Preventing Climate Change with 100% Renewable Electricity and Transportation: Part II

What Does It Look Like?
What Would It Cost?
What Would It Do About CO_2?

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Recap Part I

North Carolina has adequate solar and wind resources to supply 100% of electricity and transportation needs (assuming electrification of transport)

Implicit cost of CO_2 of $89/t in, say, 2030

How does this compare to social cost of carbon, i.e., anticipated damages due to CC?

Nordhaus proposes carbon tax of $25/t CO_2 beginning in 2015 and rising at 5% / annum

- That projects to $50/t in 2030

Study: North Carolina transition to RET

RET: Renewable Electricity and Transportation

SERENE: Simulation Engine for Renewable Energy

- Custom software package for modeling electricity grid

Generating capacity (solar and wind) and storage capacity (battery and hydrogen) are model inputs

Match hourly loads to generation and storage to determine adequacy over 4 years

Adjust parameters until load met

Extend results globally

Electricity plus transportation presently consumes the majority of energy

- N.C. 84%; U.S. 74%; World 64%

Transition scenario assumes:

- 80% of World energy can ultimately (2100) be supplied by wind and solar as electricity, transportation and natural gas generated from excess electricity (power-to-gas, P2G)
- 20% of energy will continue to come from fossil fuel in 2100 (process fuel, developing nations)

Kaya models

- Business as usual (BAU) assumptions (convention fossil electricity and transportation)
- Transition to renewable electricity and transportation
- Transition with faster population growth
- Transition with faster affluence growth

Carbon emissions with RET

Relative carbon emissions (CE) falls along an S-shaped curve from 100% in 2010 and ultimately levels off

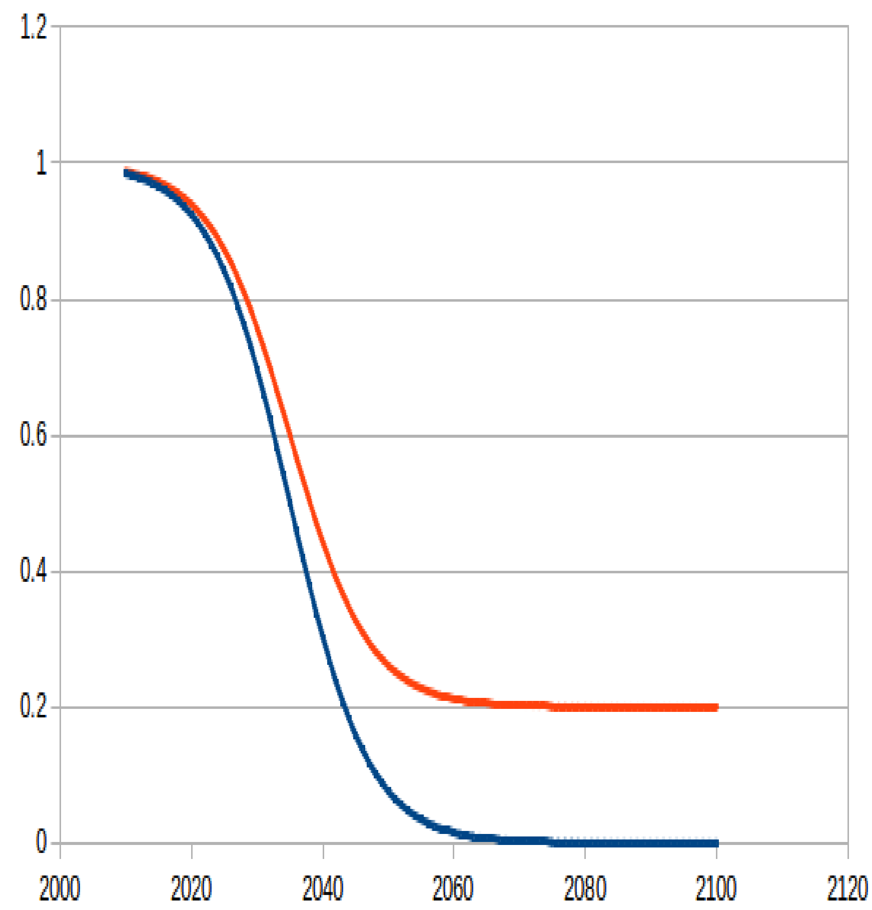
Assumption that 100% of energy is replaced (blue curve)

- CE would fall to 50% in 2035 and approach 0% in 2060
- Unrealistic to replace 100%

Assumption that 20% remains fossil fuel (red curve)

- CE crosses 60% in 2035, levels off toward 20% in 2060
- More realistic assumption

Reflects retirement of fossil generating fleet as plant wear out and are not replaced



IPAT equation

Impact = Population x Affluence x Technology

Impact is, for example, a pollution, such as carbon dioxide emissions, in t CO_2/yr

Affluence is $GDP/person/yr

Technology is t CO_2/$GDP

Concept was proposed during a debate in the 1970s among Paul Erlich, Barry Commoner and John Holdren about human impacts on the environment

Simplistic formula, better as a heuristic than for accurate projections

Kaya Identity

Modification / extension of IPAT

Proposed by Japanese economist Yoichi Kaya in 1990s specifically for application to CO_2 emissions

Split technology term into Energy/$GDP (energy intensity) and Carbon Emissions/Energy (carbon intensity)

Carbon emissions CE = P x A x EI x CI

Kaya Identity

Carbon emissions $CE = P \times A \times EI \times CI$

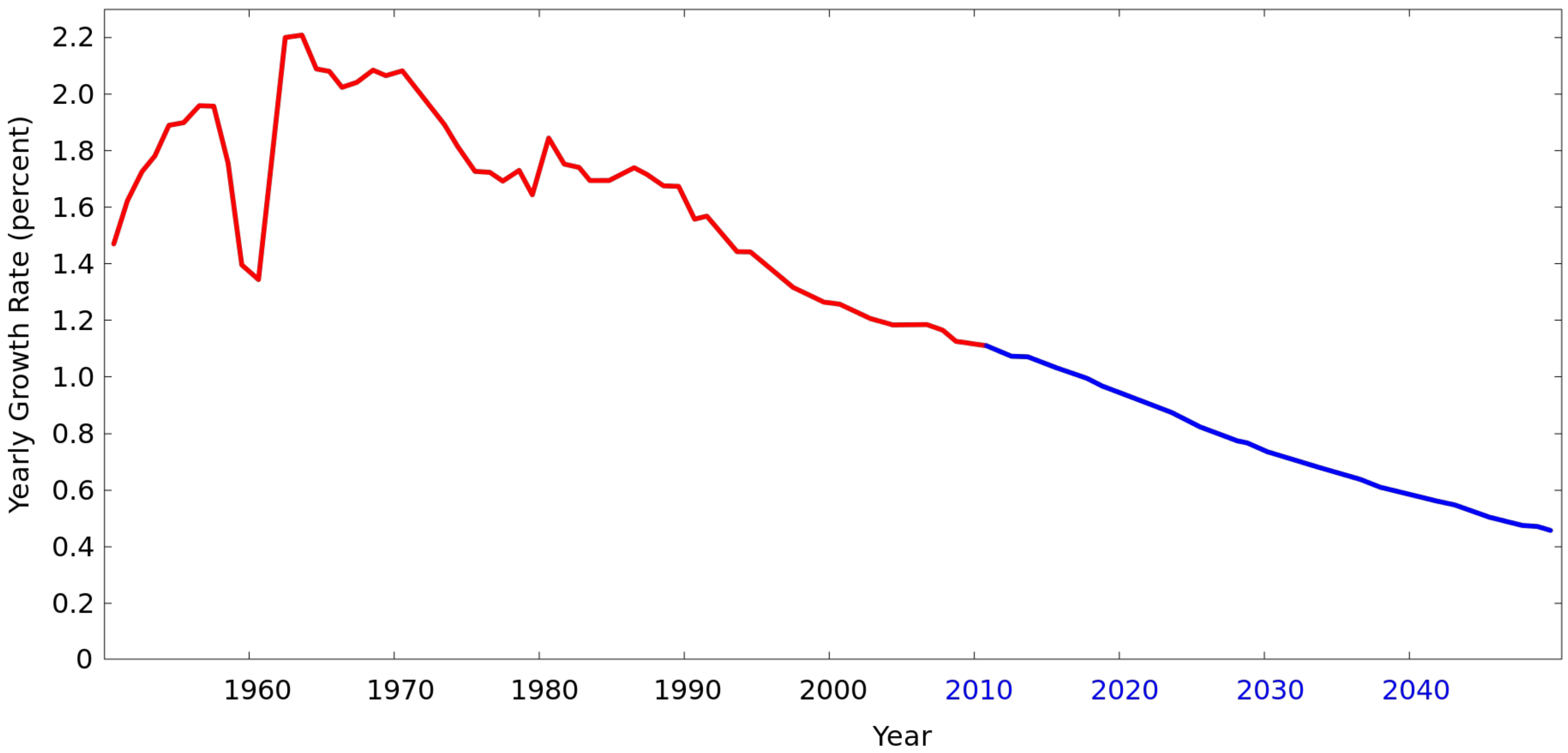
Most useful for projecting carbon emissions into the future when annual rates of change of factors (r_x) can be estimated

$CE_{i+1} = CE_i \times (1+r_P) \times (1+r_A) \times (1+r_{EI}) \times (1+r_{CI})$

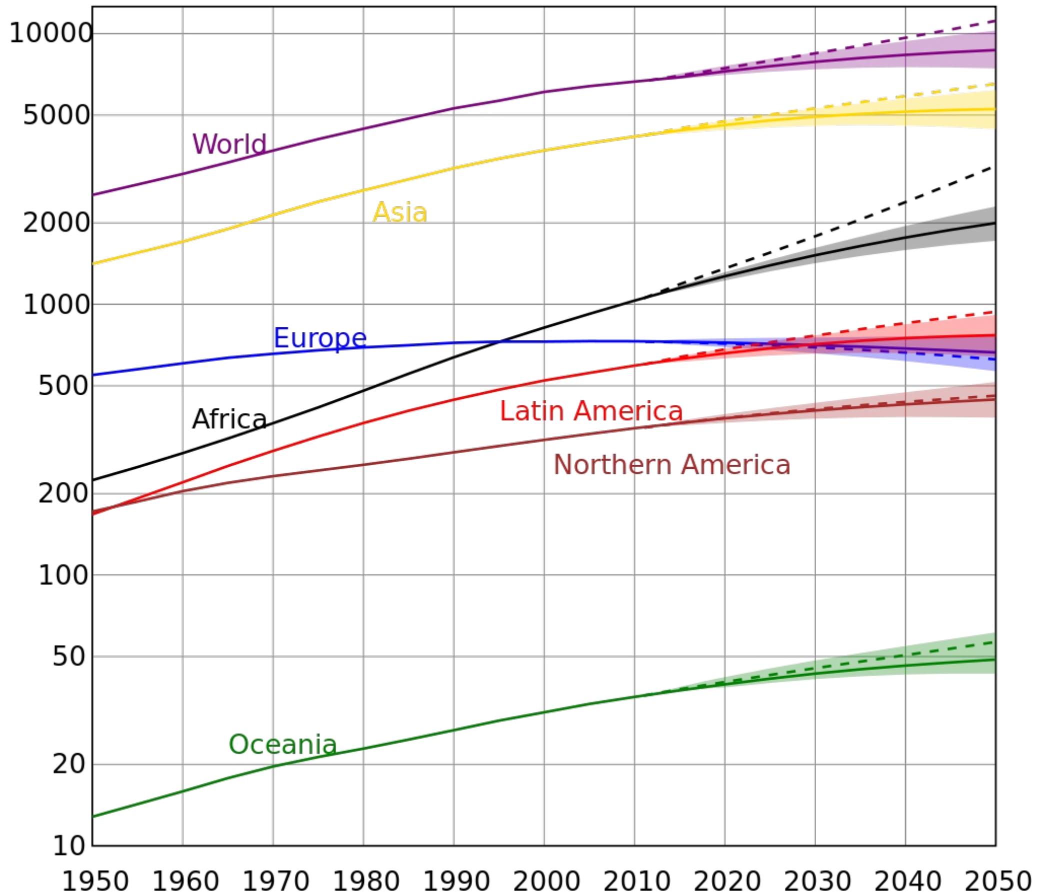
The r_x may be constant or may change over time, as will be discussed individually

Baseline CE_{2010} is 9.2 Gt-CO_2/yr

World Population Growth Rate – Observed and Projected



World Population



Population

6.9 billion in 2010

Growth rate 1.1% but declining

Projections to 2100 range from 9.0 to 10.9 billion, average 10.1

- Consistent with steady growth of 0.4%

Model: 0.75% BAU and alternative; 0.4% otherwise

Sensitivity analysis shows little effect of this parameter on results

Affluence

$GDP per person has been generally increasing world-wide, though at vastly differing rates across nations

We want affluence to increase, raising standard of living

The rate observed in Great Britain over the 180 years from 1830 to 2010 is 1.4% / yr

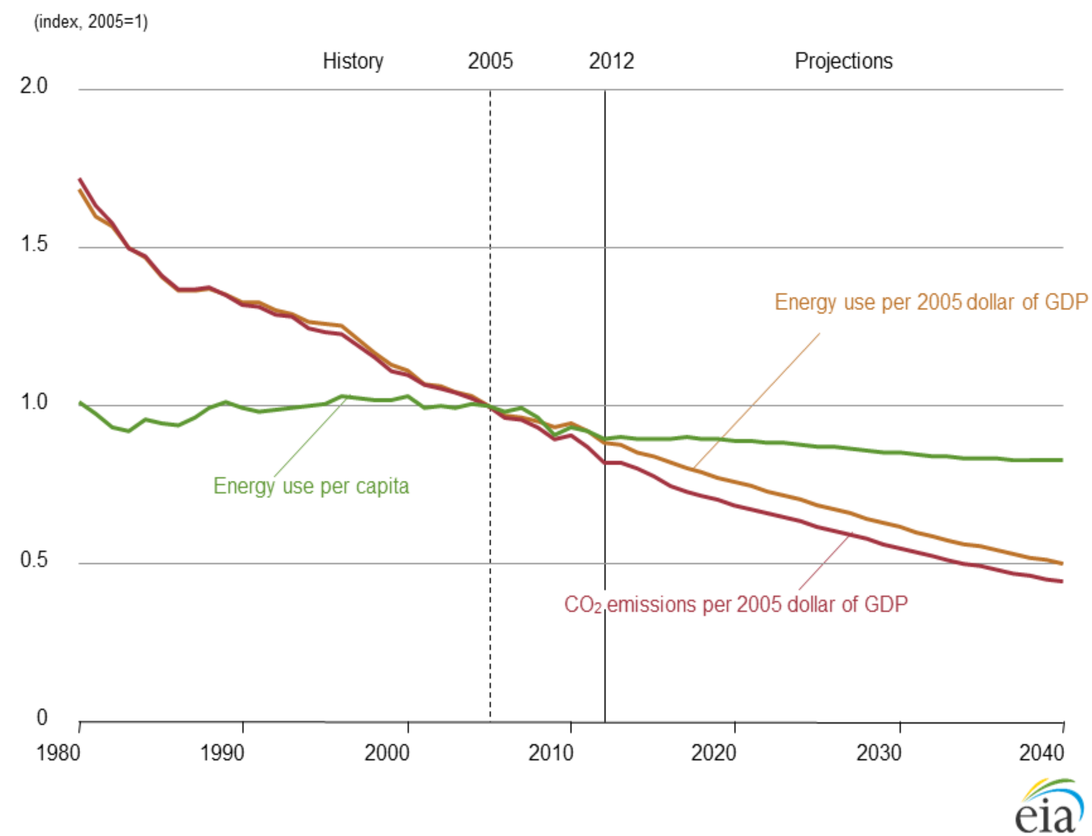
Another quoted figure is 3.2% / yr, from BAU scenario, used as alternative scenario

Energy intensity

Energy use per $GDP decreasing due to increased efficiency of production

Currently observed decline of 1.9% per year is extended to 2100

Figure 9. Energy uses per capita, energy use per dollar of GDP, and emissions per dollar of GDP, 1980-2040



Carbon intensity

Tonnes CO_2 per unit of energy use

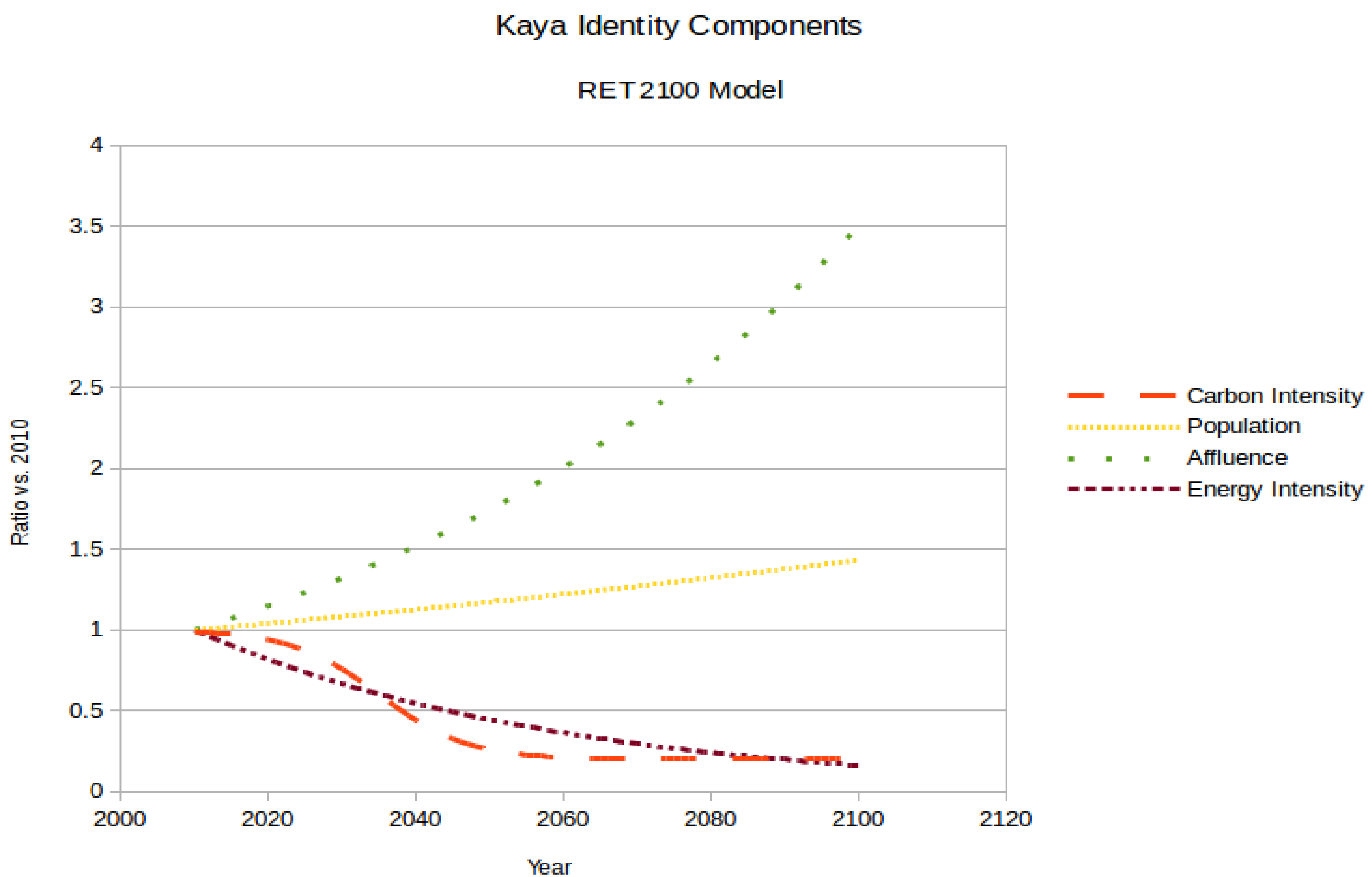
- Current and BAU rate is 0.1% / yr

This is the variable we propose to control by transition to solar and wind power

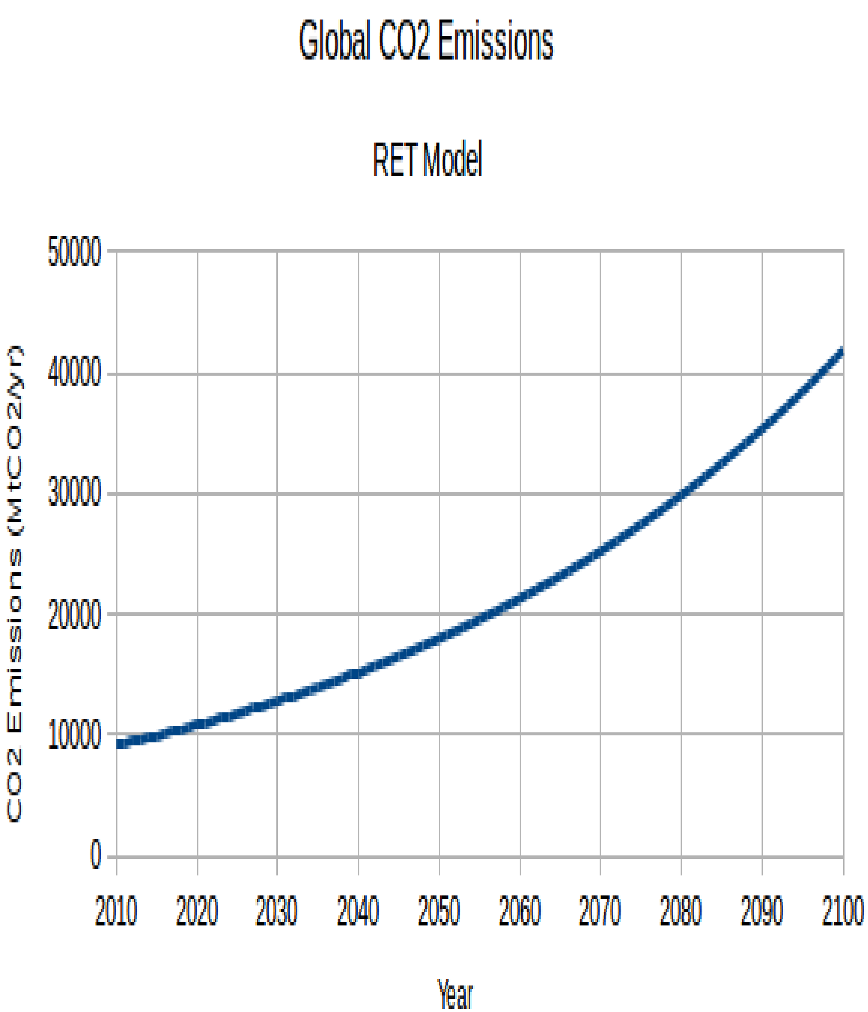
With renewable energy intervention, CI falls on S-shaped curve from current level to 20% of current level, with inflection point in 2035

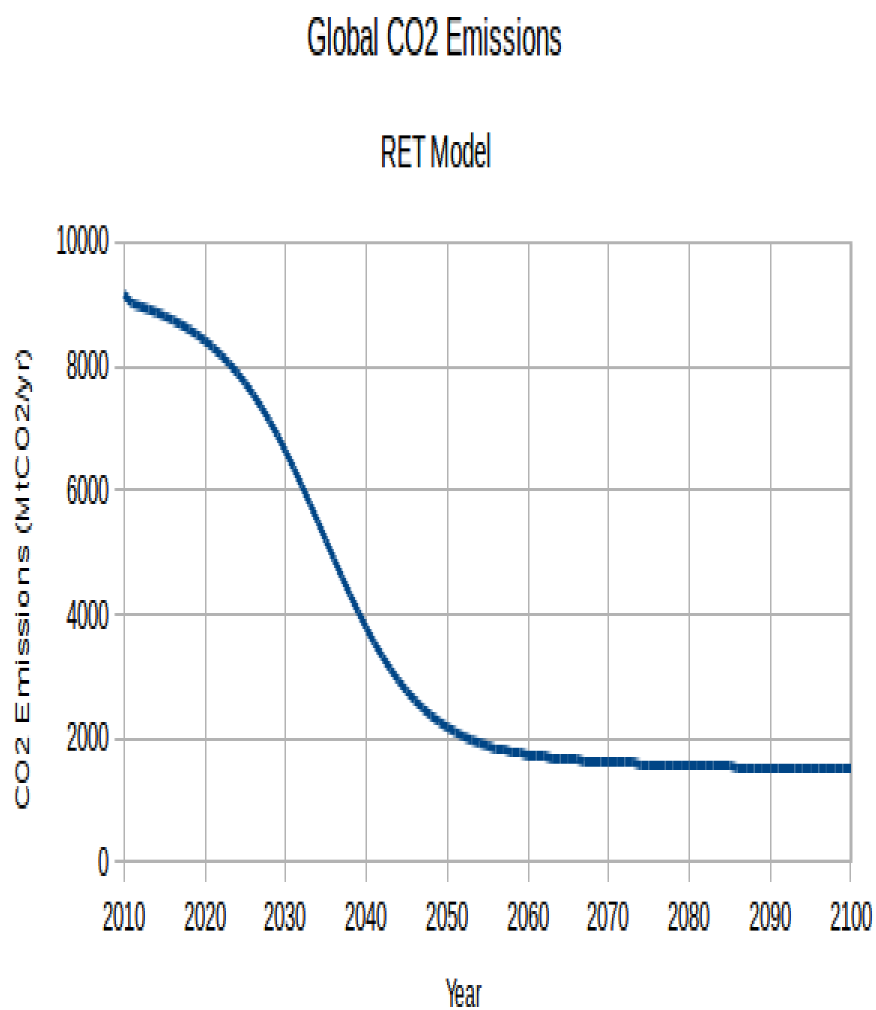
Reflects rate of retiring fossil generating plants as new solar and wind come online

Kaya Components of RET Model

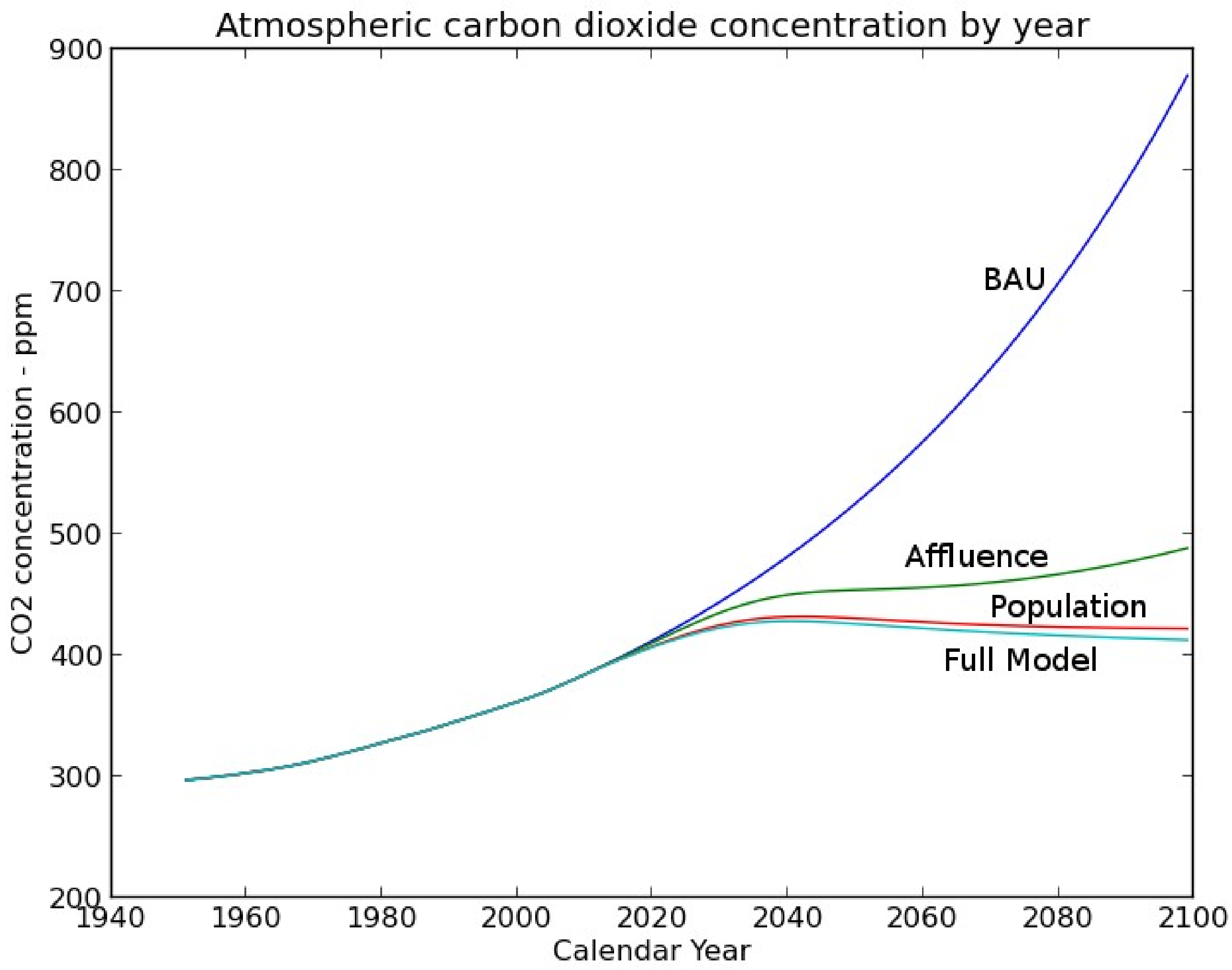


Carbon emissions: BAU vs. RE





Atmospheric CO_2 to 2100: BAU vs. 100% RE

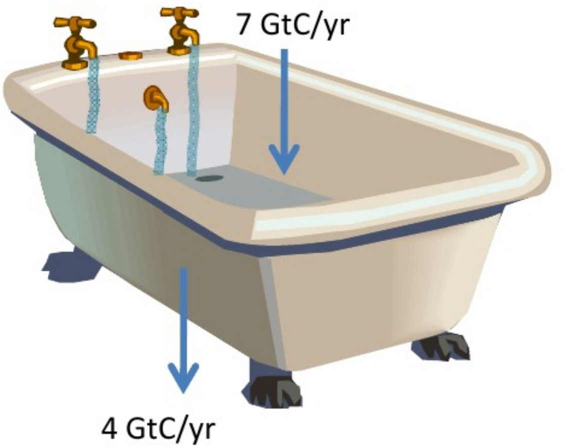


Determing CO_2 concentration from CO_2 emissions

You may be wondering...

- How do you get from emissions to concentrations?
- Empirical equations reflecting rate of removal of CO_2 vs. rate of addition by emissions
- Bathtub analogy

Bath Tub Analogy



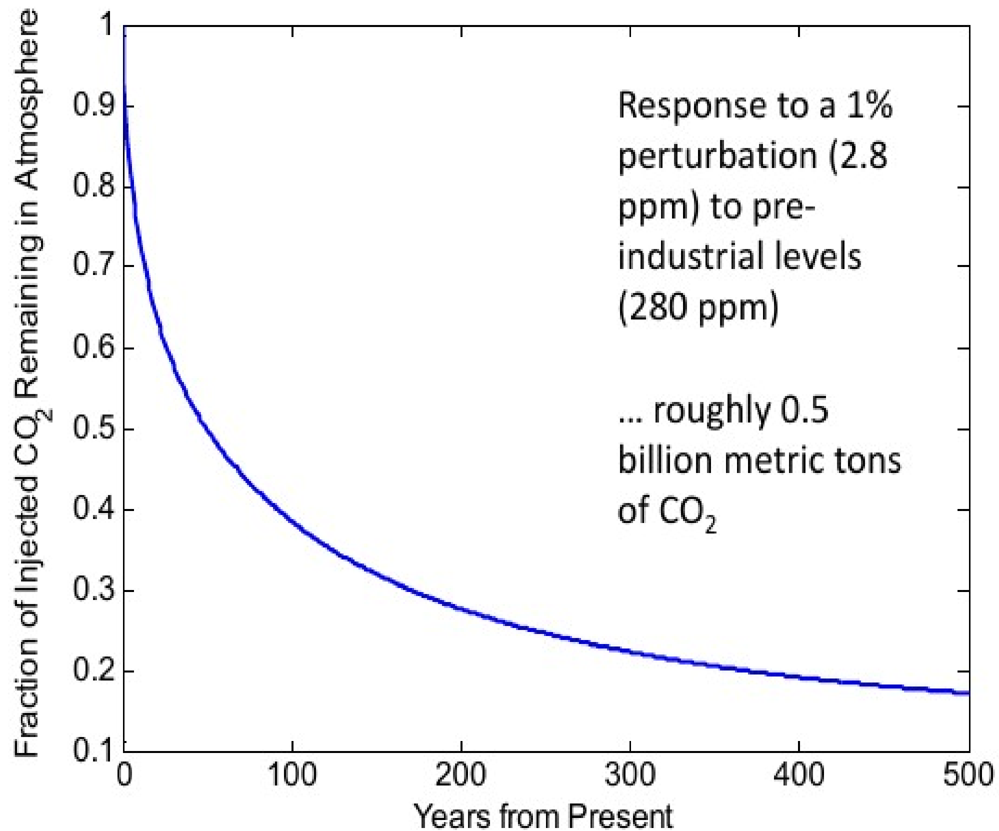
A useful analogy is filling a bathtub at a faster rate than you can drain it.

Rate of removal of one year's CO_2 emissions given by IRF

An Impulse-Response Function (IRF)

IRF drawn from Hooss (2001):

$$I(t) = 0.132 + 0.311e^{-t/237} + 0.253e^{-t/60} + 0.209e^{-t/12} + 0.095e^{-t/1.3}$$



Removal of all preceding years' CO_2 emissions

Applying the IRF

The IRF alone quantifies the fraction of emissions remaining in the atmosphere.

To estimate the impact of continuous CO_2 emissions, assume an annual pulse of emissions and calculate concentrations using a convolution integral of the form:

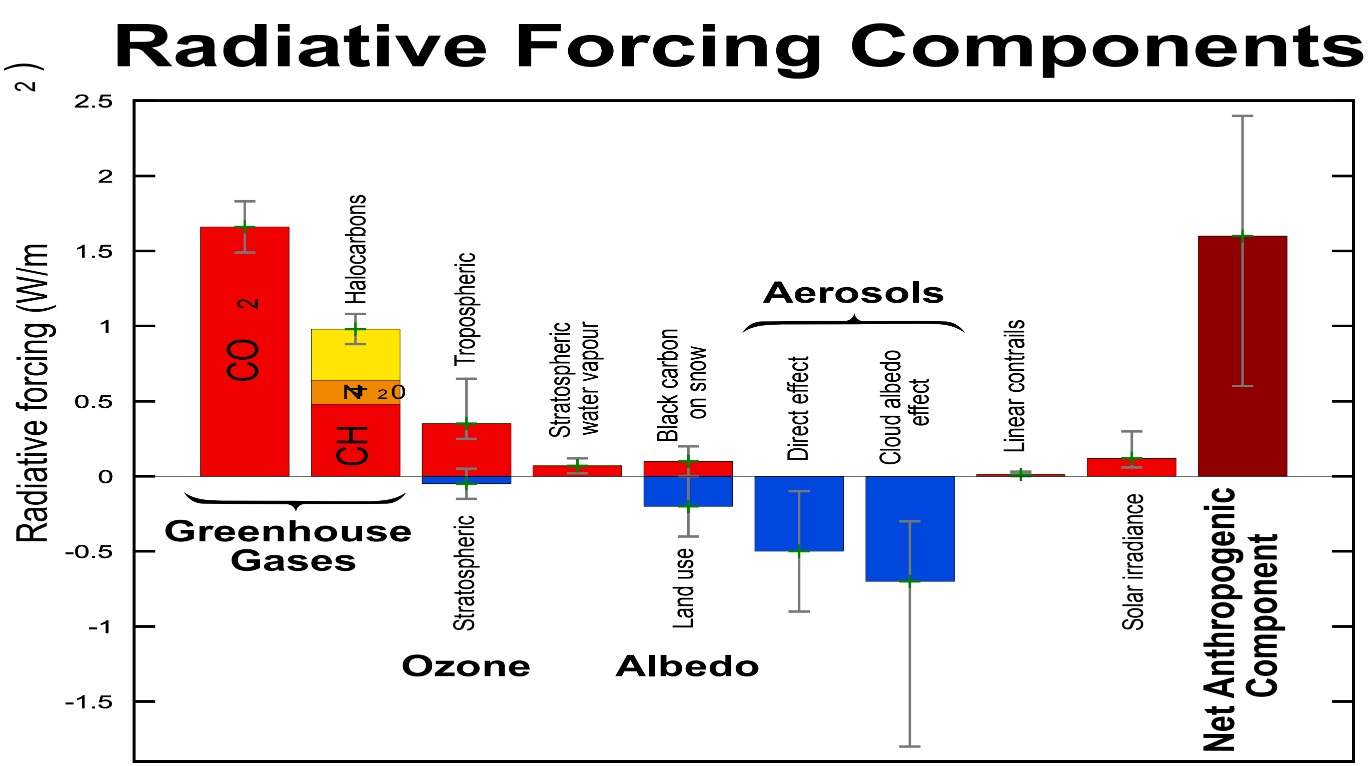
$$C(t) = \int_{t_0}^{t} a \cdot E(t') \cdot I(t - t')dt'$$

Where ***C(t)*** is the concentration in year ***t***, ***E(t')*** is the annual emissions, and ***I(t-t')*** is the impulse-response function. Note that this integral must be performed each year.

Global temperature vs. CO_2 concentration

Determined by net energy flux (incoming solar vs. outgoing infrared radiant)

Effect of various factors referred to as "forcings"



Forcing vs. CO_2 level

Radiative Forcing and Temperature Change

Radiative forcing is the change in the net (downward minus upward) irradiance (W m^{-2}) at the *tropopause* due to a perturbation.

A standard IPCC (2001) formula transforms CO_2 concentration to radiative forcing:

$$r = 3.35\left(g(C) - g(C_0)\right),$$

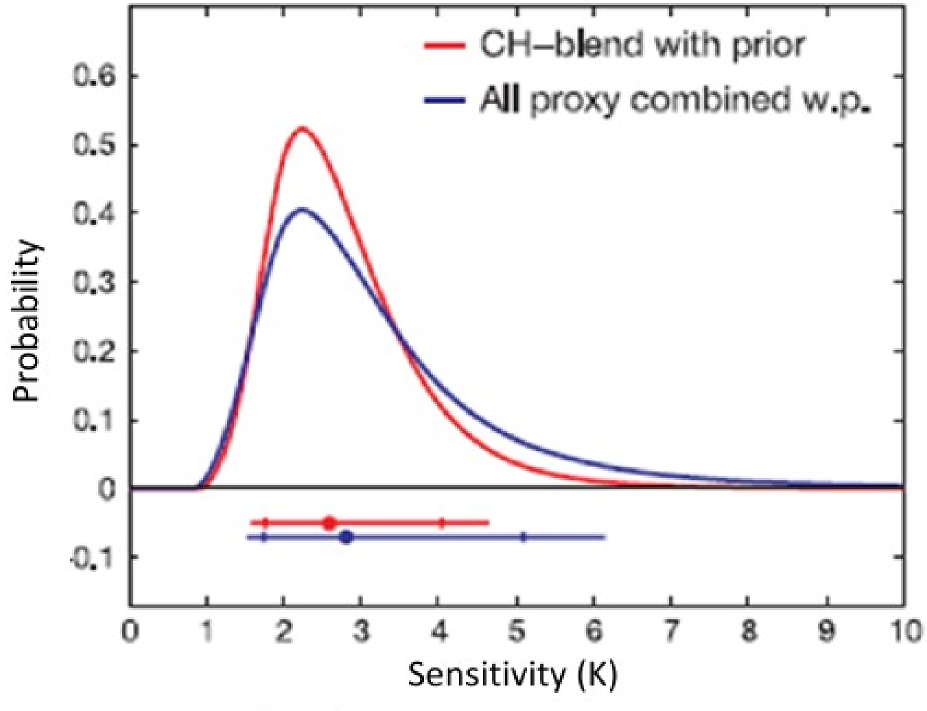
$$\text{where } g(C) = \ln(1 + 1.2C + 0.005C^2 + 1.4 \times 10^{-6} C^3),$$

C_0 is the pre-industrial CO_2 concentration, and ***C*** is the perturbed concentration.

Climate Sensitivity

Climate Sensitivity

Global average temperature change due to a change in radiative forcing is given by a proportionality constant, **λ**=0.75 K/W·m^{-2}, but …



Estimated probability density functions (PDFs) for equilibrium climate sensitivity to CO_2 doubling (in K).

The horizontal bars indicate the 5–95% range of PDFs (median is indicated by a dot, and 10th and 90th percentiles by a vertical bar).

Hegerl, G., et al. (2006). "Climate sensitivity constrained by temperature reconstructions over the past seven centuries". *Nature*, 440: 1029-1032.

Year 2100 outcomes for BAU and RE scenarios

Scenario	CO_2 Emissions Gt	CO_2 Concentration ppm	Temperature Rise °C
BAU	42	888	5.2
Wind & Solar	1.5	412	1.6

Conclusions

Assuming global wind and solar resources are reasonably comparable to North Carolina, it is technically feasible to supply electricity and transportation energy demand from renewable energy, displacing 80% of CO_2 emissions coming from fossil fuel combustion

Such a transition would reverse rising atmospheric CO_2 levels, stabilizing at 412 ppm by year 2100, with a global temperature rise of 1.6°C, by contrast to a rise of 5.2°C pursuing business as usual energy consumption patterns