Fischer-Pry Model of Technological Replacement & Application to C-Free Primary Energy Technologies

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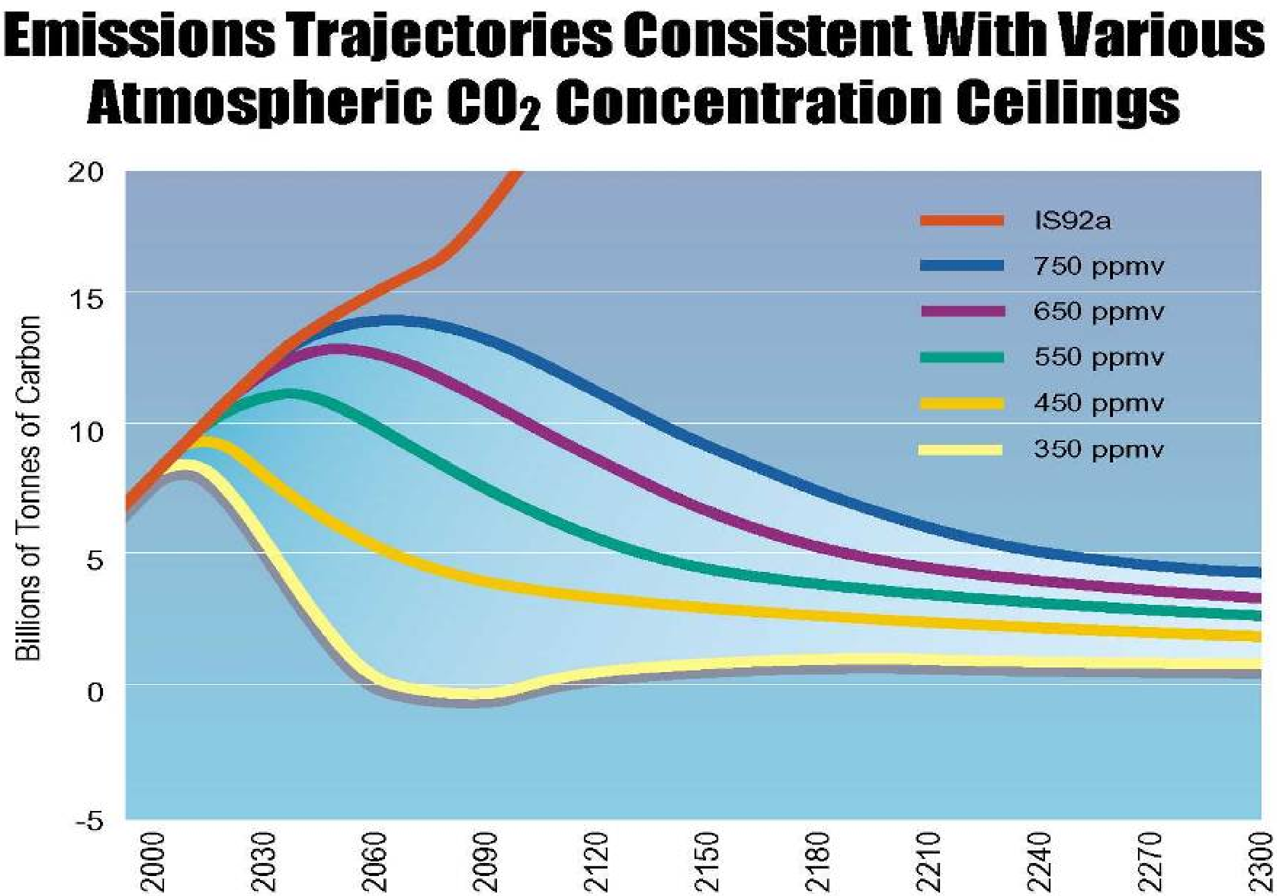
Outline of Lectures

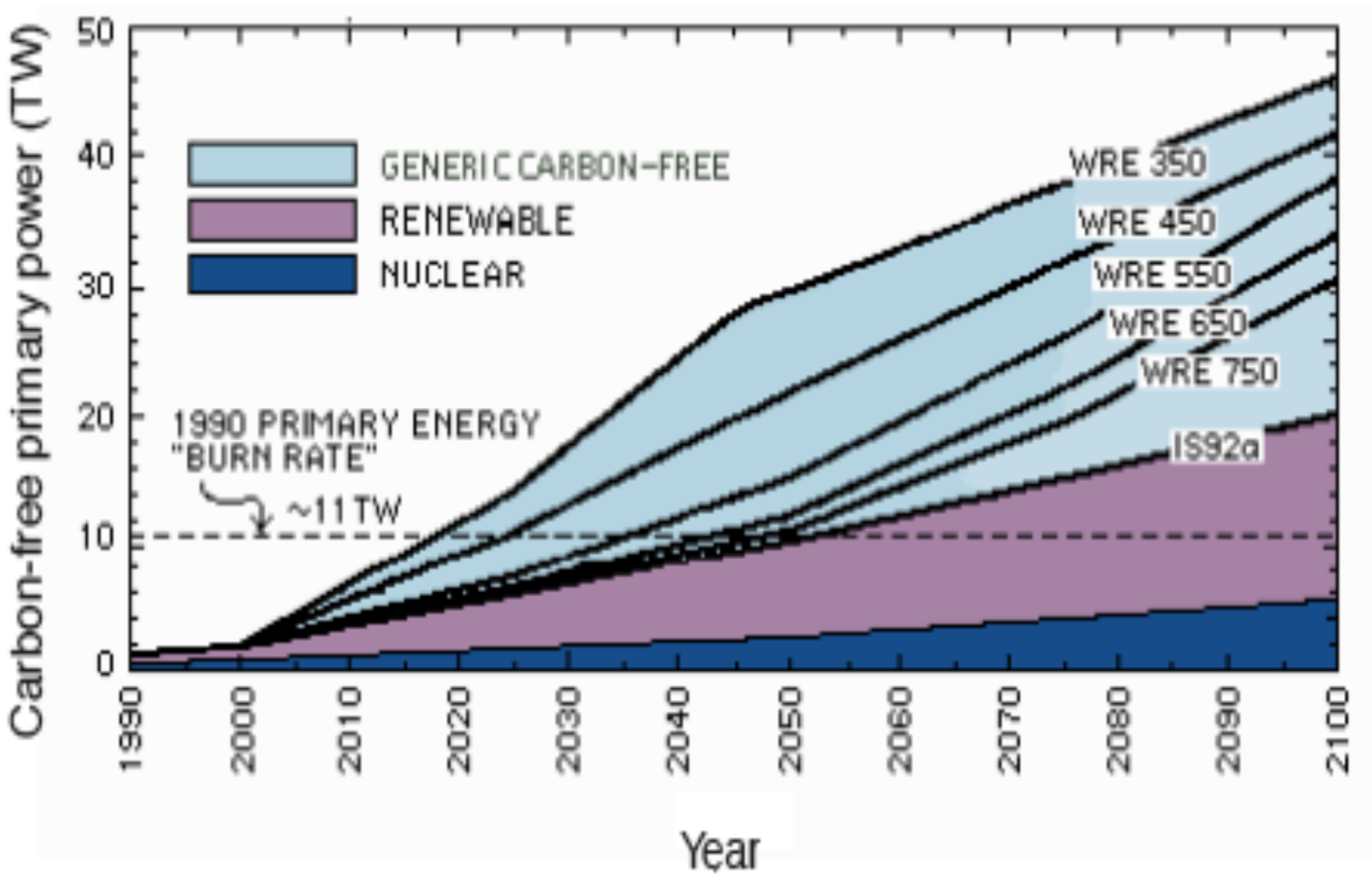
- Review C-Balance & Implications for C-free Energy Requirements
- Pose Key Question: How Quickly Can New C-free Technologies Move Into Market?
- Modeling Adoption of New Technologies: The Fischer-Pry Replacement Model
- Early Application of Fischer-Pry Model to Energy
- Review of Recent Developments in Renewable Energy
- Apply Fischer-Pry Model to Renewables for the 2010-2050 Period
- Conclusions

CO2 Emissions Trajectories are Linked to CO2 Concentration Ceilings



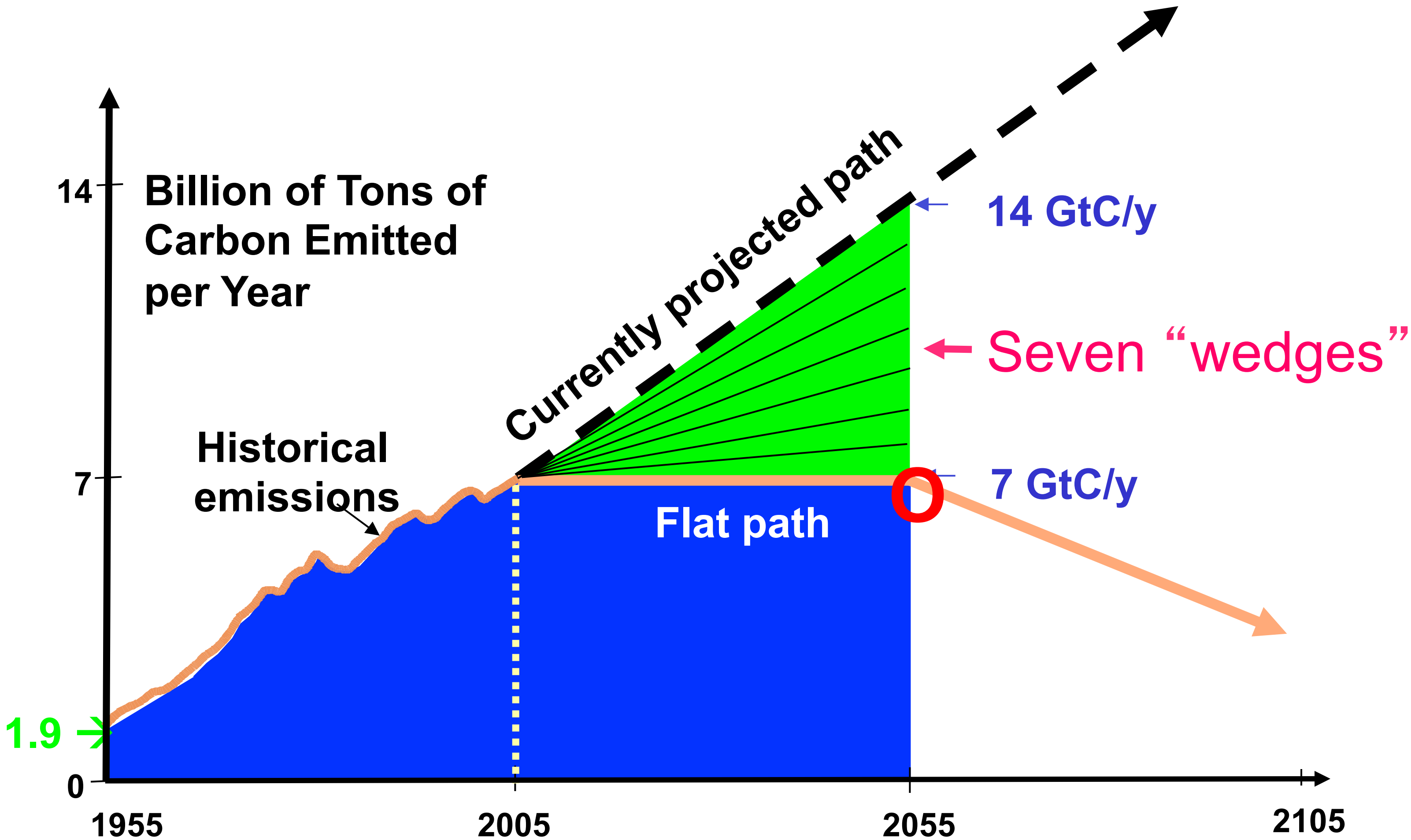
Source: IPCC, J. Holdgren 2007 AAAS Plenary Talk

Very Significant C-Free Primary Power Requirements



Source: Hoffert, Nature 1999

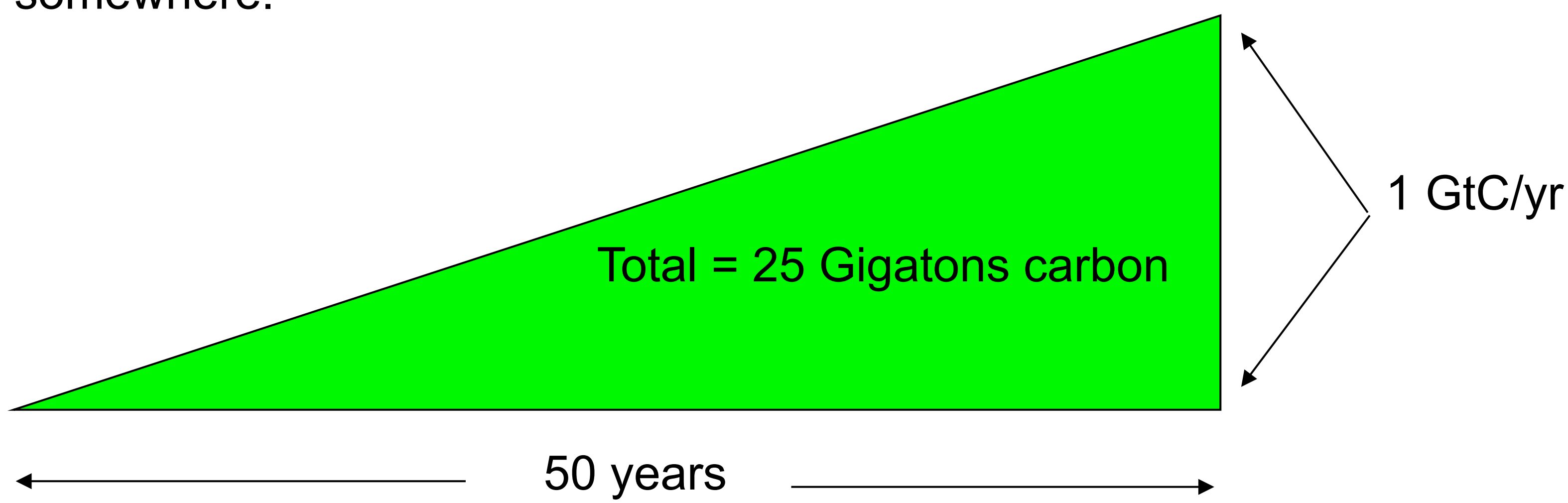
Socolow's Wedge Concept



Source: Socolow, Science 2004

What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO_2 problem should provide at least one wedge.

Source: Socolow, Science 2004

The Central Question:

What Trajectory Are We
Really Following?

How to Answer This Question?

One Approach:

Look at How New Technologies Supplant Older Technologies in the Marketplace

This is a Well-studied Subject…

The Technological Substitution Model

- Define a “Market” as an economic domain that meets a specific human or social need
- That Market is “Served” by one or more competing technical approaches that meet the need
- A particular technology can have some fraction of the market, denoted by the symbol f.
- Obviously $0<f<1$, where $f=0$ implies zero presence in the market, and $f=1$ denotes that the technology completely dominates that market.
- QUESTION: How does f evolve in time, I.e. what equation governs $f(t)$?

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Many technological advances can be considered as a competitive substitution of one technique or approach which satisfies a human need which up until that point had been met by some other approach or technique.
- If the new technique or approach begins to acquire a few percent market fraction, then it will proceed until it's substitution is "complete".
- The fractional rate of fractional substitution of new for old is proportional to the remaining amount of the old left to be substituted.

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- If a Technology Has Significant Advantages Over Competing Approaches, and has Small Market presence, then will see rapid (expontial) increase in f:

$$\frac{df}{dt} = r_0 f \quad \rightarrow \quad f(t) = f_0 \exp(r_0 t), \quad f(0) = f_0$$

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Obviously This Cannot Continue for Long (otherwise f>1!).
- So Growth Rate Must Saturate As f approaches Unity
- Modify Growth Equation to Now Read

$$\frac{1}{f}\frac{df}{dt} = r_0(1-f)$$

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- This is a Nonlinear ODE. Solution Is

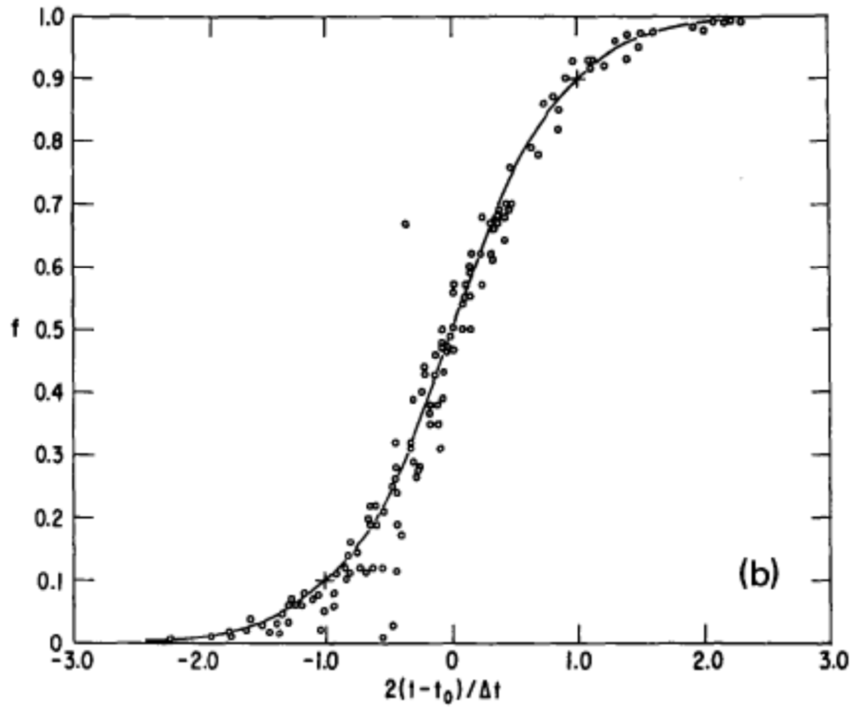
$$f(t) = \left[1 + \exp\left(-r_0(t - t_0)\right)\right]^{-1}$$

- Where t_0 is the time when f=0.5

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Fischer-Pry Model Solution:



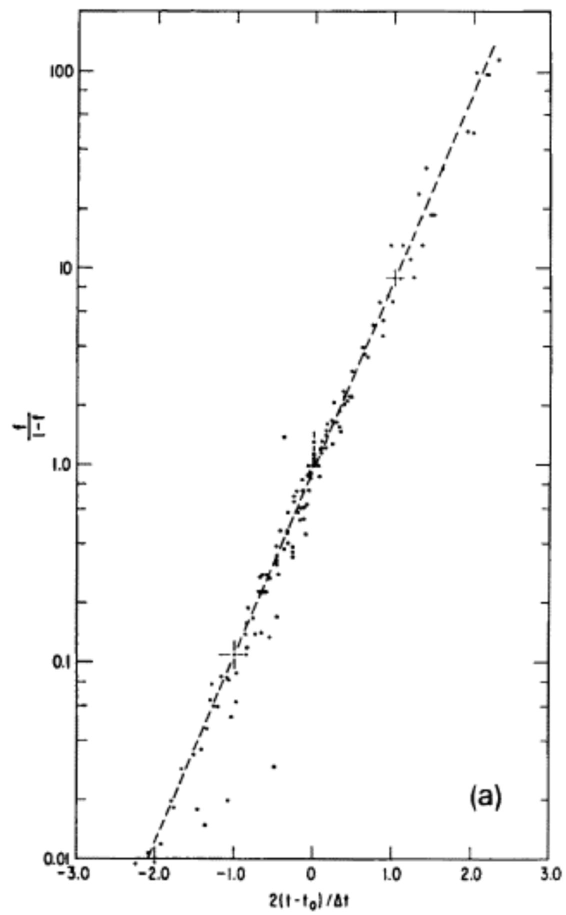
Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Can See That the Substitution Model Also Follows the Equation

$$\frac{f}{(1-f)} = \exp(r_0 t)$$

- Suggests That Semi-log Plot Should Be Straight Line



Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Can Define a "Take-Over Time", Dt, Defined as Time to go from f=0.1 to f=0.9
- Use Solution for f(t) to Find

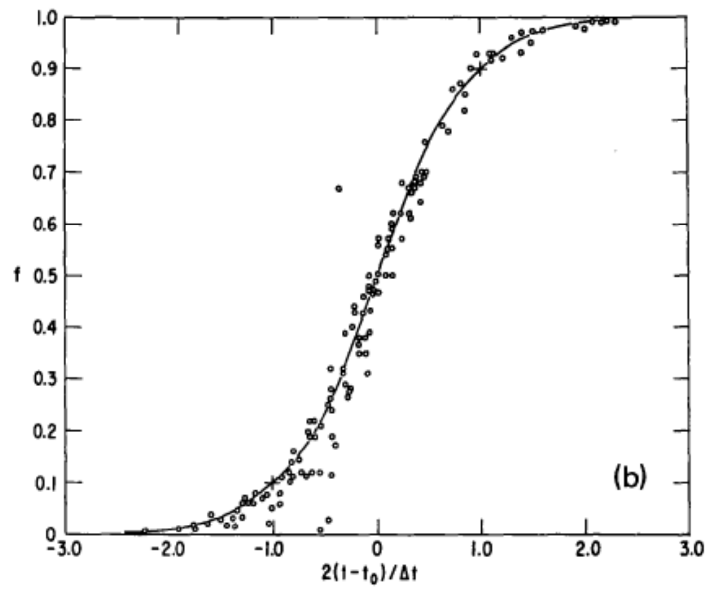
$$\Delta t \equiv t_{f=0.9} - t_{f=0.1} \simeq \frac{4.4}{r_0}$$

- **Key Implication:** Take-Over Time Determined by Early Growth Rates!

Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

The Technological Substitution Model

- Fischer-Pry Model Solution Successfully Captures Penetration of Many Different Markets:

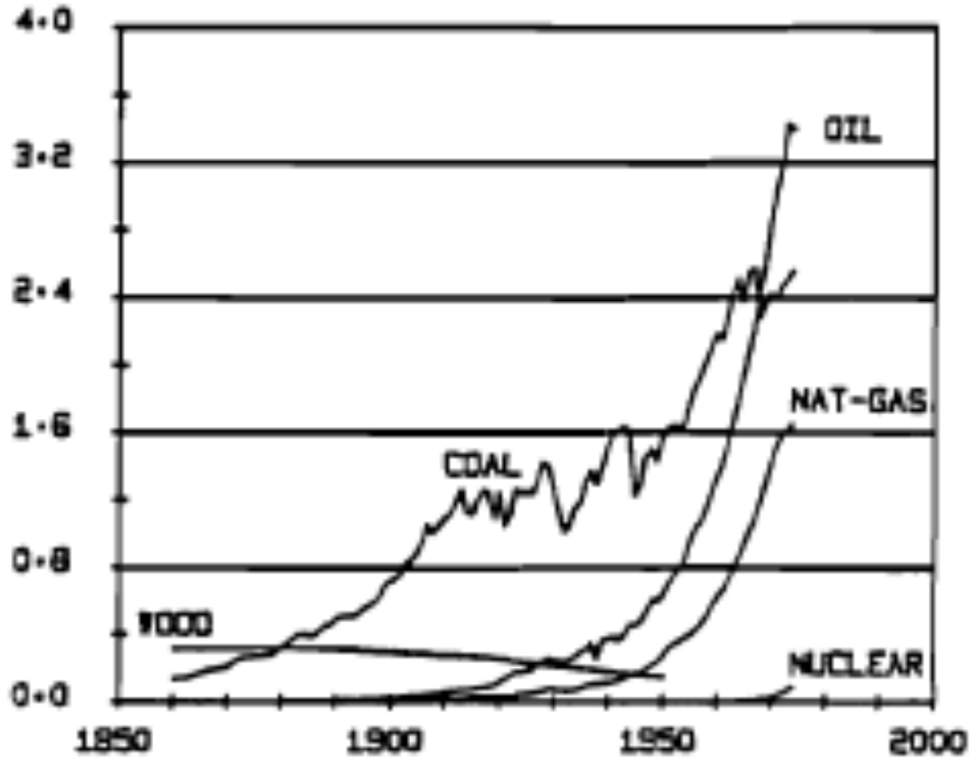


Source: Fischer & Pry, Tech. Forecasting and Social Change, 3, 75-88 (1971)

Application of This Model to Adoption of New Energy Technologies

- Marchetti [Tech. Forecasting and Social Change 10, 345-356 (1977)] Made First Application to Energy
- Needed to Make One Modification: Account for Fact that there are Multiple Primary Energy Technologies Used.
- Introduces the "First-in/First-out" Assumption
  – The Oldest Energy Source is the First to Die Out

Absolute Historical Energy Usage in the US



Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

Methodology

- Take Historical Data for Absolute Energy Use
- Find Total Energy Demand v. Time
- Find f(t) for Each Energy Source
- Use Fischer-Pry Approach to Model Data
- Result…

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

Market Penetration of Primary Energy Sources - 1860-1980

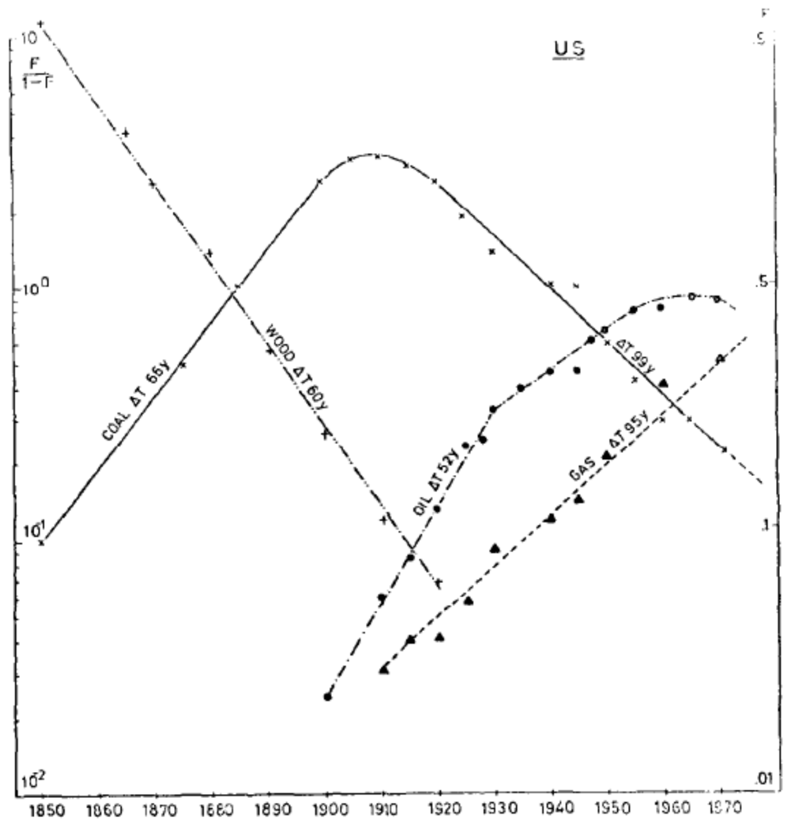
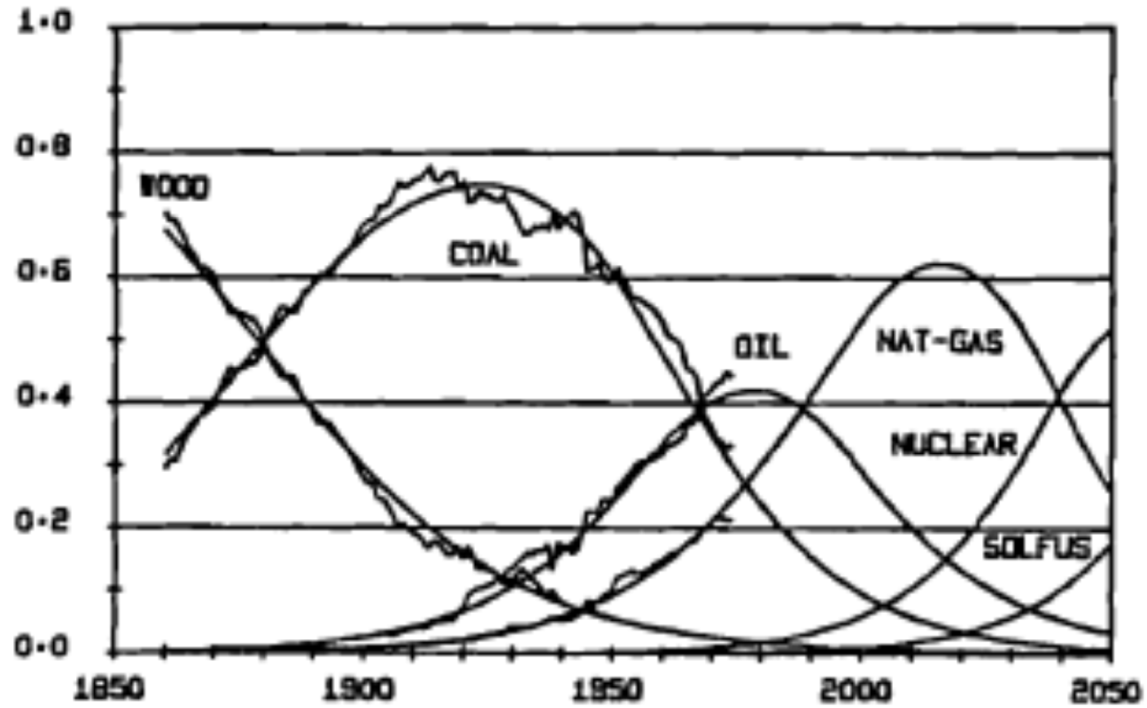


Fig. 5. Fitting of the statistical data on primary energy consumption in the U.S. Straight lines are represented by equations of type (2). Rates of penetration are indicated by the time to go from 1% to 50% of the market (ΔT years). The knee in the oil curve and the saturation regions can be calculated by the rule "first in–first out".

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

Market Penetration of Primary Energy Sources - 1860-1980



Here the contributions of the various primary sources are shown as fractions of the total market. The smooth curves are two-parameter logistics assembled in a system of equations as described in the text. *The fitting appears perfect for historical data.*

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

Market Penetration of Primary Energy Sources - 1860-1980

- Time to go from 1% to 50% of Energy Market Is Long (>50years!)

Primary Source	Penetration Time (years)
Wood	-60 years
Coal	66 years
Oil	52 years
Gas	95 years

Source: Marchetti, Tech. Forecasting and Social Change 10, 345-356 (1977)

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Application of This Model to Adoption of C-free Energy Technologies

- Laurmann made first application to the CO2 Emission Problem [Laurmann,Energy, 10, 762 (1987)]
- He Looked at Only Two Classes of Primary Energy: Fossil Fuels and Fission
- Tried to Predict Development of Fission Power…

Goal: Estimate Contribution to Reducing C Emissions

- Look at Market Growth Data
- Look at Cost Trends
- Estimate Parameters for Logistics Model (e.g. Fisher-Pry type model)
- Extrapolate Possible Future

Market Penetration of Fission

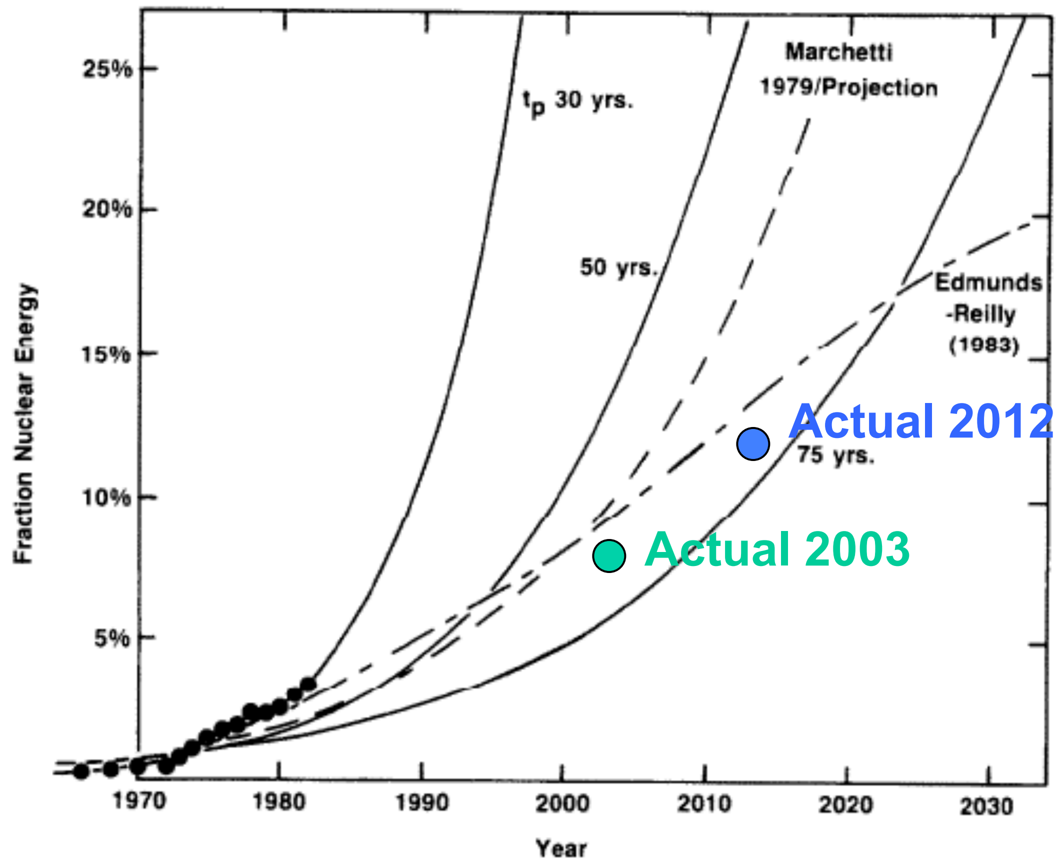

Fig. 2. Past and projected world nuclear energy production as a function of total energy use. Logistic growth curves assume a 1% market share by 1975; t_p is the time for increase from 1% to 50% of market share. Nuclear data are from EIA.[3]

Source: Laurmann, Energy 10 (1987), IEA 2004 World Energy Outlook, http://www.nei.org/Knowledge-Center/Nuclear-Statistics/World-Statistics, accessed March 2015

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Impact of Introduction & Penetration Times on Projected CO2 Inventory

- Assumed an Annual Growth Rate in Global Energy Demand
- Used Two Different Penetration Times
- Introduced 2nd Variable: Time when C-free Source is Introduced (Relative to 1975)

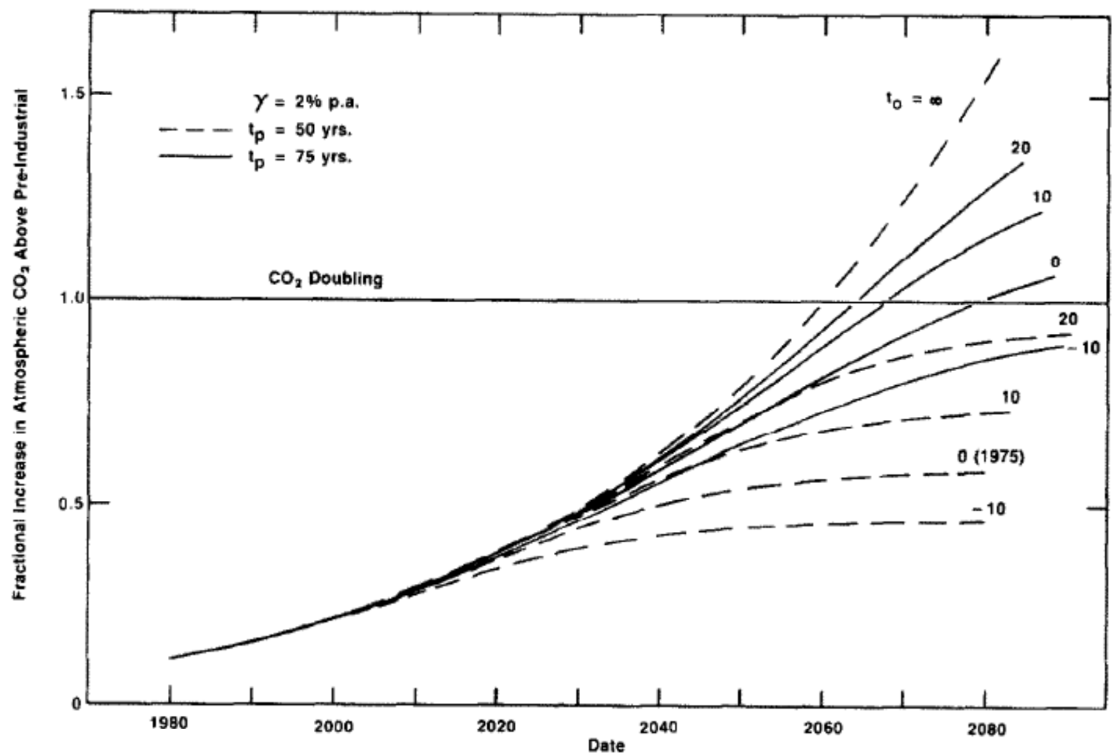

Fig. 5. Atmospheric CO_2 increase for a total exponential energy growth rate of 2% per annum.

Source: Laurmann, Energy 10 (1987), IEA 2004 World Energy Outlook

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Key Conclusions from Previous Studies

- The Replacement Time Is Determined By the Early Growth Rate
- Early Application to Energy Studies Shows Very Long (>50 Years) Replacement Times
- C-Balance and Climate Models Suggest Need to Act Faster Than This Time Scale
- **Q: How Quickly Are Renewables Moving Into the Primary Energy Market?**

Methodology

- Use Historical Installed Peak Power, Capacity Factor, and Global Electricity Demand to find f(t) for 1990-2006 period
- Find growth rate, r_0, from this data
- Assume Logistics Model Will Hold and Project f(t) into the Future
- Assume Global Electricity Demand Growth
- Taking CF, f_{crit} into Account Estimate Actual Power Delivered & Required Installed Power
- Estimate C-Emissions Avoided Assuming This Power displaces Fossil Fuel Power

Important Things to Keep in Mind

- Renewables Currently Have Small (~1% or less) Market Fraction
  - Projections will have significant uncertainties
- Capacity Factors ($CF=P_{actual}/P_{peak}$) Significantly Less than Unity
  - CF_{wind}~25%, CF_{PV}~30-40%,
- Variability & Grid Stability Concerns Lead to Maximum Allowable Load Fraction
  - f_{crit}~0.2-0.3

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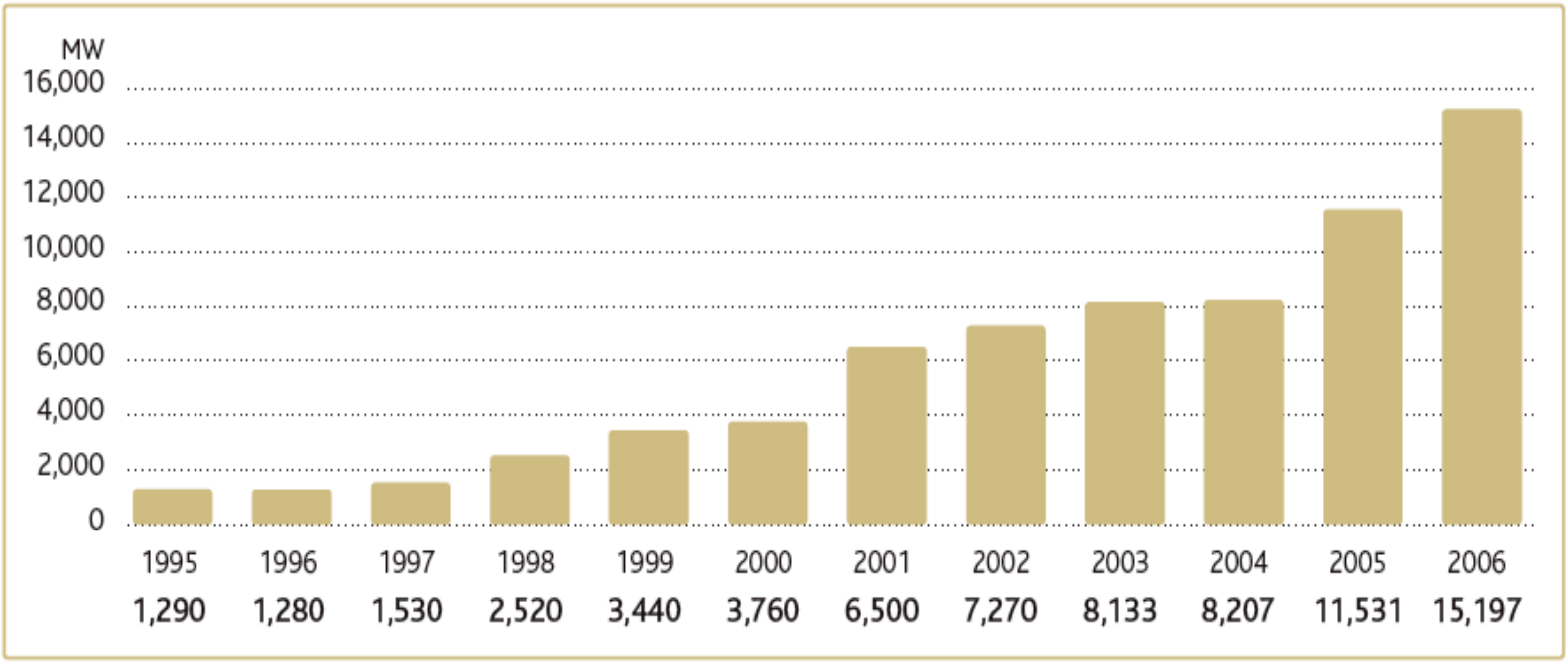
Annual Installation of New Wind Generation Capacity – thru 2006

GLOBAL ANNUAL INSTALLED CAPACITY 1995-2006



Source: GWEC, Global Wind 2006 Report

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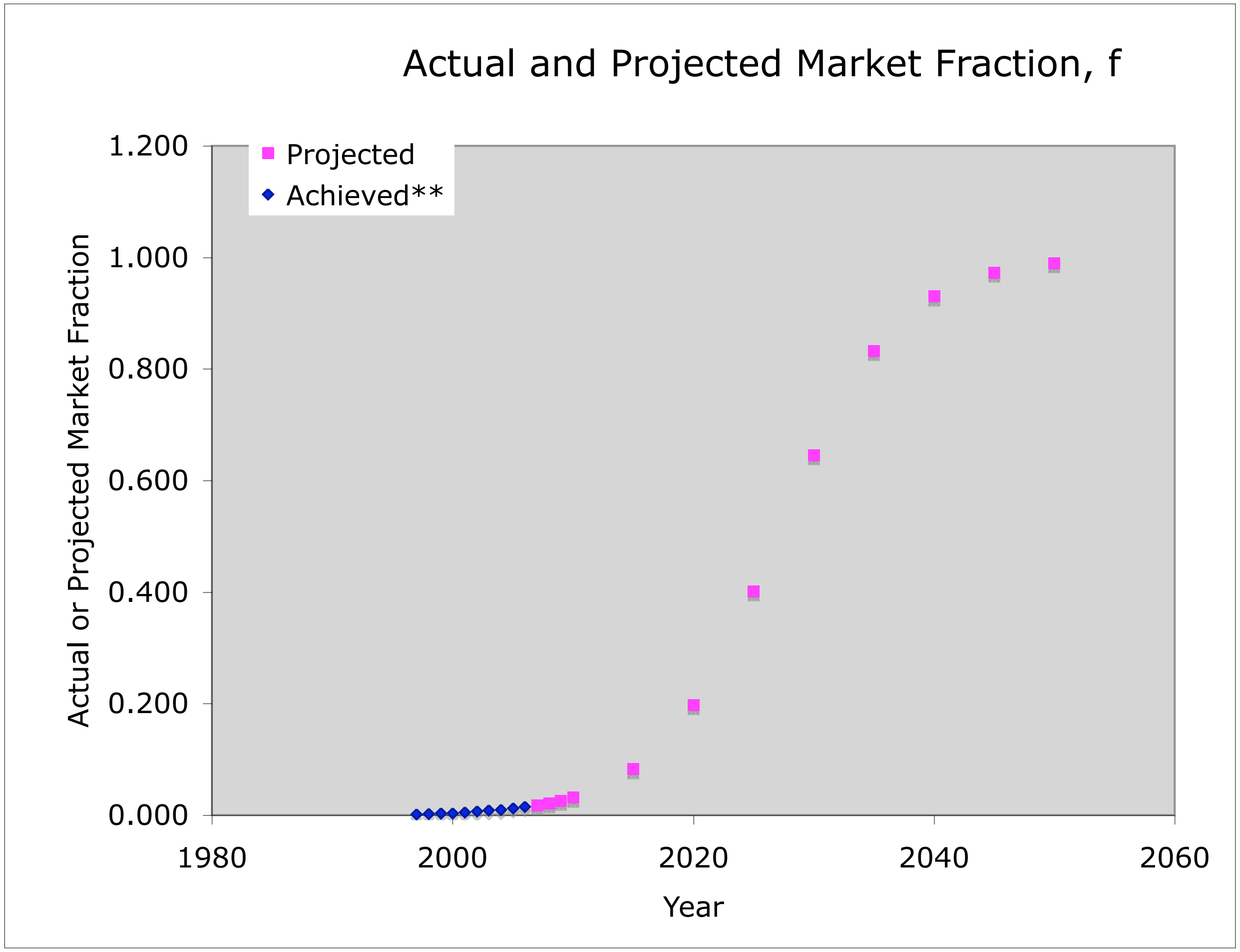
Fit to early wind power market fraction evolution...(2006 data)



Early Growth Rate, r_0=20%

Expect 22 Year Takeover Time

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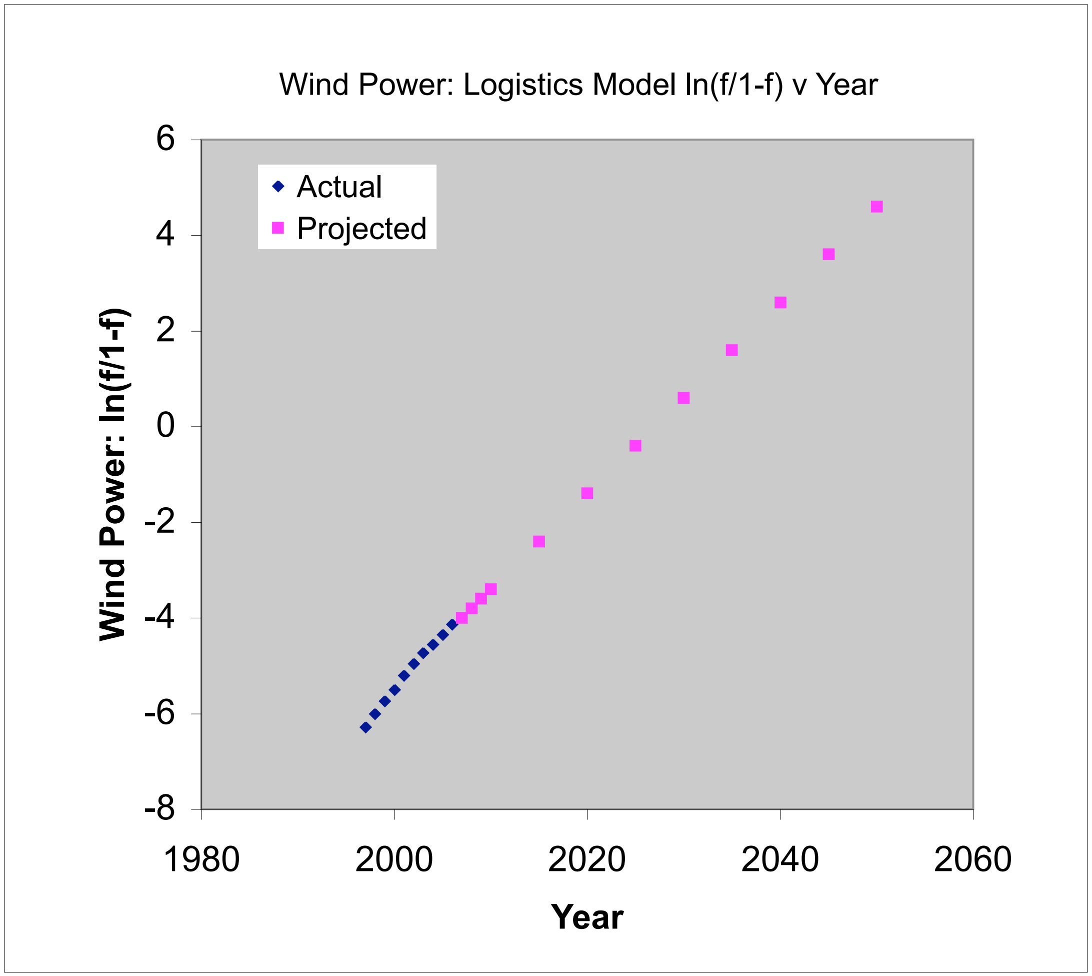
Reasonable Fit to Wind Power Growth – 2006



Early Growth Rate, r_0=20%

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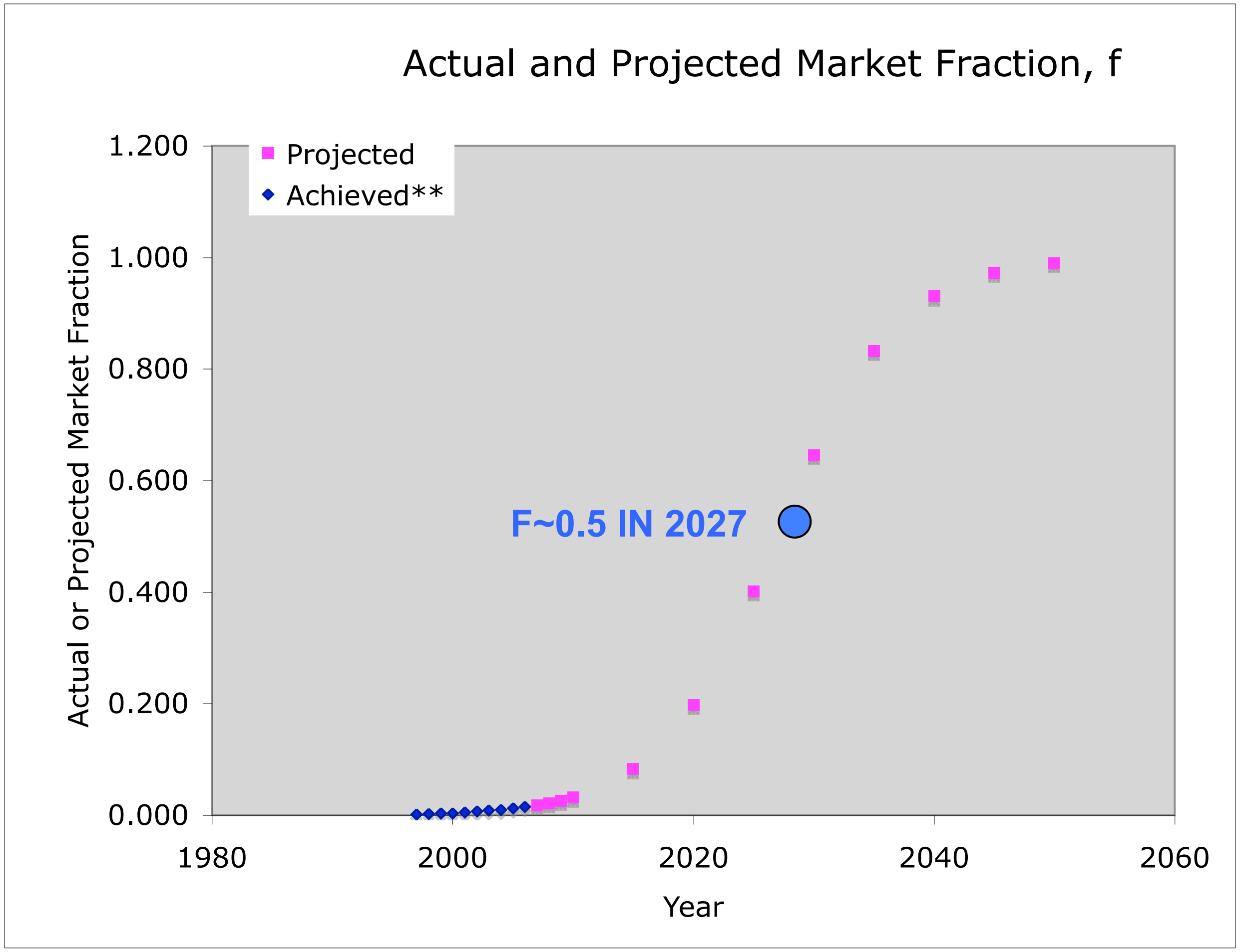
Project f_{Wind}=0.5 in 2027



Early Growth Rate, r_0=20%

Expect 22 Year Takeover Time

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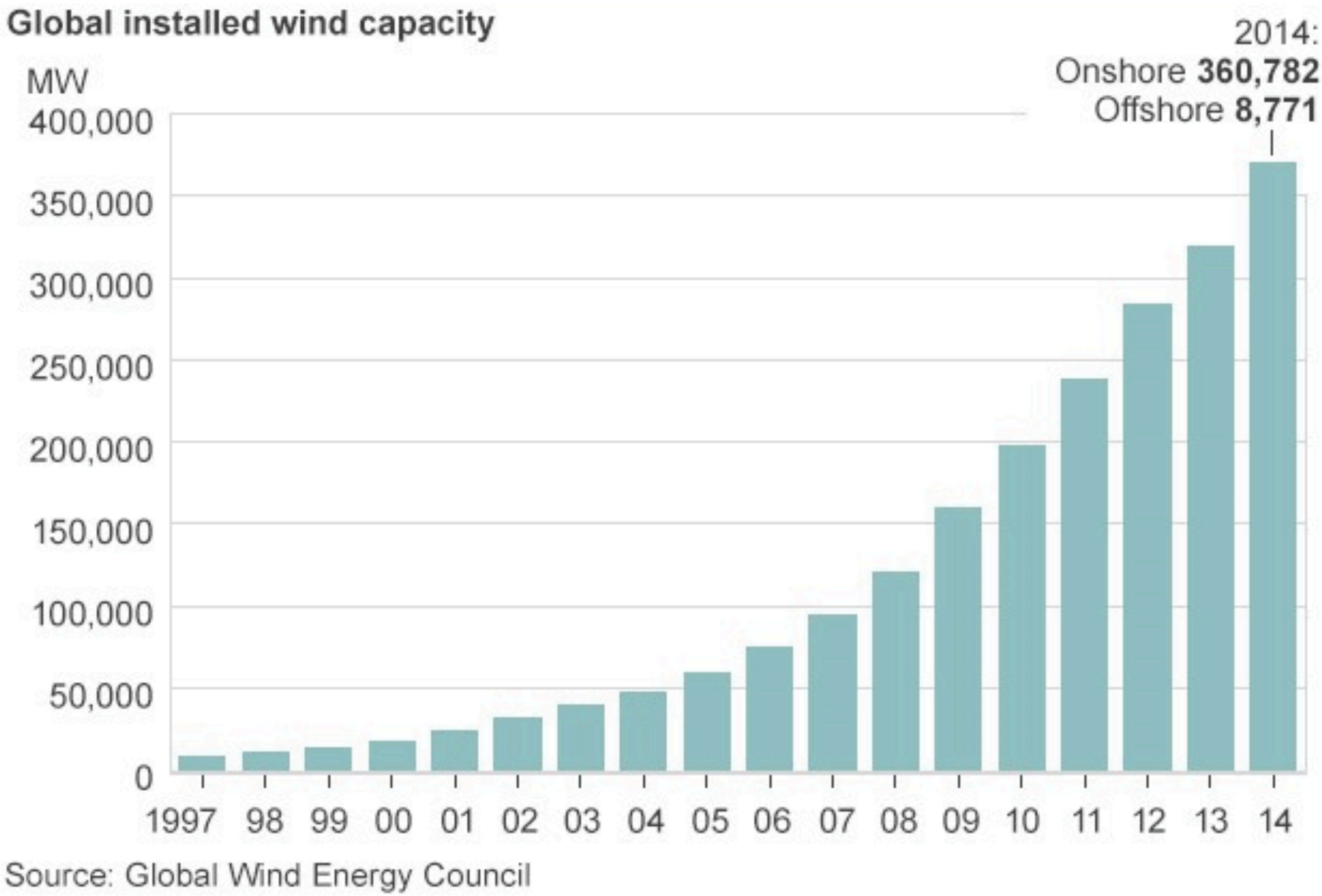
Update: *Annual Installation of New Wind Generation Capacity thru 2014*



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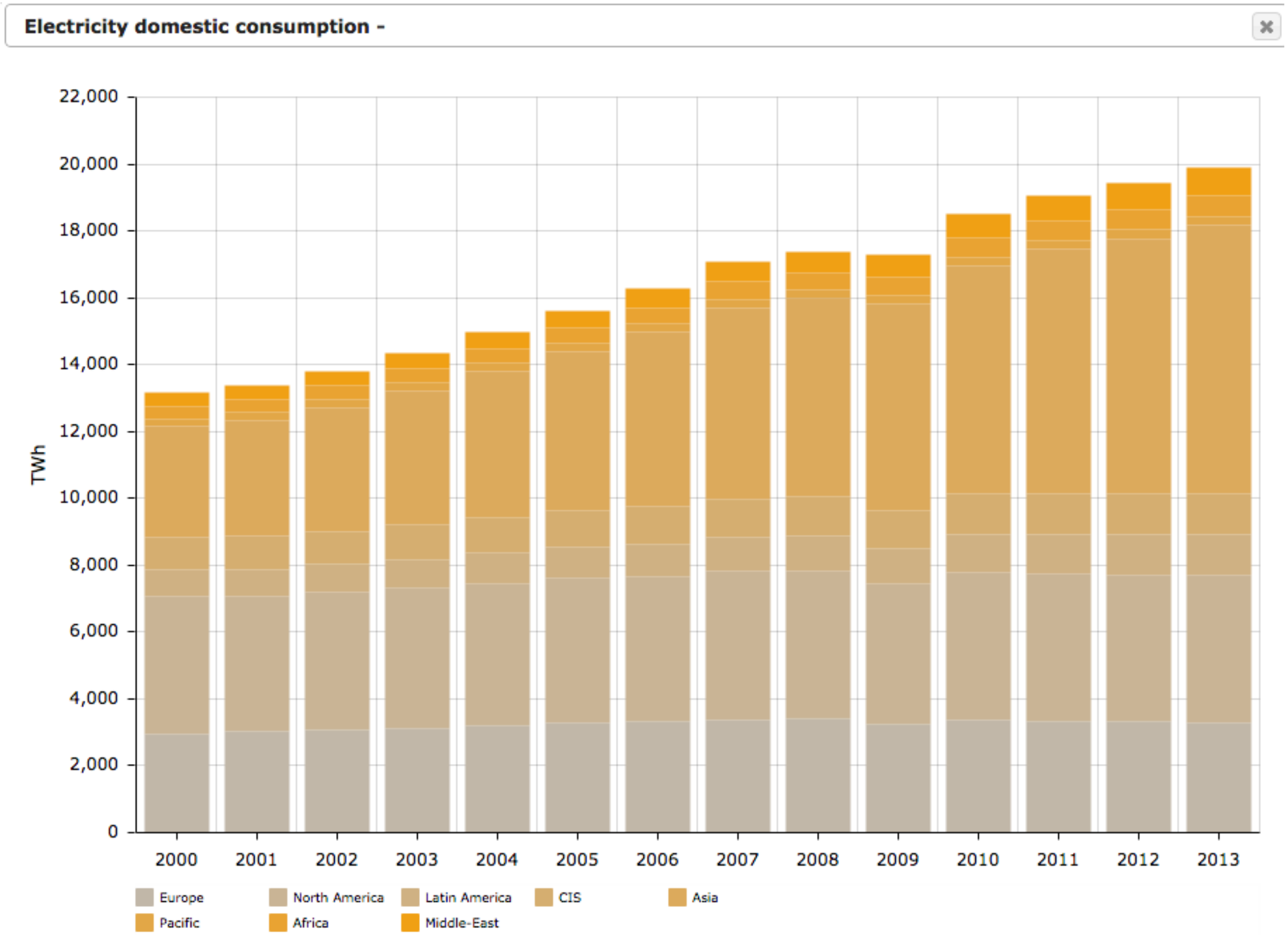
GLOBAL ELECTRICAL ENERGY DEMAND THRU 2013



https://yearbook.enerdata.net/electricity-domestic-consumption-data-by-region.html

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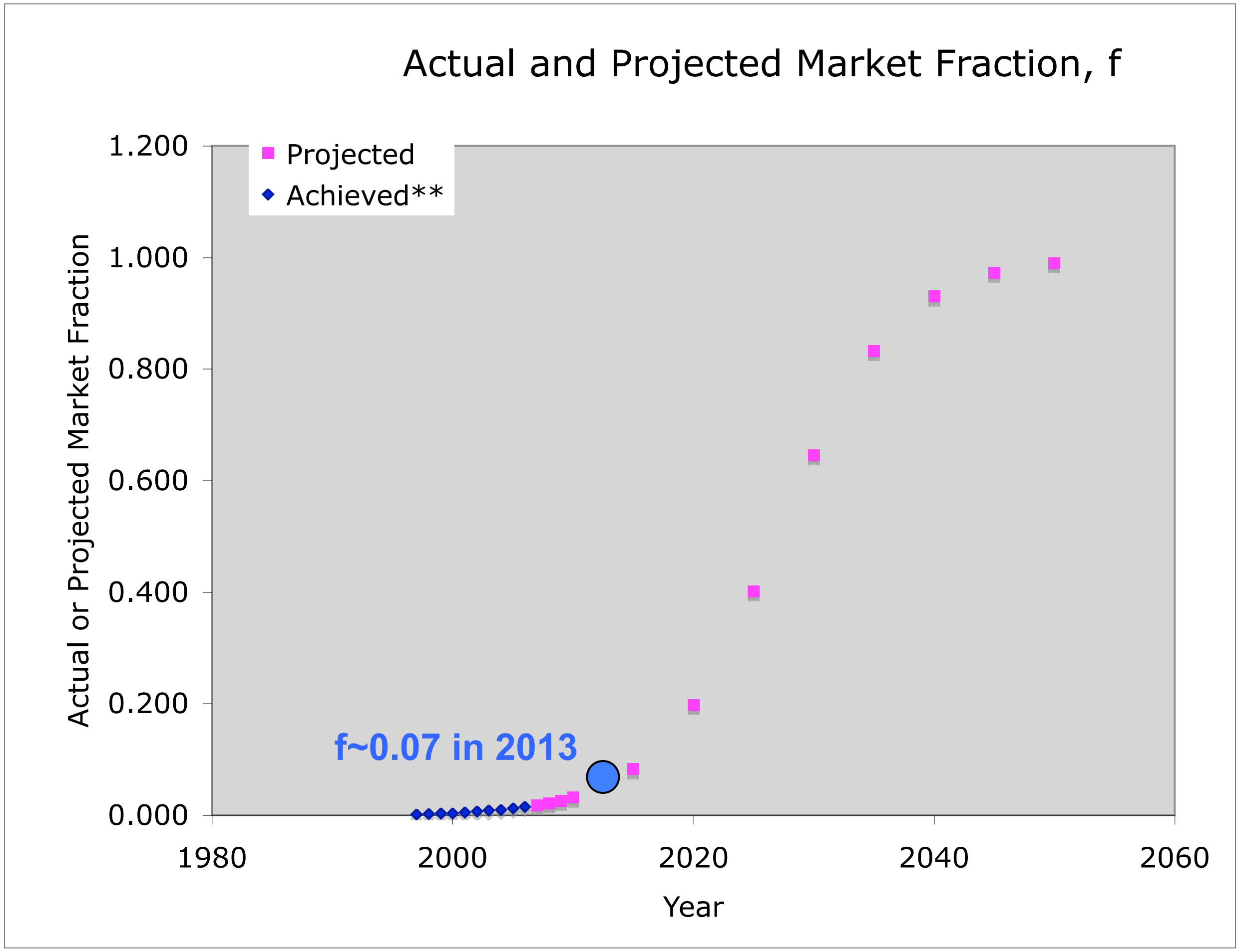
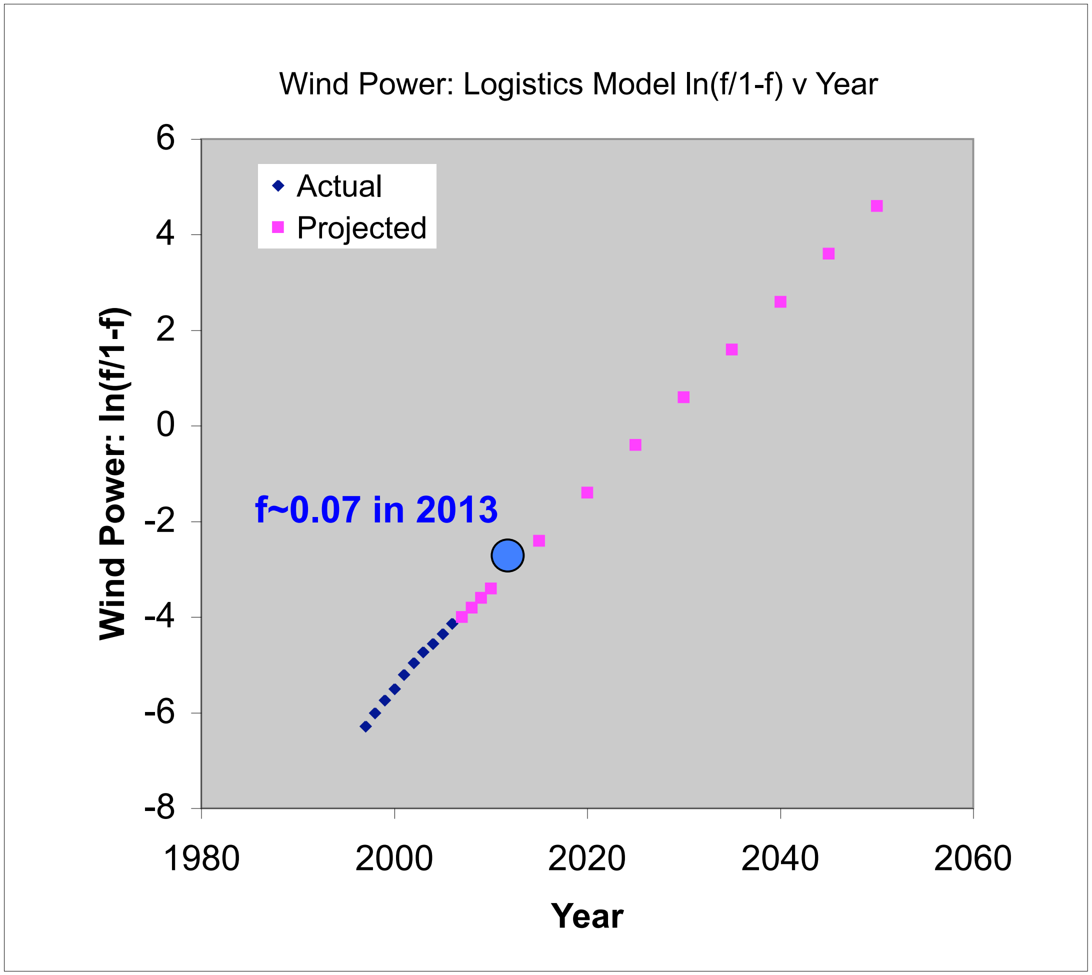
Projections in 2006 continue to hold in 2013···Reasonable Fit to Wind Power Growth



Early Growth Rate, r_0=20%

Expect 22 Year Takeover Time

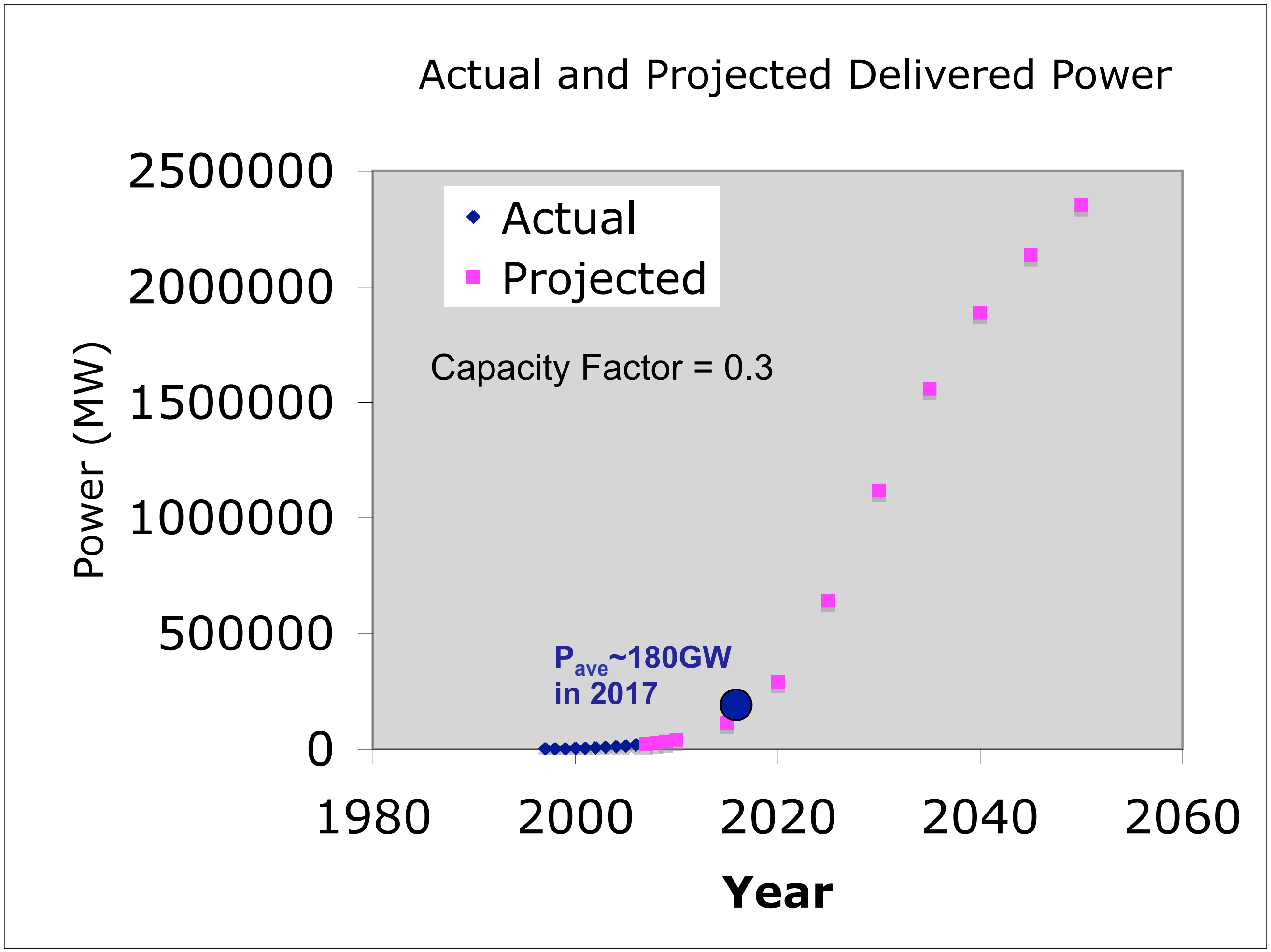
Projections in 2006 continue to hold in 2013…
Reasonable Fit to Wind Power Growth



Early Growth Rate, r_0=20%

Expect 22 Year Takeover Time

This Will Lead to Large (>1TW) Wind Power by 2025



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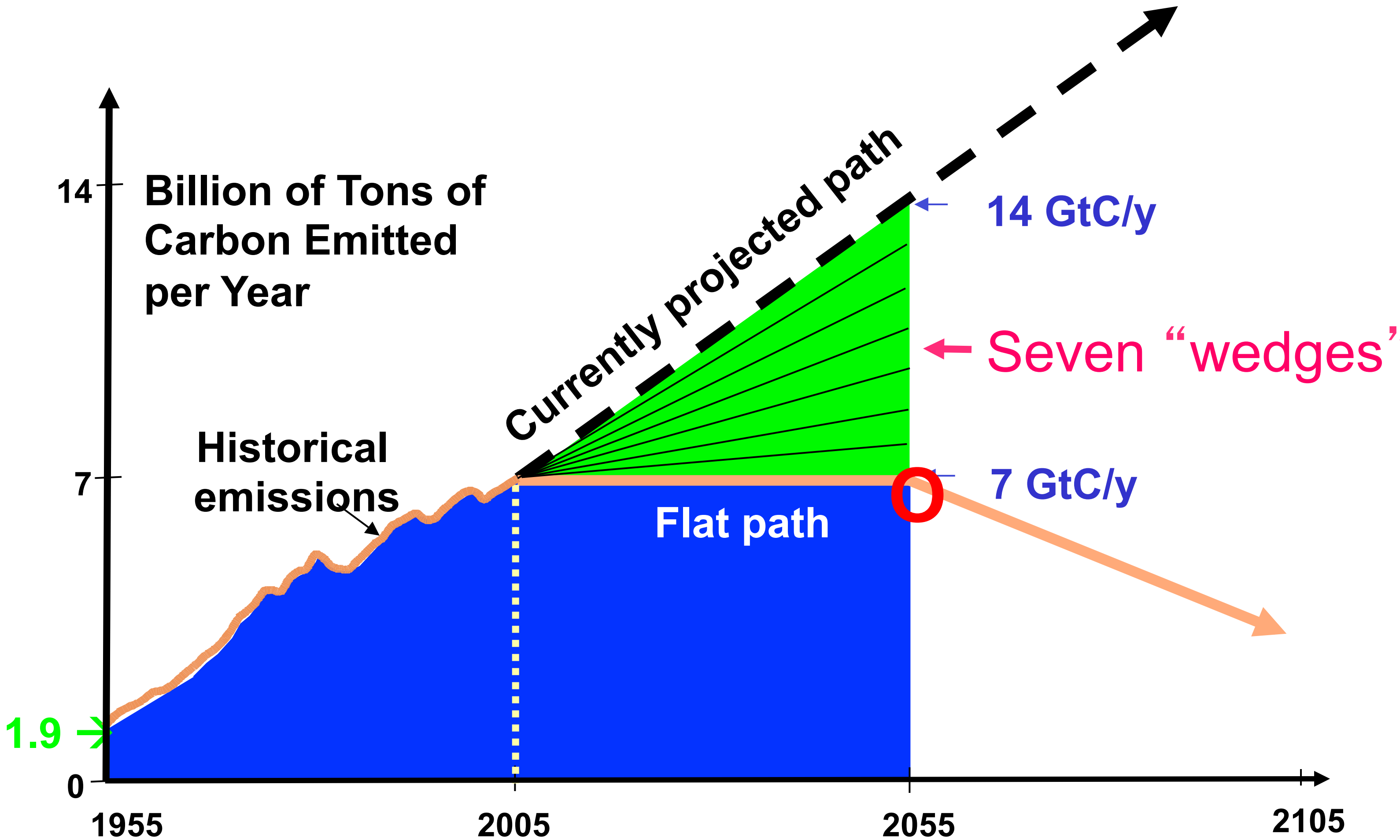
Let's compare to Socolow's Wedge



Source: Socolow, Science 2004

Efficient Use of Electricity

industry

buildings

power

Effort needed by 2055 for 1 wedge:

.

25% - 50% reduction in expected 2055 electricity use in commercial and residential buildings

Socolow, Science 2004

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Efficient Use of Fuel

Effort needed by 2055 for 1 wedge:

2 billion cars driven 10,000 miles per year at 60 mpg instead of 30 mpg.

1 billion cars driven, at 30 mpg, 5,000 instead of 10,000 miles per year.

Source: Sokolow, Science 2004

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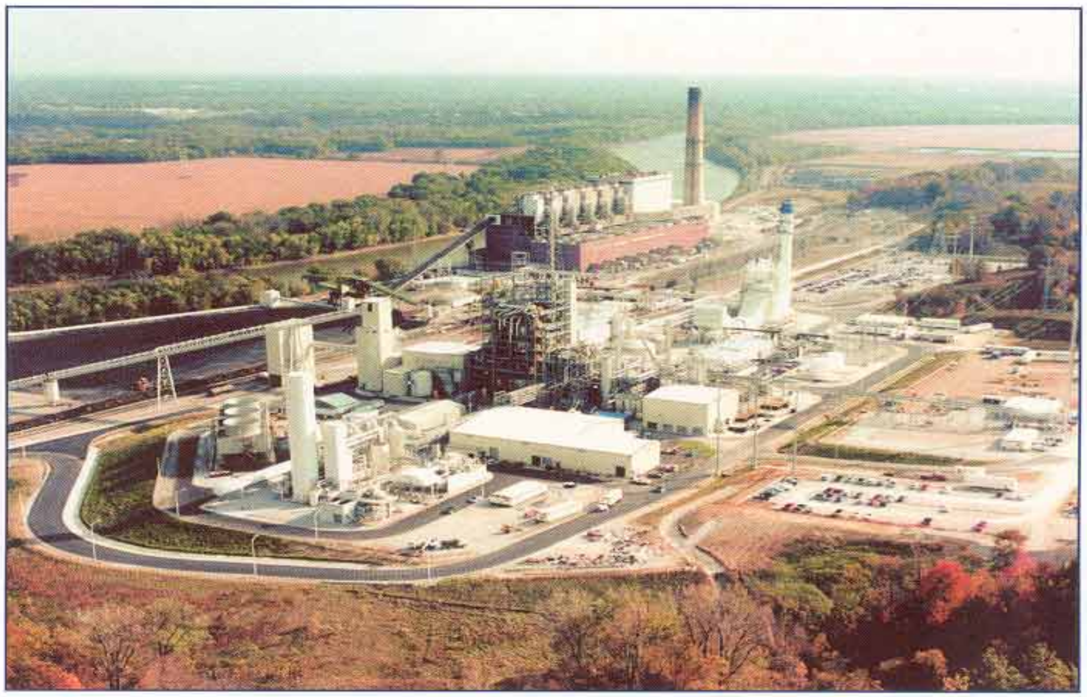
Carbon Capture and Storage



The Wabash River
Coal Gasification Repowering Project

Effort needed by 2055 for 1 wedge:

Carbon capture and storage at 800 GW coal power plants.

Sokolow, Science 2004

Graphics courtesy of DOE Office of Fossil Energy

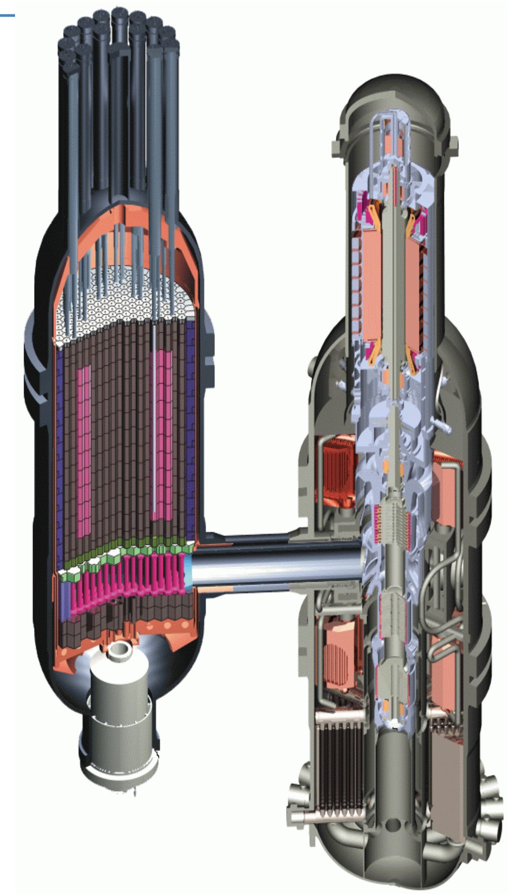
Next Generation Nuclear Fission

- Passively Safe Reactor Core
- Proliferation Resistant Fuel Cycle w/ Reprocessing
- Process Heat, H Production
- Electricity
- Geological Waste Disposal

Effort needed by 2055 for 1 wedge:

700 GW (twice current capacity) displacing coal power

Source: Sokolow Science 2004



Graphic courtesy of General Atomics

Will Require ~100km x 100 km PV installation or ~100 Million Rootops

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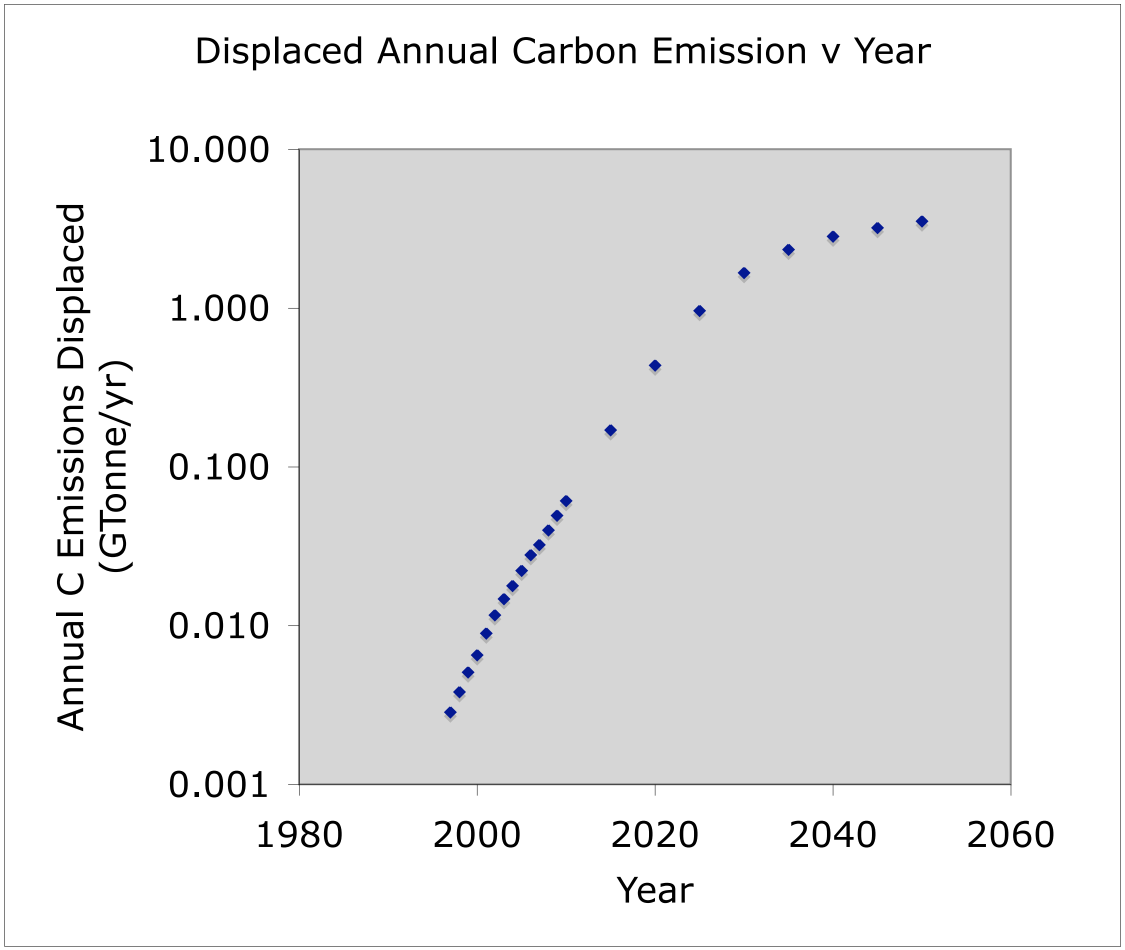
How does rate of wind deployment compare with a Socolow Wedge?

Total C-emissions Displaced THRU 2050: ~50 Gtonnes



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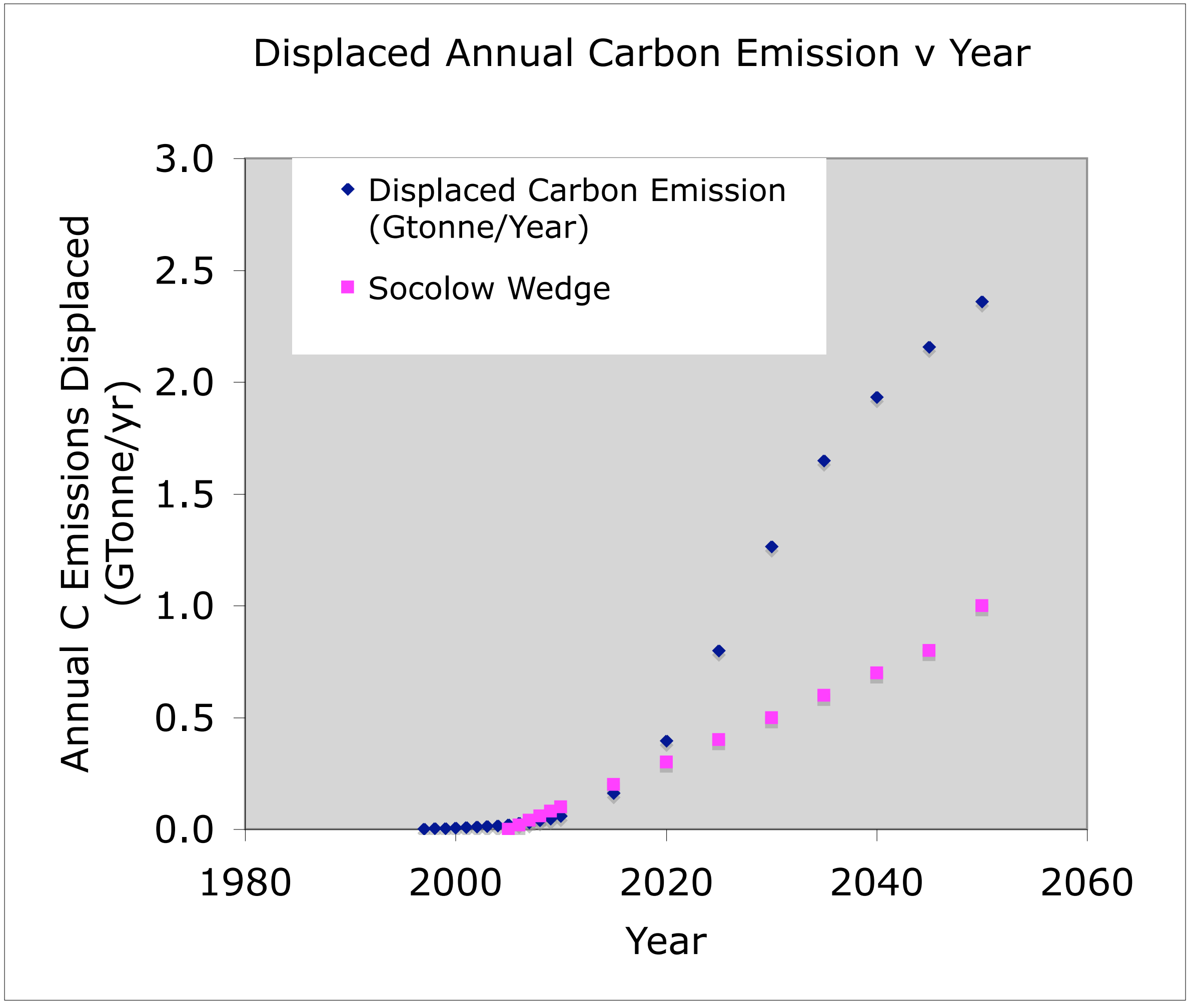
Current rate of wind deployment leads to 50 Gtonne avoided C (~2 Wedges)



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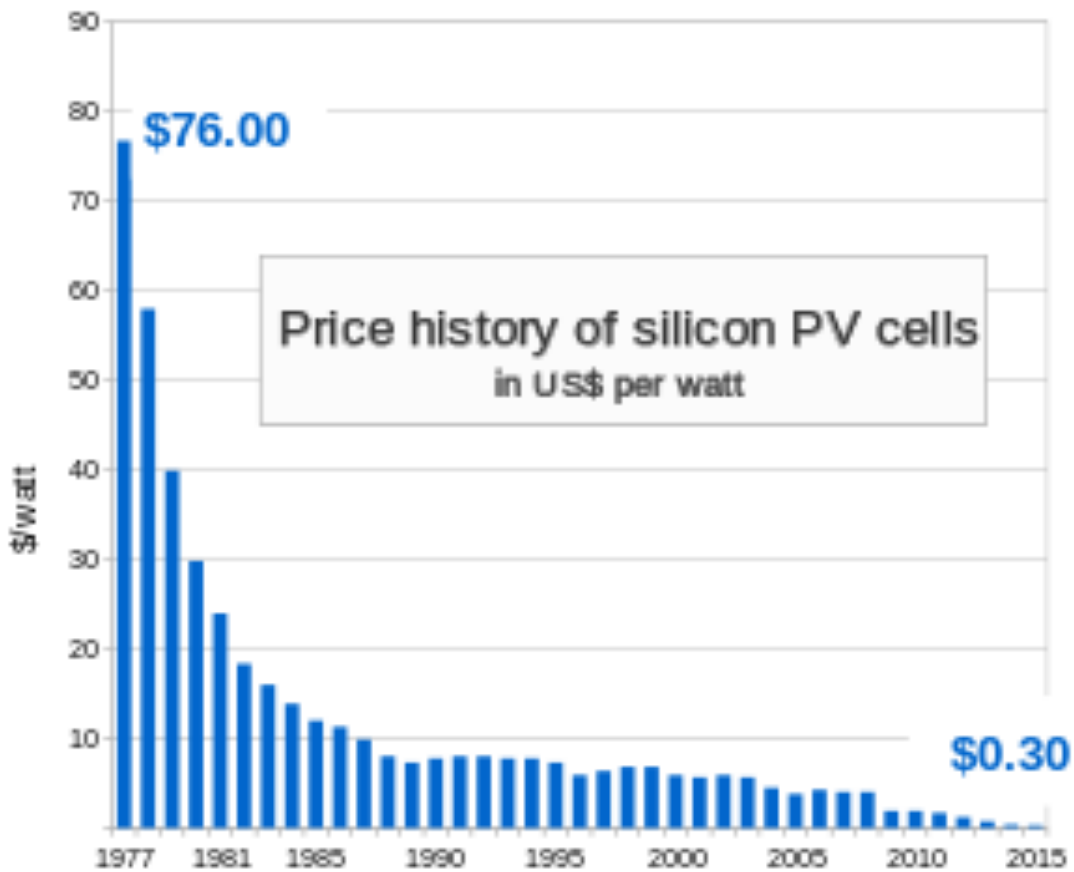
Will Lead to ~2M Large (3-5MW) Wind Turbines Covering ~10^6 km^2

APPLY TO SOLAR PV TECHNOLOGY….

SOLAR PV COSTS HAVE DROPPED DRAMATICALLY…



Source: Bloomberg New Energy Finance & pv.energytrend.com

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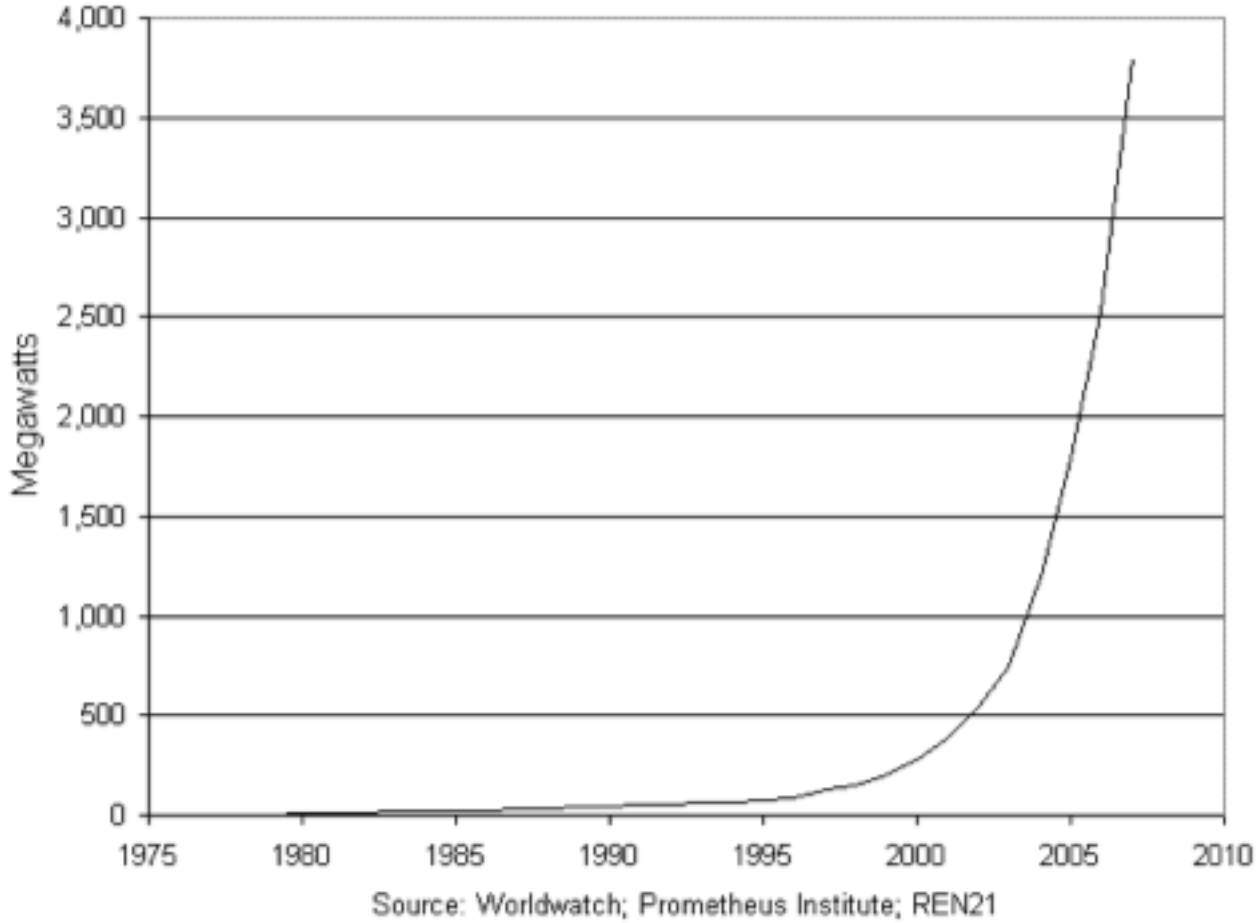
Solar PV Annual Production – THRU 2007



http://www.earth-policy.org/Indicators/Solar/2007.htm

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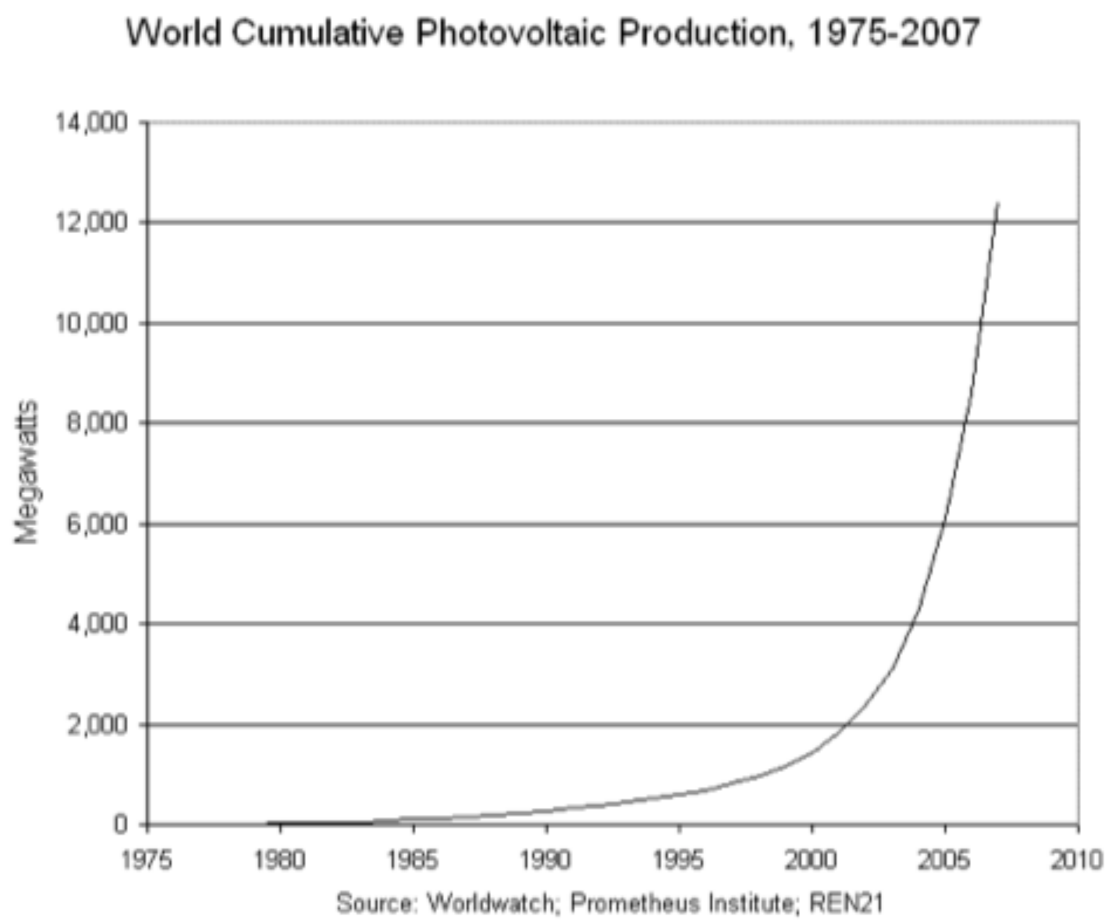
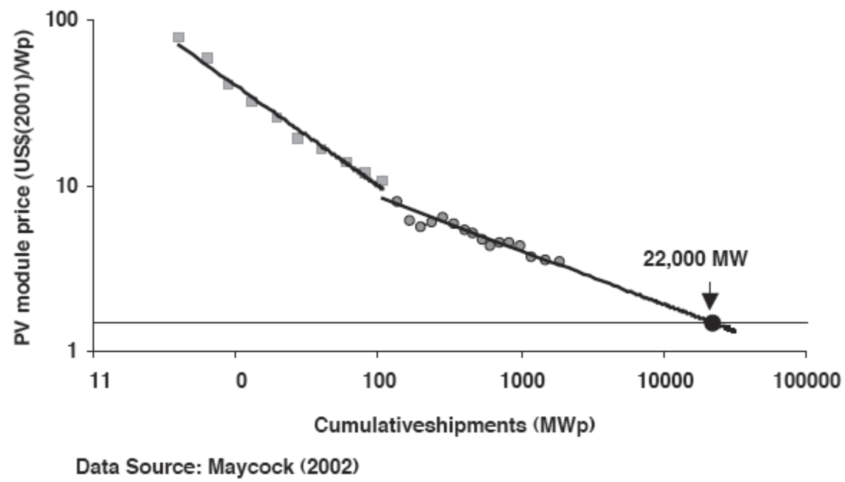
Solar PV Cumulative Production THRU 2007



http://www.earth-policy.org/Indicators/Solar/2007.htm

Solar PV Learning Curve

- Current Annual Manufacturing Capacity (2005) ~ 1GW/year
- 32% annual Growth in Capacity (1998-2003)
- World-Wide Installed Capacity ~3.2 GW (2003)
- Costs Coming Down
- Projected Competitive w/ 20-30 GW/year Production
- At Current Growth Rates ~10-15 Years More…



Byrne, J. Energy Policy 2004

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Methodology

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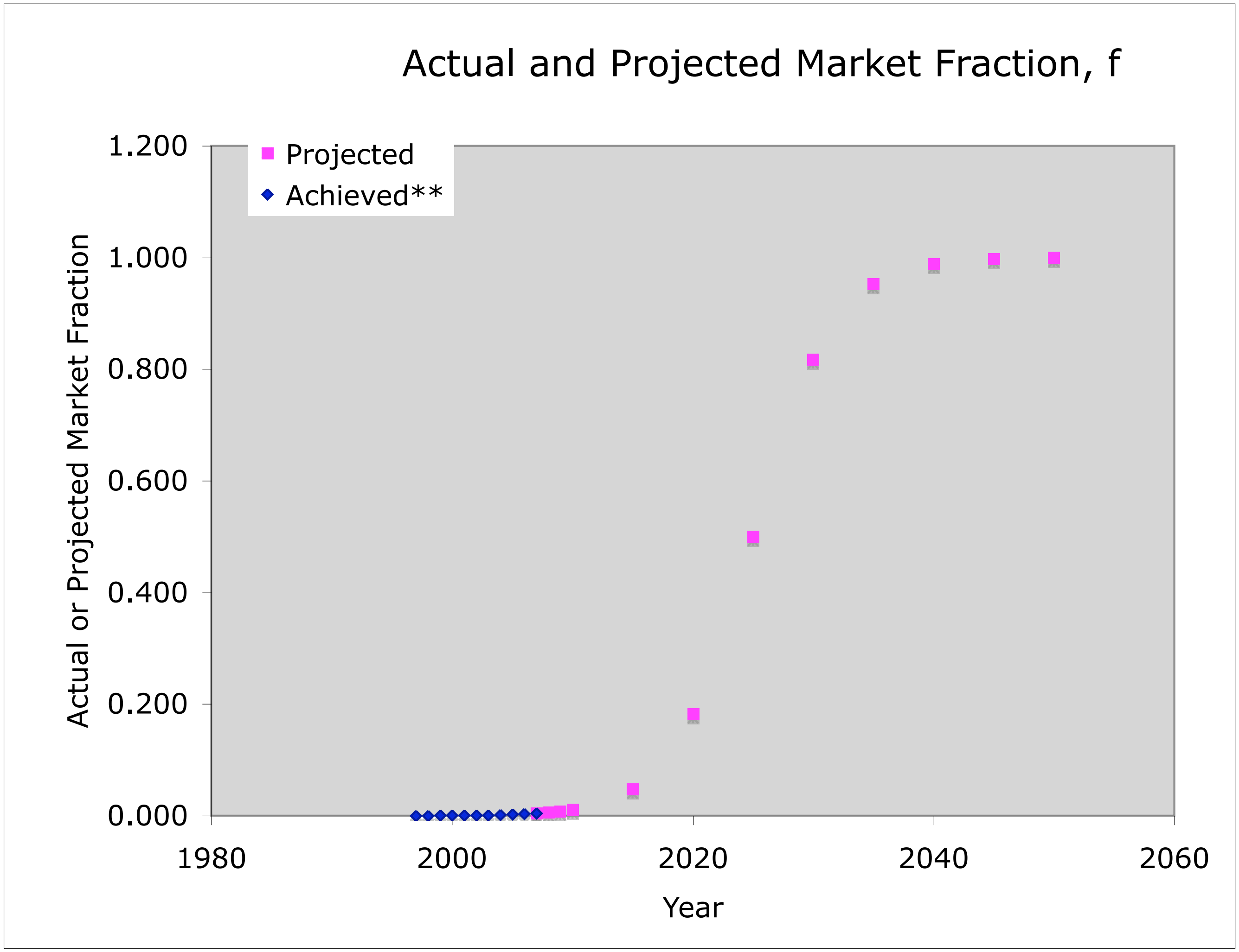
Logistics Model of Solar PV Power Growth (as of 2006)



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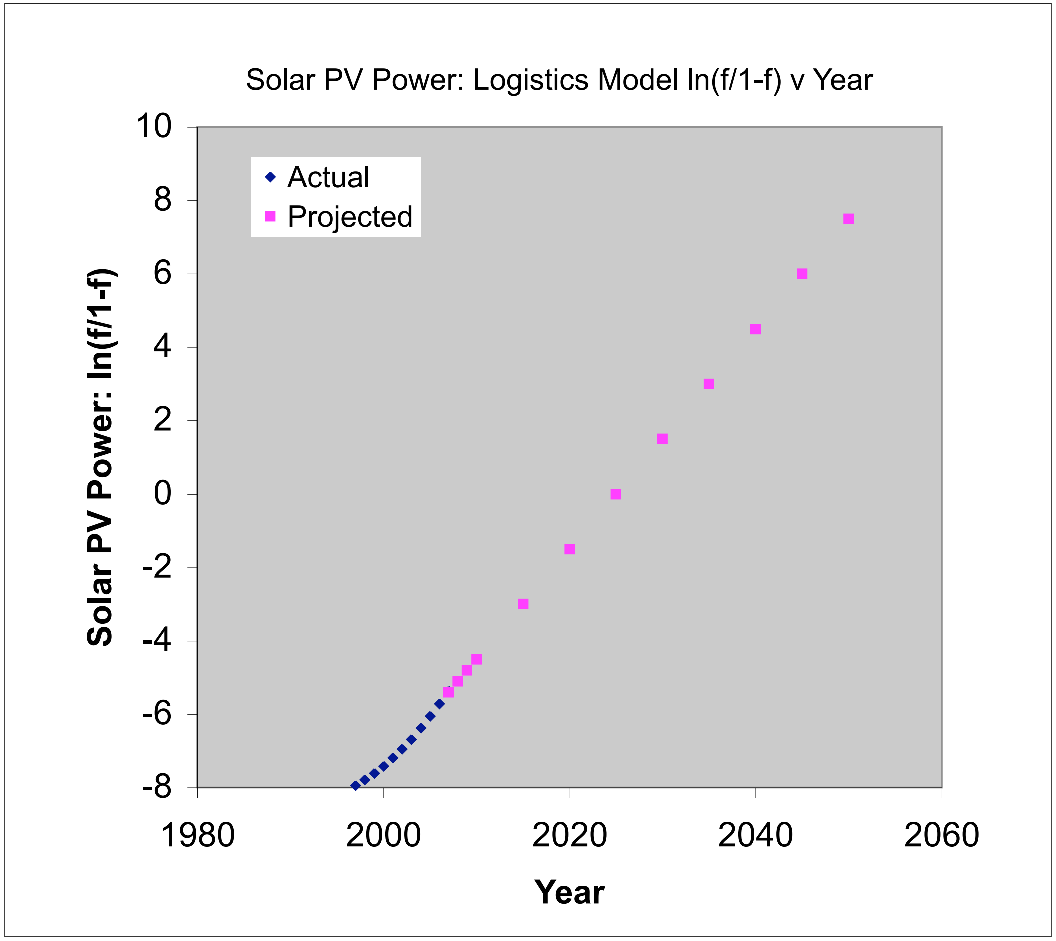

- Early Growth Rate, r_0~20%
- f=10% in ~2020
- Expect ~25 Year Takeover Time

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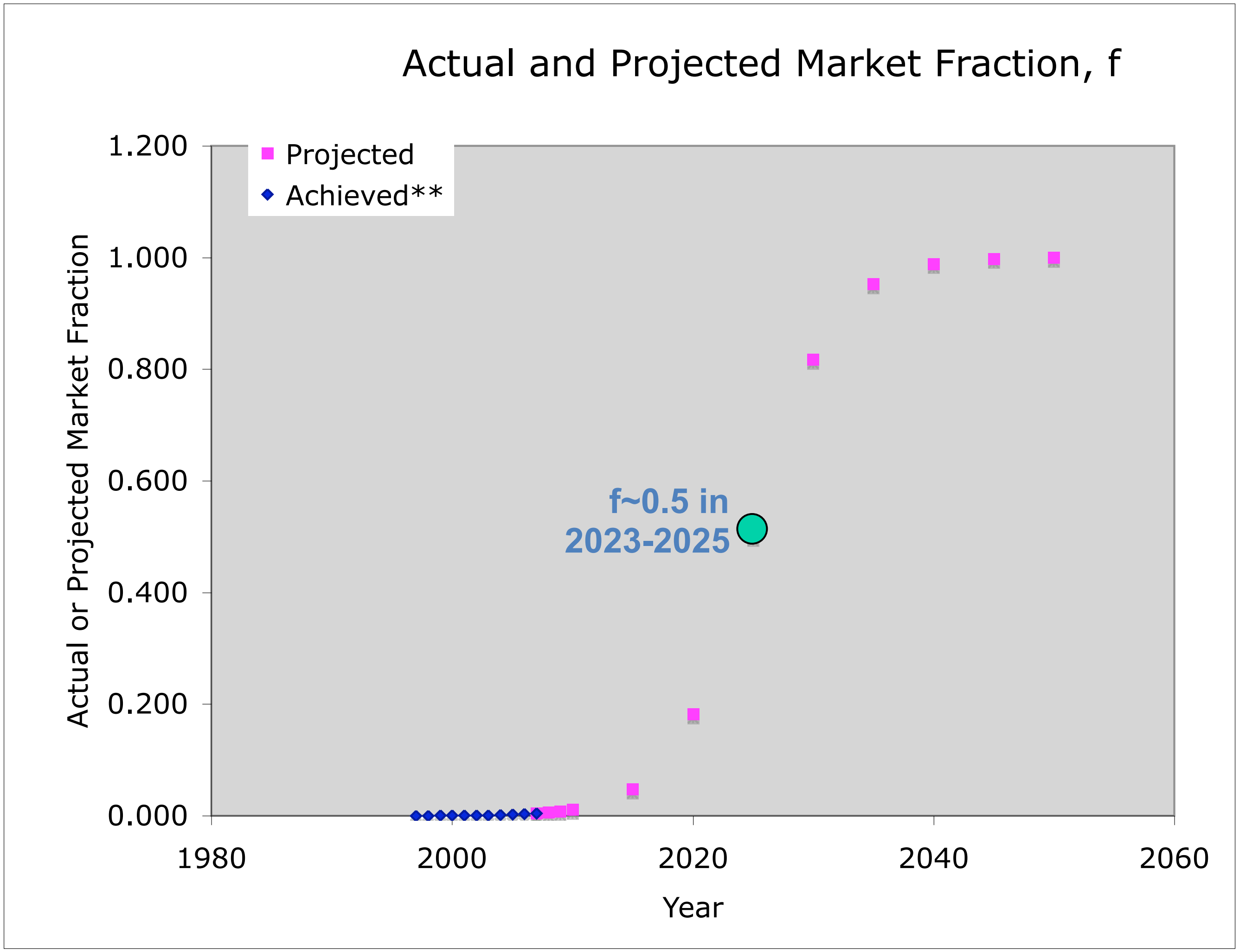
Project f_{PV}=0.5 in 2025-2030



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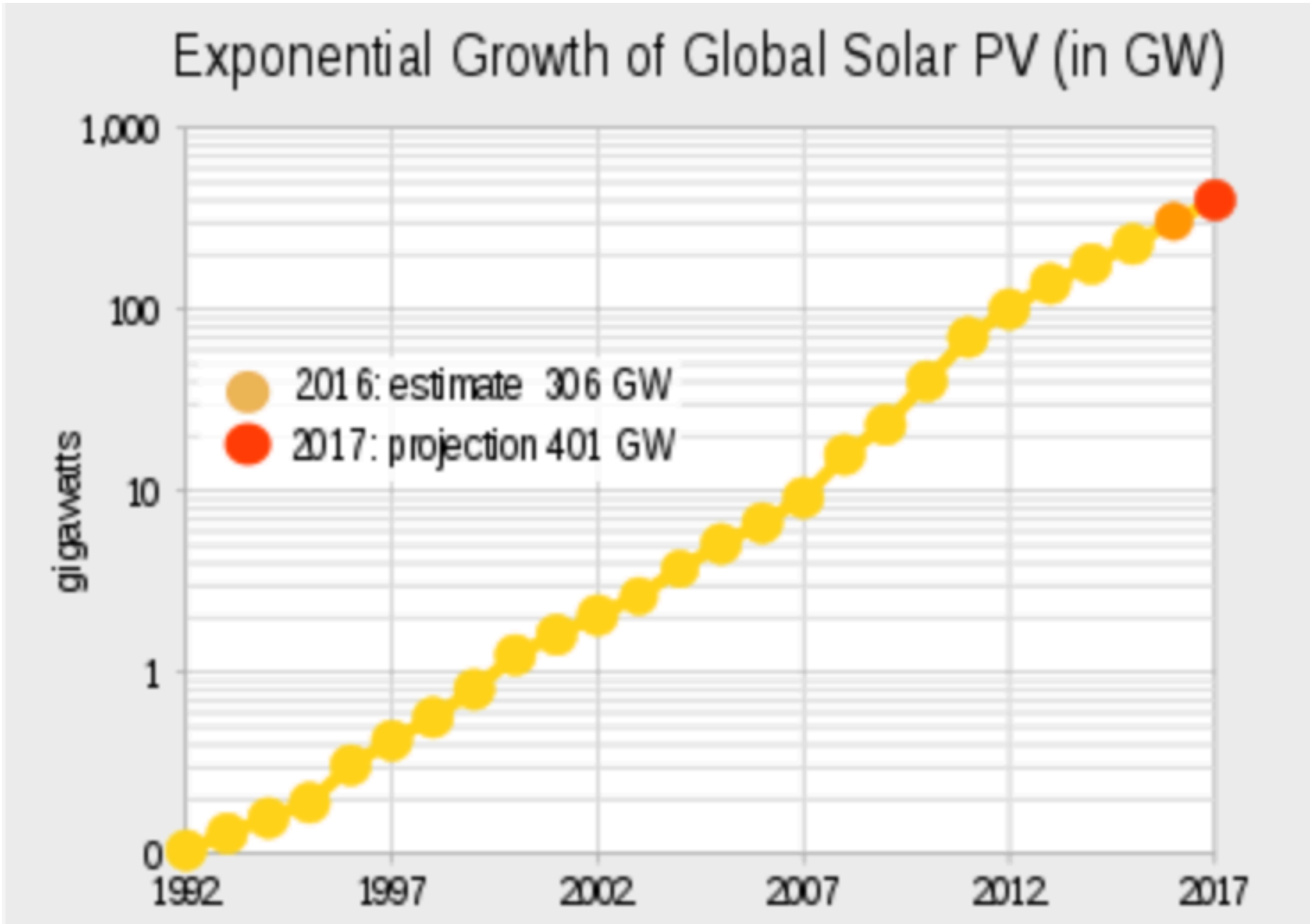
12 Years later: how did our projections do? Updated Global Installed Solar PV Capacity



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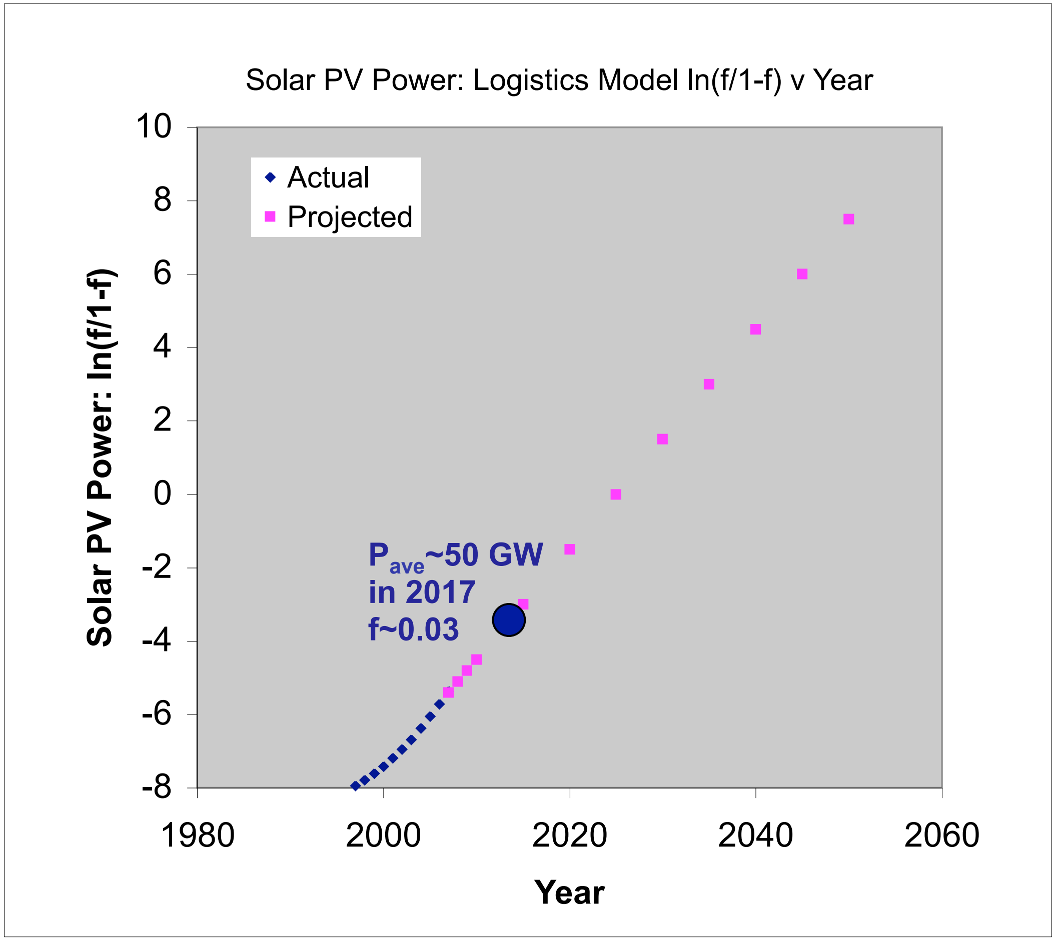
2006 Logistics Model Projections Captured Actual Solar PV Power Growth



- Early Growth Rate, r_0~20%
- f=10% in ~2020
- Expect ~25 Year Takeover Time

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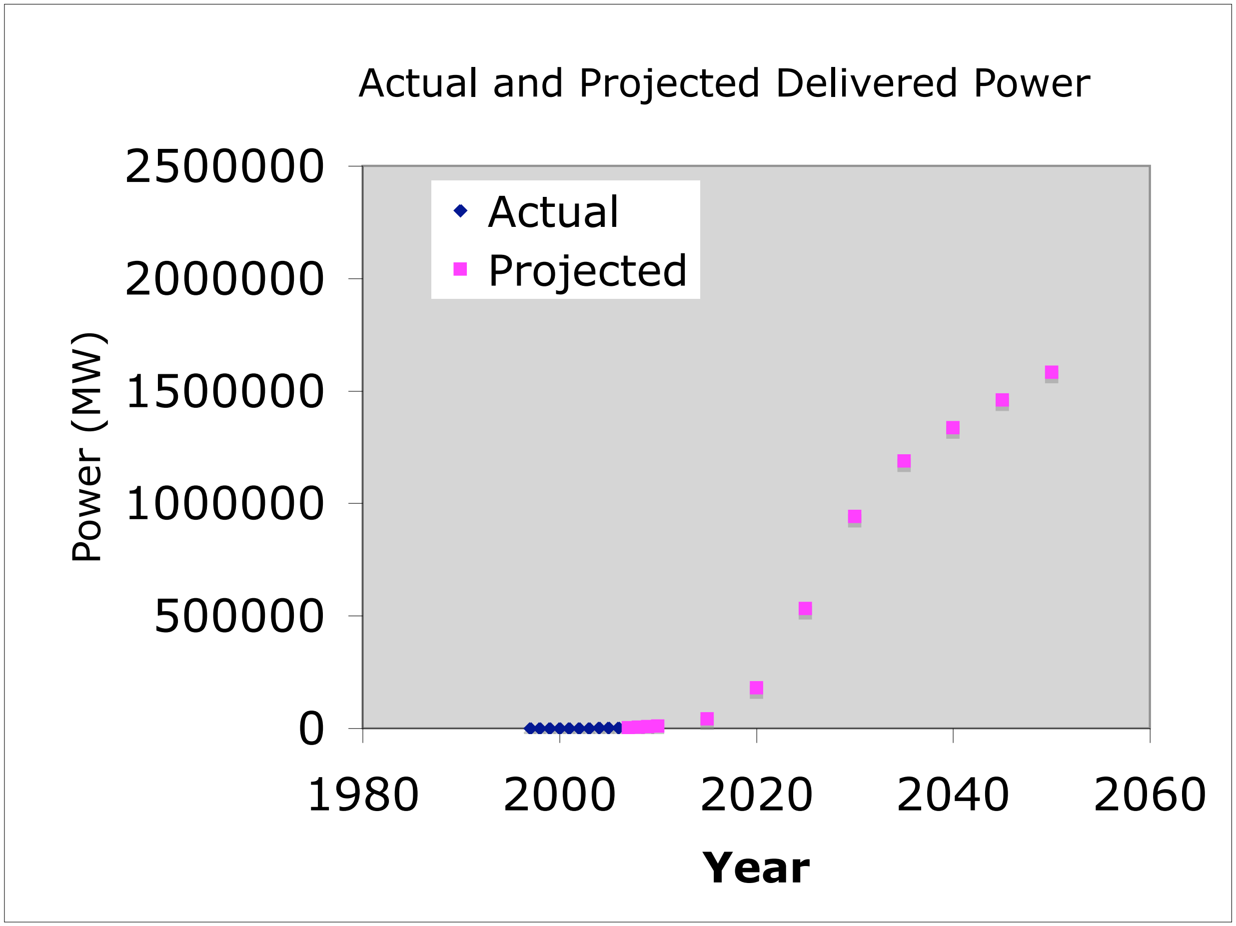
This Will Lead to Large (>1TW) Solar PV Power by 2030



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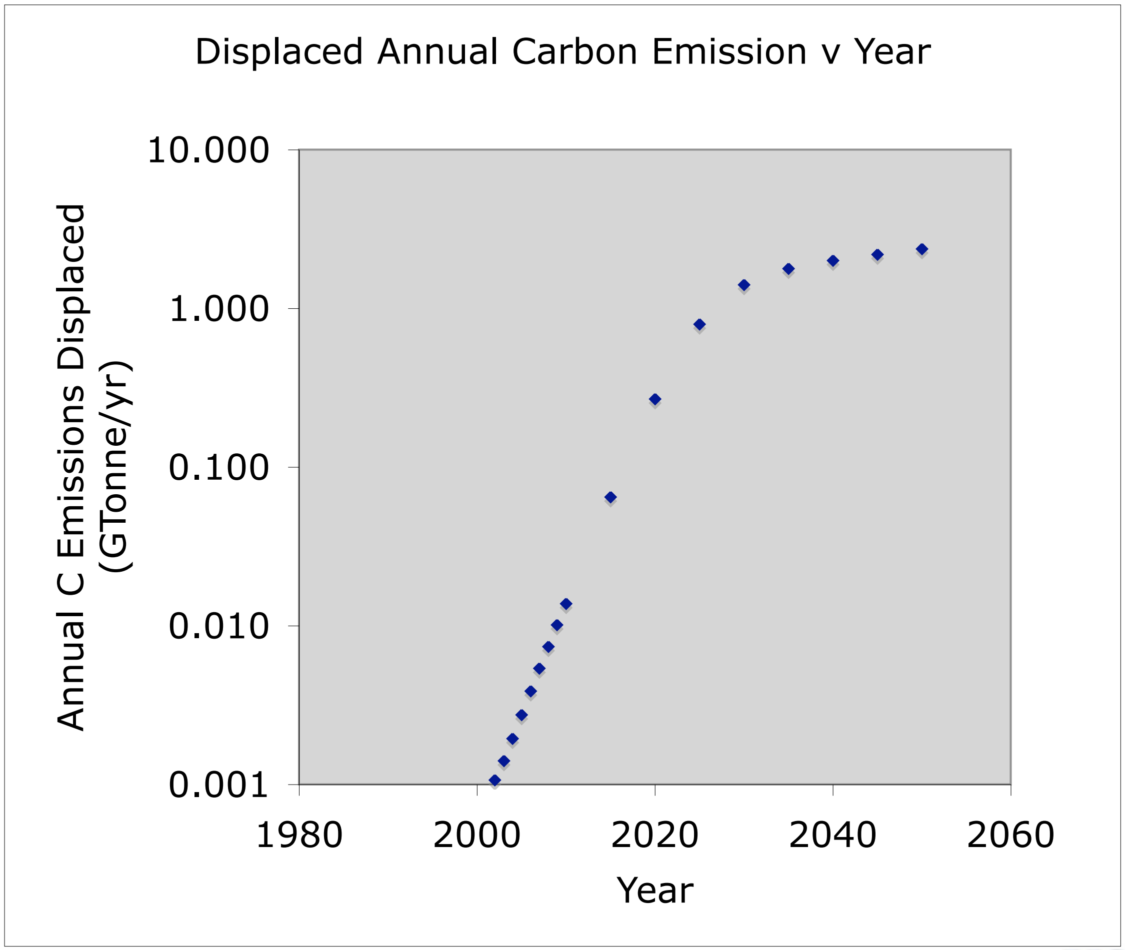
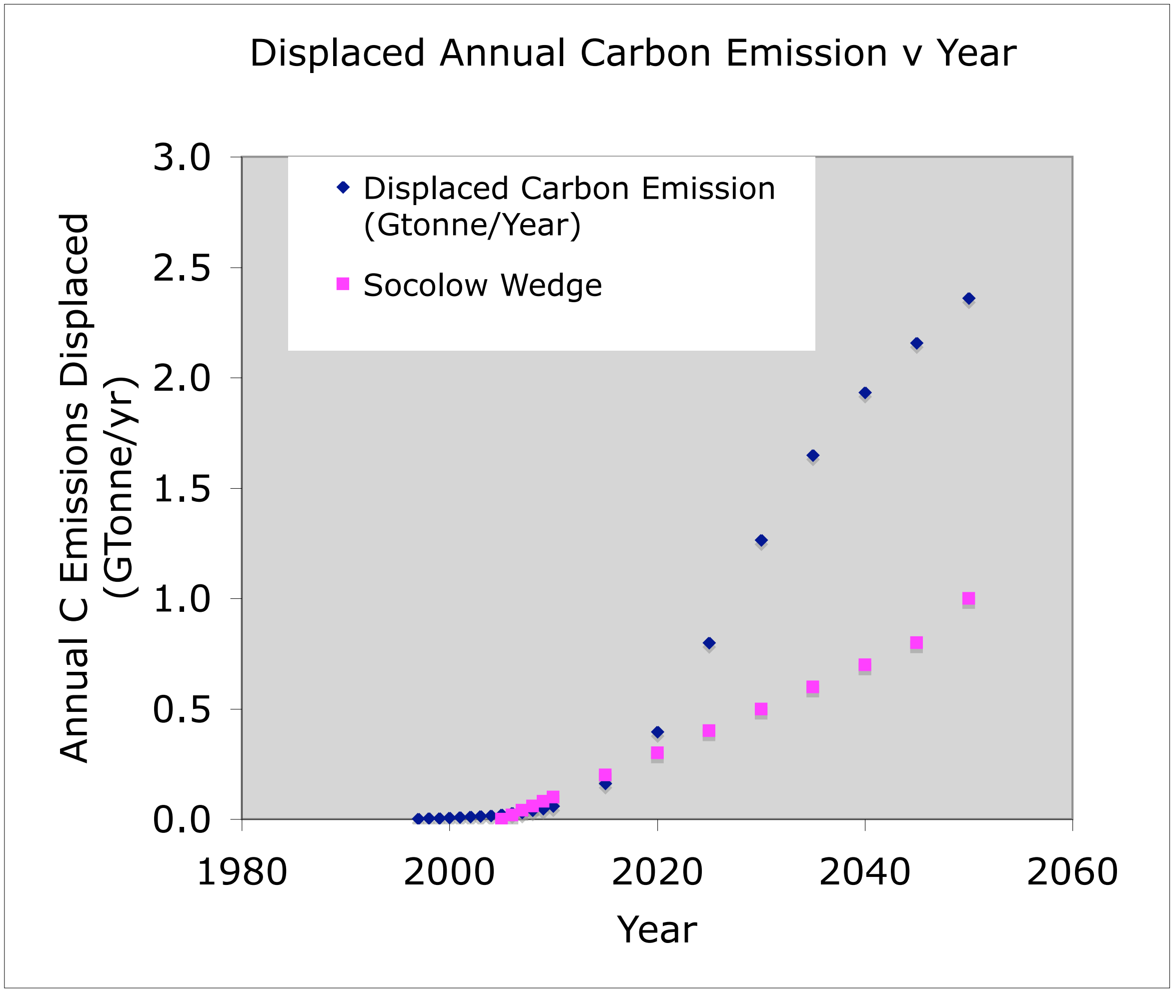
If This Renewable Power Replaces Fossil Fuels Can Estimate C-emissions Displaced

Total C-emissions Displaced: 54 Gtonnes
Savings Heavily Weighted to 2030-2050 Timeframe



Compare This With One of Socolow's Wedges
Estimate ~50 Gtonnes Total Displaced C (~2 Wedges)



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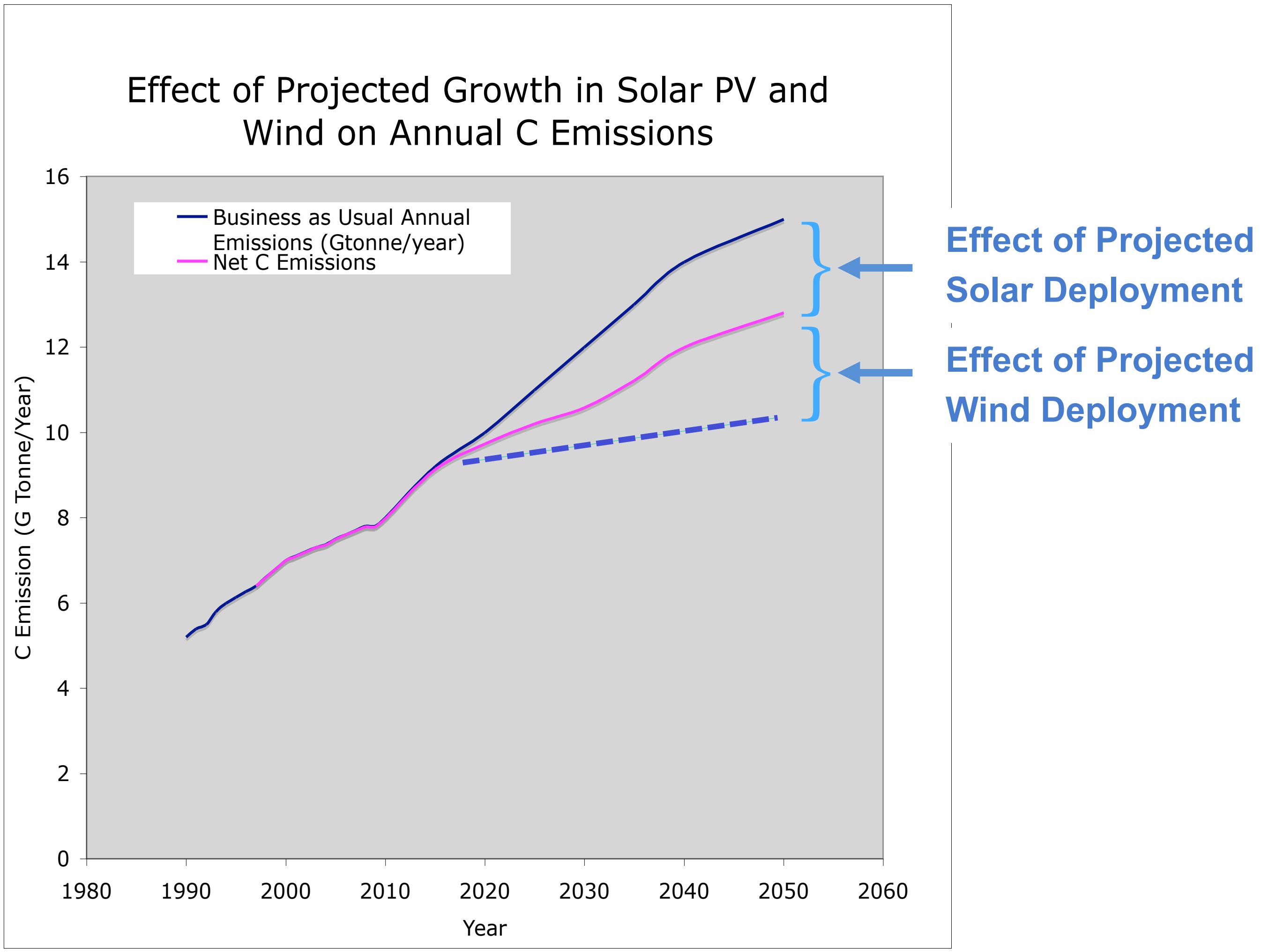
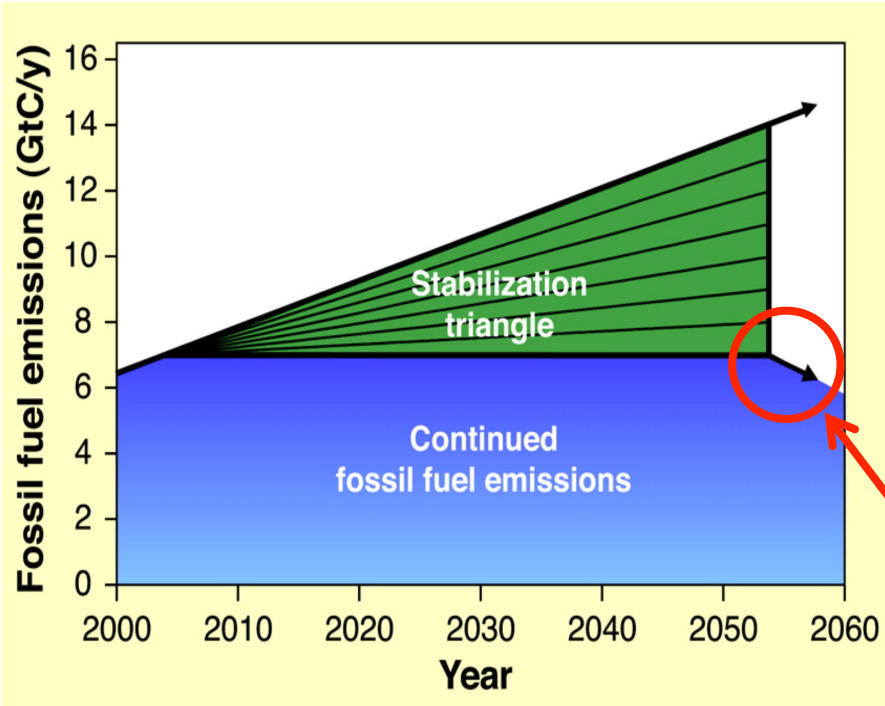
This Enormous Growth in Almost Stabilizes C Emissions



CONCLUSIONS FOR 2050 TIMEFRAME

- Historical Experience Suggests Time to 50% Market Penetration is >50 years for new primary energy sources
- Solar & Wind Currently Experiencing Rapid (~15-30%/ year) Growth Rates…Could Lead to Shortened (25-30 years) Replacement Times
- Current Market Share is Growing (e.g. for Solar PV Total World Installed Base is ~ 400 GW, growing at >10%/yr)
- Wind & Solar on track to displace ~50 Gtonnes-C cumulative by 2050
- But...we need even more C reductions
- HOW???

Near-term Technologies Can and Should be Used to Stabilize Emissions over the Next 50 Years



Improved Efficiency
Electricity from Natural Gas
Reduced Rate of Deforestation
CO_2 Sequestration
Nuclear Fission
Wind, Solar, Biomass

Pacala and Socolow, Science, 2004

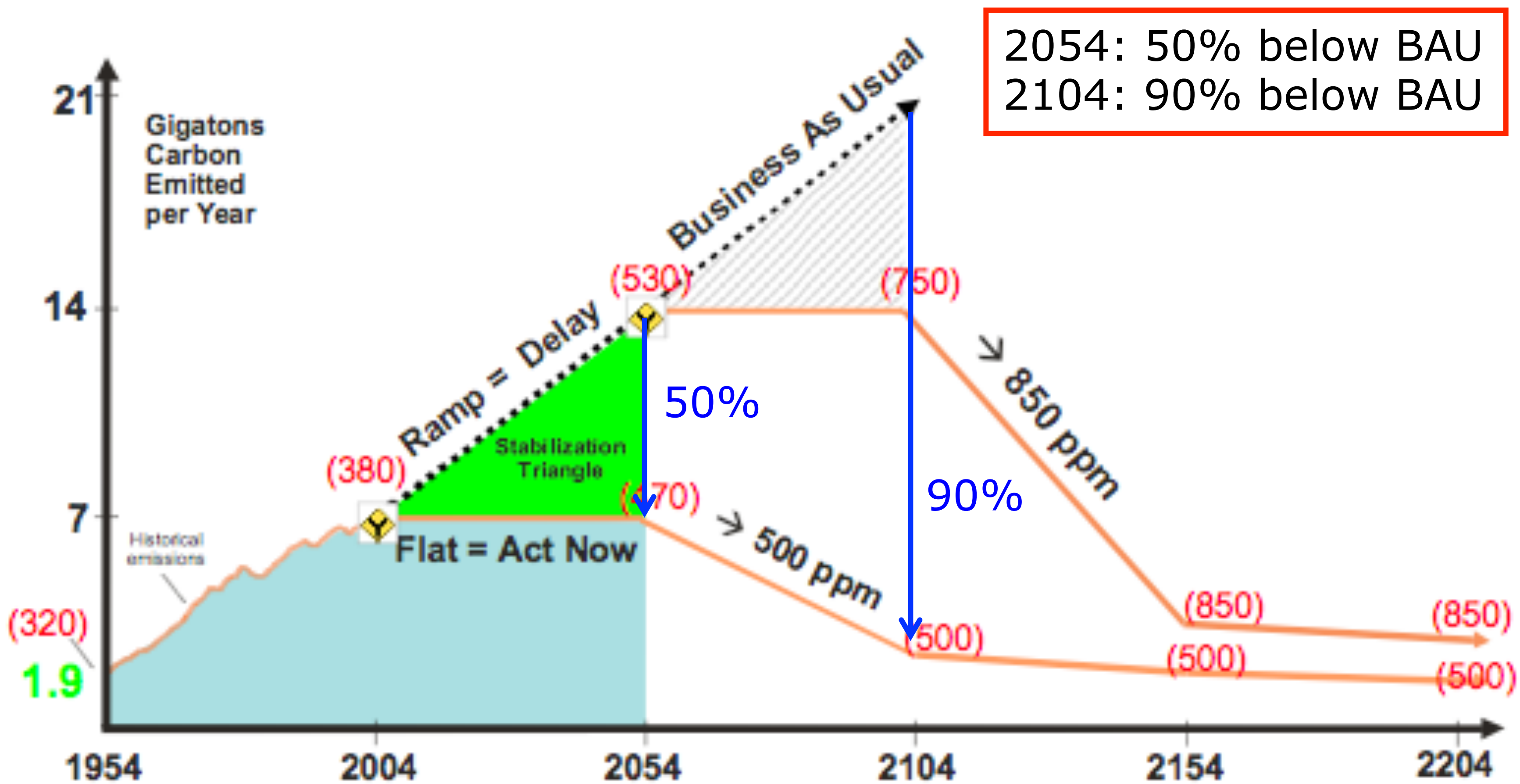
Can near-term technologies address the whole, long-term problem?

Issues: Maximum annual capacity, total resources, environmental impact, proliferation, variability in space and time, land use.

Pacala and Socolow: "We agree that fundamental research is vital to develop the revolutionary mitigation strategies needed in the second half of this century and beyond."

LONGER TERM: REQUIRE A REVOLUTION IN ENERGY PRODUCTION AND USE

Rob Socolow



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