Transitioning to Zero Fossil Fuel CO_2 Emissions by 2100

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Presentation at the
Aspen Global Change Workshop

Climate Sensitivity on Decadal to Century Timescales:
Implications for Civilization

21 May 2012

Outline of this (and Friday's) talk:

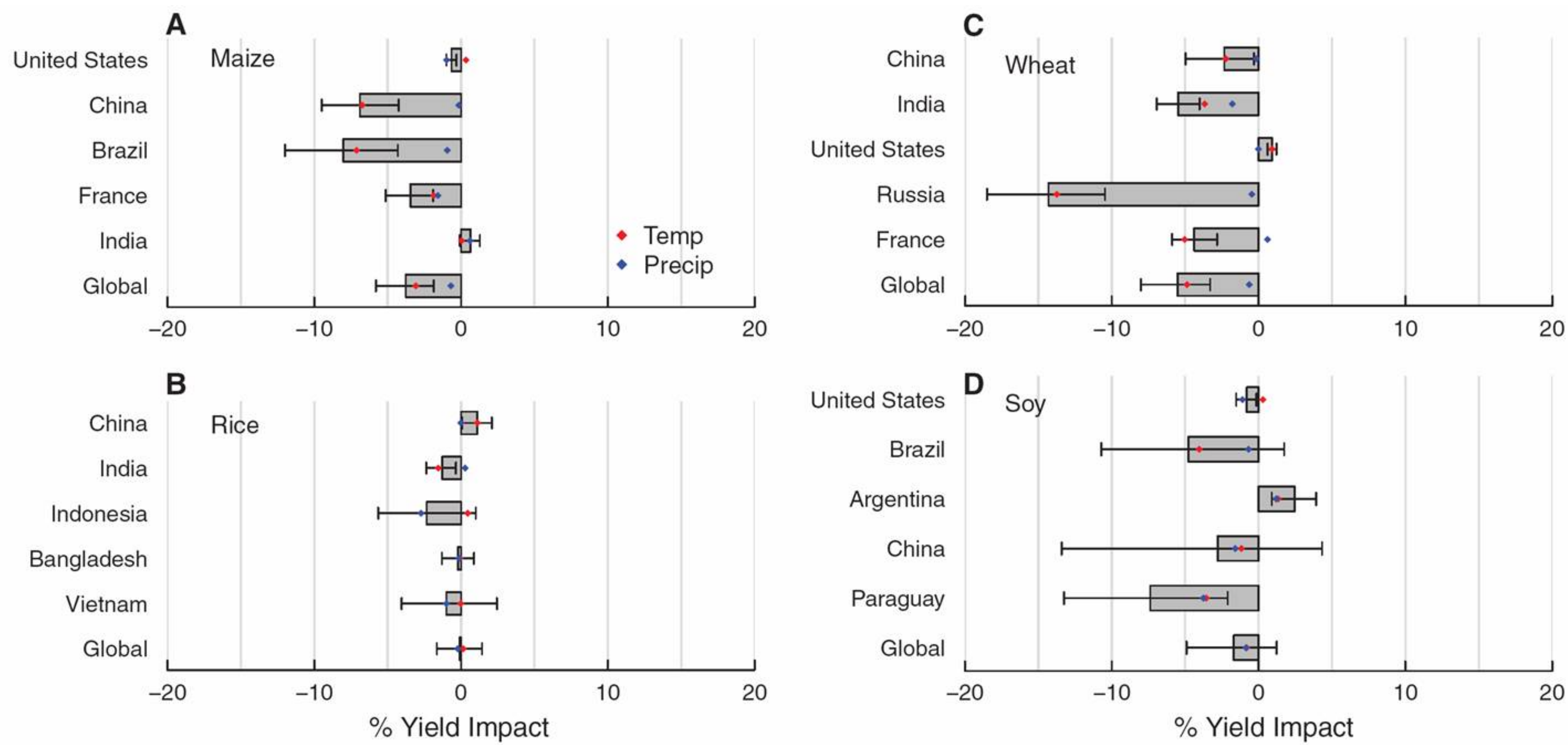
- Part 1: Assessment of what constitutes 'catastrophic' global warming, and what it would take (in terms of reduced CO_2 emissions) to have a > 50% chance of avoiding it
- Part 2: Brief overview of my own scenarios directed at (hopefully) avoiding catastrophic global warming
- Part 3 (on Friday): Changes in thinking that would be needed to achieve a scenario that eliminates fossil fuel CO_2 emissions by the end of this century

Premises (open to discussion and modification):

- 2-3°C global mean warming is flirting with "catastrophic" warming
- 5°C global mean warming is unquestionably catastrophic
- The fast-feedback climate sensitivity is very likely to be between 2-4°C
- Slow feedbacks could enhance this sensitivity of 25-50%
- Fossil fuel emissions therefore need to be eliminated by the end of this century to have a better than 50% chance of avoiding catastrophic climatic change

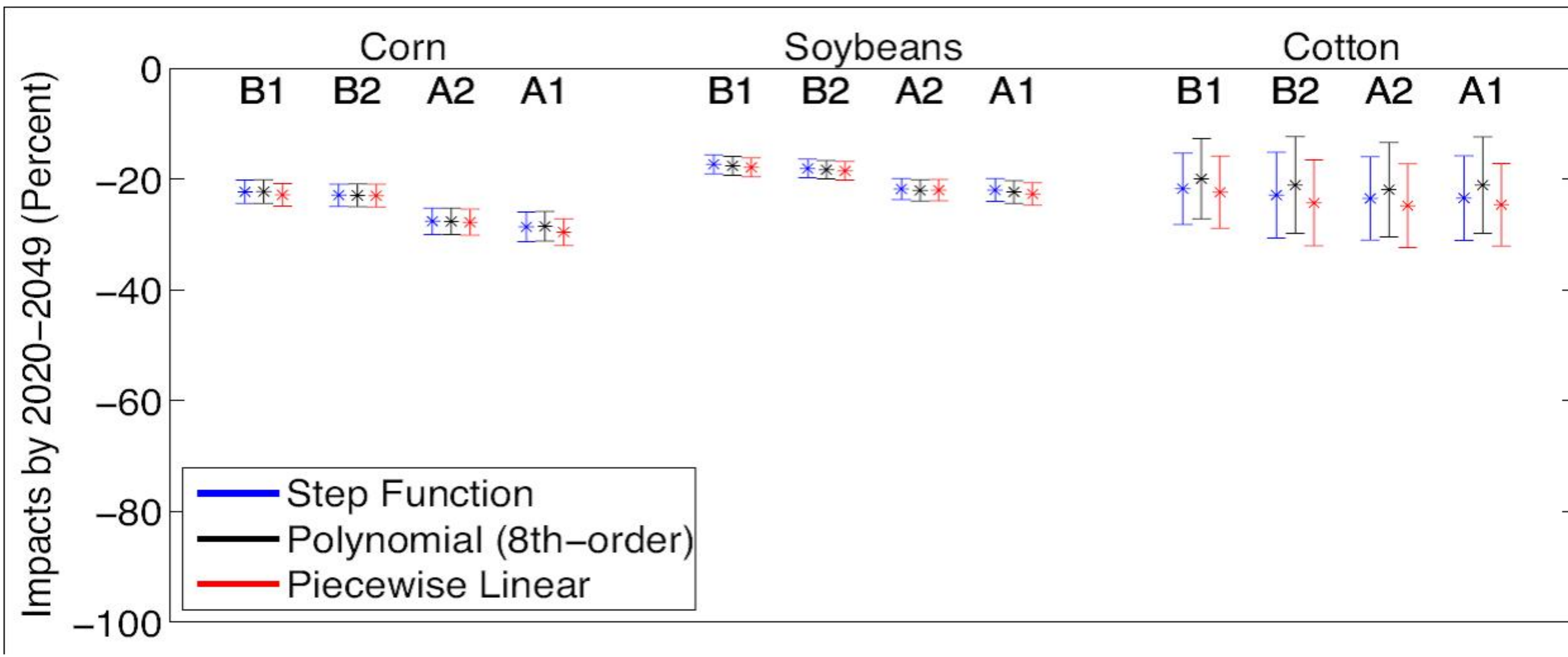
Some highlights concerning impacts not covered (it appears) by people at this workshop

Estimated impact of changes in climate trends from **1980-2008** on yields of major crops in major regions. In most regions, the decreases due to climatic trends are superimposed on large increases due improved agricultural technology and techniques. The grey bars show the most likely changes and the horizontal lines indicate the uncertainty of the estimate (i.e., the true changes are thought to lie anywhere within the changes spanned by the lines)



Source: Lobell et al. (2011, Science, Vol. 333, 616-620)

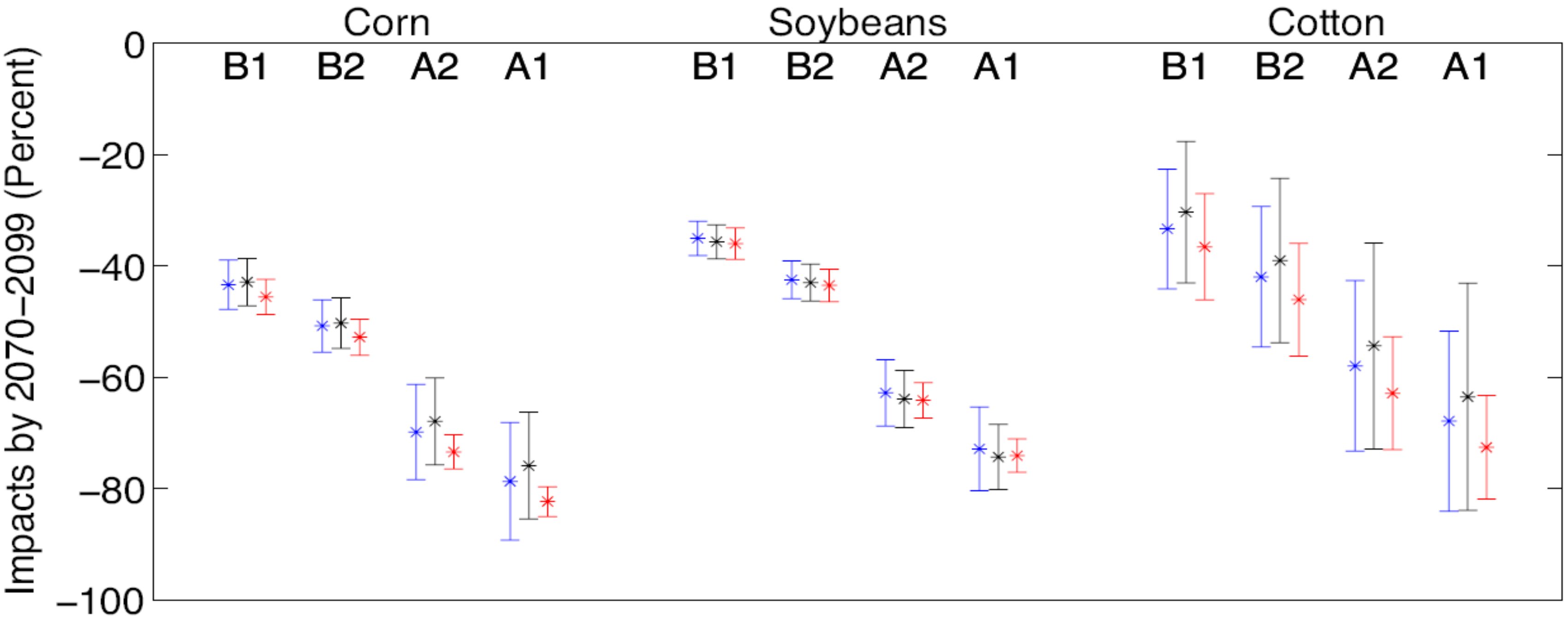
Changes in **US crop yields** by **2020-2049** compared to 1960-1989 for 4 different radiative forcing scenarios (B1, B2, A2 and A1, shown in Exhibit 2-19), computed by adding the changes in monthly mean temperature as simulated by the Hadley Centre AOGCM to the distributions of daily temperatures shown in the previous slides (thus, it is assumed that there is no change in the shape of the temperature frequency distribution – all temperatures during a given month in the growing season are shifted by the same amount). Effects of changes in precipitation are also included, but not adaptations or the possible beneficial direct effects of higher CO_2 concentration.



Source: Schlenker and Roberts (2009, Proc. Nat. Acad. Sci., Vol. 106, 15594-15598)

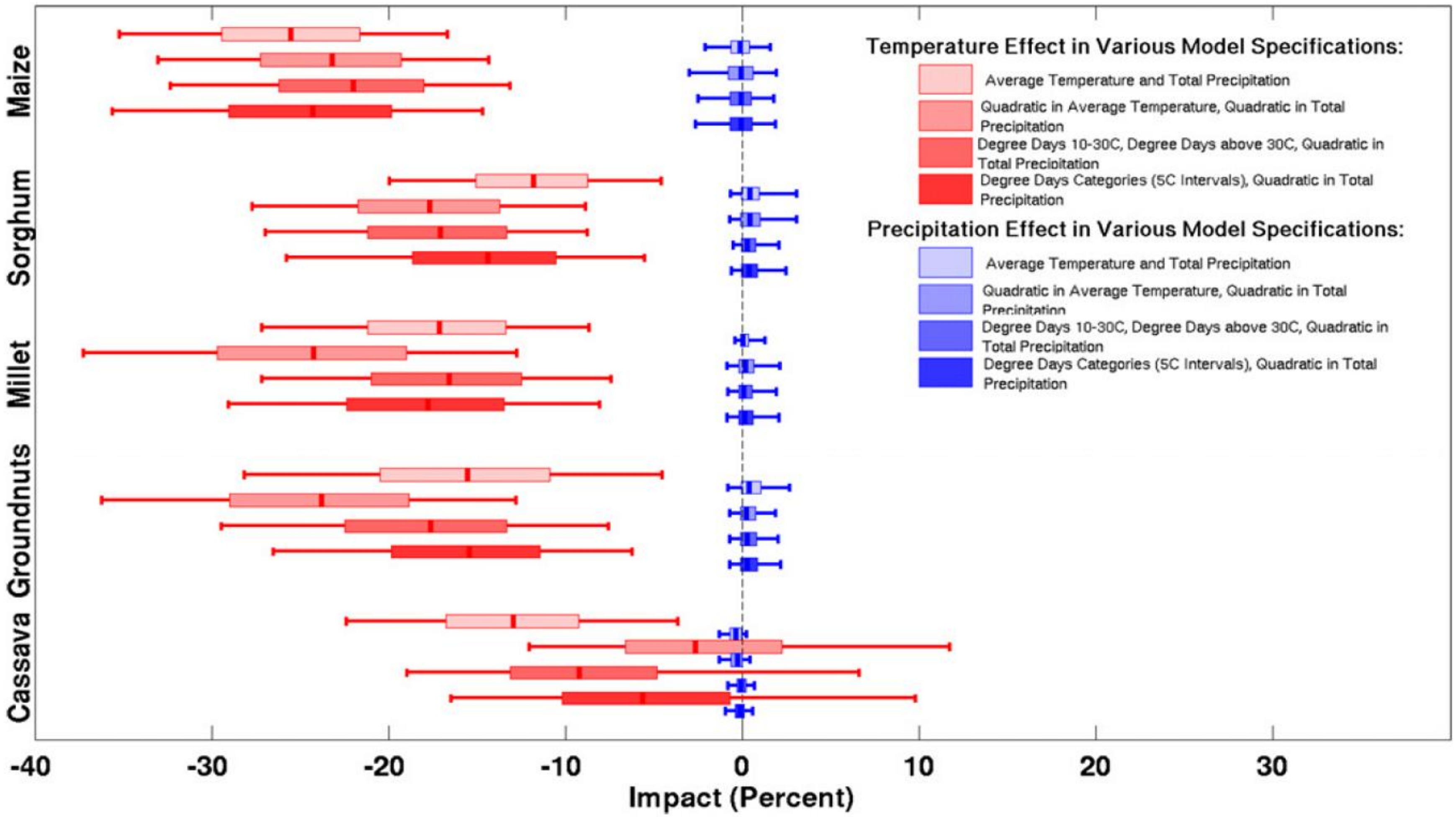
Same as in previous slide, except that changes by 2070-2099 are shown.

Adaptation and (for soybeans and cotton) the direct physiological effects of higher atmospheric CO_2 would reduce these losses to some extent)



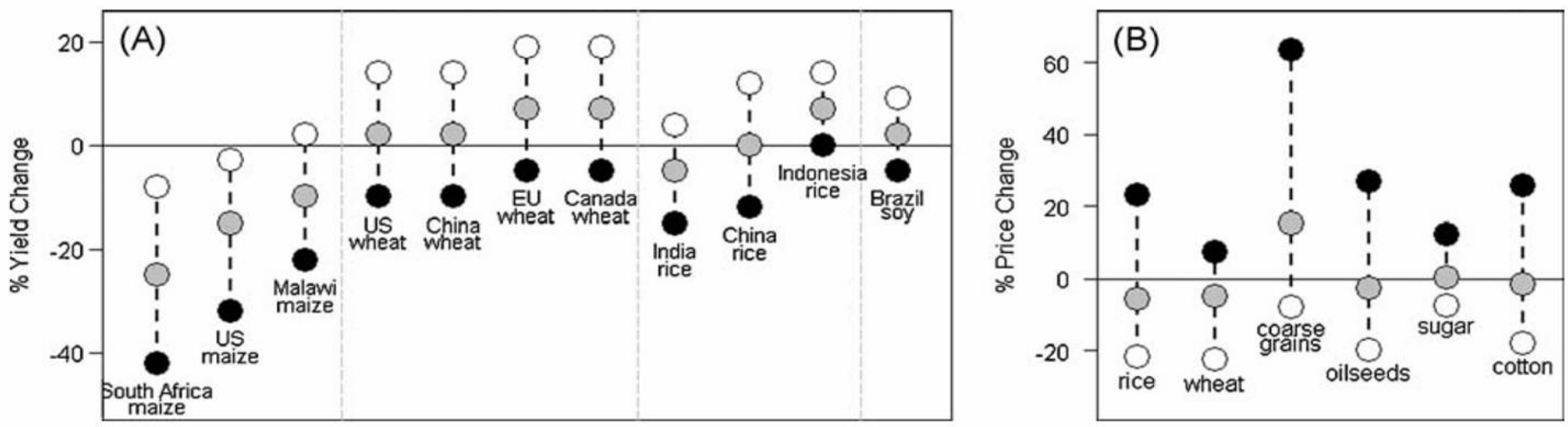
Source: Schlenker and Roberts (2009, Proc. Nat. Acad. Sci., Vol. 106, 15594-15598)

Projected impacts by **mid-century** of global warming on African staple crops (excluding adaptation).



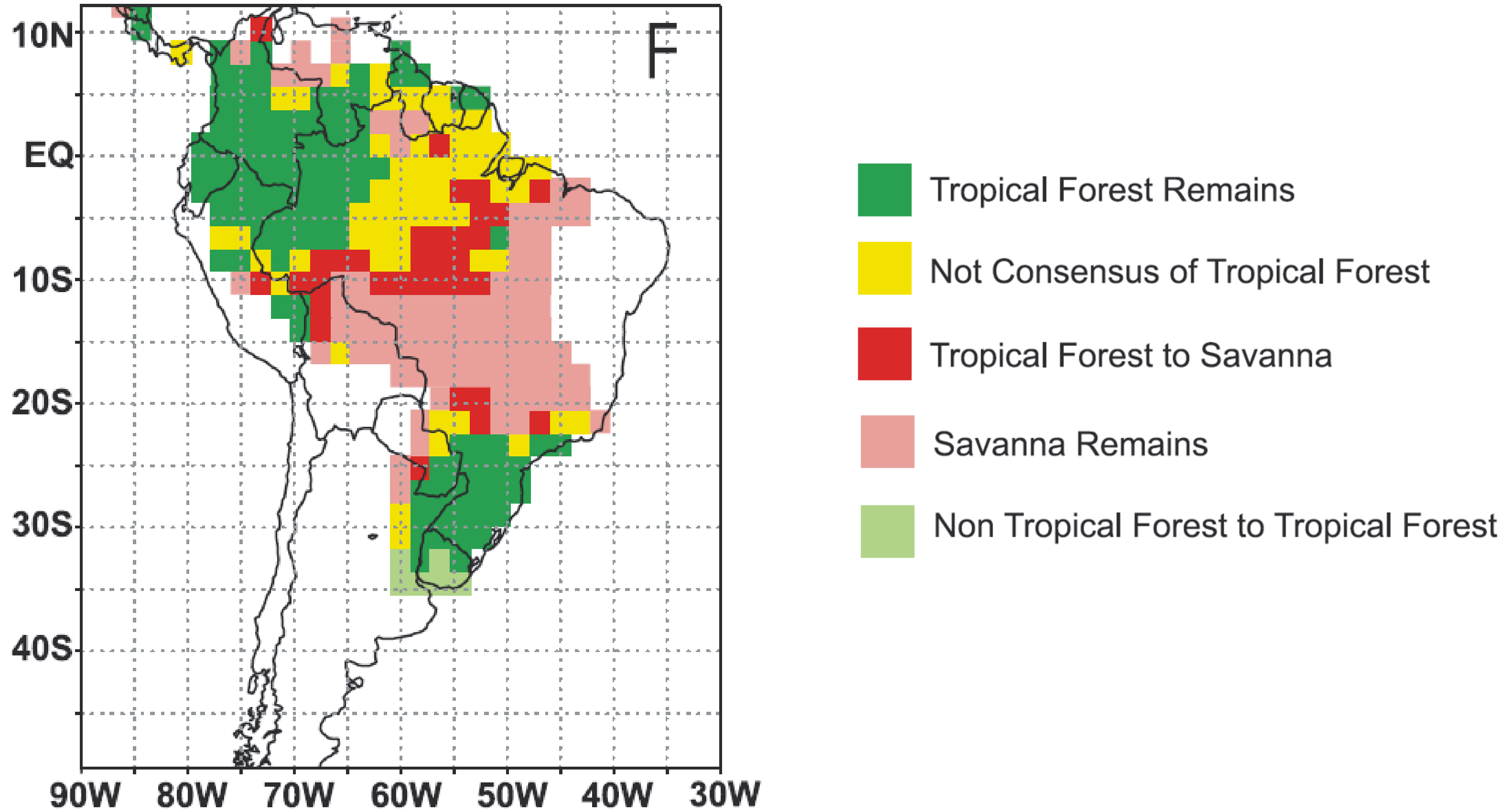
Source: Schlenker and Lobell (2010, ERL)

Estimate of the impact on crop production (left) and international prices (right) of the **2030 climate** compared to the 1990 climate. Worst case: high climatic change, high crop sensitivity, and low CO_2 fertilization benefits. Best case: low climatic change and crop sensitivity, maximal CO_2 fertilization benefits.



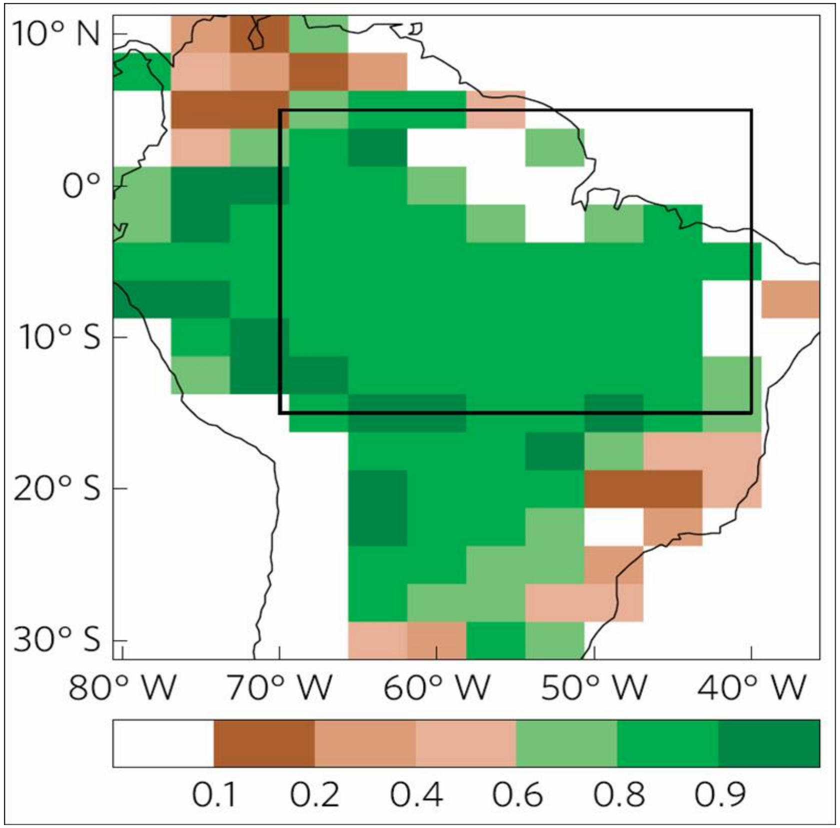
Source: Hertel et al. (2010, Glob. Env. Change 20, 577-585)

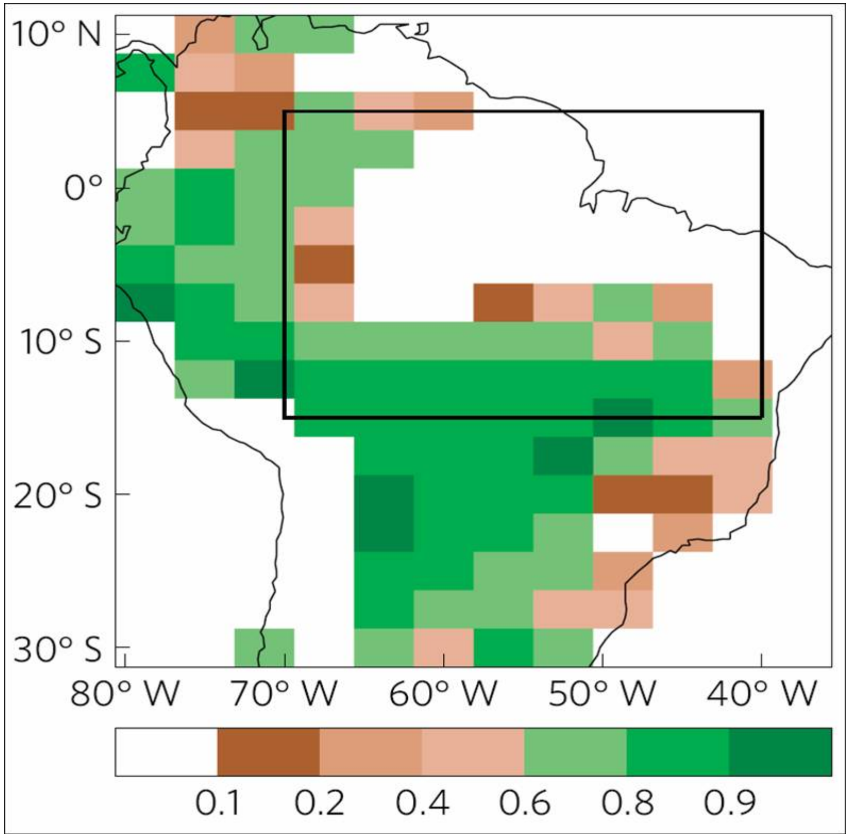
Biosphere model projections of fate of the Amazon rainforest by 2090-2100 under the A2 GHG emission scenario. Shown is the extent of agreement using the changes in climate simulated by 15 different AOGCMs as input to a the LPJ dynamic vegetation model.



Source: Salazar et al. (2007, Geophys. Res. Lett., Vol. 34, L09708)

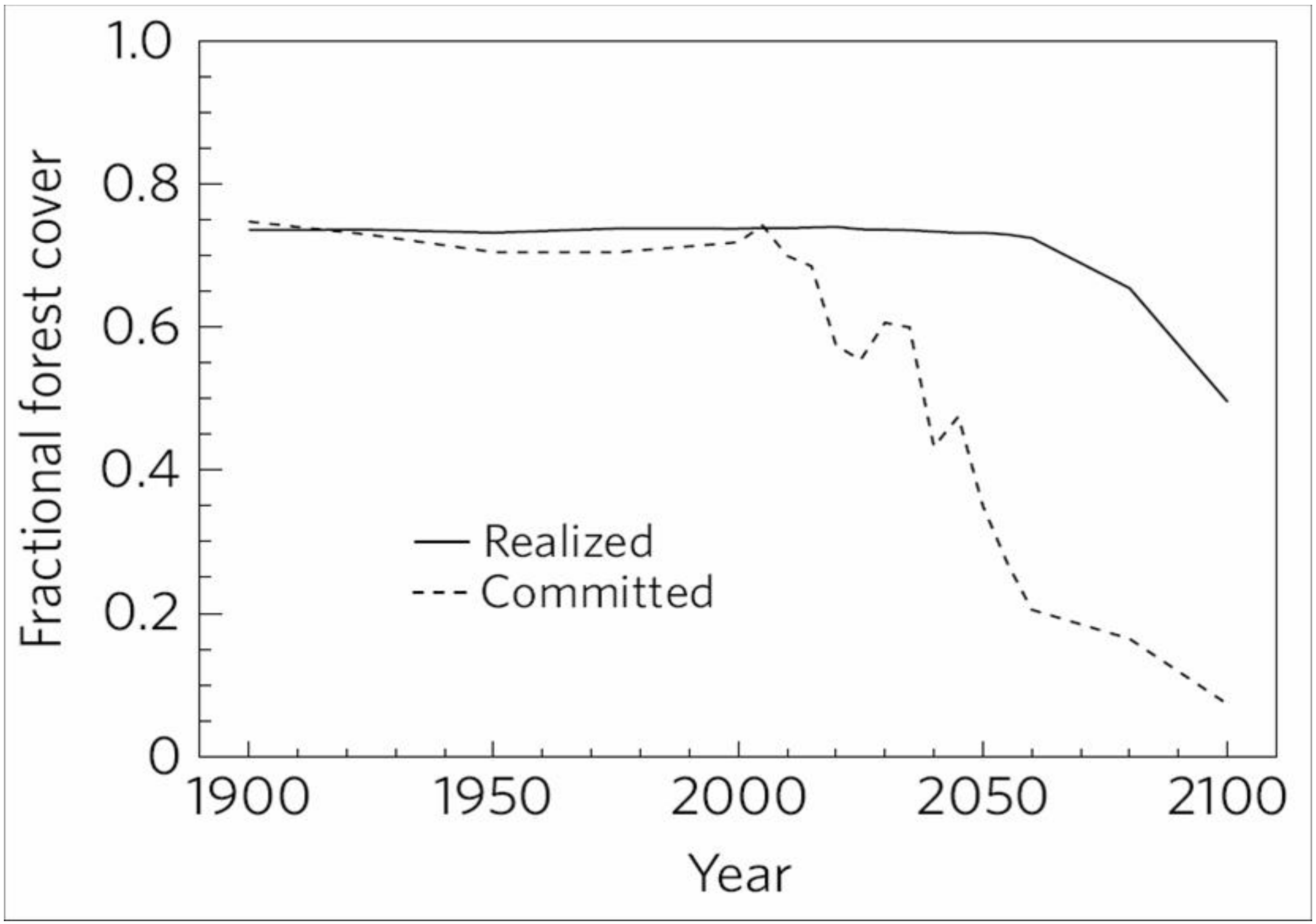
Left, distribution of grid cells with different amounts of forest cover in 2050 as simulated by the Hadley Centre AOGCM coupled to the LPJ DGVM for the A2 emission scenario. **Right:** Fractional forest cover in grid cells if the climate is held at its state in 2050 and the rainforest is allowed to eventually fully respond to the change in climate.





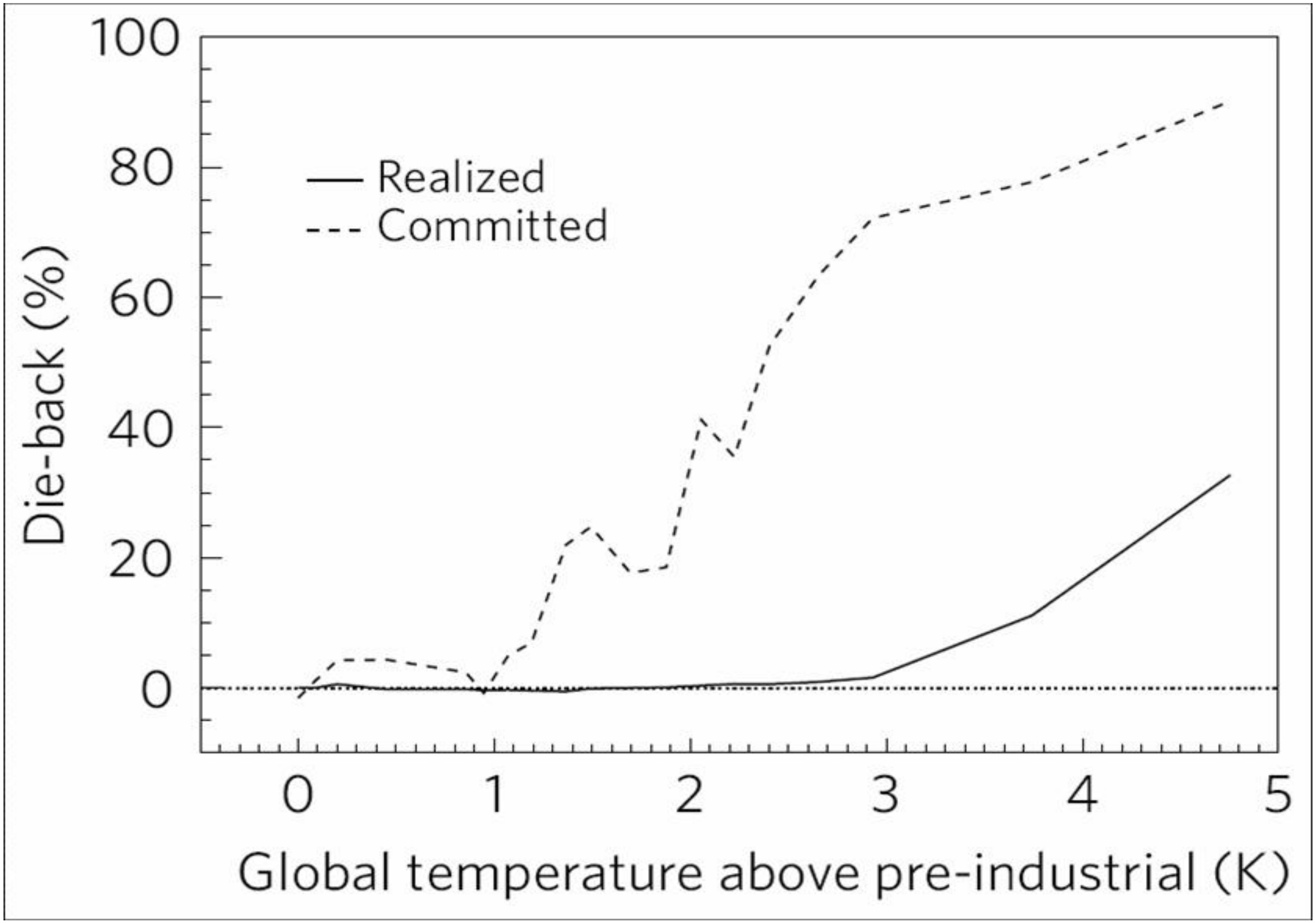
Source: Jones et al. (2009, Nature Geoscience, Vol 2., 484-487)

Comparison of the actual Amazonian forest cover (“realized”) at various times in the future in a global warming simulation, and the fractional cover that would eventually remain (“committed”) if the warming at the time in question were to persist.



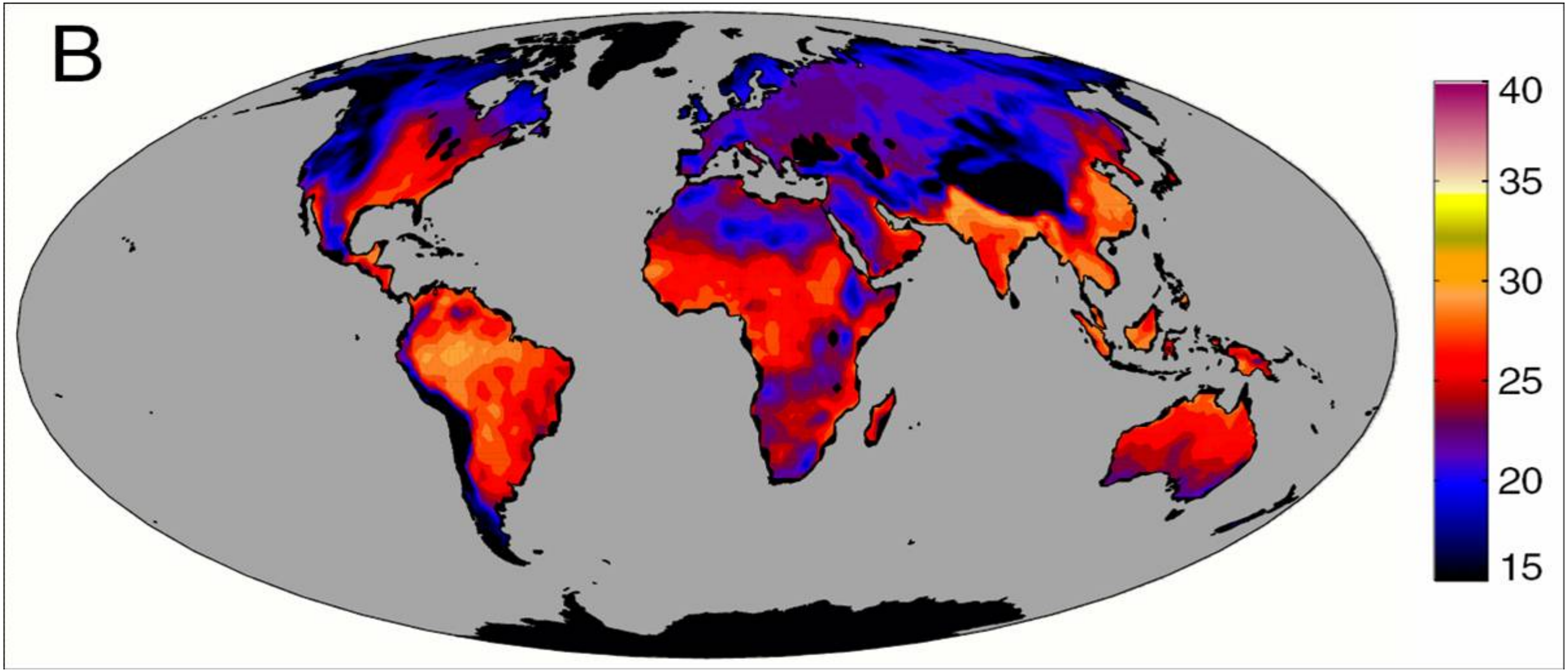
Source: Jones et al. (2009, Nature Geoscience, Vol 2., 484-487)

Same data as shown in previous slide, but in terms of realized and committed dieback as a function of the realized temperature change.



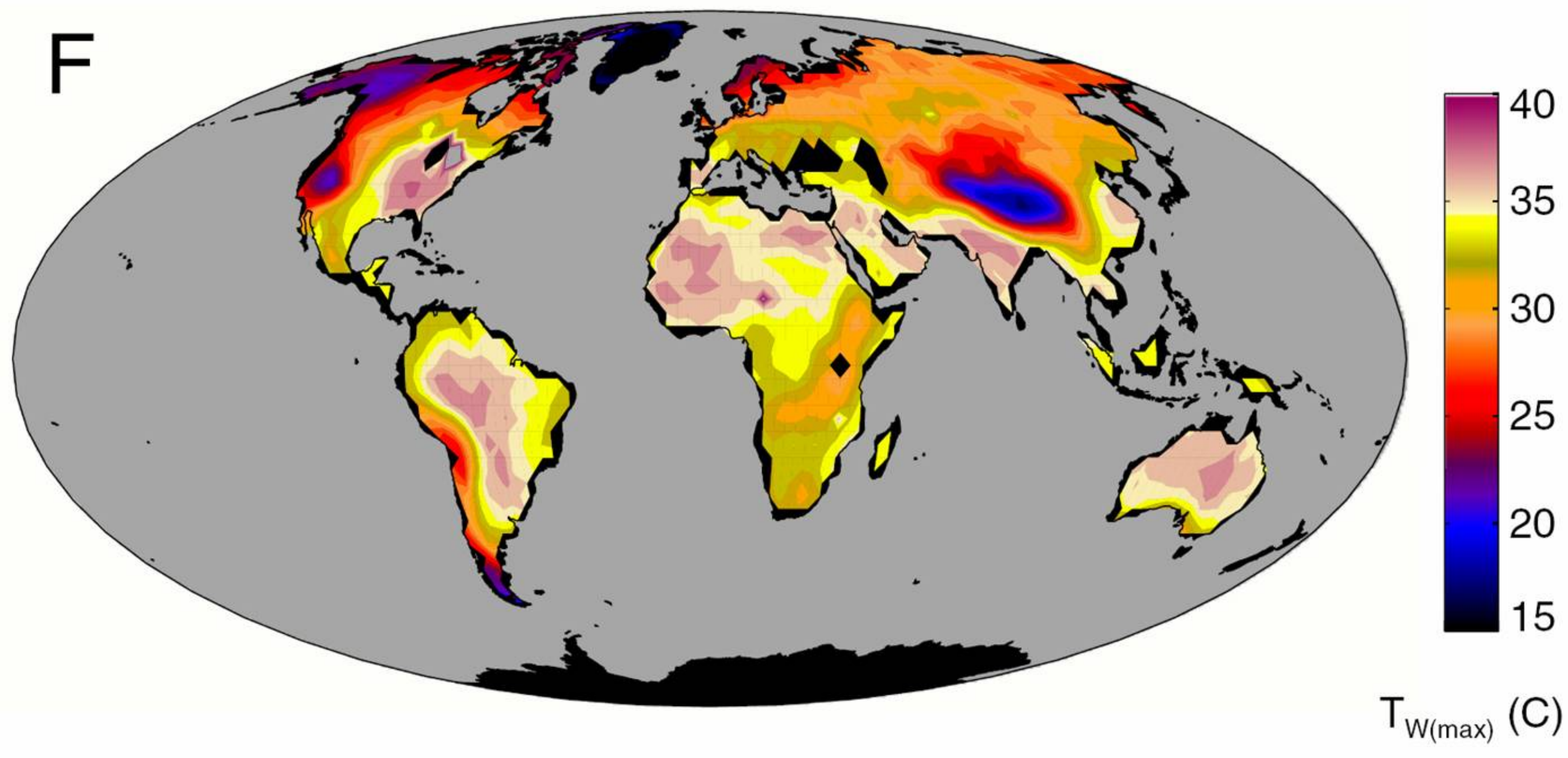
Source: Jones et al. (2009, Nature Geoscience, Vol 2., 484-487)

Distribution of maximum wetbulb temperature (T_w) that occurred at any time during the decade 1999-2008. The warmest T_w to have occurred anywhere is about 30^{o}C.



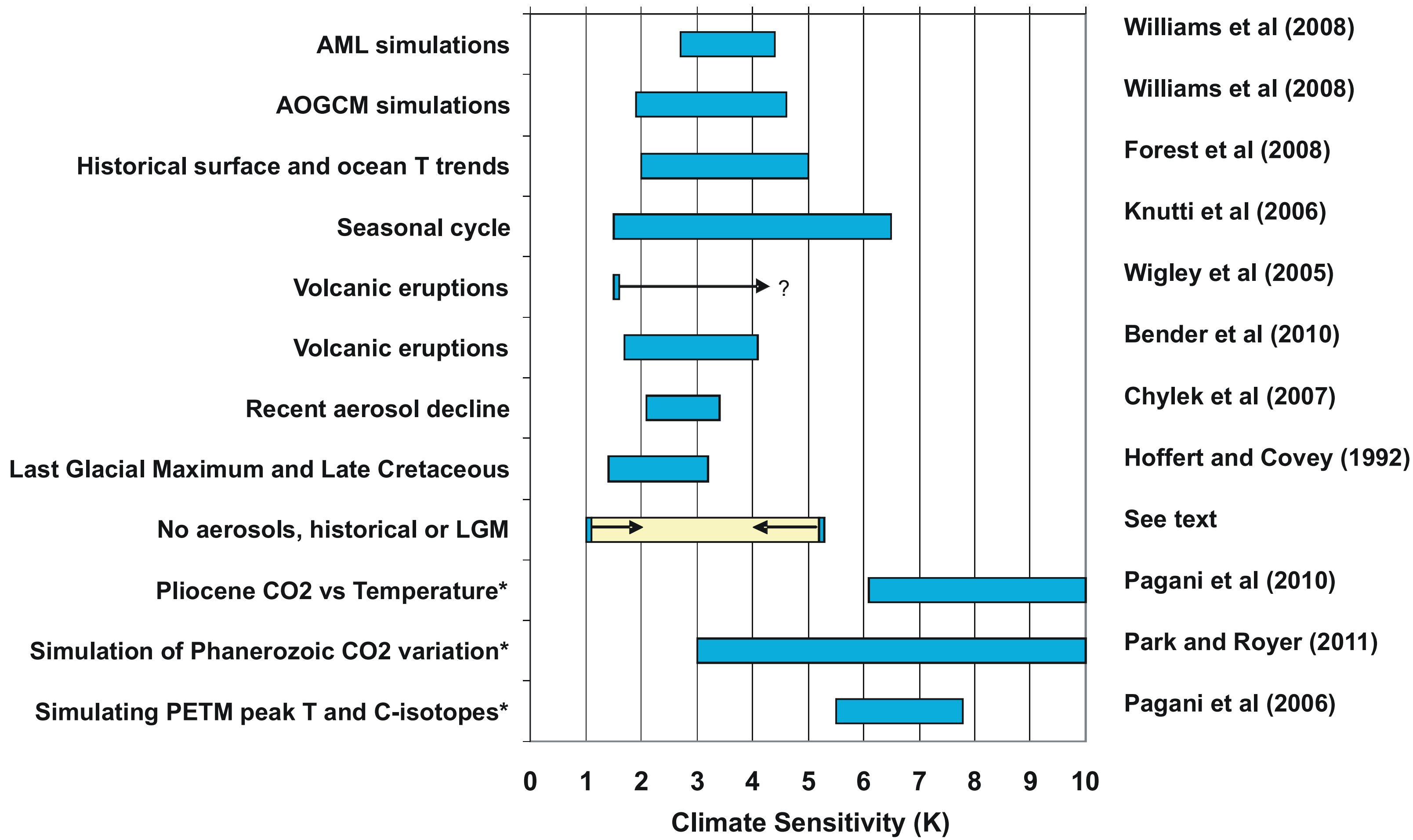
Source: Sherwood and Huber (2010, Proc. Nat. Acad. Sci., Vol. 107, 9552-9555)

Maximum annual T_w as simulated by an AGCM-ML ocean model after the global mean temperature has warmed by 10°C relative to 1999-2008.



Source: Sherwood and Huber (2010, Proc. Nat. Acad. Sci., Vol. 107, 9552-9555)

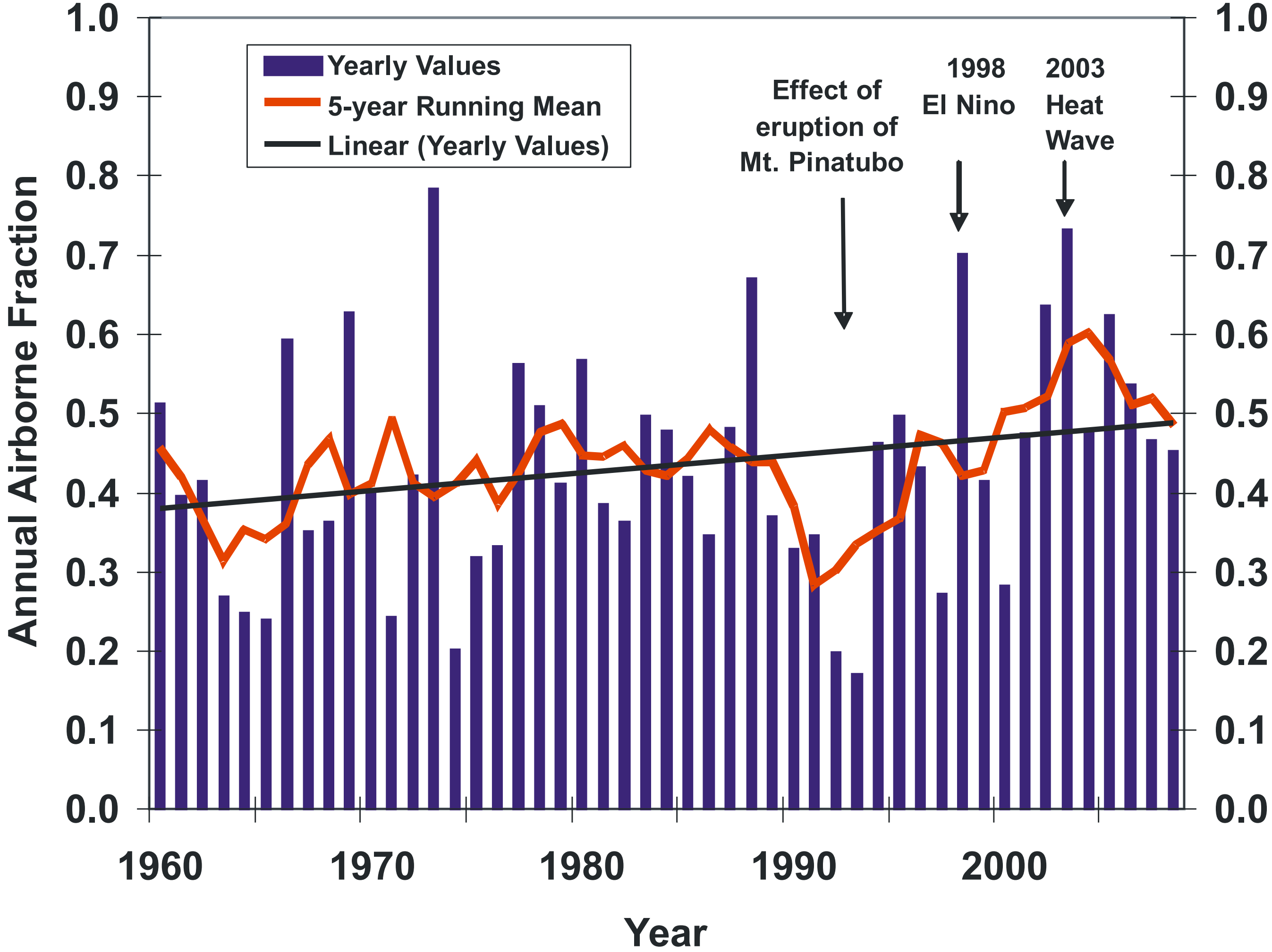
Summary of recent estimates of the magnitude of the fast-feedback climate sensitivity



Methods marked with an asterisk include the effect of changes in vegetation distribution and the full response of ice sheets, but do not include the effect of positive climate carbon cycle feedbacks as the GHG concentrations are taken as a given in computing the climate sensitivity.

Source: Harvey (2012, Fast and Slow Feedbacks in Future Climates, in *Future of the World's Climate*)

The annual CO_2 airborne fraction (ratio of annual atmospheric increase to annual human emission) has been increasing, and is expected to continue to increase as the cumulative emission grows, even in the absence of climate-C cycle feedbacks



In-your-head climate projection, grounded in observations

- BAU cumulative fossil fuel emissions of 2000 GtC (most would say 5000 GtC is possible)
- Average airborne fraction of 0.6
- Peak atmospheric increase is thus 1200 GtC or 600 ppmv
- This give a peak concentration of ~ 900 ppmv.
- With irreducible increases in other GHGs, this is the equivalent of a CO2 quadrupling compared to pre-industrial (which was 280 ppmv)
- For a climate sensitivity of 1.5-4.5ºC, this gives an expected equilibrium warming of 3-9ºC
- Peak warming could be reduced by 10-20% as the CO_2 concentration begins to fall, due to the lag in the full climate response
- HOWEVER – the above does not include all the potential additional CO_2 from positive climate-C cycle feedbacks, nor potential feedbacks involving climate and methane

Scenarios that eliminate global fossil fuel emissions before 2100

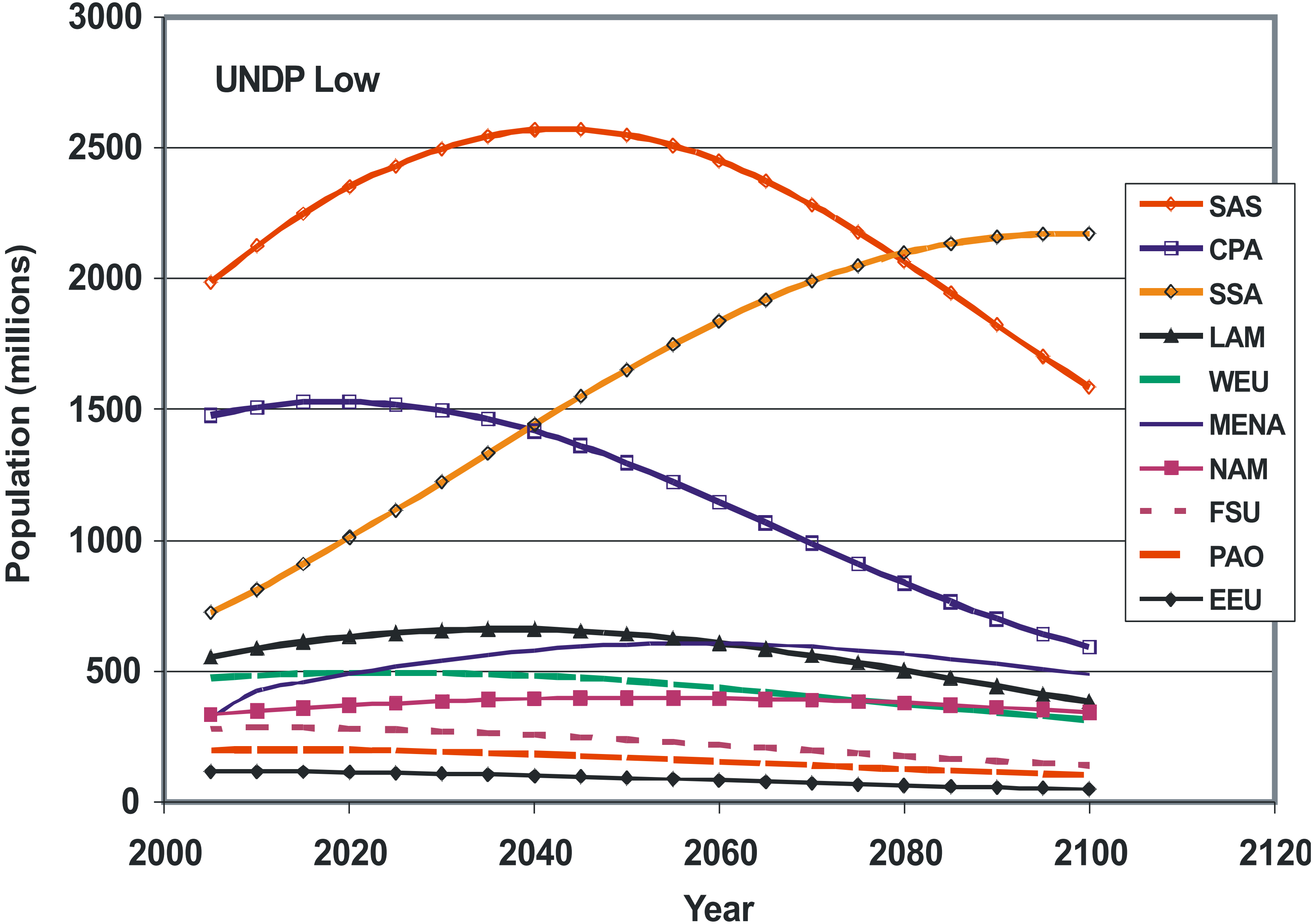
Original Kaya Identity:

Emission = Population
x GDP/P
x Energy Intensity (MJ/$)
x C intensity (kgC/MJ)

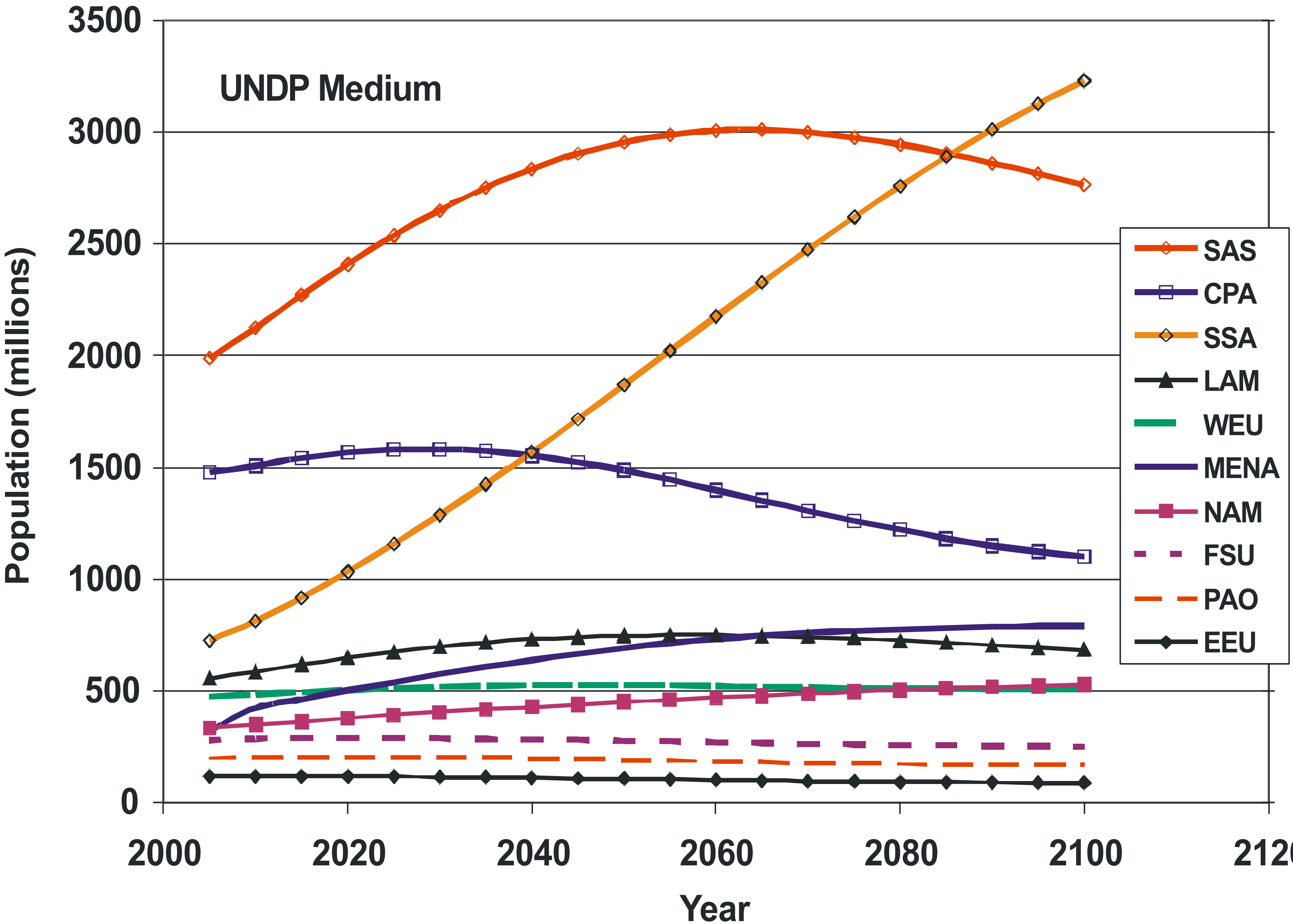
Modified Kaya Identity:

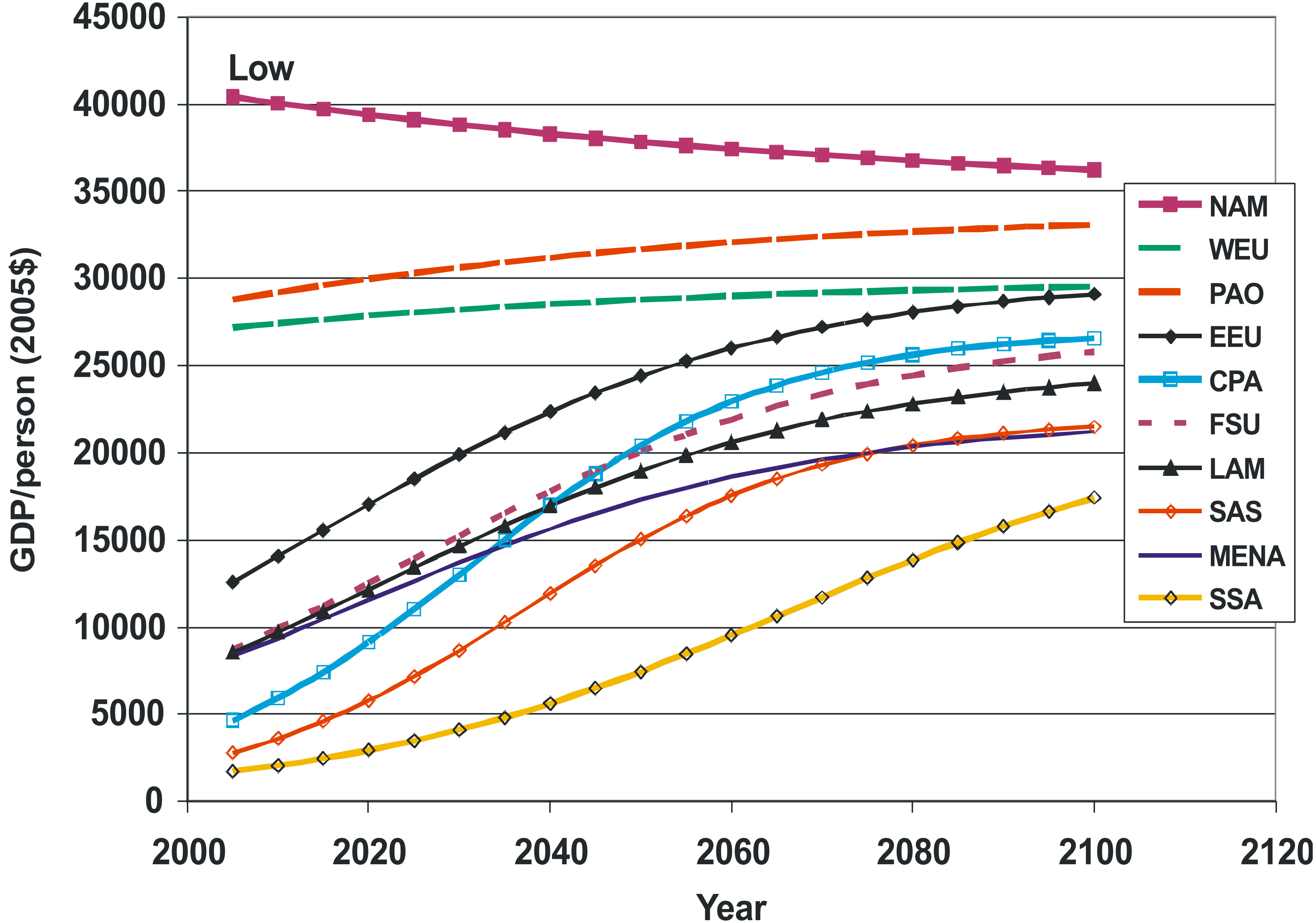
$$\text{Emission} = \text{Population} \times \Sigma(\text{Activity}(\text{GDP}/\text{P}) \times \text{Energy}/\text{Activity} \times \text{C intensity})$$

Low population scenarios

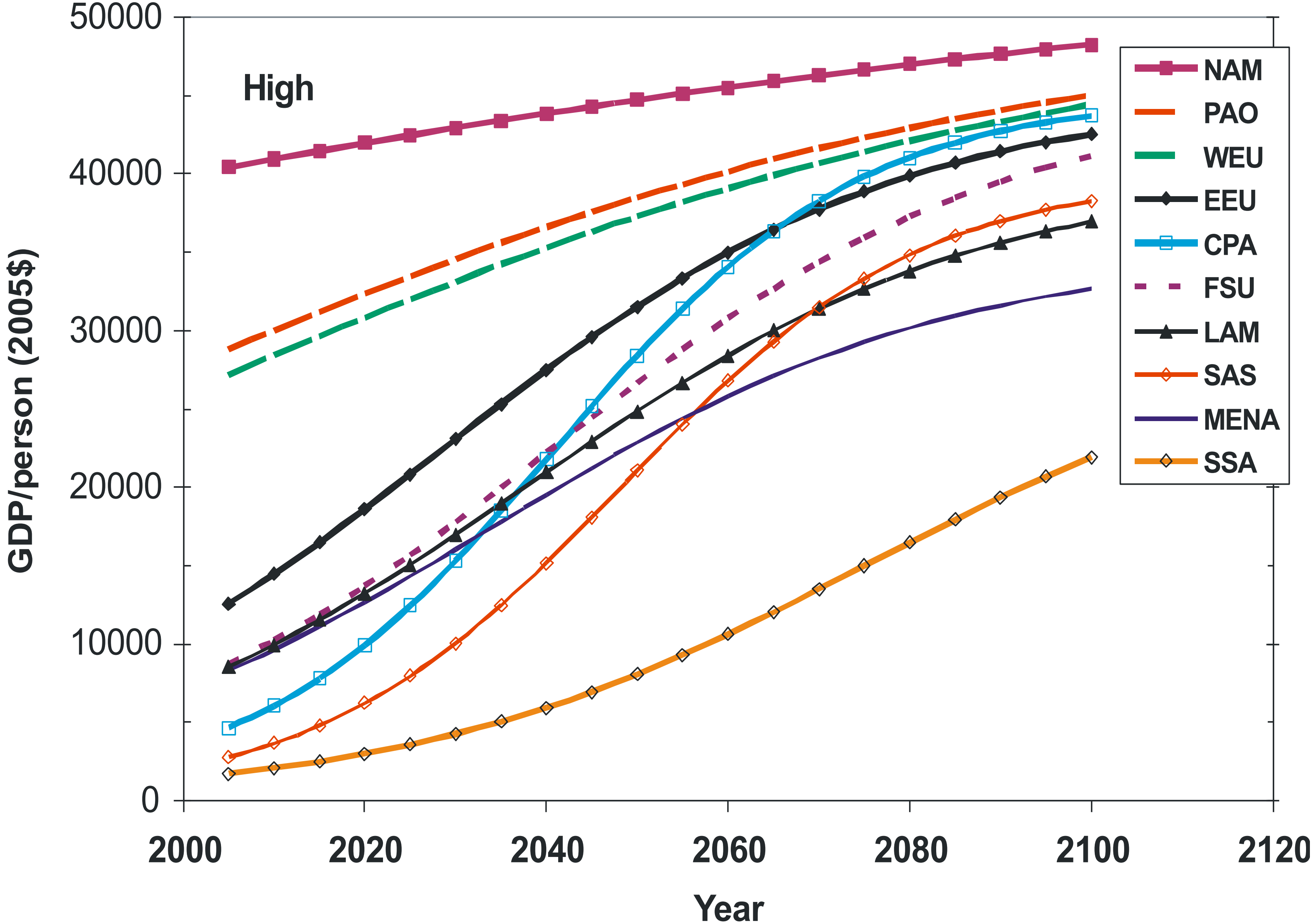


High population scenario



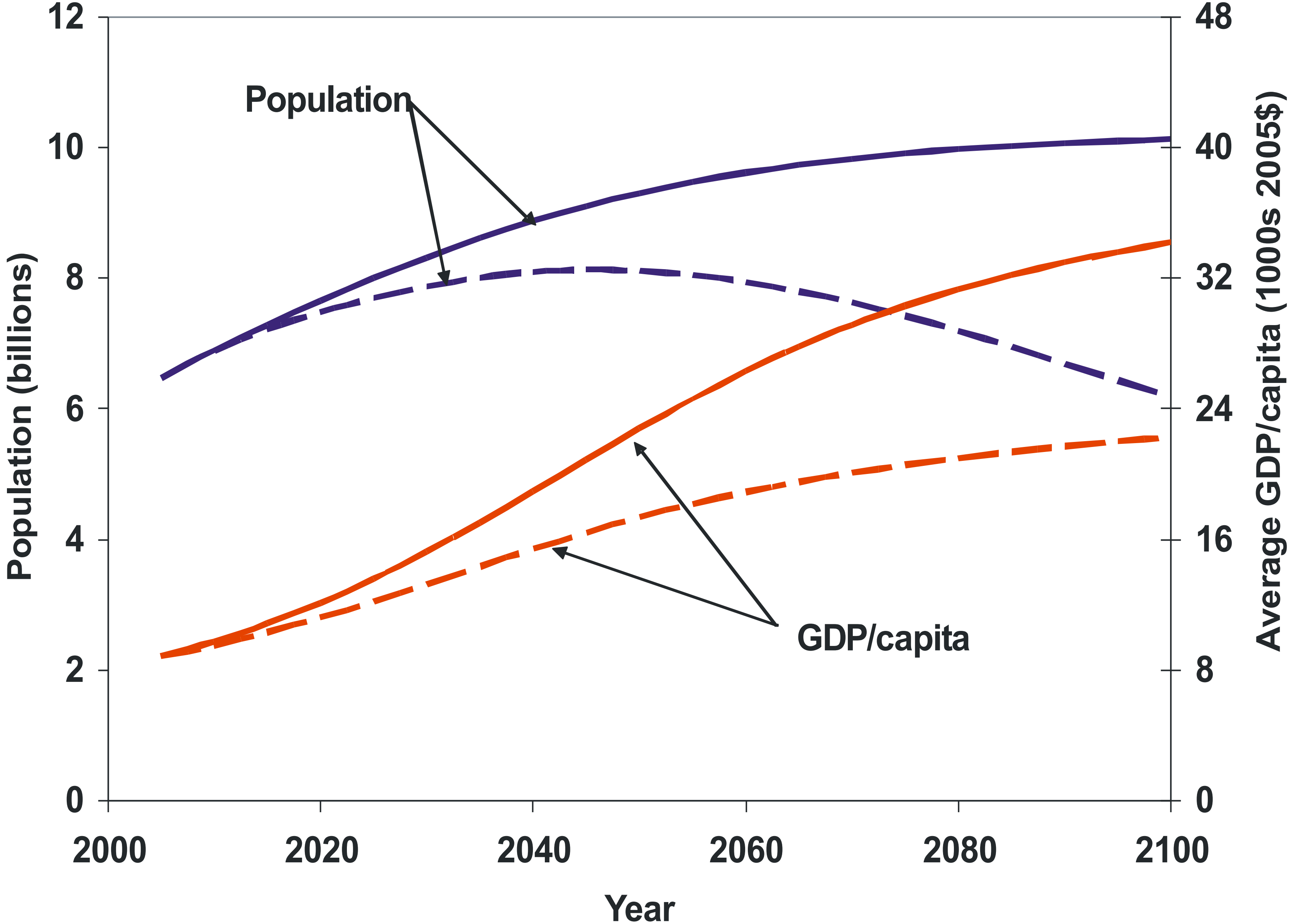


Low
GDP/person (2005$)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
2000
2020
2040
2060
2080
2100
2120
Year
NAM
WEU
PAO
EEU
CPA
FSU
LAM
SAS
MENA
SSA

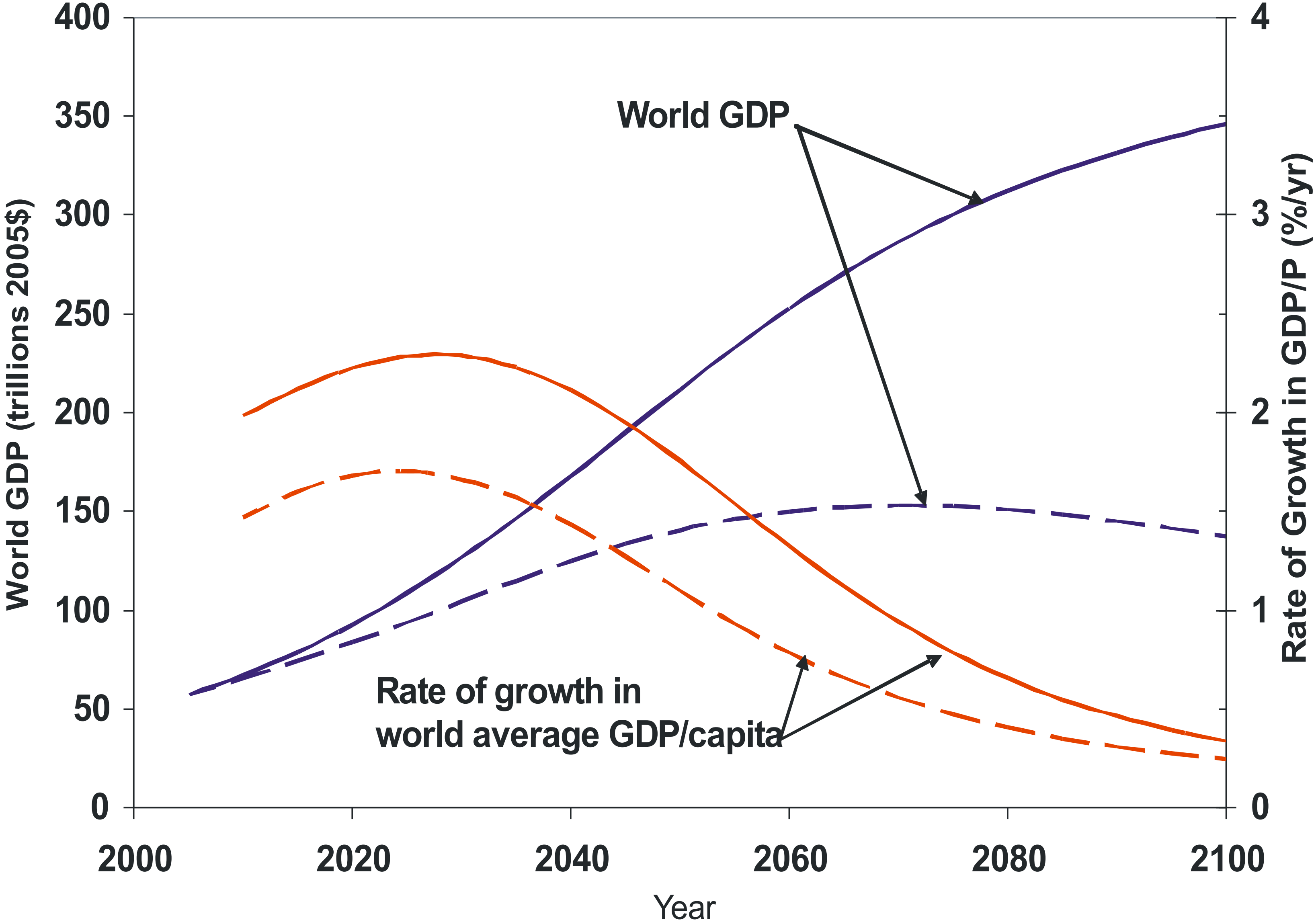


High
GDP/person (2005$)
0
10000
20000
30000
40000
50000
2000
2020
2040
2060
2080
2100
2120
Year
NAM
PAO
WEU
EEU
CPA
FSU
LAM
SAS
MENA
SSA

Global Results: Population and GDP/P

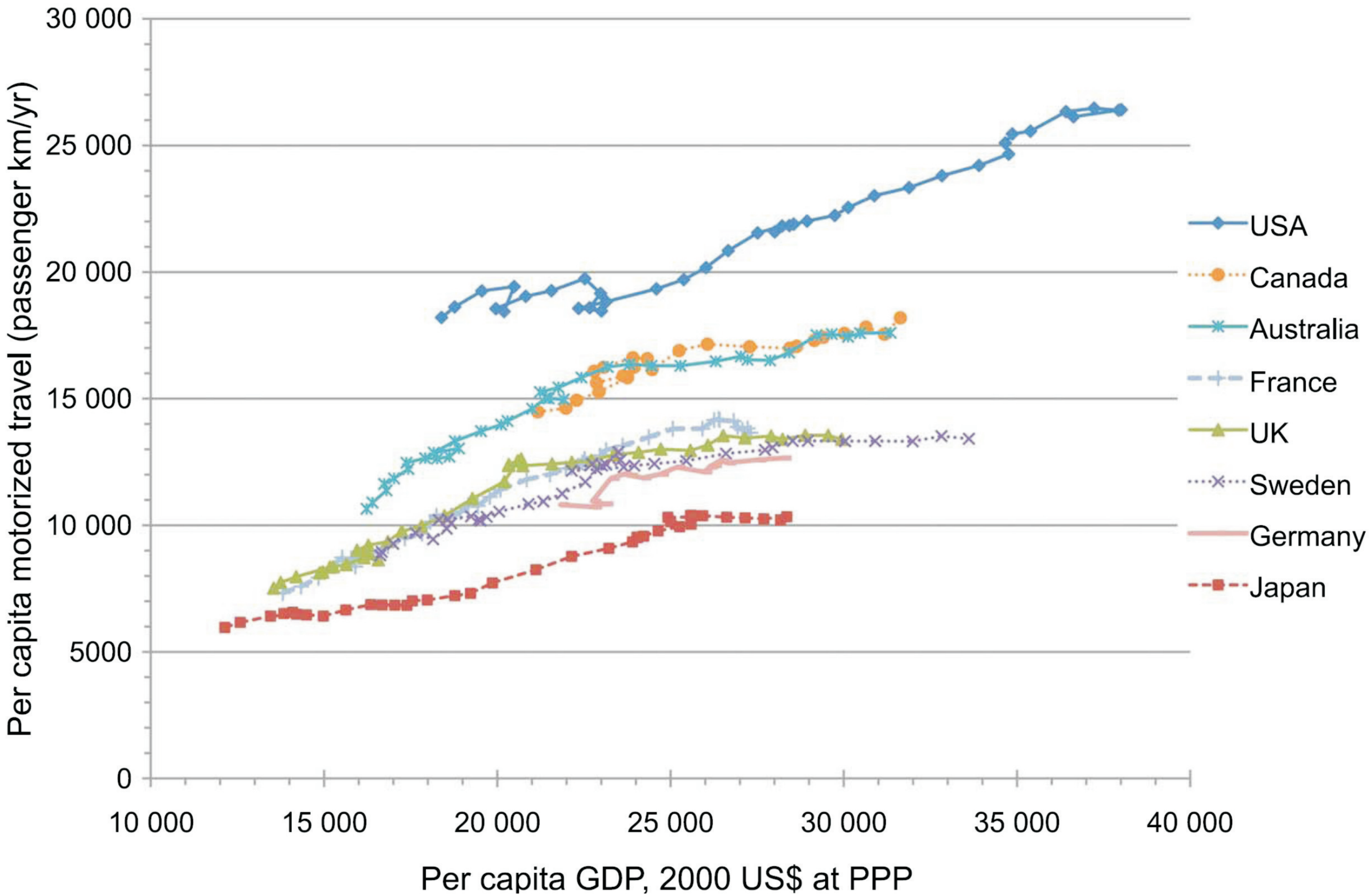


Global Results: GDP and rate of growth in GDP/P



Increasing income is used in a logistic function, calibrated to each socio-economic region in the model, to drive increasing residential and commercial floor area per capita, increasing total distance travelled per year per capita, and shifts in the proportion of total travel by light duty vehicles (LDVs – cars and light trucks) and by air

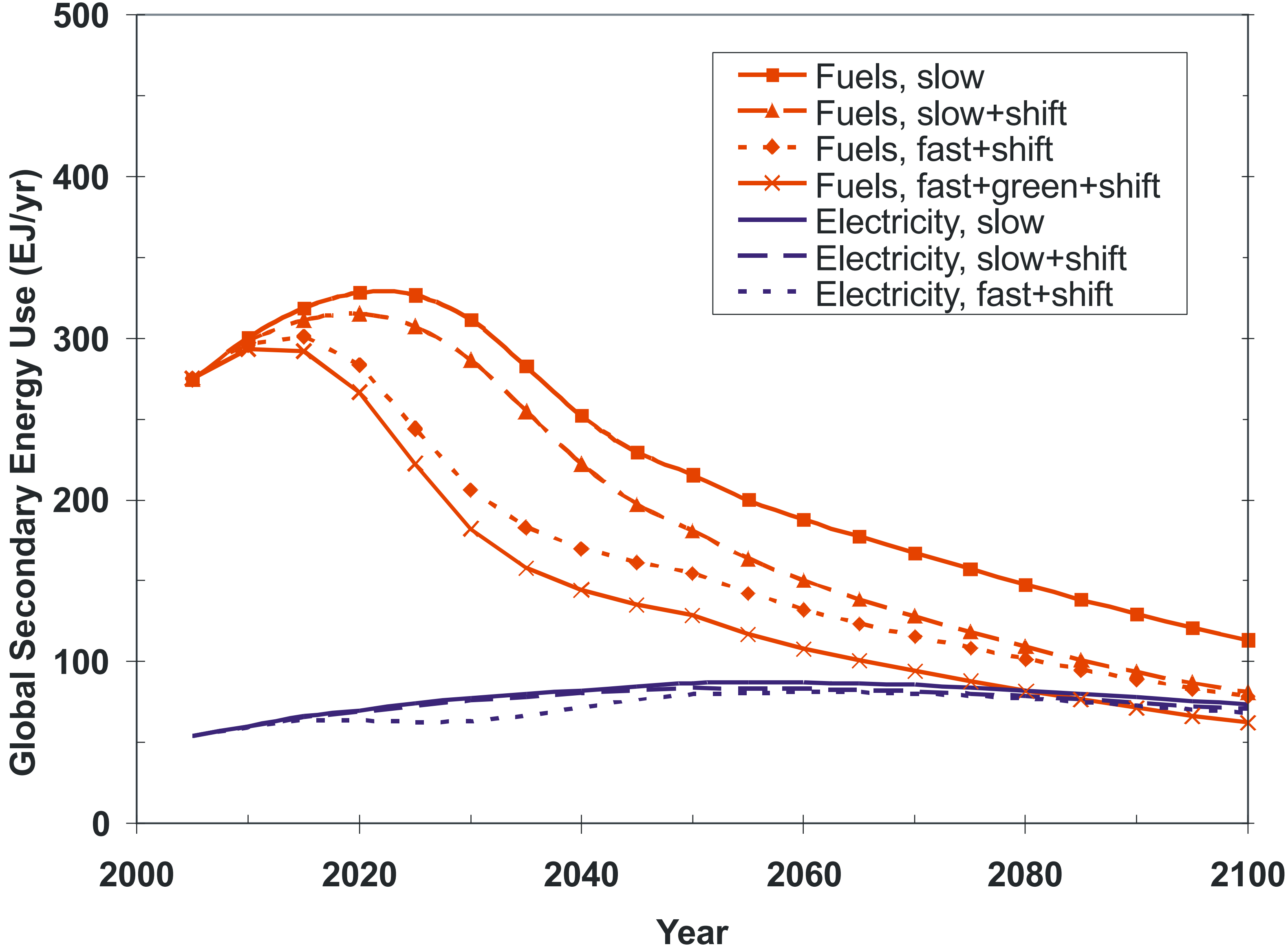
Illustration of saturation of activity with increasing income, but at different levels in different regions



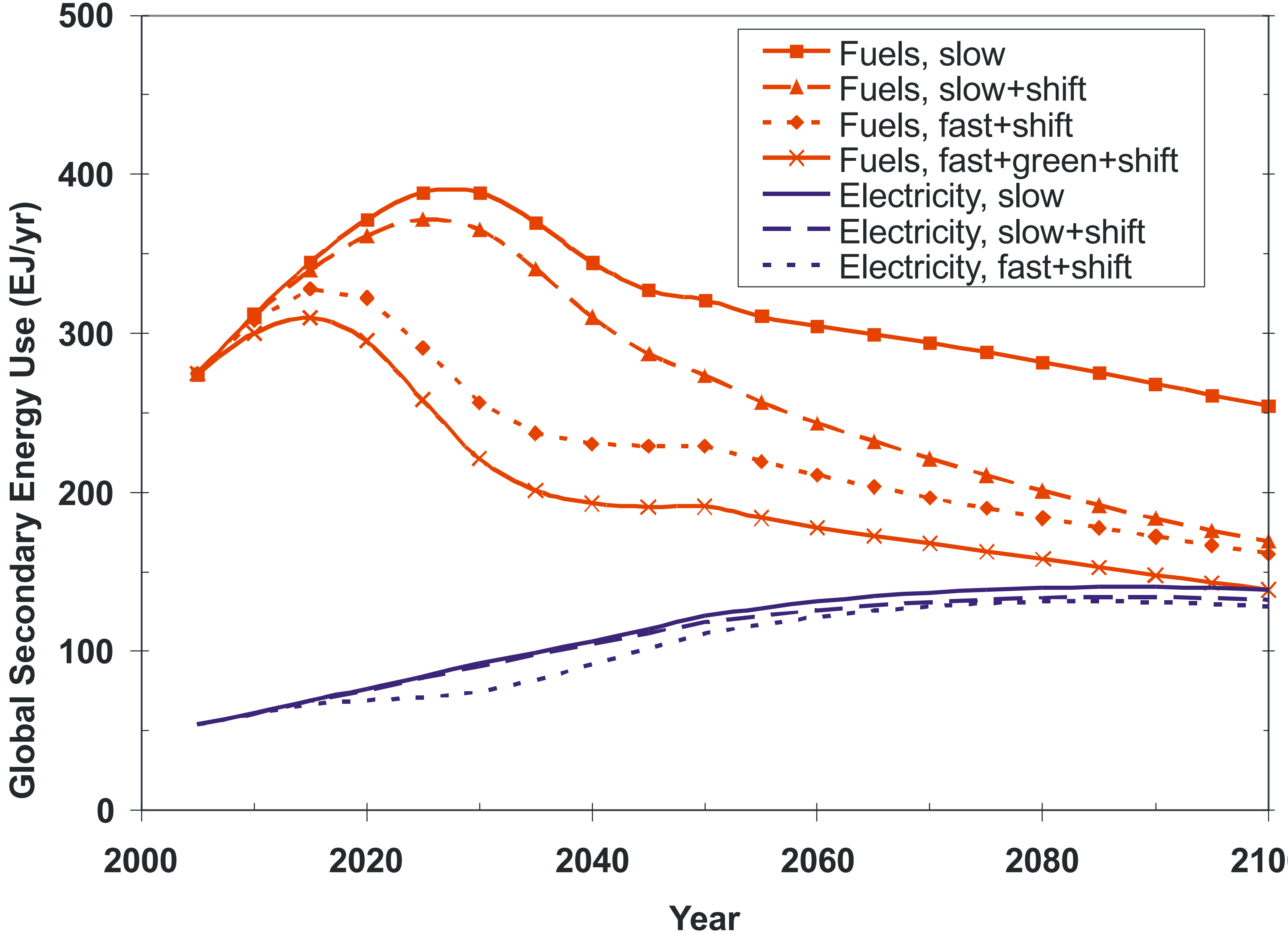
Energy Intensity Assumptions

- Energy performance of new buildings improved by a factor of ~ 4 by 2020 (fast) or 2050 (slow) compared to the performance of recent new buildings
- Retrofits of existing buildings eventually achieve factor of ~ 2-3 reduction in energy use
- Complete retrofit or replacement of the entire building stock by 2050 and again by 2100
- Close to maximum currently feasible improvements in transportation vehicle efficiencies for new vehicles by 2025 or 2035 (this is a factor of 2-3 reduction for a given drive train), and slower improvements thereafter
- Change in modal split (i.e., LDVs to rail) and shift to more energy efficient vehicles in the LDV fraction
- Maximum currently known potential to reduce industrial energy intensities by 2050 + reach 90% recycling of materials by the time the economy reaches a steady state (end of century)

Net Result, Low GDP Scenario:

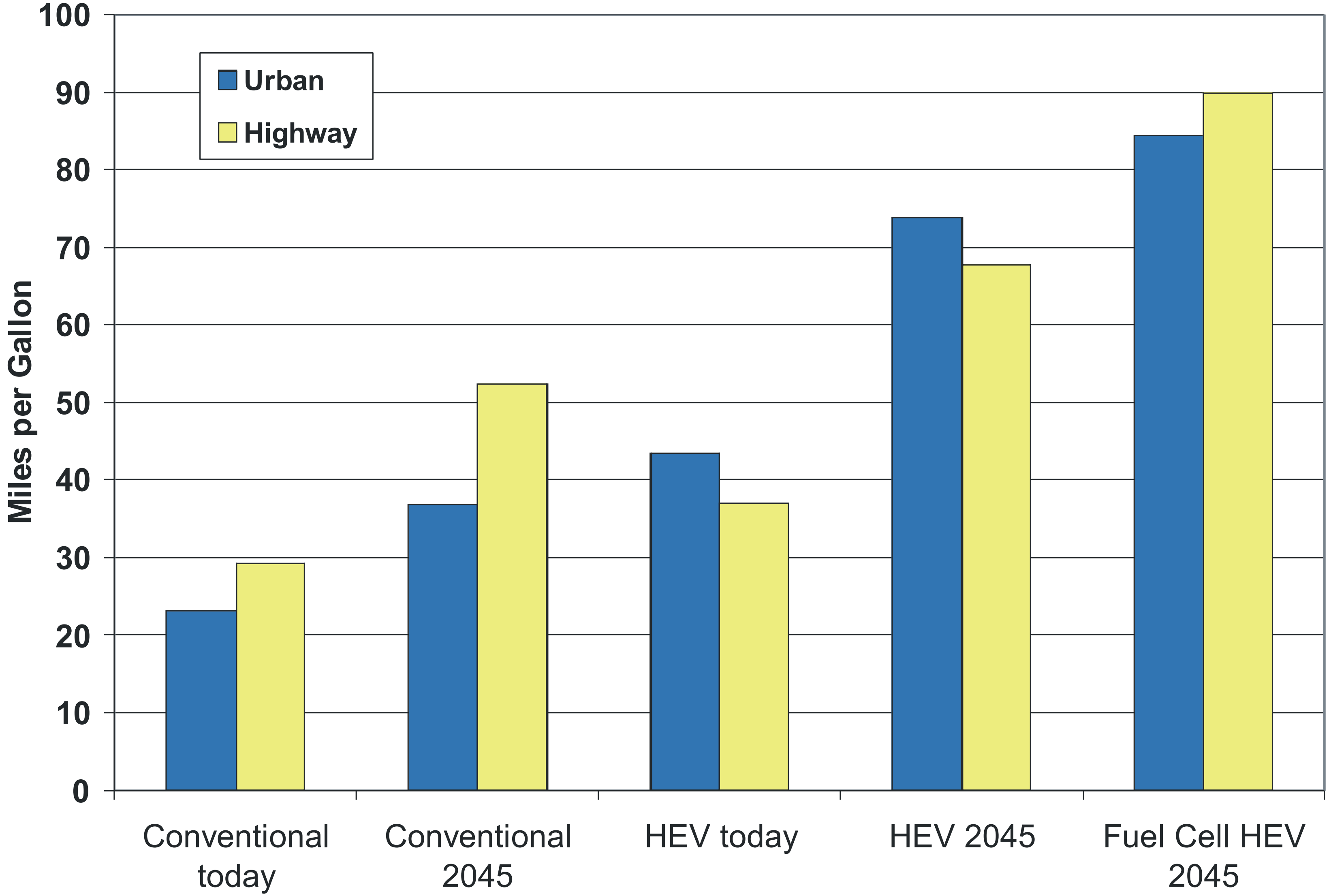


Net Result, High GDP Scenario:

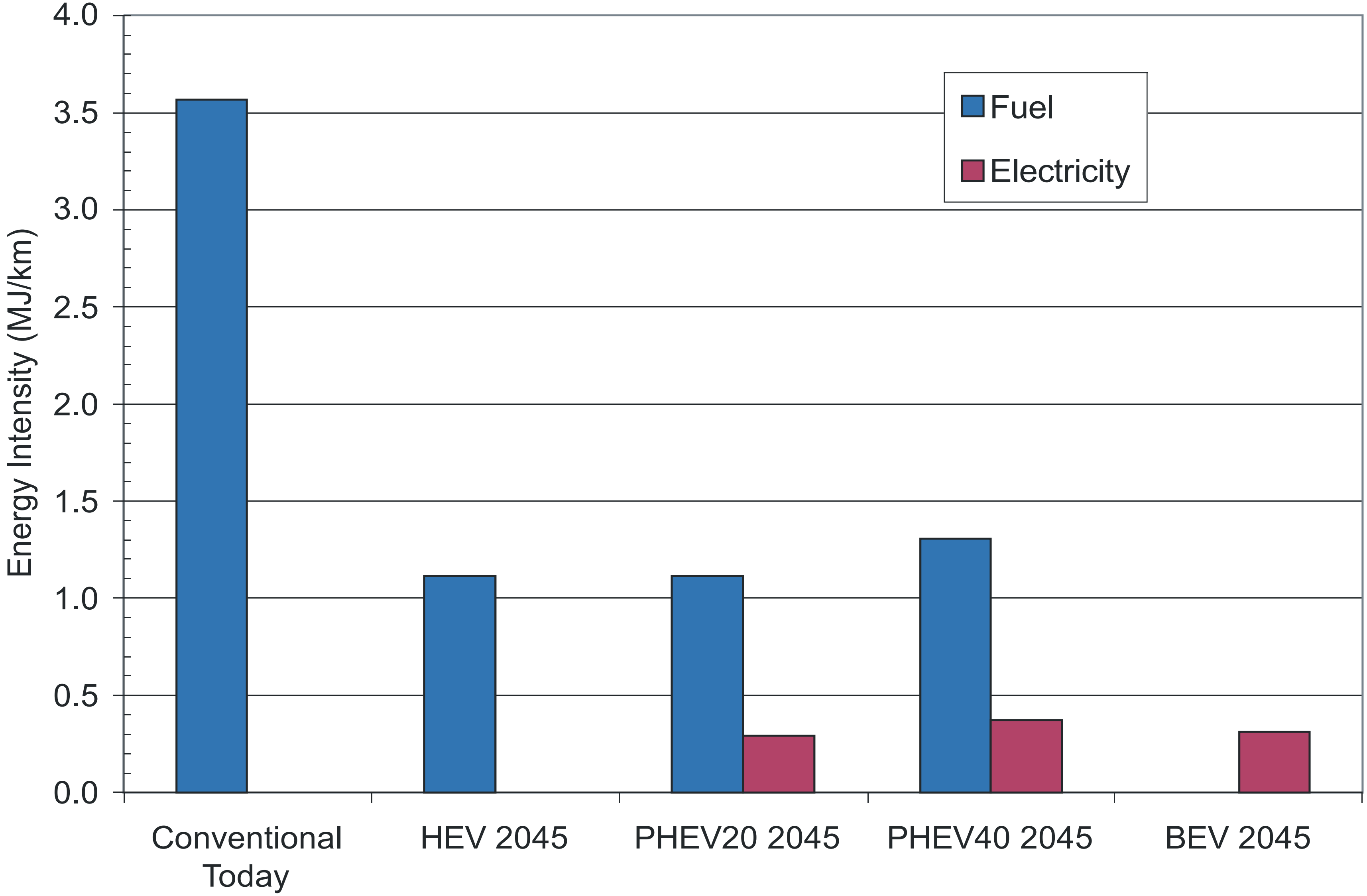


Decomposition of the transition, BAU to zero CO_2 emissions in the transportation sector

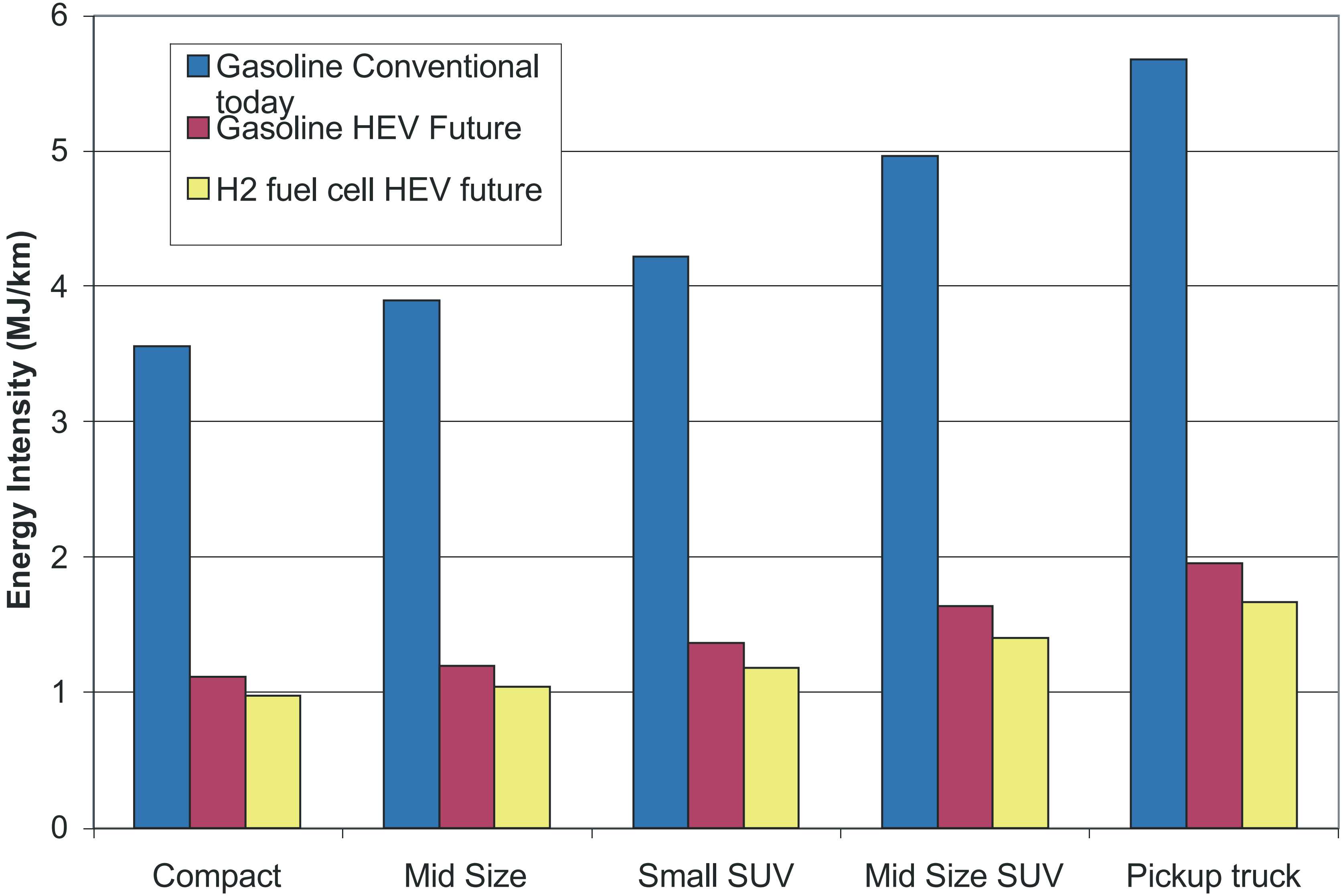
Argonne National Lab 2011 study, potential improvements in the fuel economy for compact cars (adjusted from standardized tests to reflect real-world driving conditions, including aggressive driving behaviour)



Argonne National Lab study, fuel and electricity energy intensity for compact cars



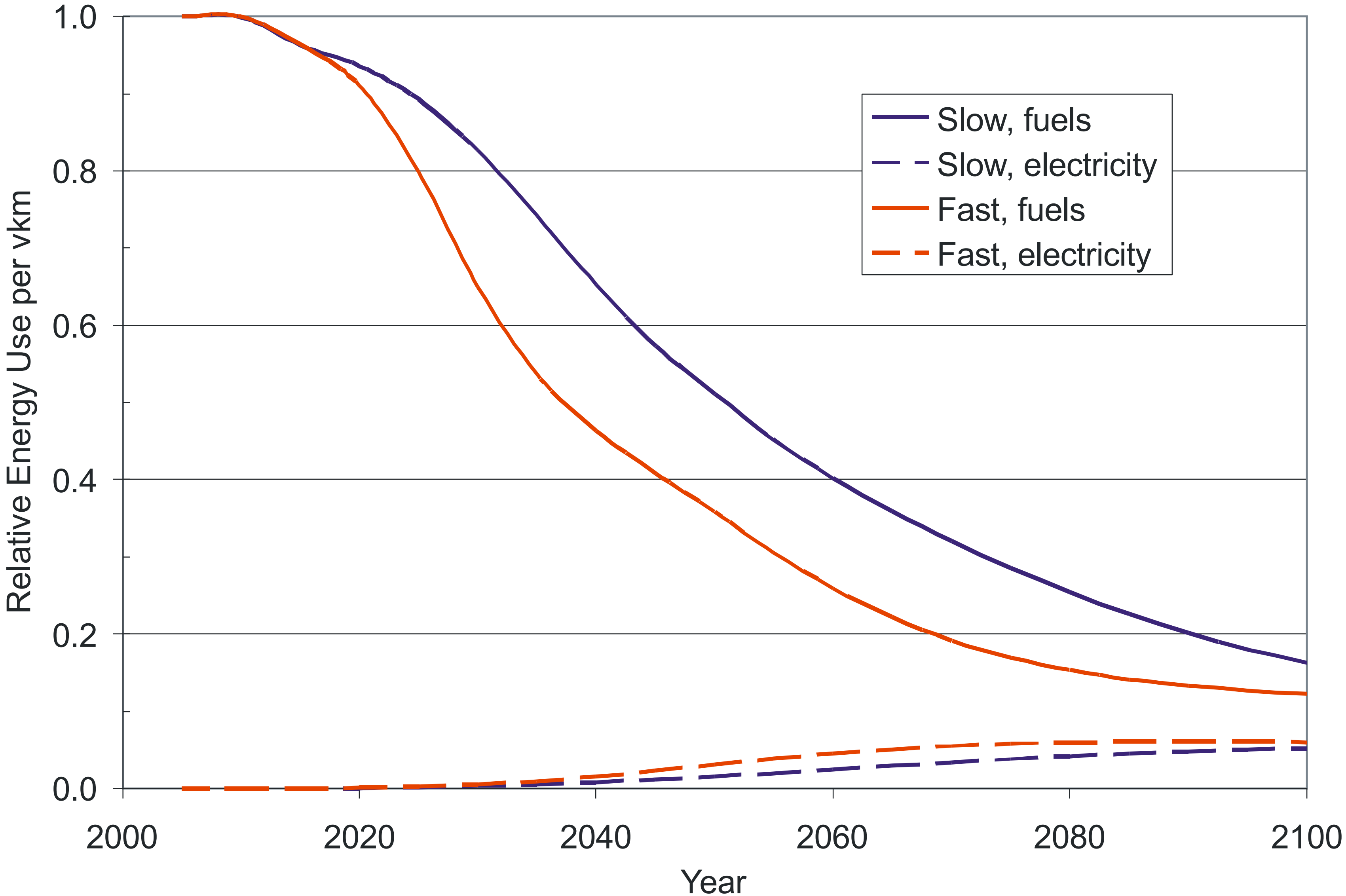
Argonne National Lab study, fuel energy intensity for different vehicle market segments



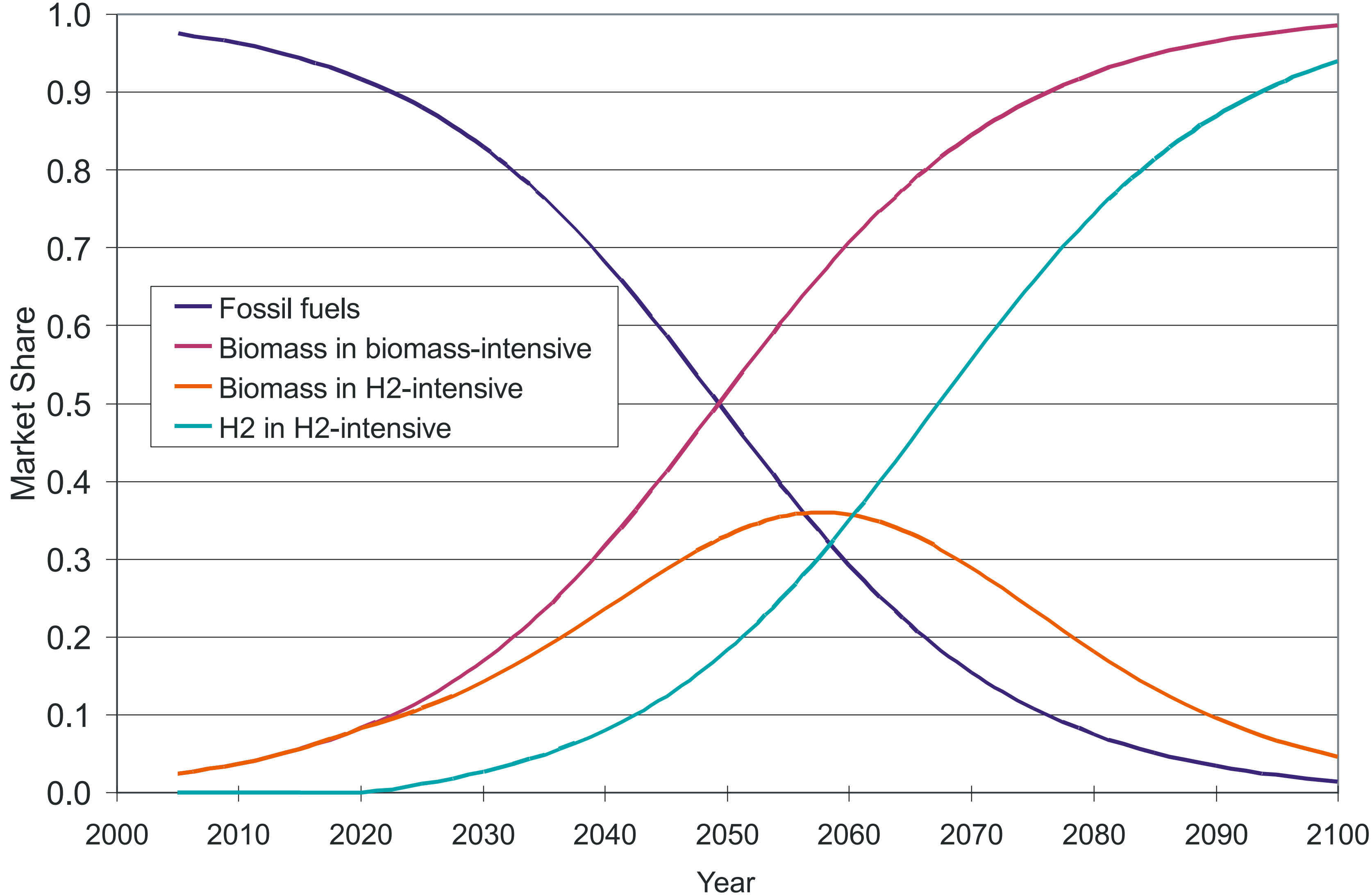
Technical scenario

- Transition from current to Argonne energy intensities for new vehicles between 2015-2035 or 2015-2045
- Further improvement at 0.5%/yr thereafter
- Transition from conventional to PHEV40 drive train over the same time period
- Shift entirely away from pickup trucks and partly away from SUVs to more efficient vehicles

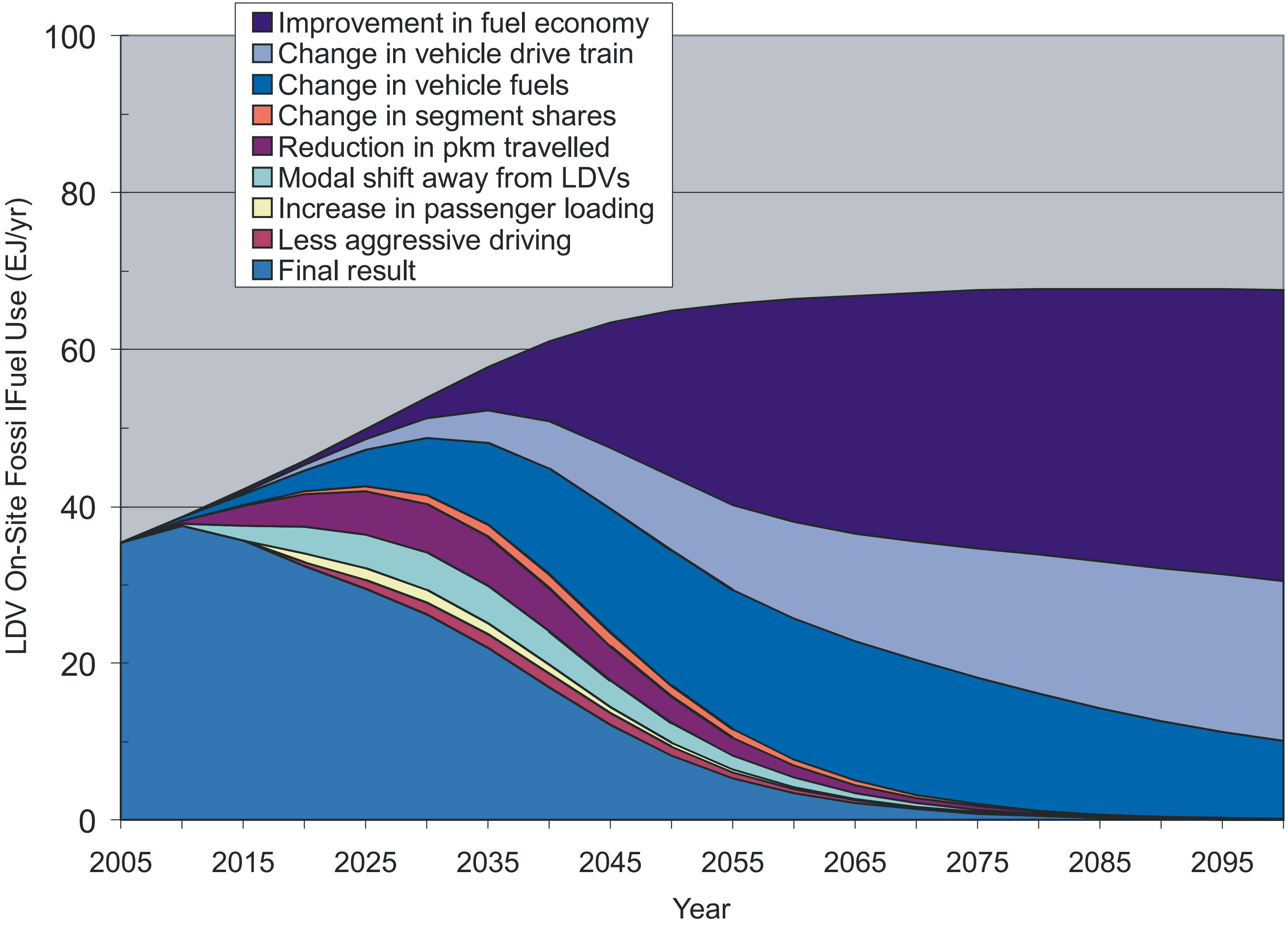
Resulting global fleet average energy intensity:



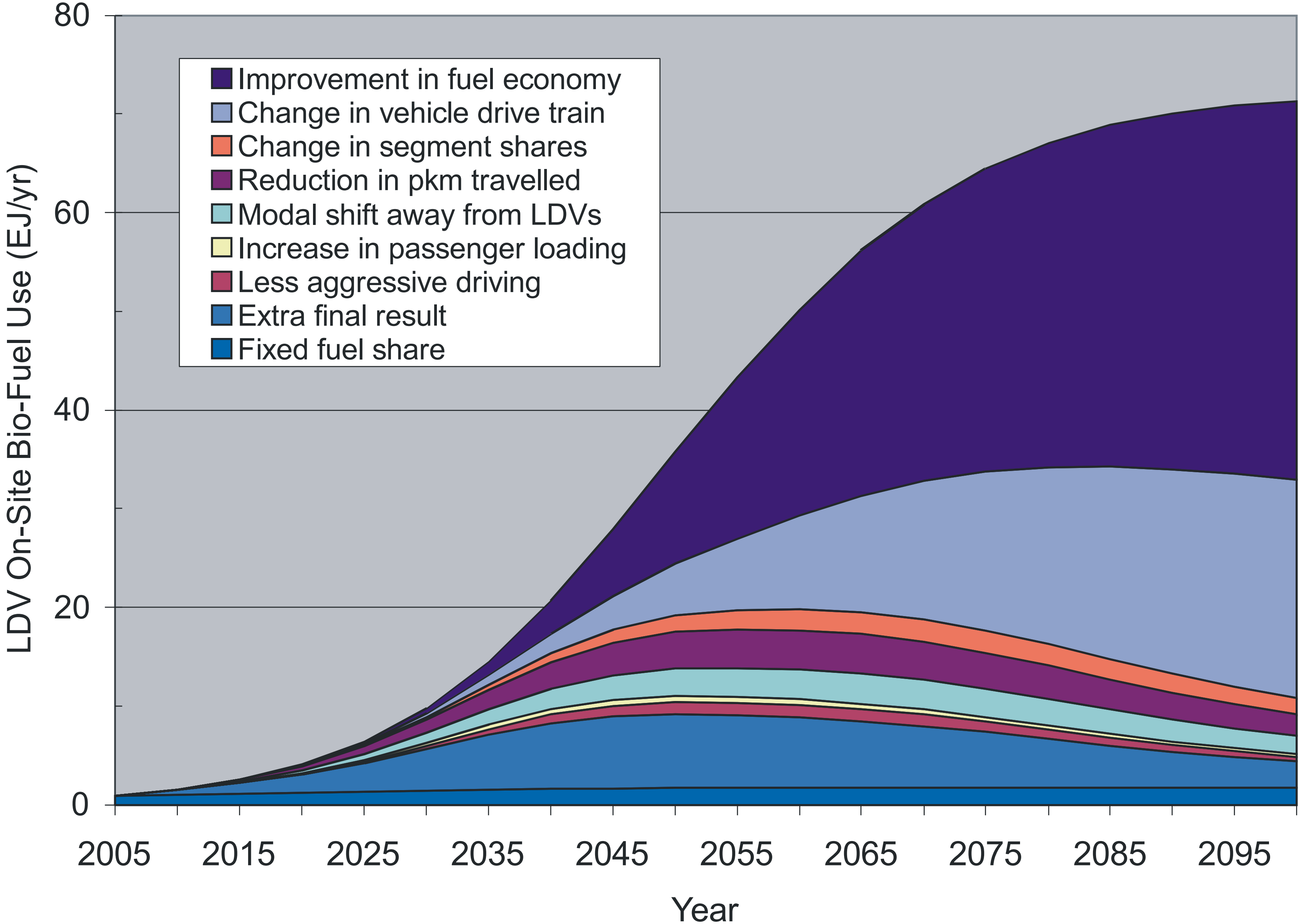
Market shares of the rapidly declining fuel demand



Global fossil fuel use by LDVs, Low GDP scenario



Reductions in global biofuel use by LDVs, Low GDP scenario



The Brazilian *cerrado*, potential land for soybean and sugarcane cultivation and home to > 900 species of birds and 300 species of mammals, many threatened with extinction

Source: (C) by Luiz Claudio Marigo/naturepl.com

Supply Options, Approach:

- Postulate buildup to enough C-free energy sources to completely displace all fossil fuels by 2100 for each demand scenario
- Consider biomass-intensive and hydrogen intensive supply scenarios
- In the hydrogen-intensive scenario, hydrogen is used in place of biofuels for transportation and industrial uses
- Hydrogen is assumed to be produced by electrolysis of water using C-free electricity sources, and so accounts for about half of the total electricity demand in the H_2-intensive scenarios
- Deduce the consequences (in terms of material, energy, and financial flows, and land area requirements), of the postulated buildup of C-free energy supply
- Evaluate feasibility of the deduced consequences

Electricity Supply Assumptions for the H2-Intensive Scenarios

- Wind – 1500 GW (low GDP) or 3000 GW (high GDP), vs 239 GW by 2011
- Solar PV – 2000 GW or 4000 GW (vs 40 GW by 2011)
- Concentrating solar thermal power – 4500 GW or 9000 GW (vs 1.2 GW by 2010 but posed for rapid growth)
- Biomass – 500 GW or 1000 GW (vs 62 GW in 2010)
- Geothermal – 300 GW or 600 GW (vs 11 GW in 2010)
- Hydro – increases from 1010 GW in 2010 to 1200 GW in either scenario
- No Carbon Capture and Storage
- Phase-out of nuclear power (currently at 381 GW)

The total C-free electricity supply in 2100 is thus 11,000 GW for the Low GDP scenario, and 20,800 GW for the High GDP scenario, compared to a total global electricity generating capacity of about 4800 GW in 2010.

That is, the C-free electricity capacity required by 2100 is 2-4 times total current electricity capacity

From C. Macilwain (2010, ‘Supergrid’, *Nature* 468, 624-625)

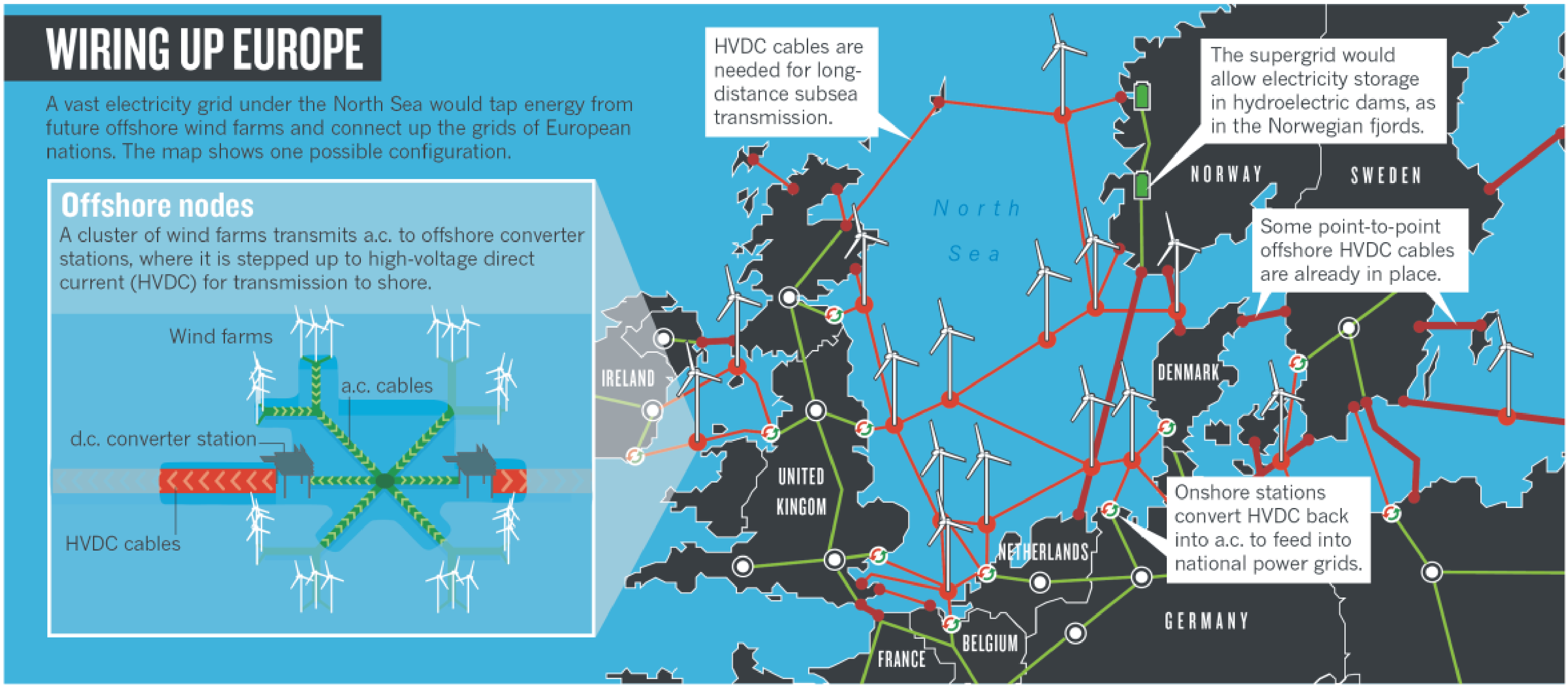


Figure 2.35a Parabolic Trough Thermal Electricity, Kramer Junction, California

Figure 2.35b Parabolic Trough Thermal Electricity, Kramer Junction, California

Figure 2.35c Close-up of parabolic trough

Molten salt storage tanks at Andasol-1, Spain

Source: Garvin Heath (2009, LCA of Parabolic Trough CSP….), www.nrel.gov/docs/fy09osti/46875.pdf

Figure 12.1c Minimum of CSTP and wind electricity cost (cents/kWh) (excluding transmission cost)

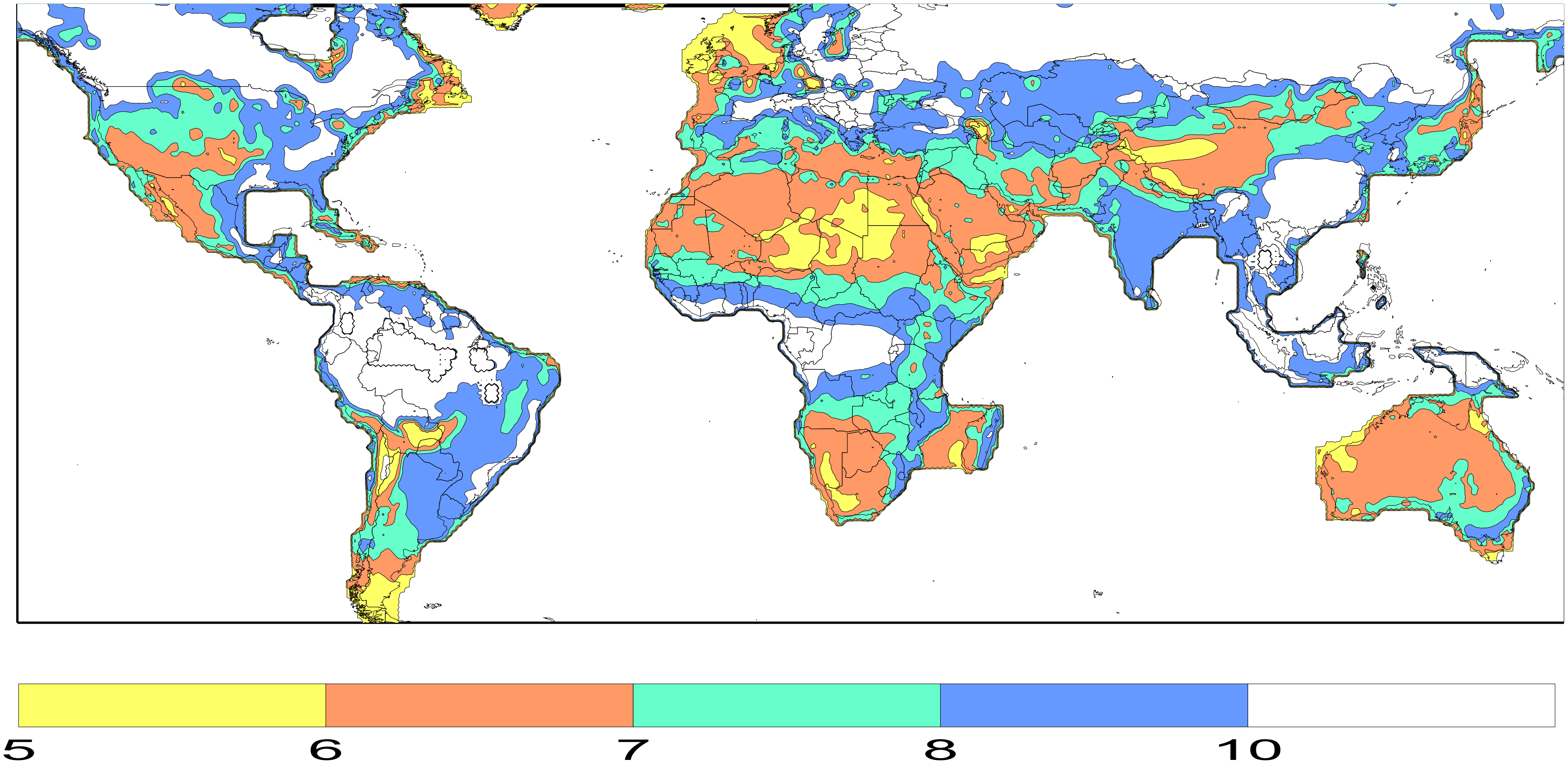
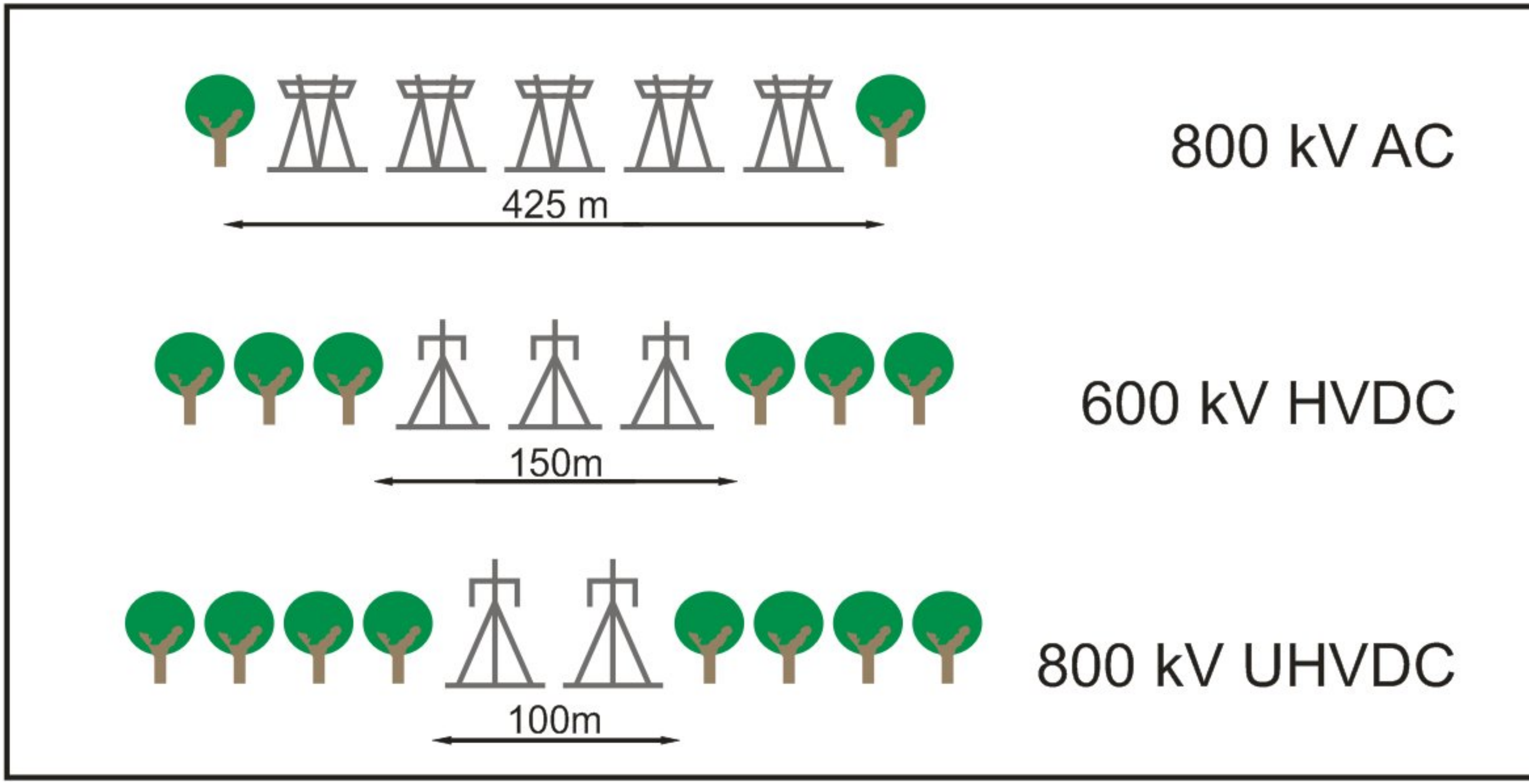
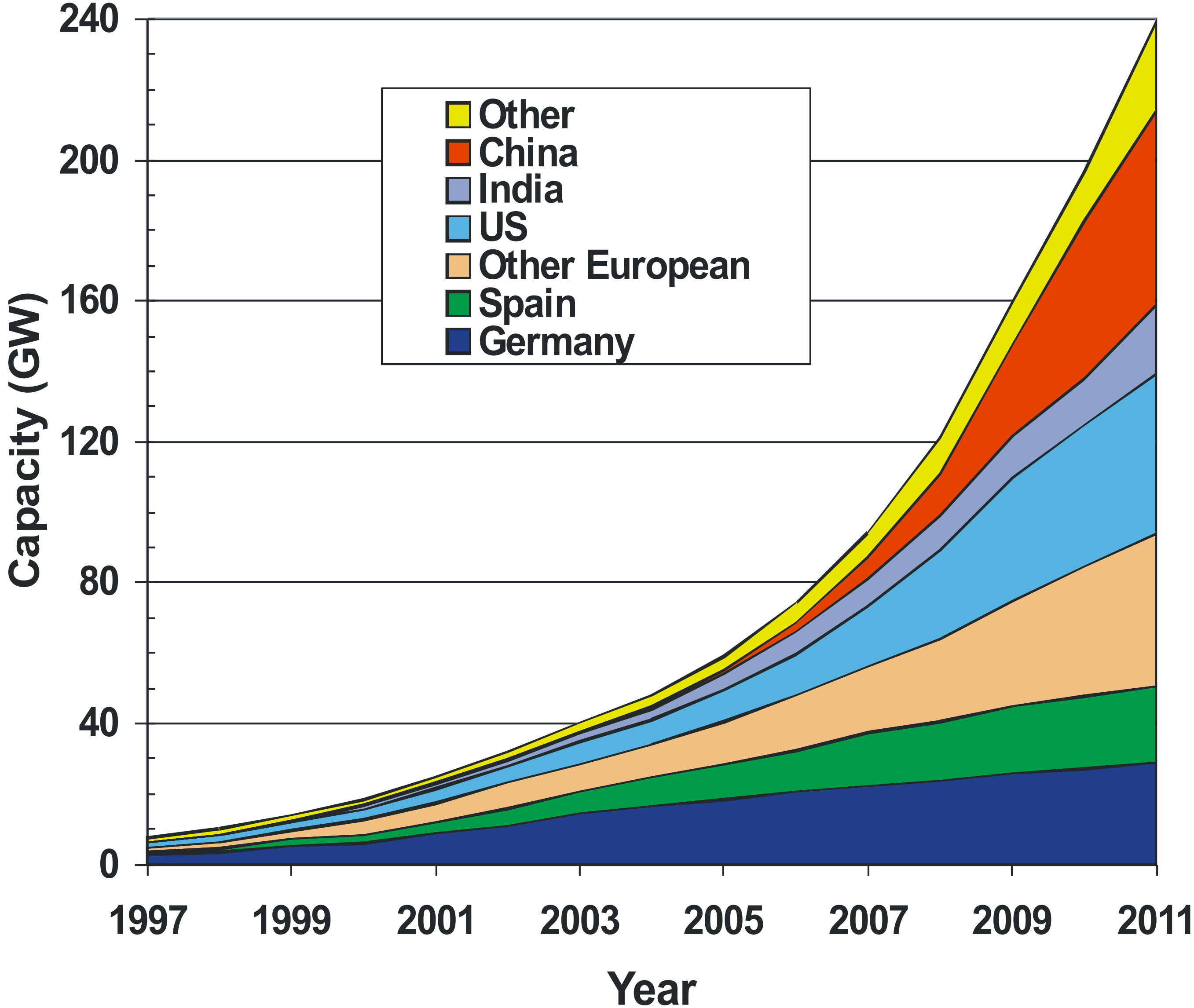


Figure 3.33 Transmission corridors transmitting 10 GW of electric power

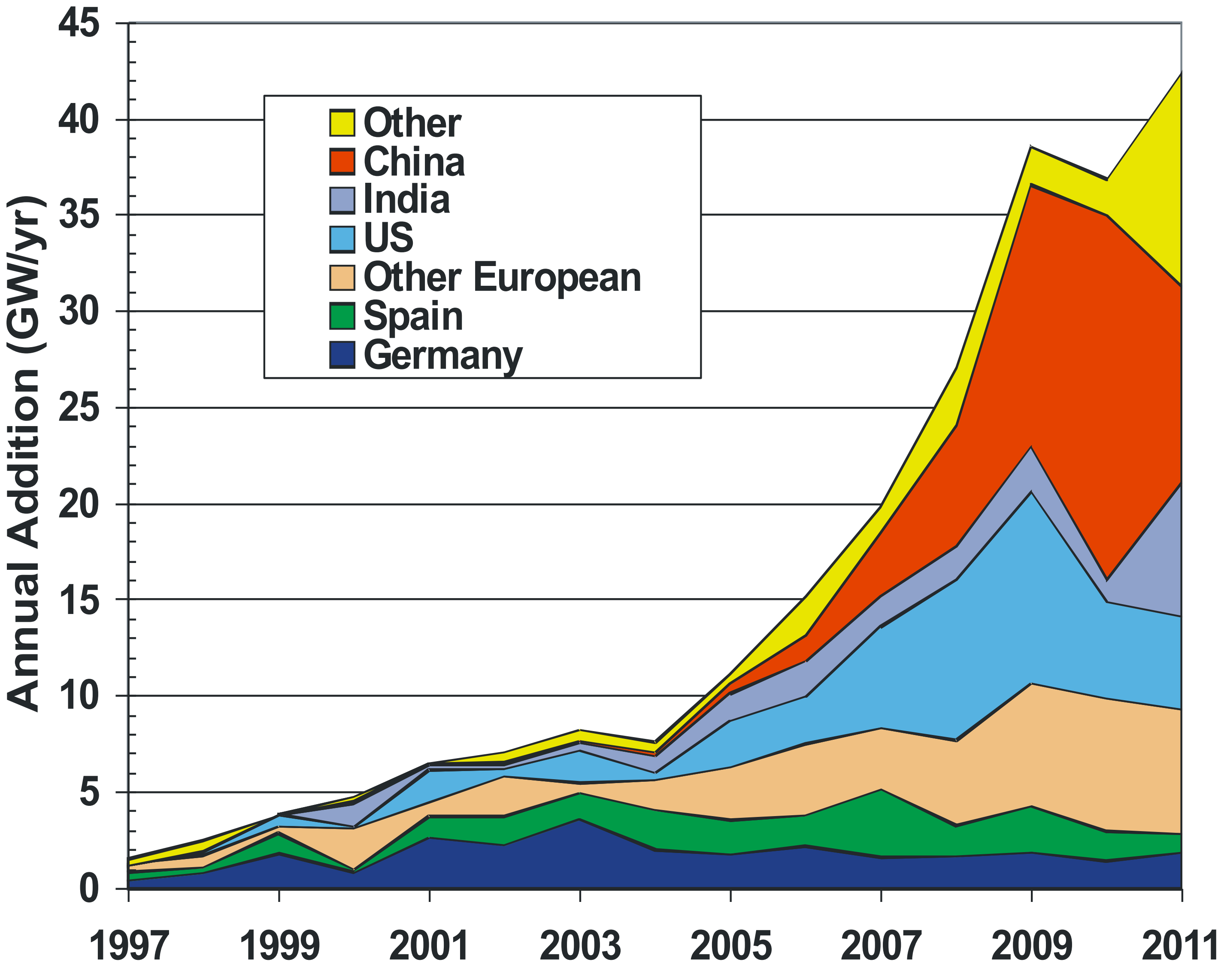


Source: GAC (2006, *Trans-Mediterranean Interconnection for Concentrating Solar Power, Final Report*, GAC, www.dlr.de/tt/trans-csp)

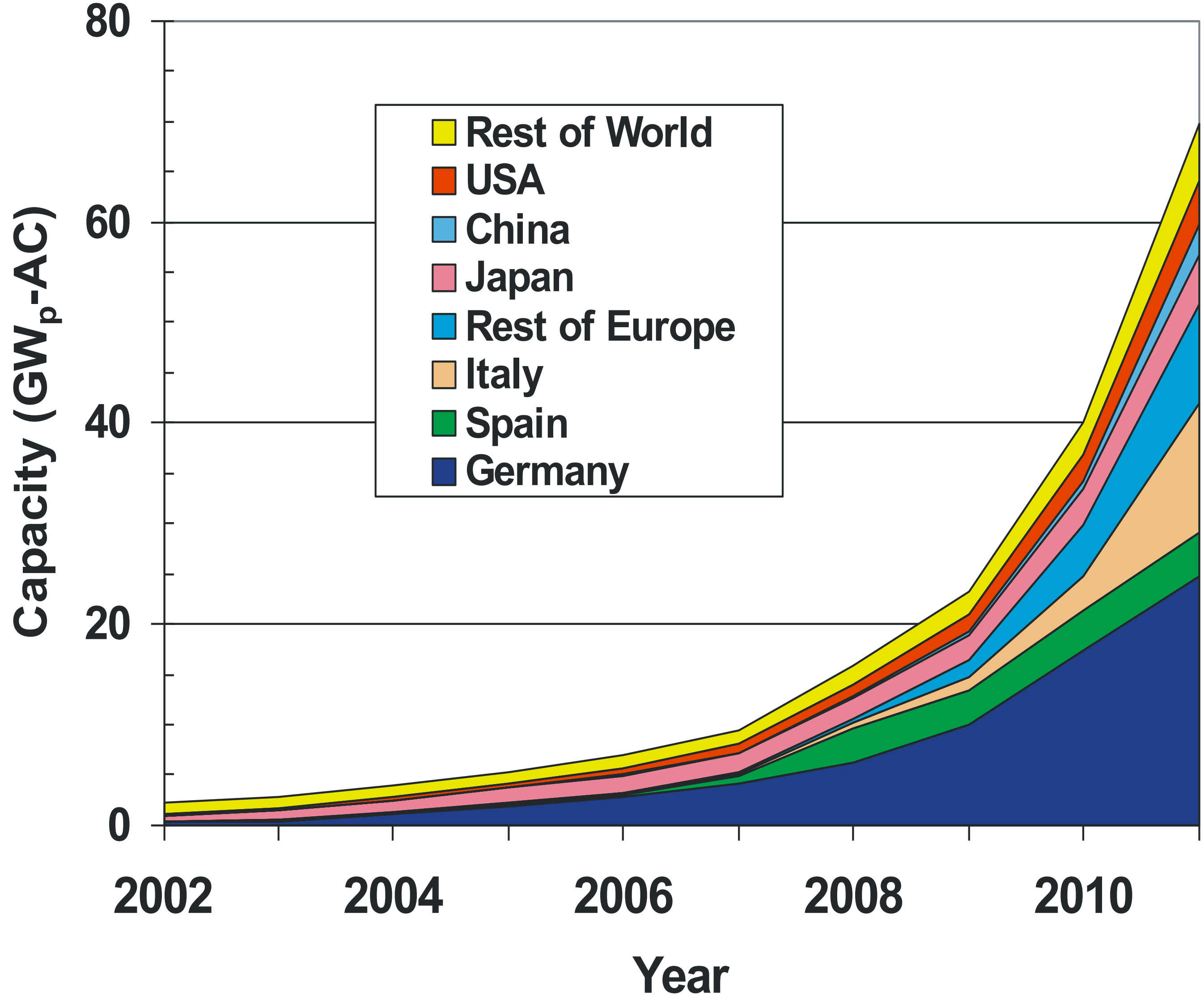
Recent Growth in Global Wind Capacity



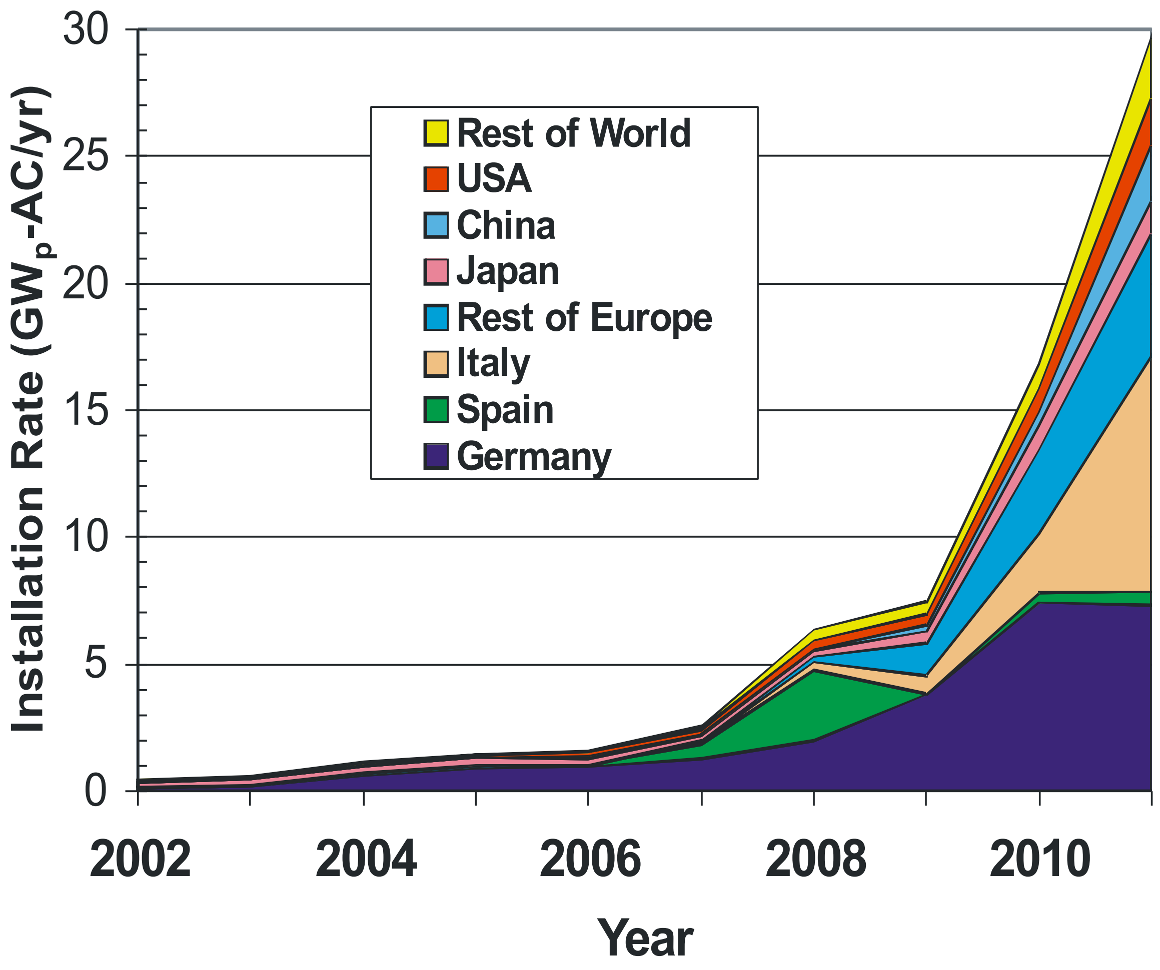
Growth in Annual Additions of Wind Capacity



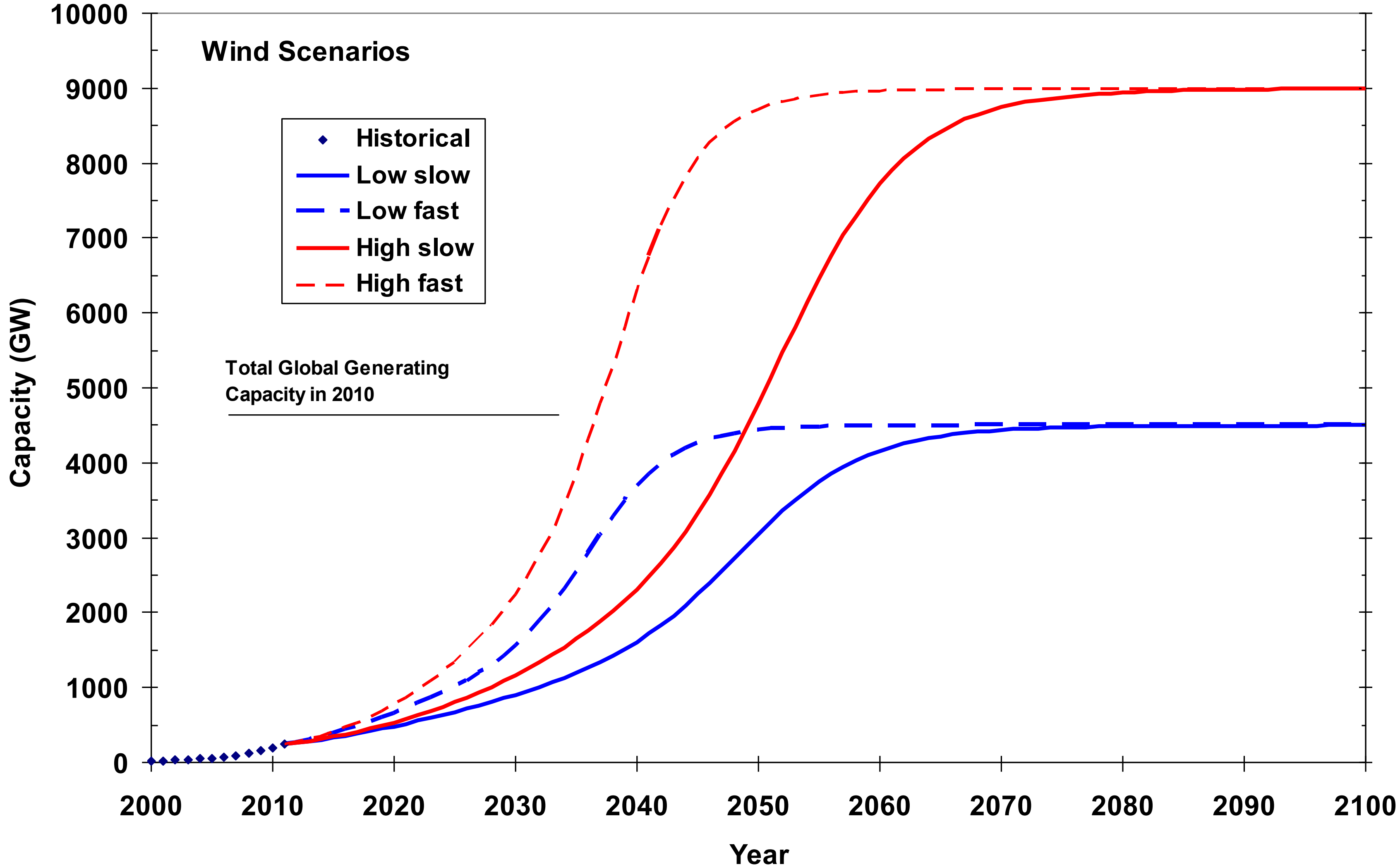
Recent Growth in Global PV Capacity

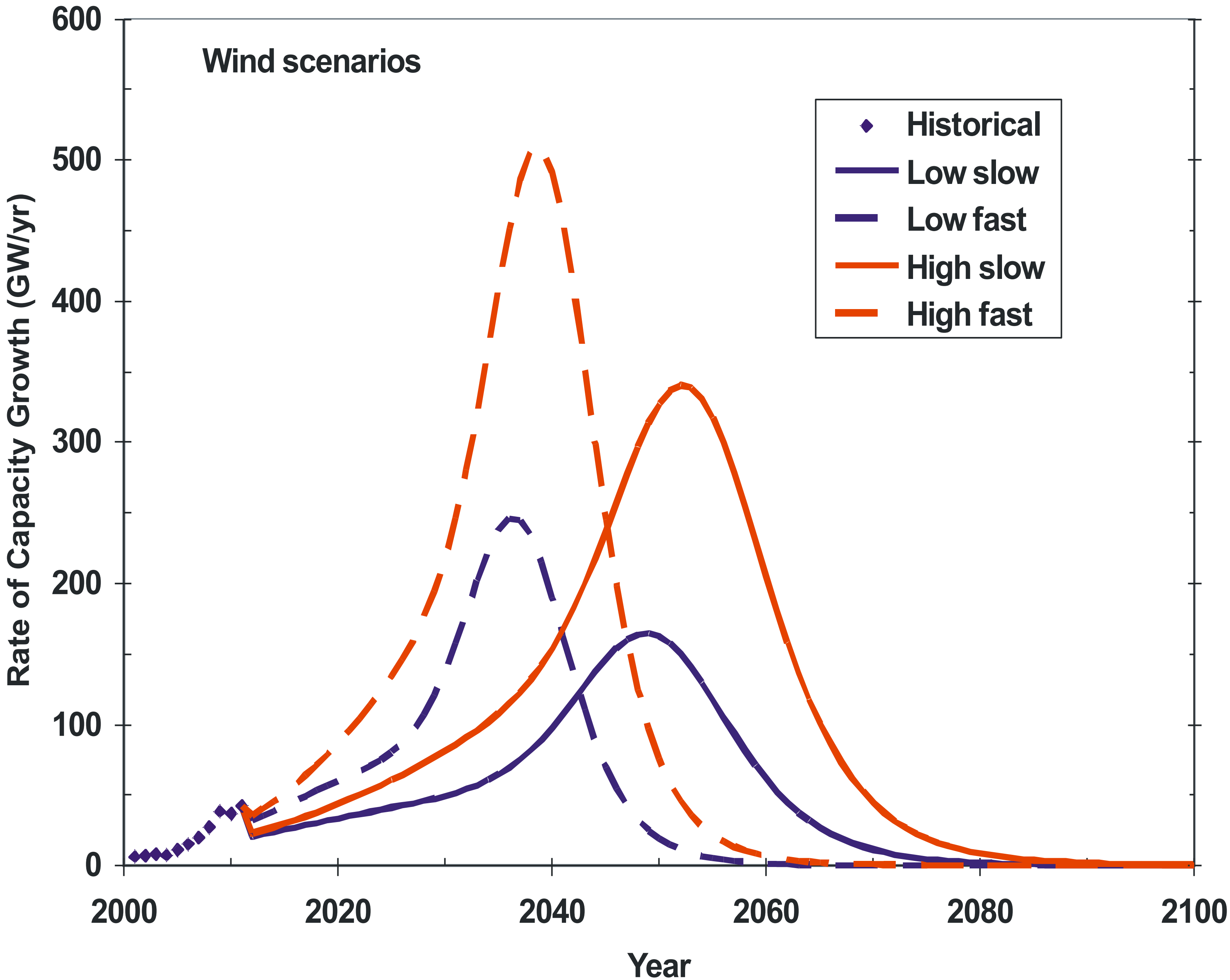


Growth in Annual Additions of PV Capacity

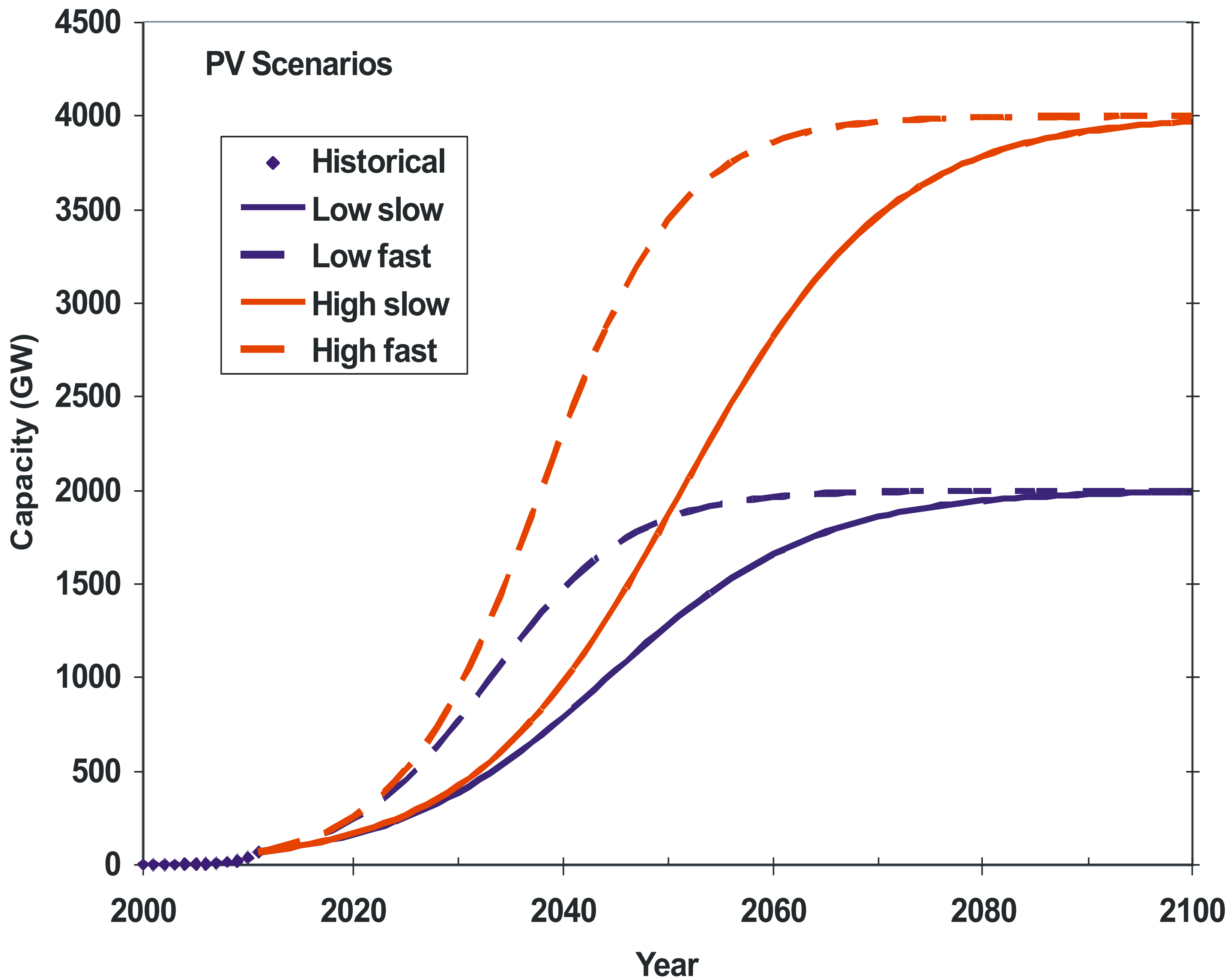


Global wind capacity scenarios

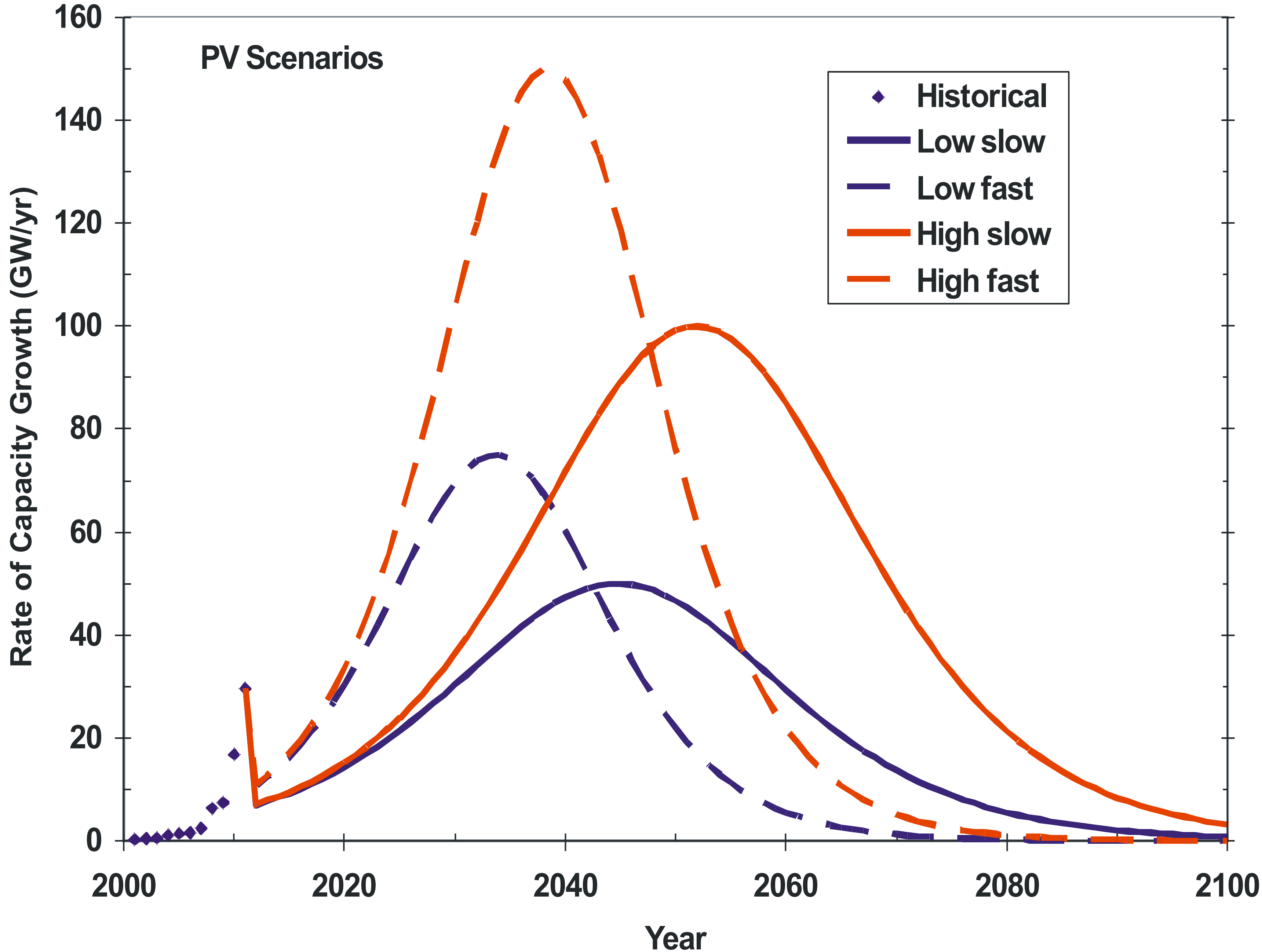




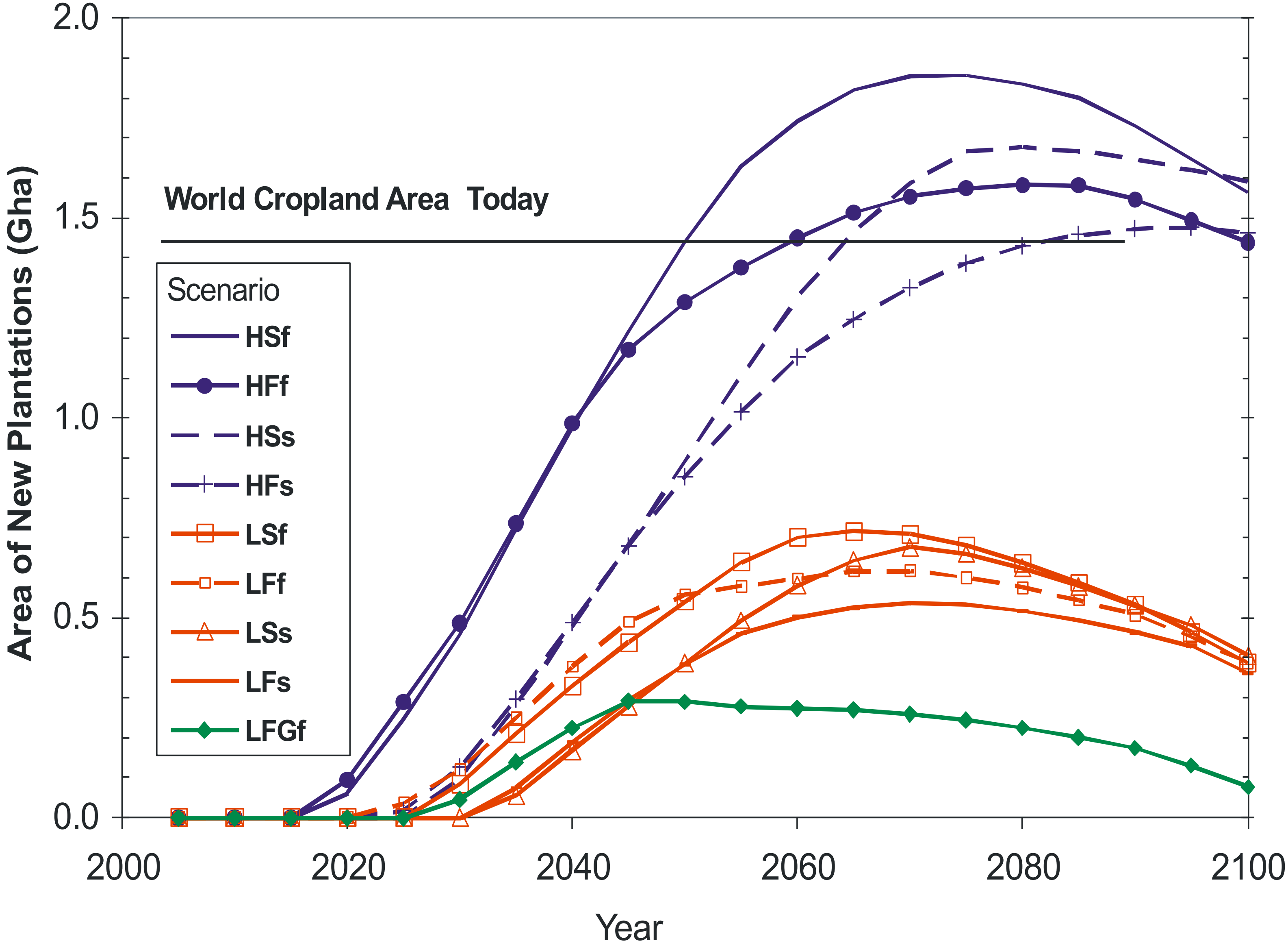
Wind scenarios
Historical
Low slow
Low fast
High slow
High fast
Rate of Capacity Growth (GW/yr)
Year
0
100
200
300
400
500
600
2000
2020
2040
2060
2080
2100



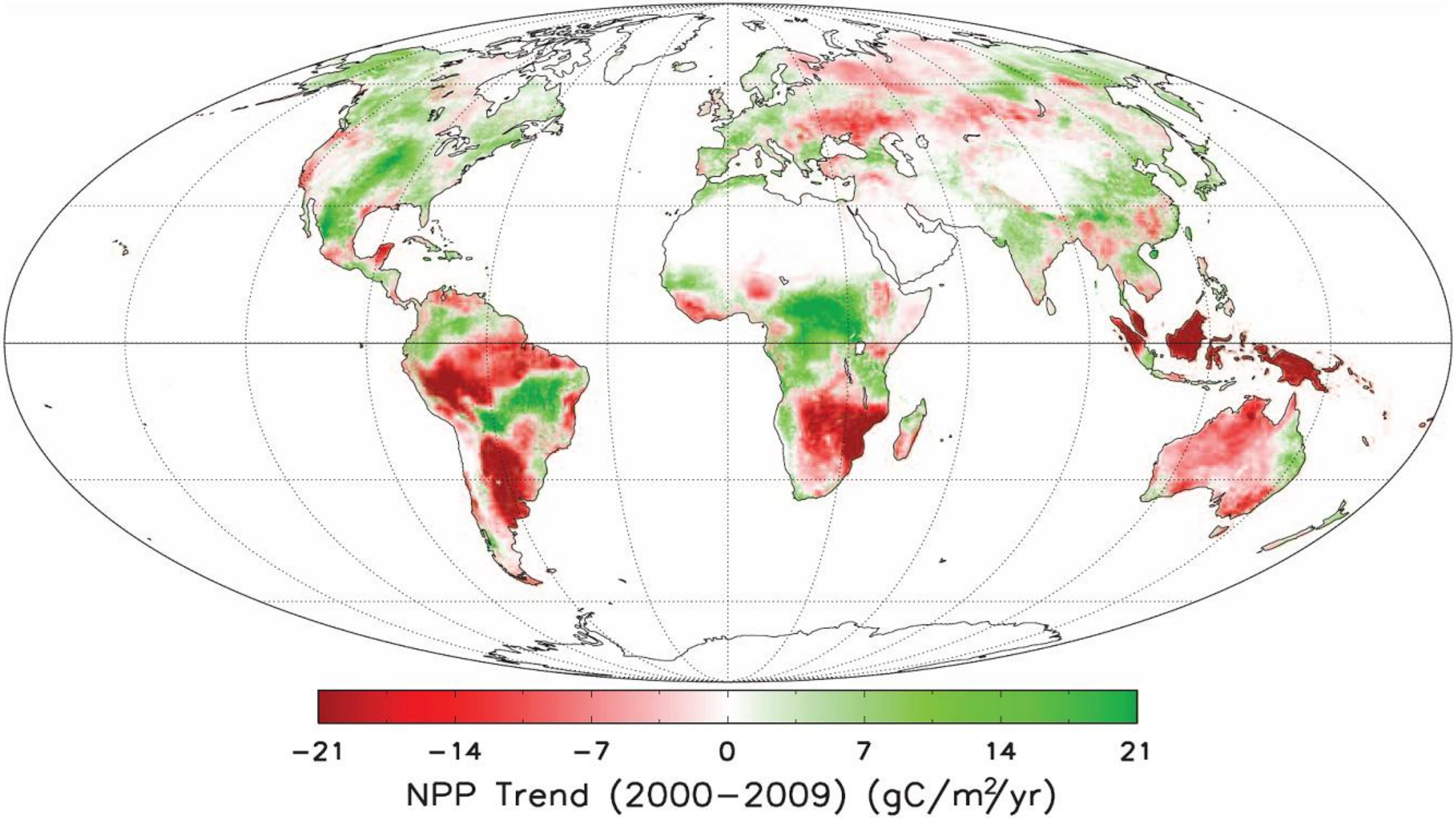
PV Scenarios
Historical
Low slow
Low fast
High slow
High fast
Capacity (GW)
Year
0
500
1000
1500
2000
2500
3000
3500
4000
4500
2000
2020
2040
2060
2080
2100


PV Scenarios
Historical
Low slow
Low fast
High slow
High fast
Rate of Capacity Growth (GW/yr)
0
20
40
60
80
100
120
140
160
2000
2020
2040
2060
2080
2100
Year

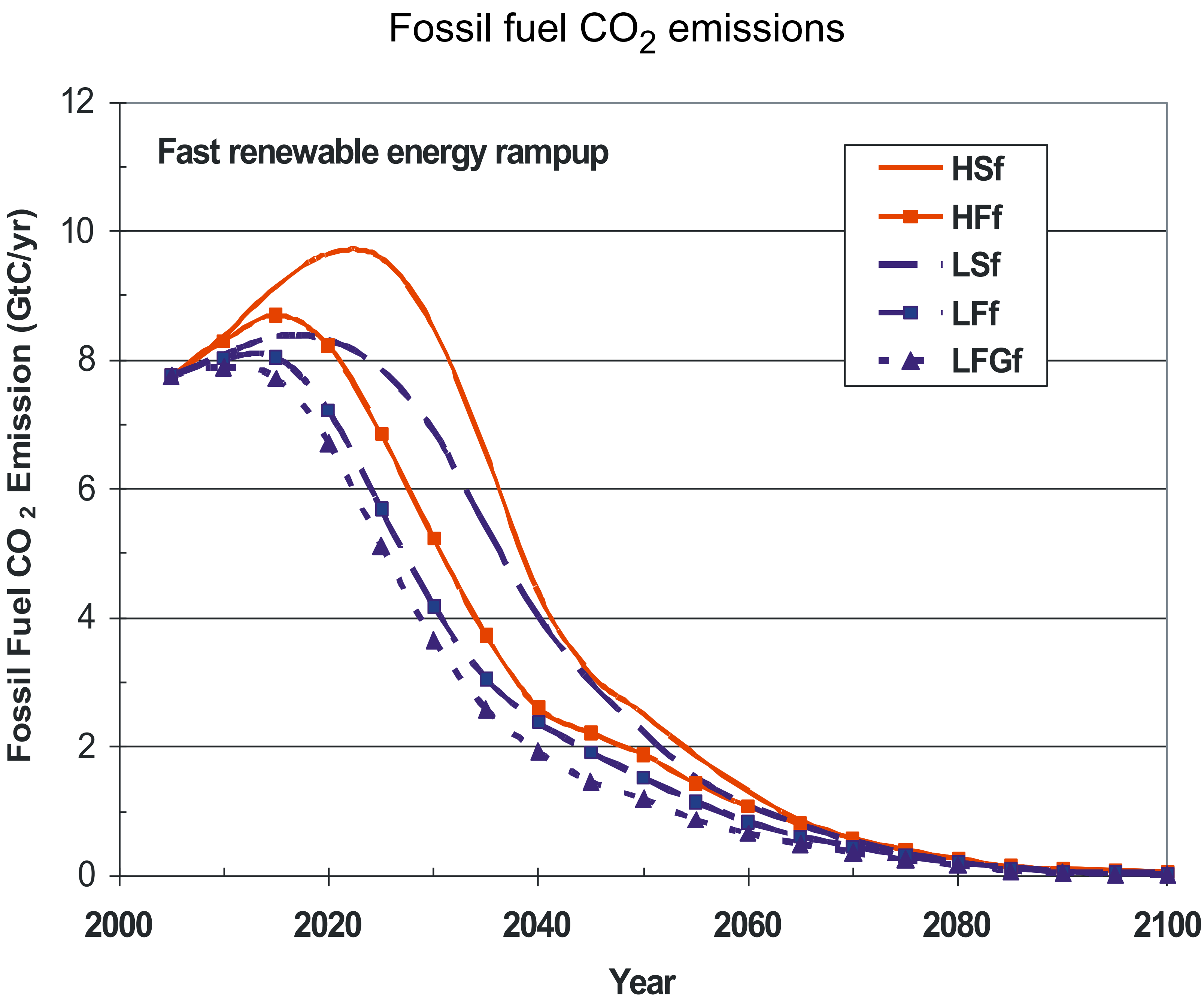
Areas of bioenergy plantation needed for the biomass-intensive scenarios

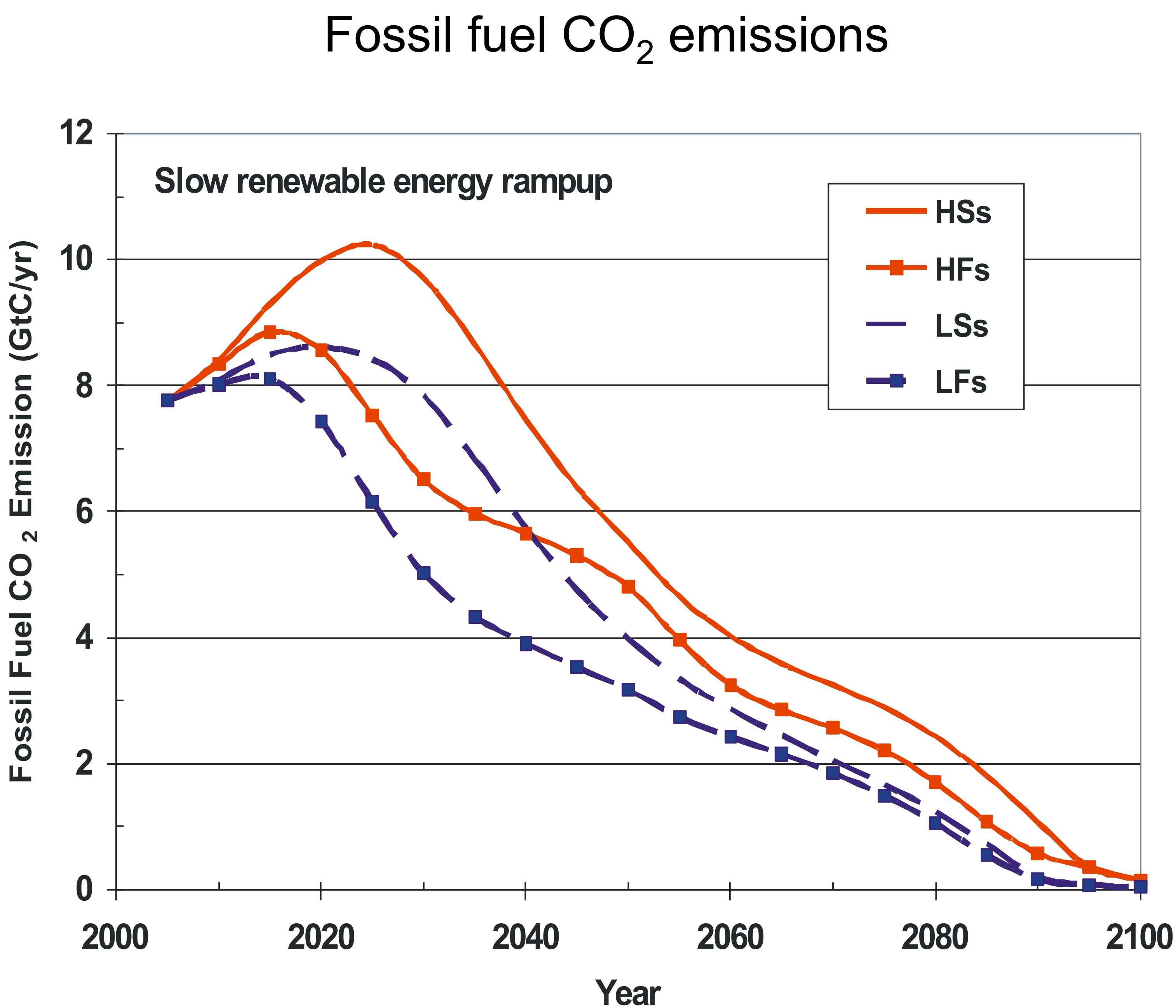


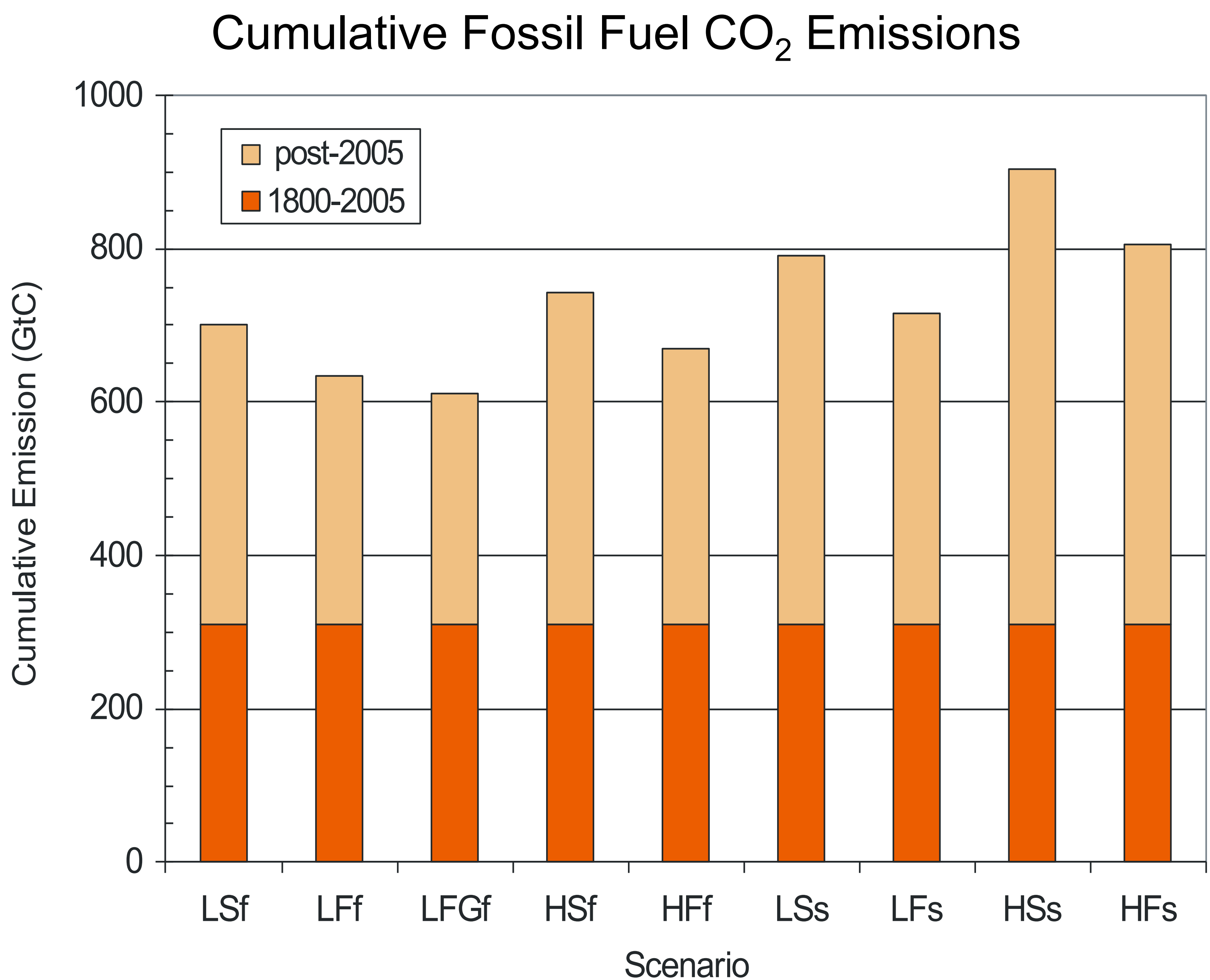
Spatial pattern of the change in NPP over the period 2000-2009 based on the linear trend of satellite-based estimates.



Source: Zhao and Running (2010, Science, Vol. 329, 940-943)


Fossil fuel CO_2 emissions
Fast renewable energy rampup
HSf
HFf
LSf
LFf
LFGf
Fossil Fuel CO_2 Emission (GtC/yr)
0
2
4
6
8
10
12
2000
2020
2040
2060
2080
2100
Year


Fossil fuel CO_2 emissions
Slow renewable energy rampup
HSs
HFs
LSs
LFs
Fossil Fuel CO_2 Emission (GtC/yr)
12
10
8
6
4
2
0
2000
2020
2040
2060
2080
2100
Year


Cumulative Fossil Fuel CO_2 Emissions
post-2005
1800-2005
Cumulative Emission (GtC)
0
200
400
600
800
1000
LSf
LFf
LFGf
HSf
HFf
LSs
LFs
HSs
HFs
Scenario