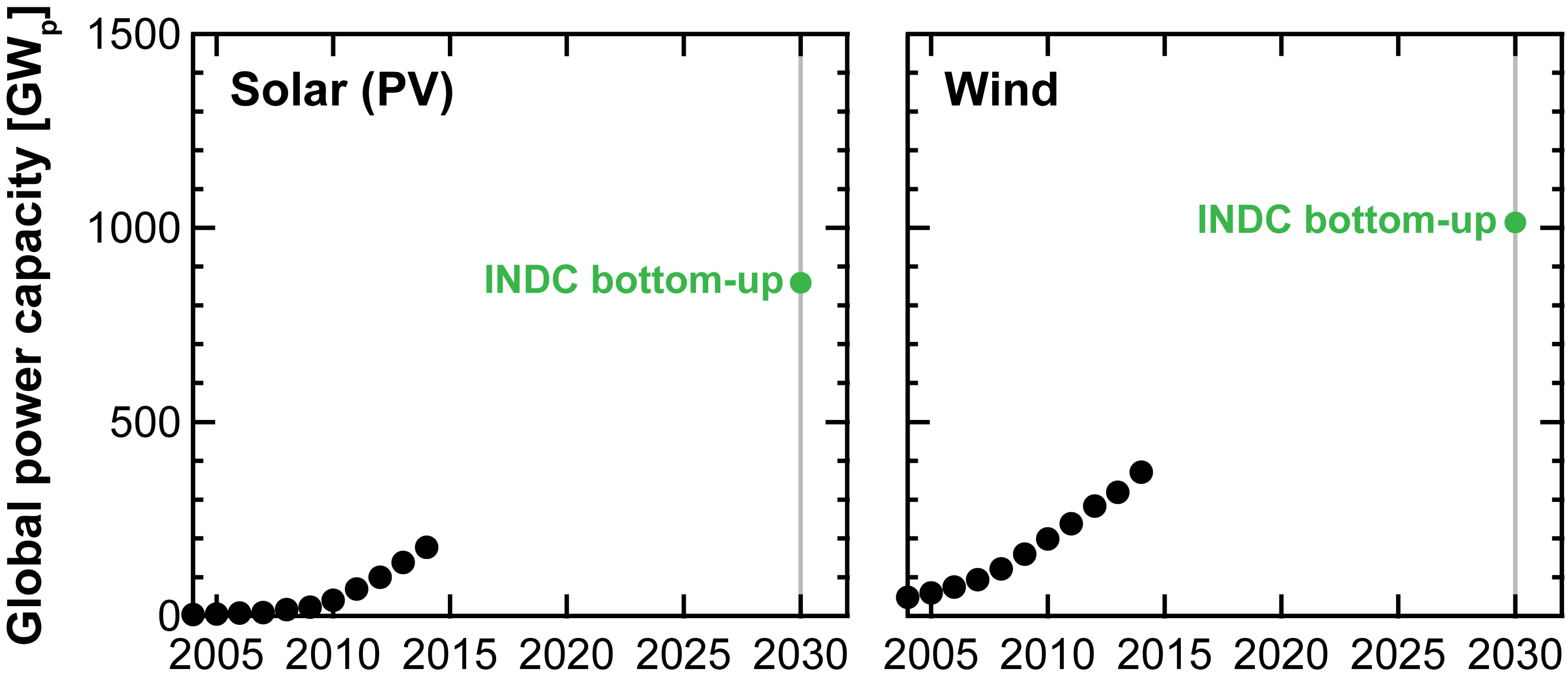



Solar (PV) and wind could grow by factors of nearly 5 and 3 under countries' Intended Nationally Determined Contributions (INDCs) – to provide an estimated 4% and 9% of electricity in 2030.

Trancik, Brown, Jean, Kavlak, Klemun, Edwards, McNerney, Miotti, Mueller, Needell, Technical Report, 2015

# Kaya Identity

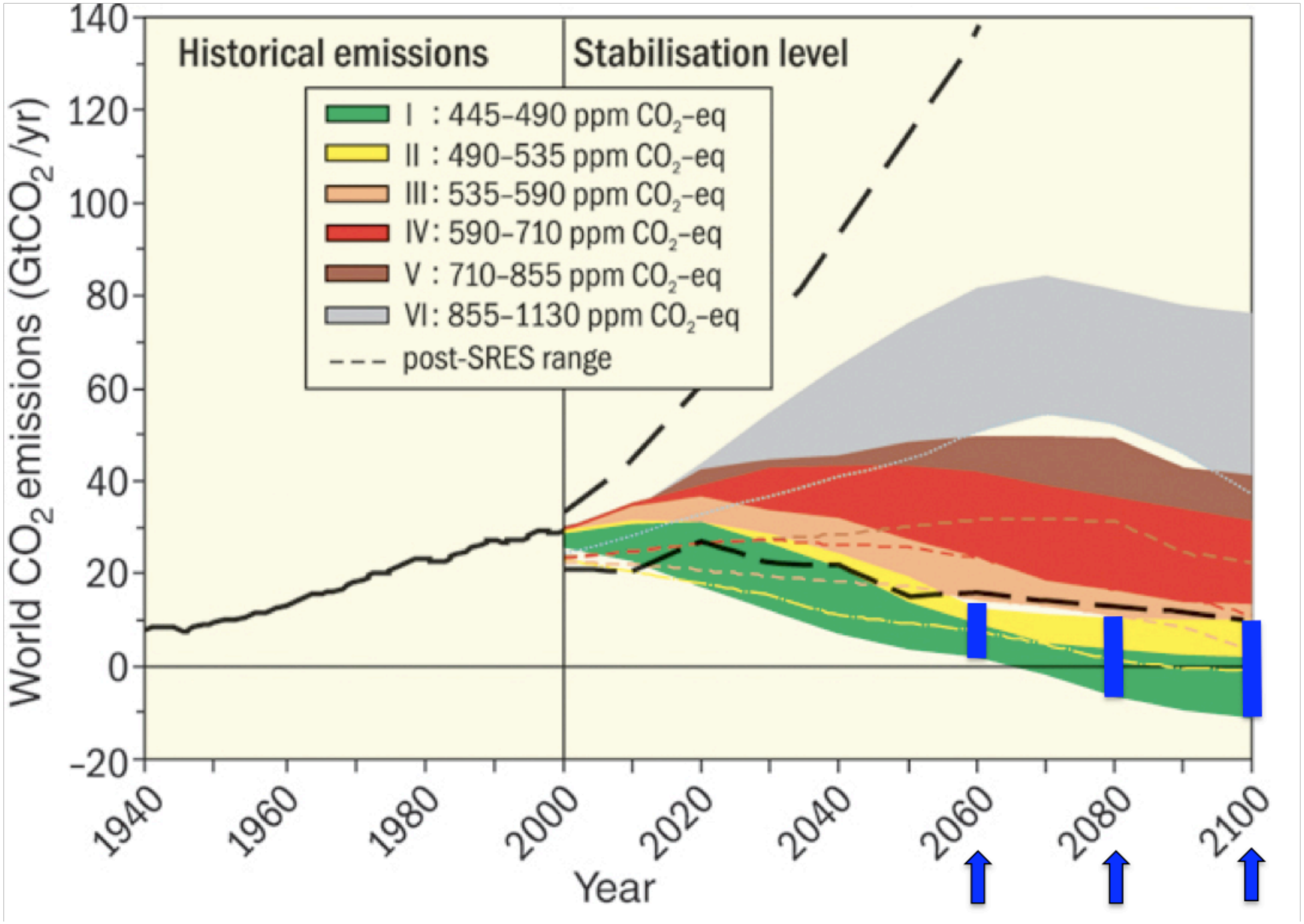
demand side changes
(involve technology,
behavior)

$$C = N\left(\frac{GDP}{N}\right)\left(\frac{E}{GDP}\right)\left(\frac{C}{E}\right)$$

carbon intensity of energy (and cost):
key technological lever

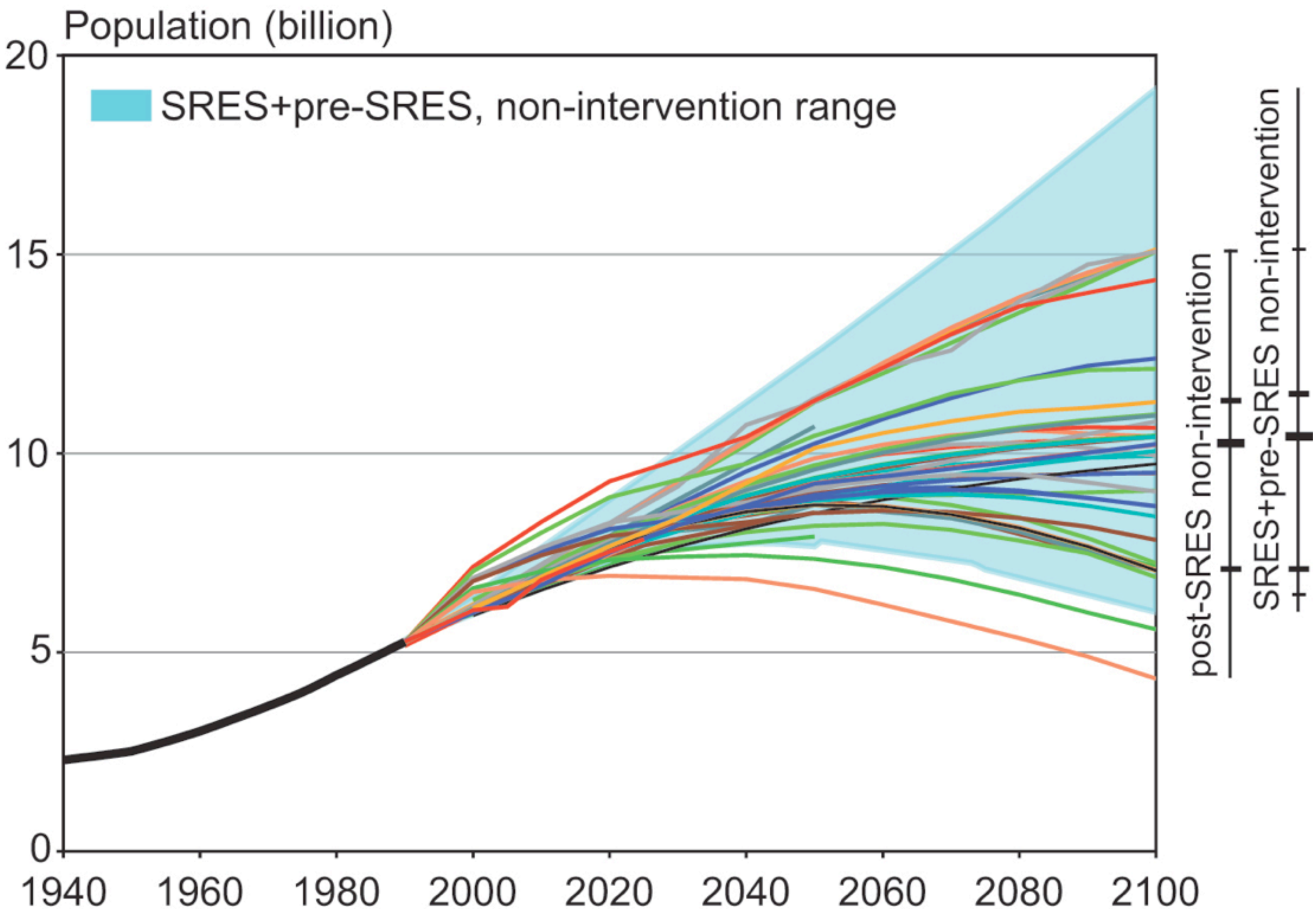
C=emissions, N=population, E=energy

# Emissions scenarios



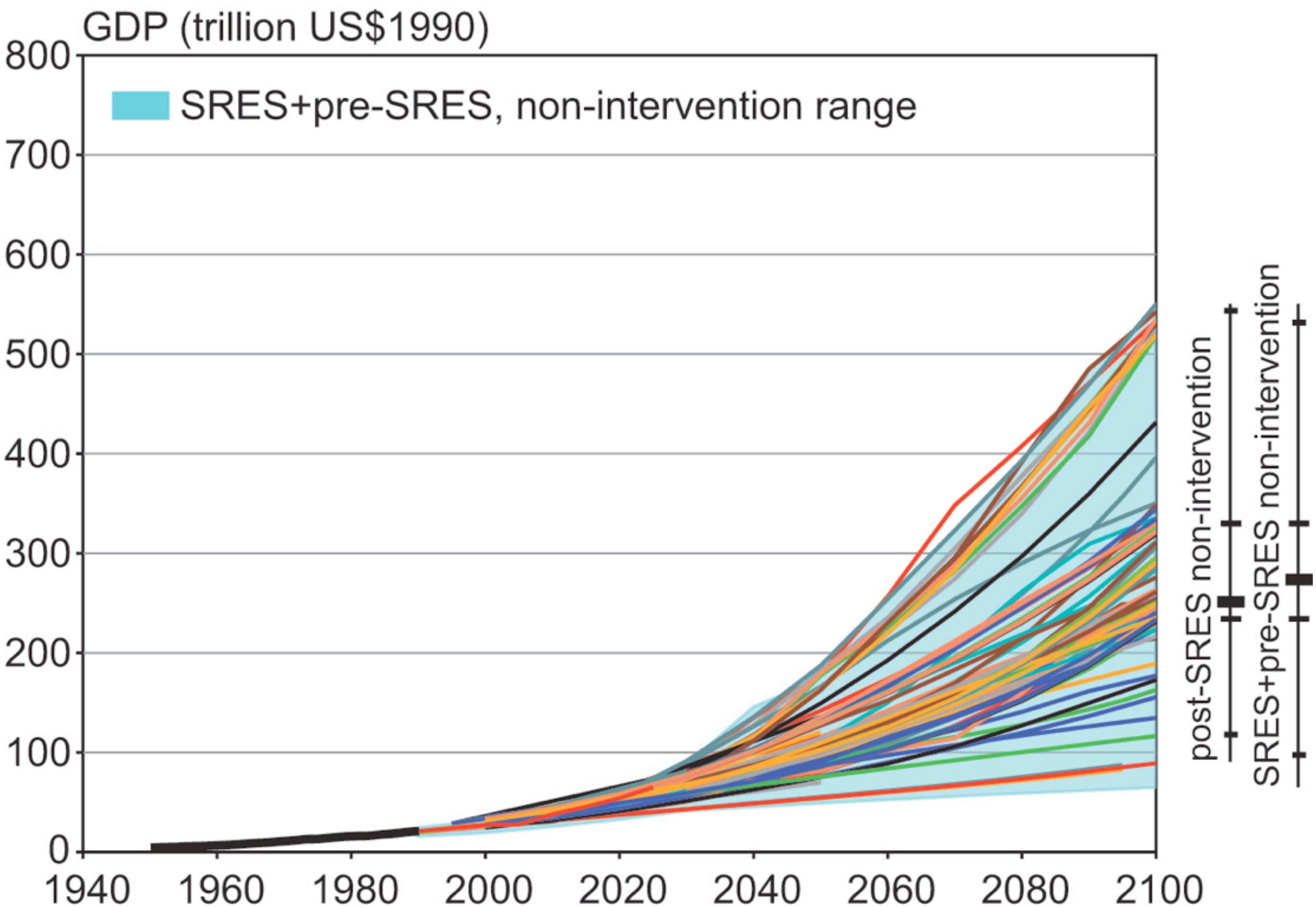

Data from: IPCC, 2007

# Population projections

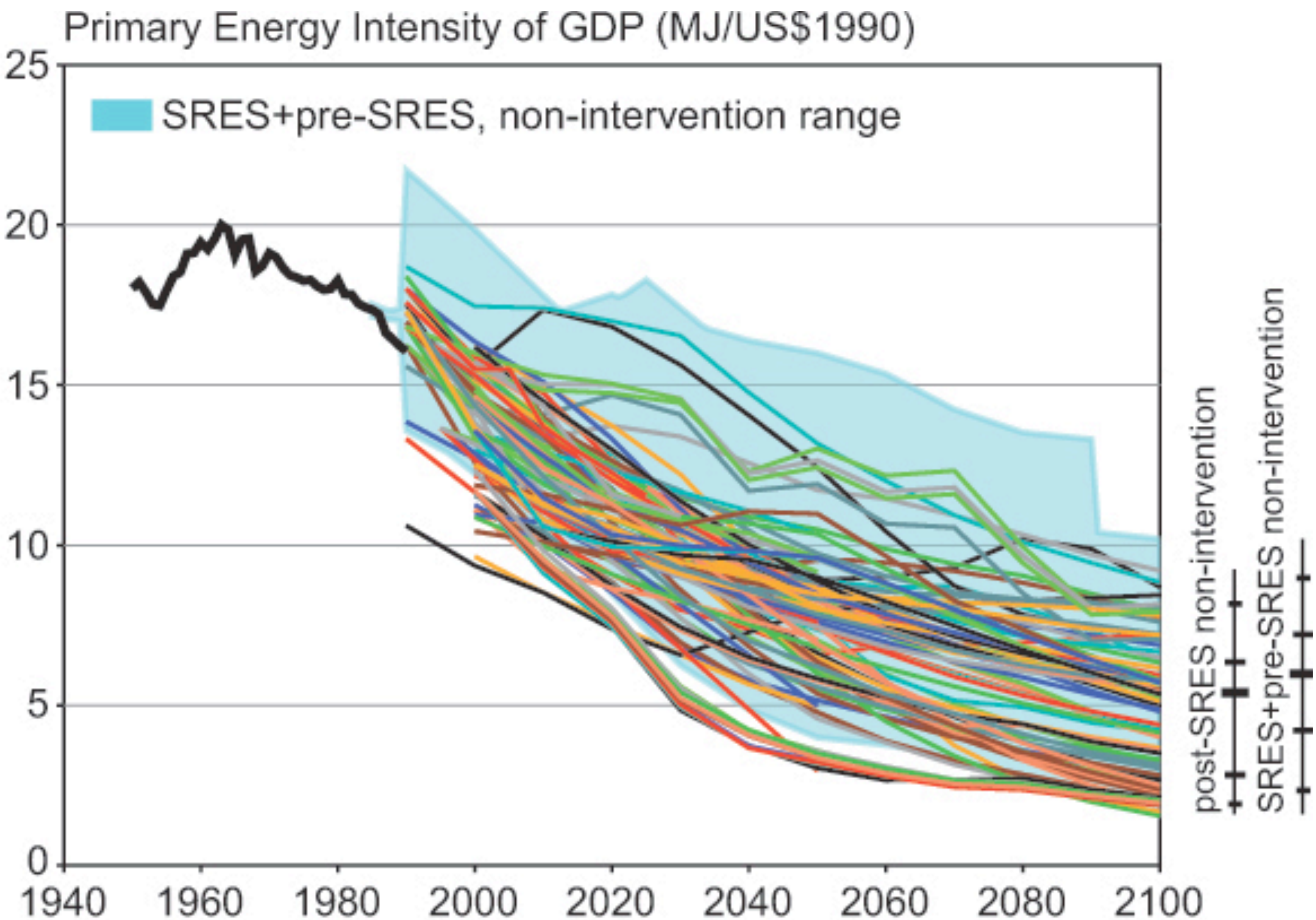



Data from: IPCC, 2007

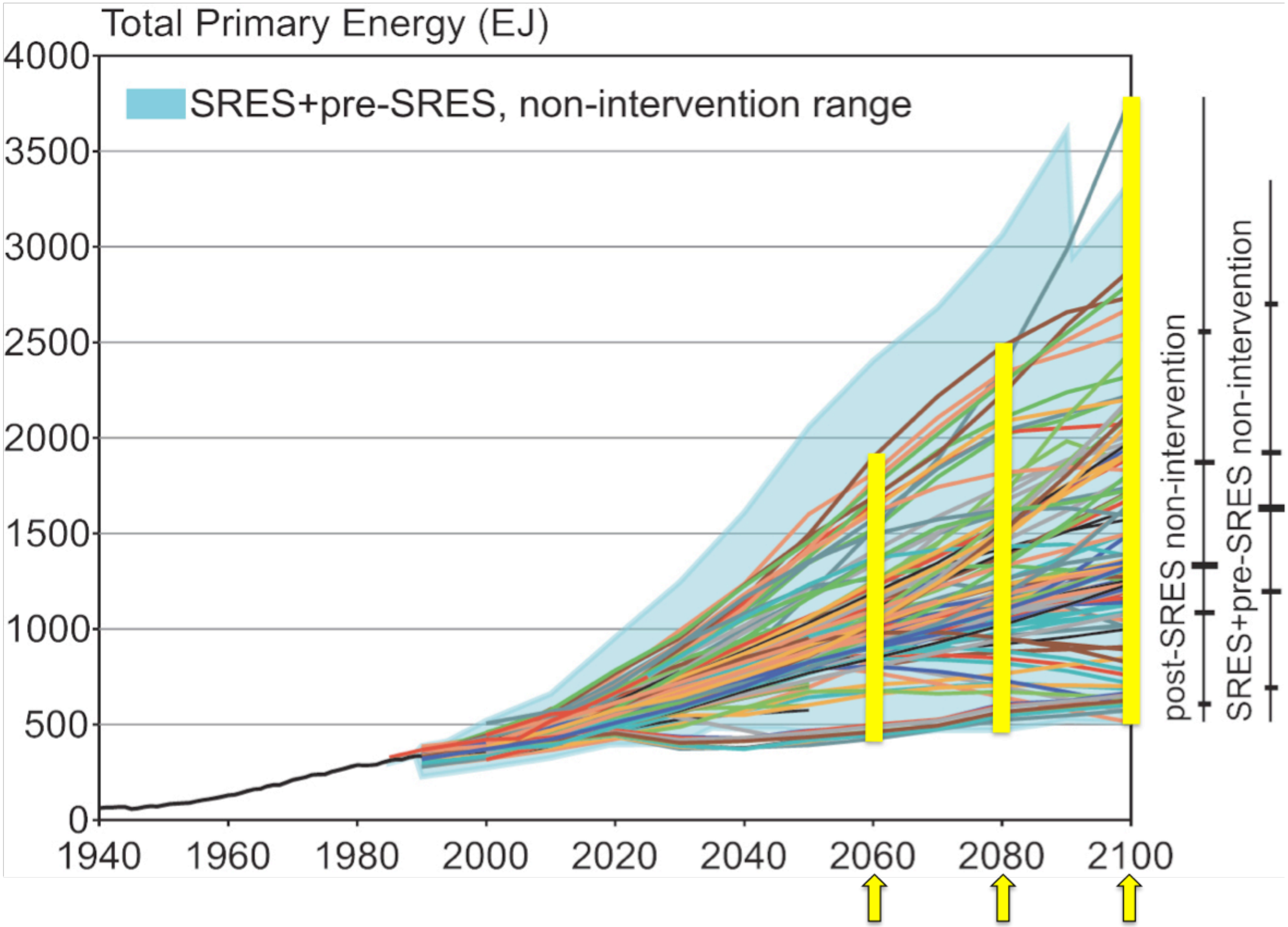
# World GDP


GDP (trillion US$1990)
SRES+pre-SRES, non-intervention range
800
700
600
500
400
300
200
100
0
1940
1960
1980
2000
2020
2040
2060
2080
2100
post-SRES non-intervention
SRES+pre-SRES non-intervention

# Energy Intensity of GDP



# Energy demand scenarios



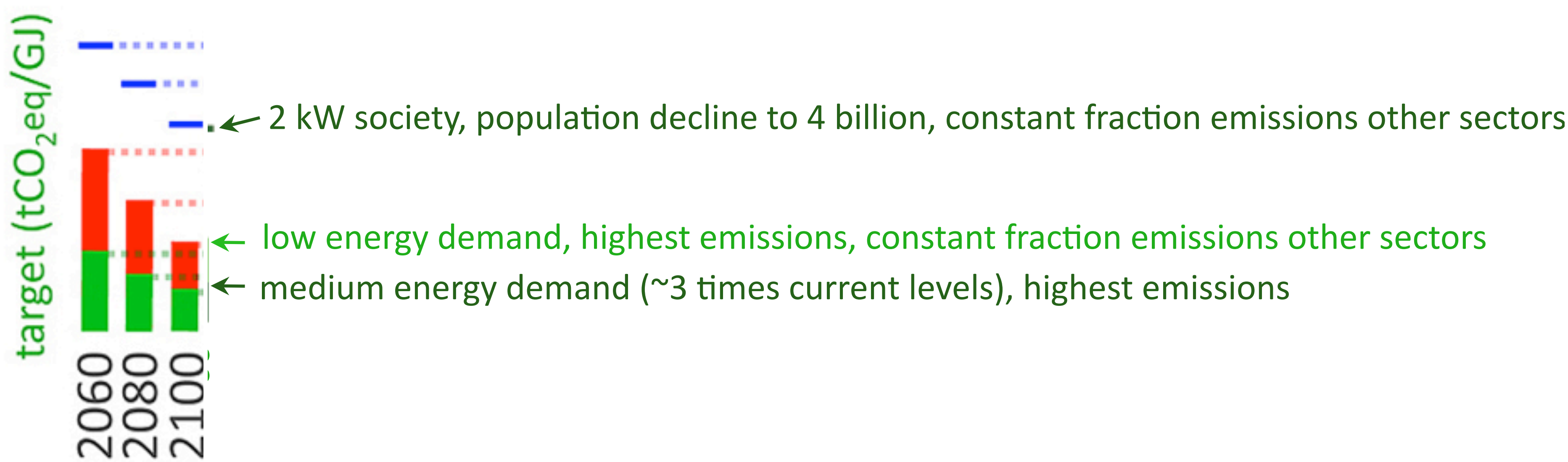

Data from: IPCC, 2007

# Performance target for energy systems (for stabilization between ~450 and 550 ppm $CO_{2eq}$)

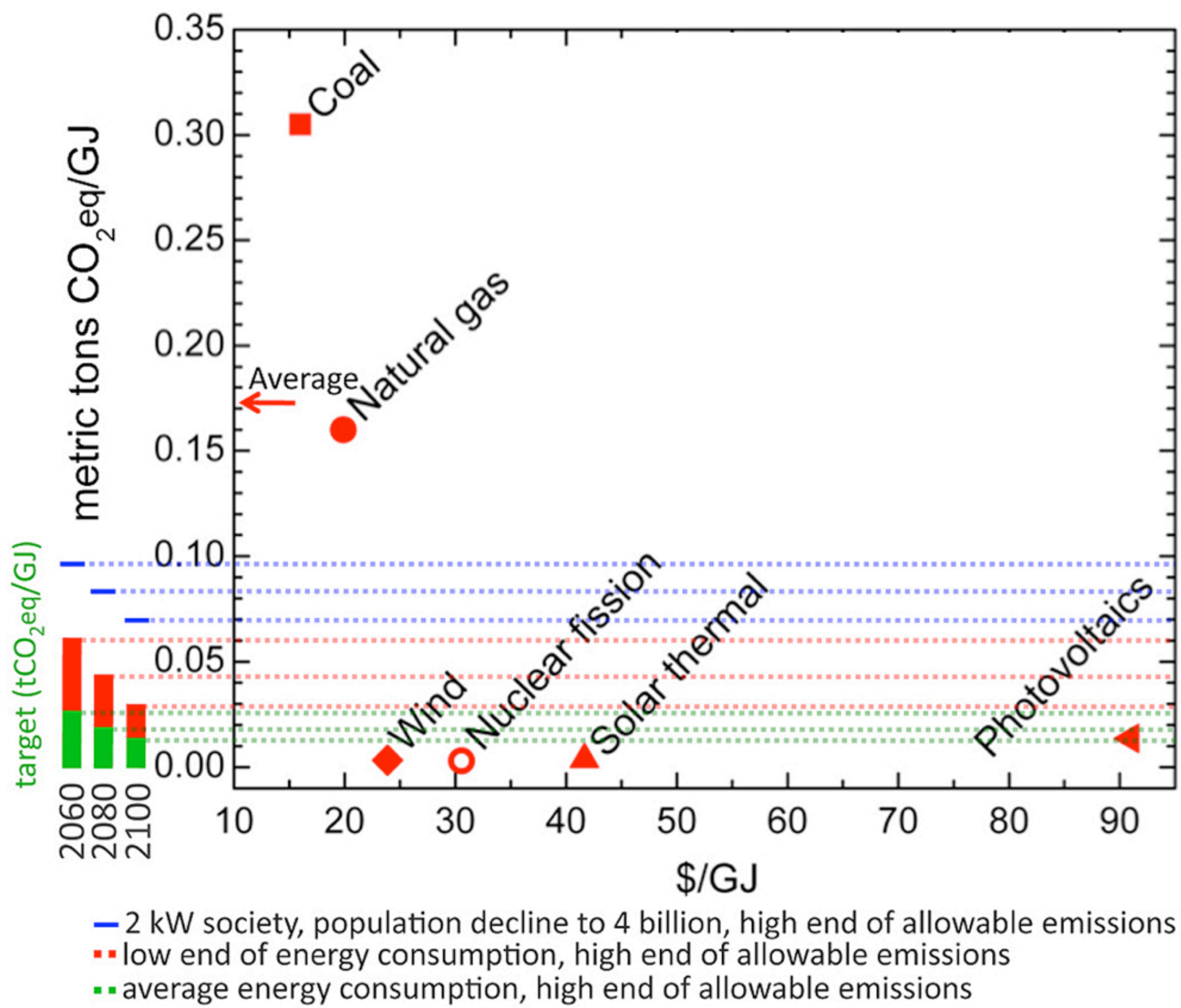
$$C = N\left(\frac{GDP}{N}\right)\left(\frac{E}{GDP}\right)\left(\frac{C}{E}\right)$$

carbon intensity of energy (and cost): key technological lever

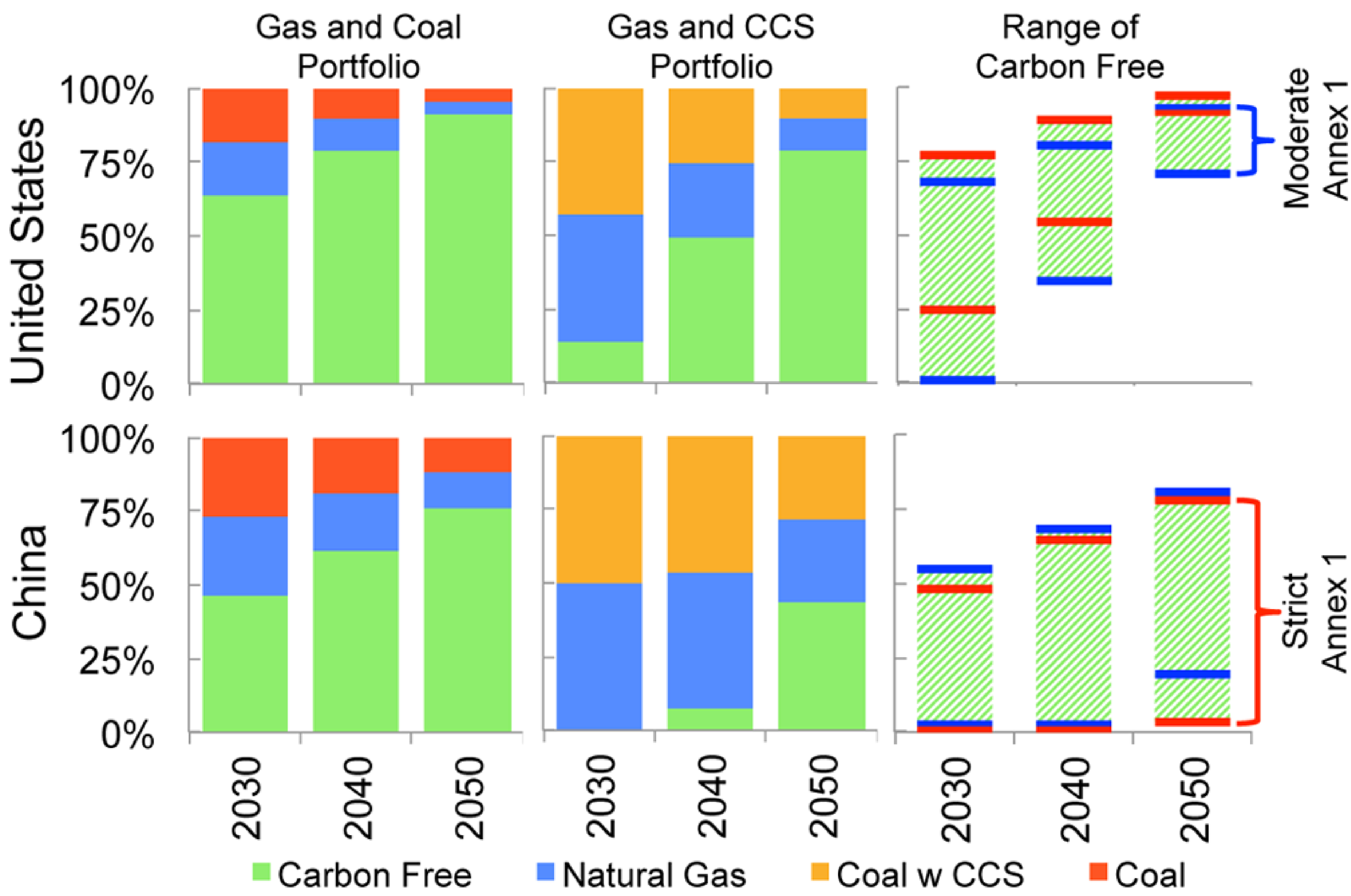
C=emissions, N=population, E=energy



# Global supply-side targets compared to energy technologies

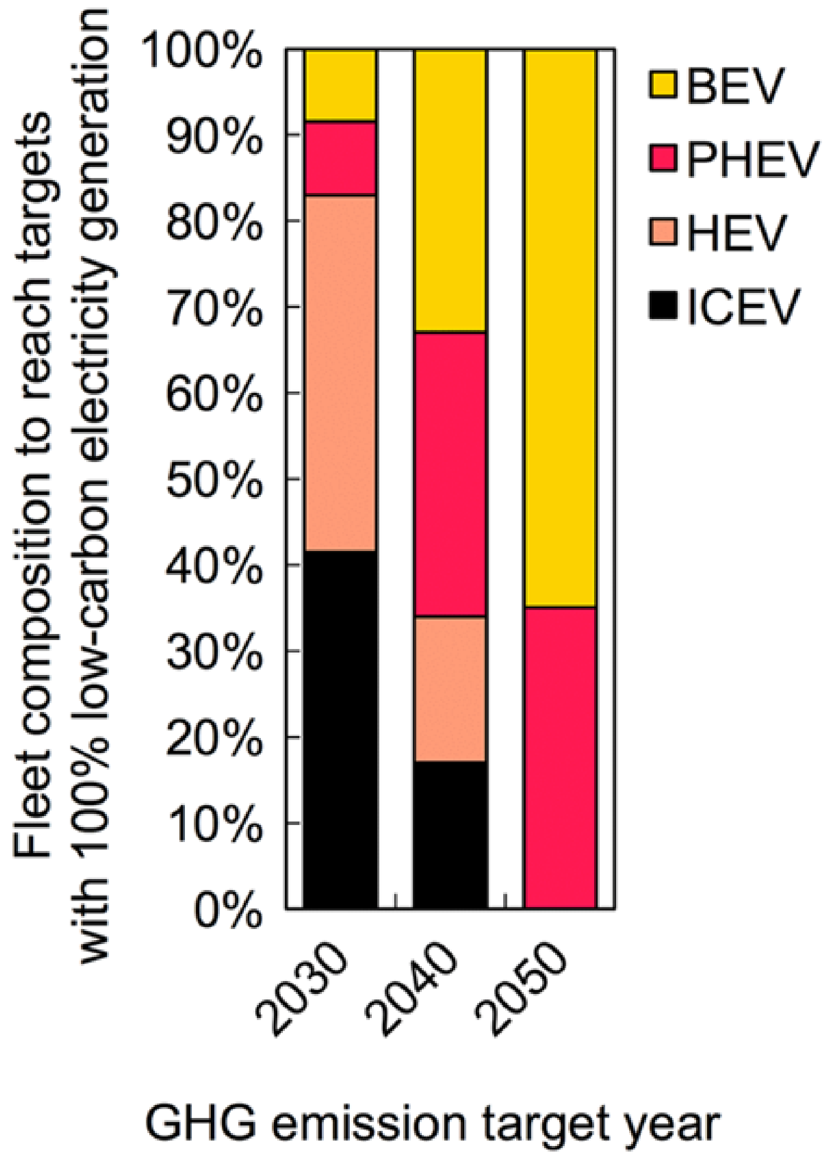



Adapted from: Trancik, Cross-Call, *ES&T*, 2013




CCS=carbon capture and storage

Trancik, Cross-Call, *ES&T* 2013




BEV=battery electric vehicle; PHEV=pumped hydro electric vehicle; HEV=hybrid electric vehicle; ICEV=internal combustion engine vehicle

Miotti, Supran, Kim, Trancik, to appear in *ES&T* 2016

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