Preventing Global Climate Change by Economically Recycling Carbon Dioxide Into Useful Products

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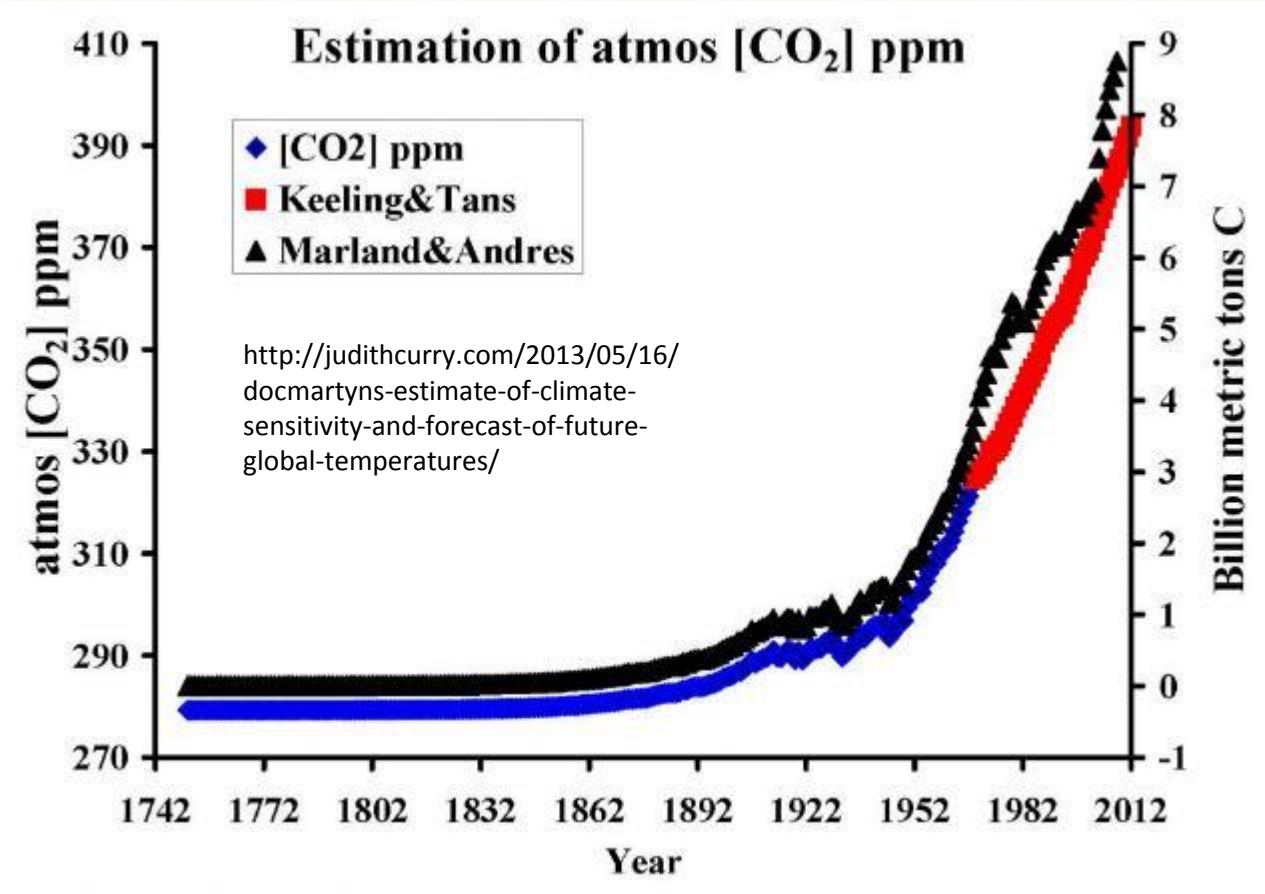
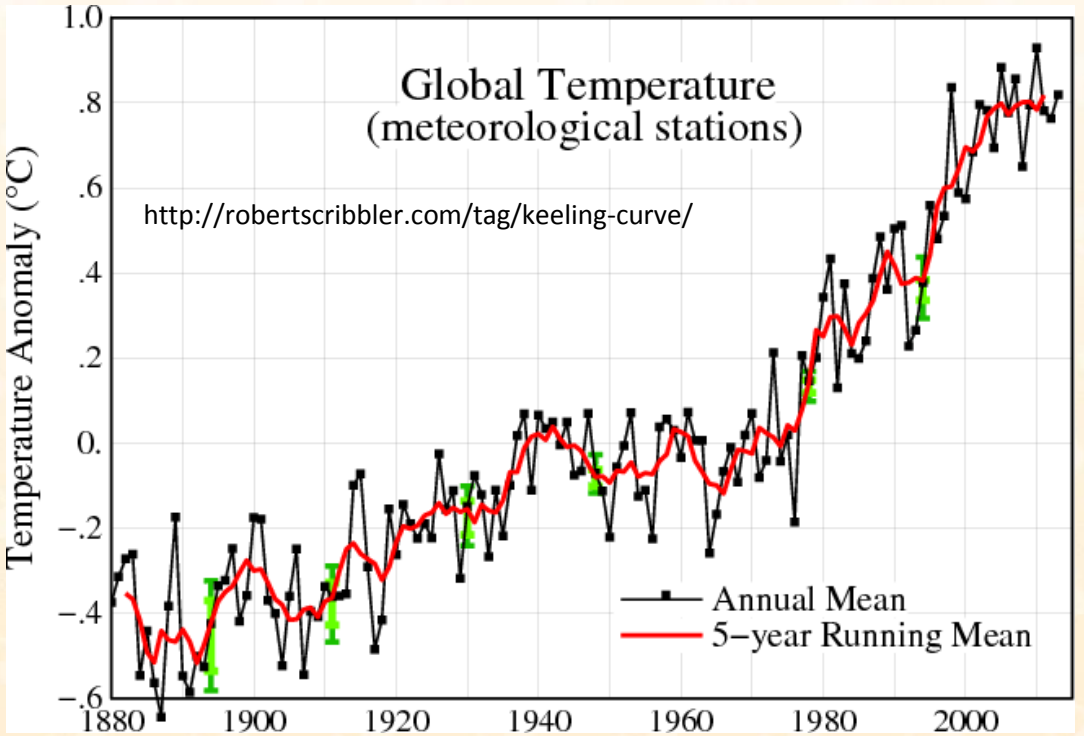
Outline

- CO_2 Concentration Is Rising (Data, Reasons, Impact)
- Intergovernmental Panel On Climate Change (IPCC) Has Considered A Number Of Scenarios To Reduce Global Warming
- How Will Humans Be Affected By High CO_2 Concentrations? (Effects Other Than Global Warming)
- Why Are The Current Plans Insufficient?
- A Plan To Limit CO_2 Buildup In The Atmosphere
  - CO_2 Capture From The Atmosphere
  - CO_2 Conversion
    - Converting CO_2 To Useful Products
    - CO_2 Based Syngas To Fuels & Chemicals
- Government Support Needed
- Summary

Global CO_2 is Rising





Why is it Rising?

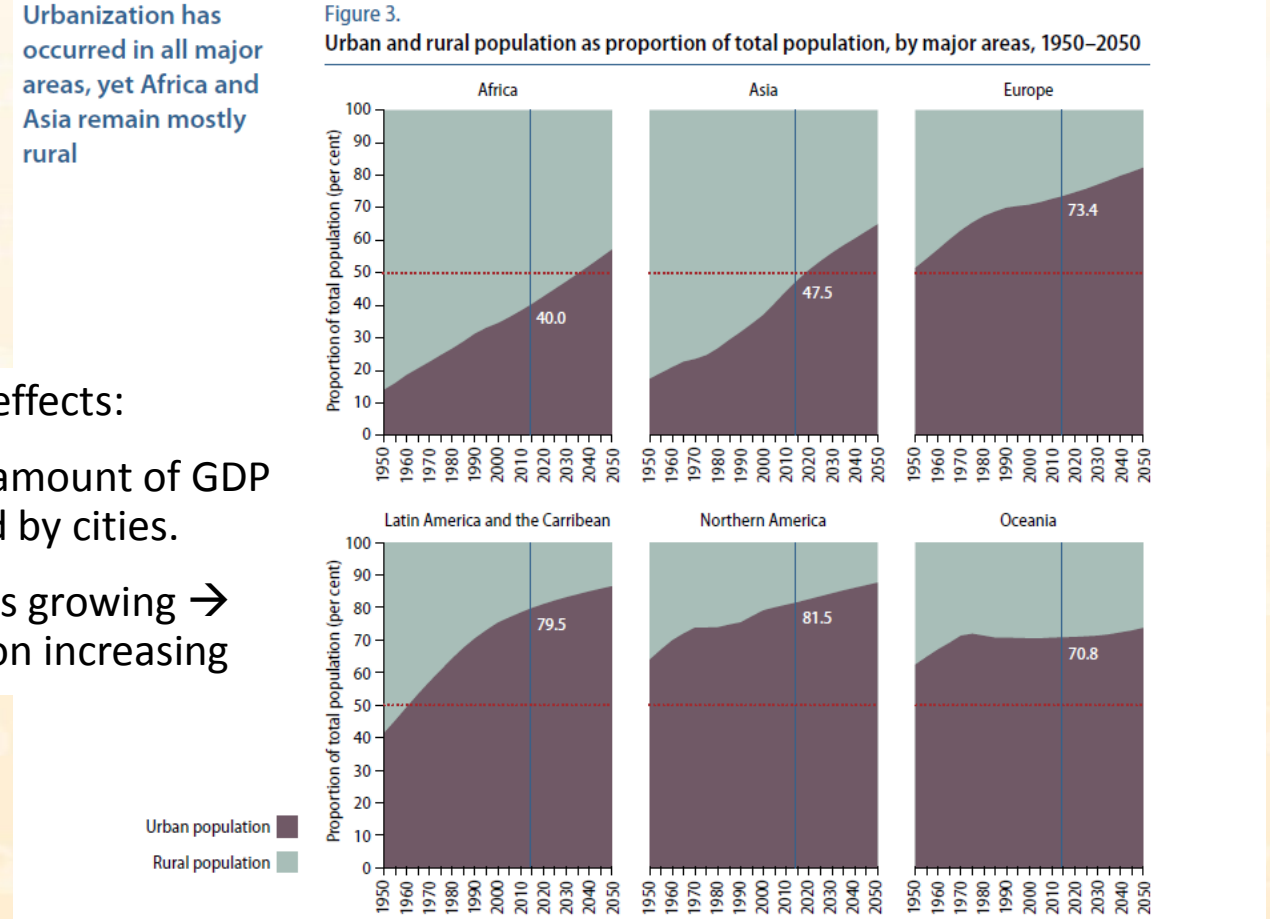
- Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including
  - population growth
  - economic growth
  - changing energy prices
  - new technologies
  - changing behavior
  - seasonal temperatures

http://www3.epa.gov/climatechange/ghgemissions/gases/co2.html

Urbanization has occurred in all major areas, yet Africa and Asia remain mostly rural

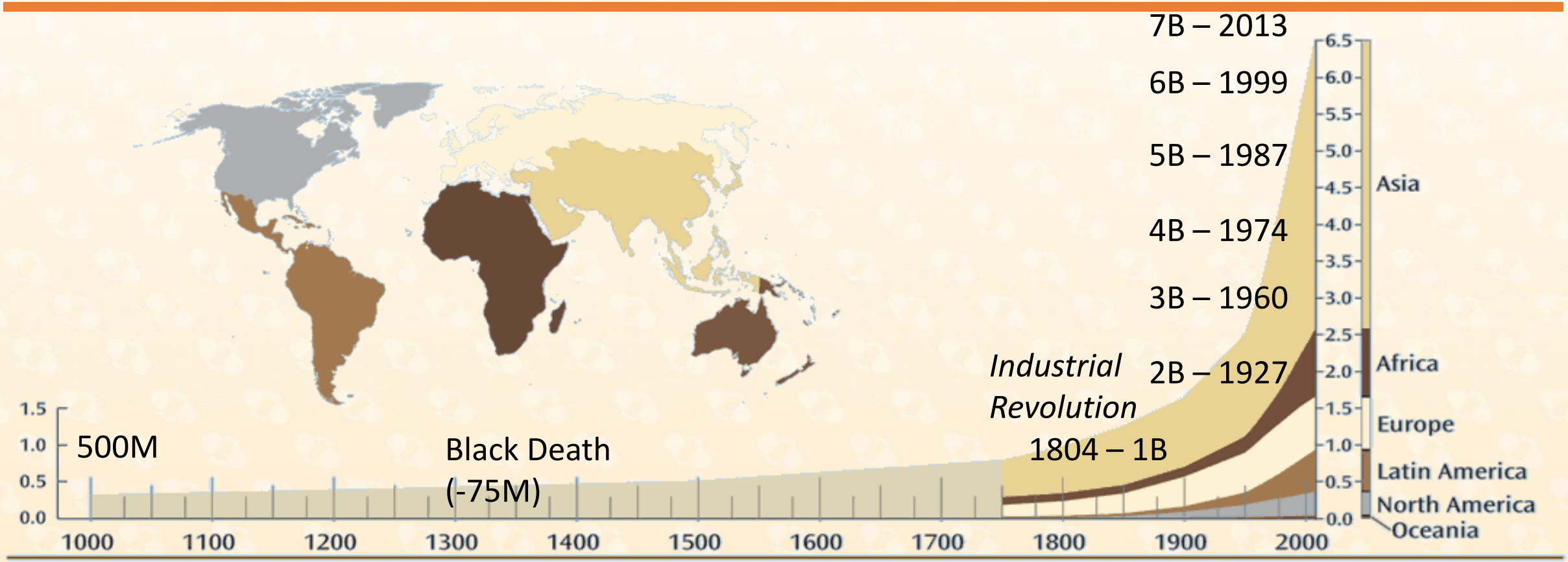
Urbanization effects:

- Increasing amount of GDP contributed by cities.
- Middle class growing → consumption increasing



Source: UN, World Urbanization Prospectus 2014

Global population growth



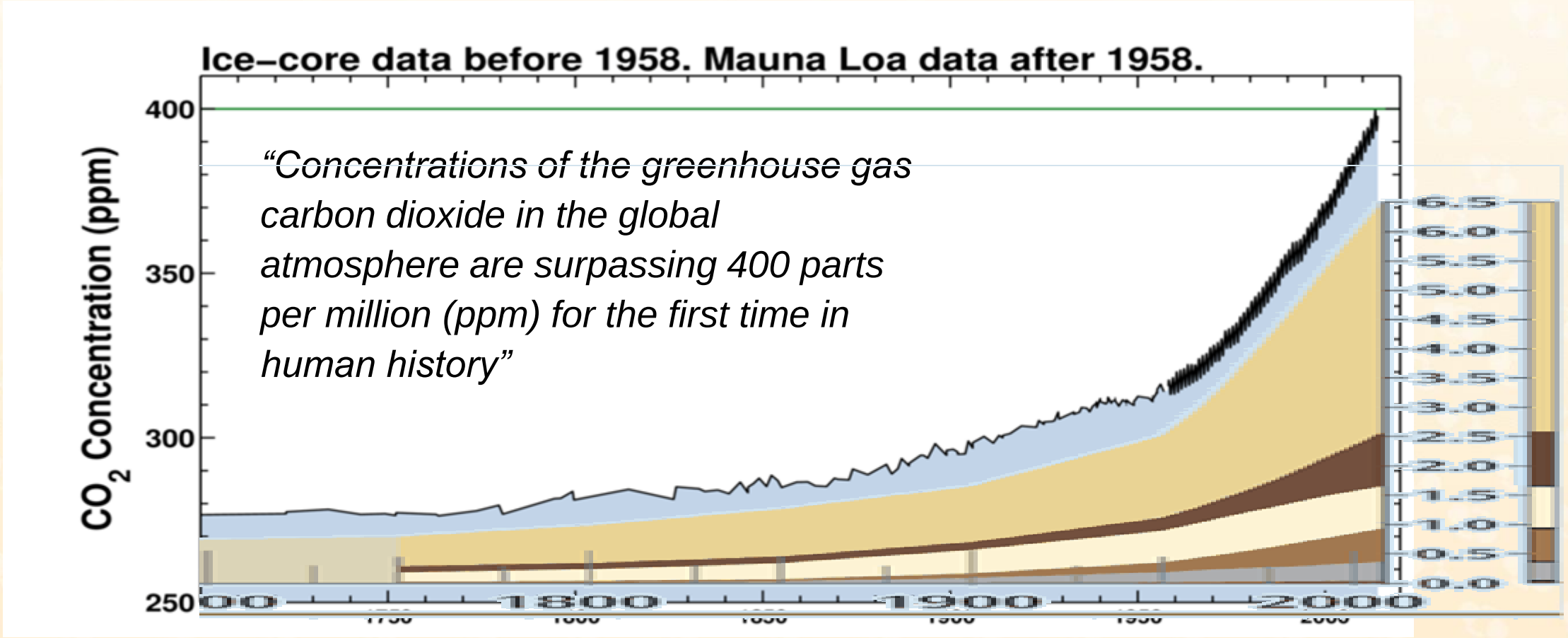
Sources: 1 - The World at Six Billion; Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2004 Revision and World Urbanization Prospects: The 2003 Revision, <http://esa.un.org/unpp> 2 - United Nations, 1973. "The Determinants and Consequences of Population Trends, Vol.1" (United Nations, New York). United Nations, (forthcoming). "World Population Prospects: The 1998 Revision" (United Nations, New York). <http://www.geohive.com/global/>

Exponential Change: Impact of Population Growth, Economic Growth

- between 1950 and 2000 …
  - population doubled
  - economy grew seven-fold
- increasing agriculture
  - food consumption tripled
  - water use tripled
- and energy use
  - fossil fuel use increased four-fold

Source: J Foley, Institute on the Environment, University of MN, 2011

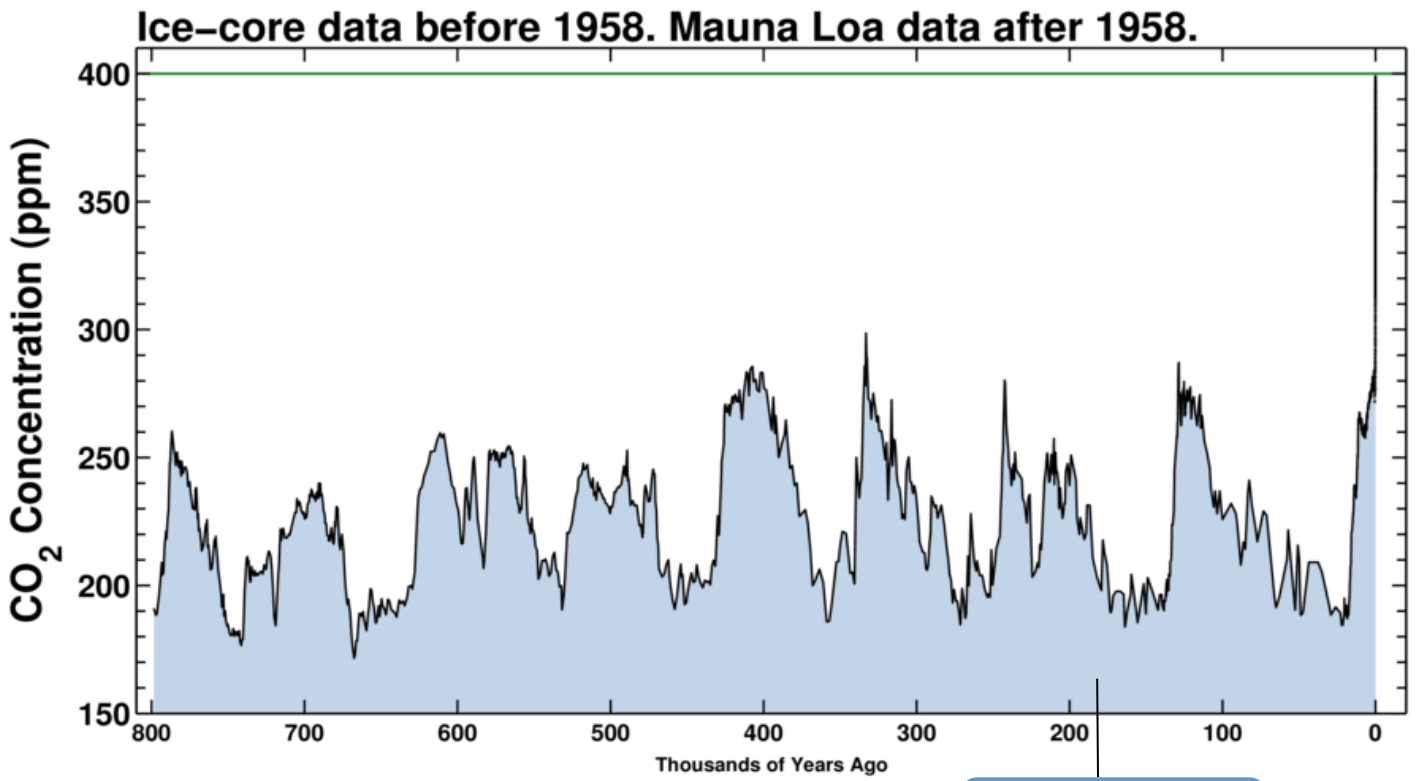
Population Growth and CO_2 concentration



"Concentrations of the greenhouse gas carbon dioxide in the global atmosphere are surpassing 400 parts per million (ppm) for the first time in human history"

http://keelingcurve.ucsd.edu/

Unprecedented CO_2 (GHG) Concentration in Atmosphere in Human History



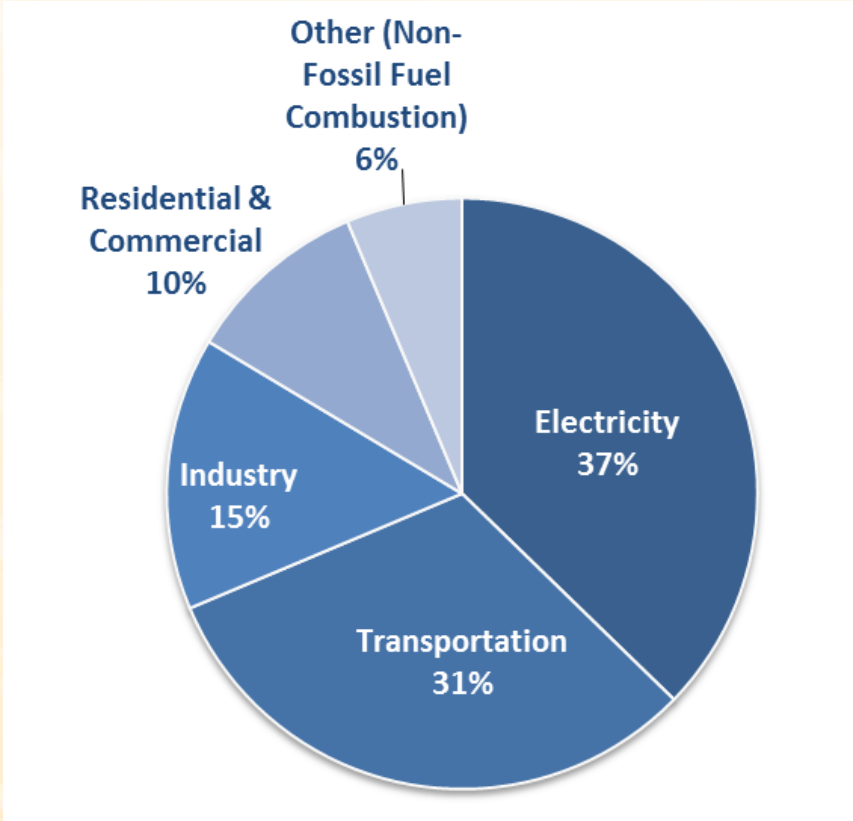
- Where is it coming from and what are we going to do about it?

http://keelingcurve.ucsd.edu/

Main Sources of CO_2 emissions in the U.S.

- The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation, although certain industrial processes and land-use changes also emit CO_2.

U.S. Carbon Dioxide Emissions, By Source



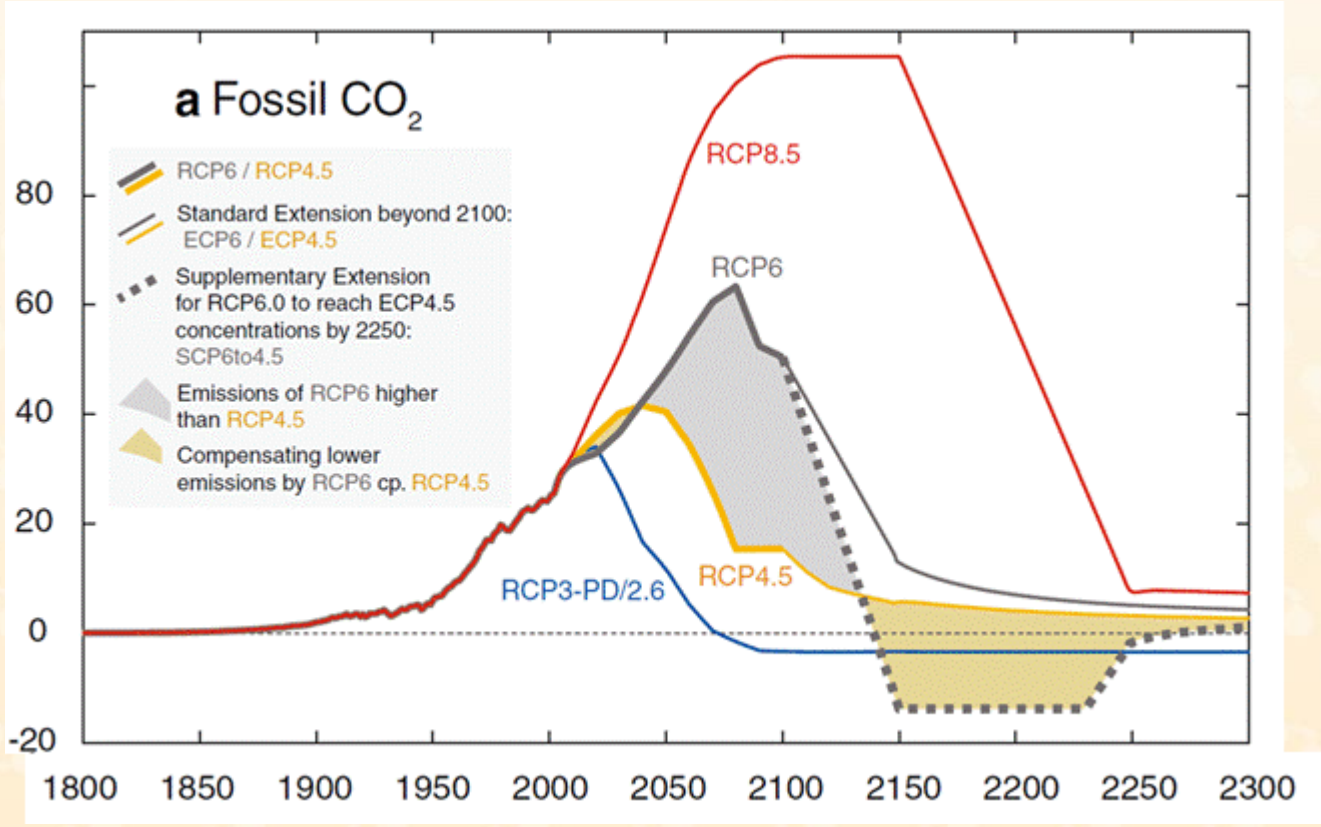
http://www3.epa.gov/climatechange/ghgemissions/gases/co2.html

Summary

- More people, making more CO_2 because the average rate of consumption is increasing, becoming more like the West
- All this is building up to a level that's going to cause us problems

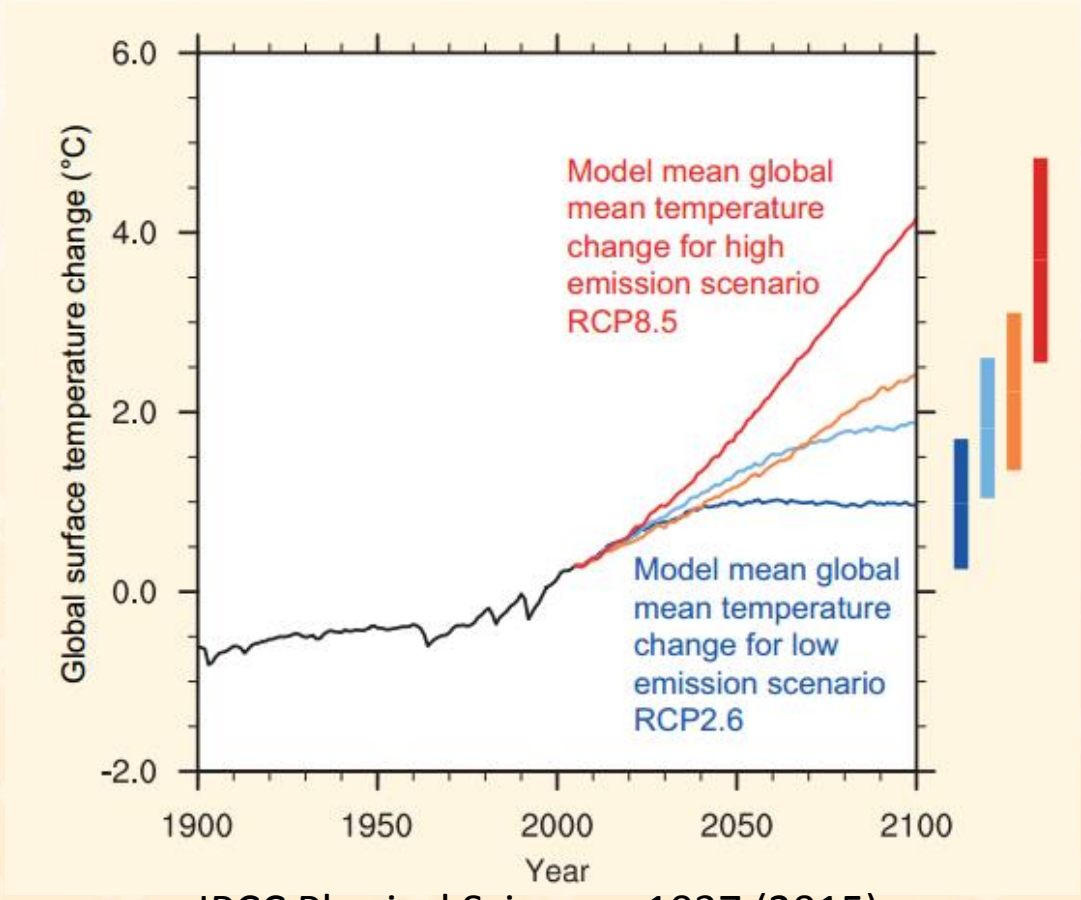
Intergovernmental Panel On Climate Change (IPCC) Has Considered A Number Of Scenarios To Reduce Global Warming

Fossil CO_2 Emissions In Each Scenario

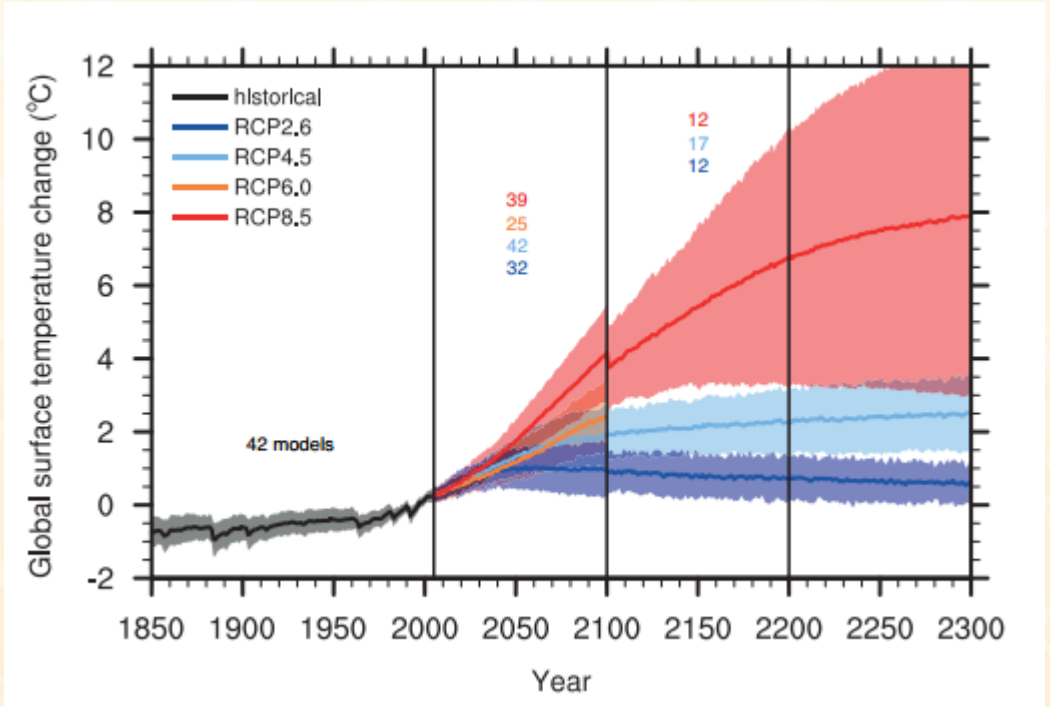


Meinshausen et al. Climatic Change (2011) 109:213–241

If We follow RCP2.6 or RCP4.5 Can Hold Temp Rise to 2°C



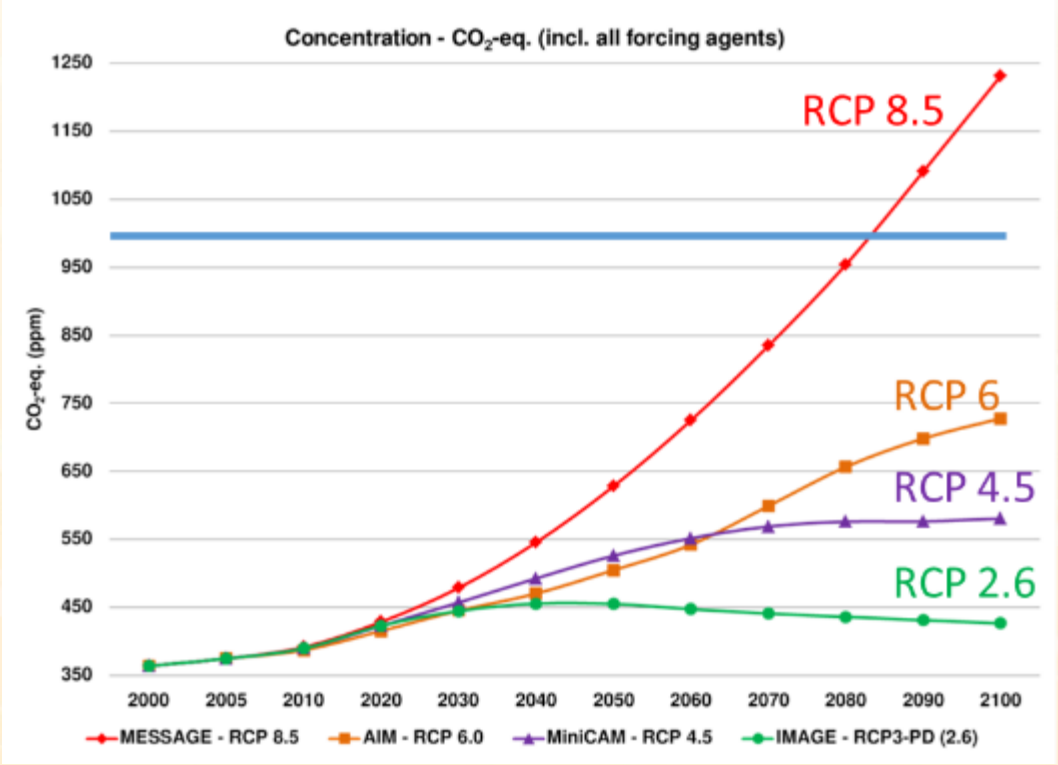
IPCC Physical Science p1037 (2015)



IPCC Physical Science p1054 (2015)

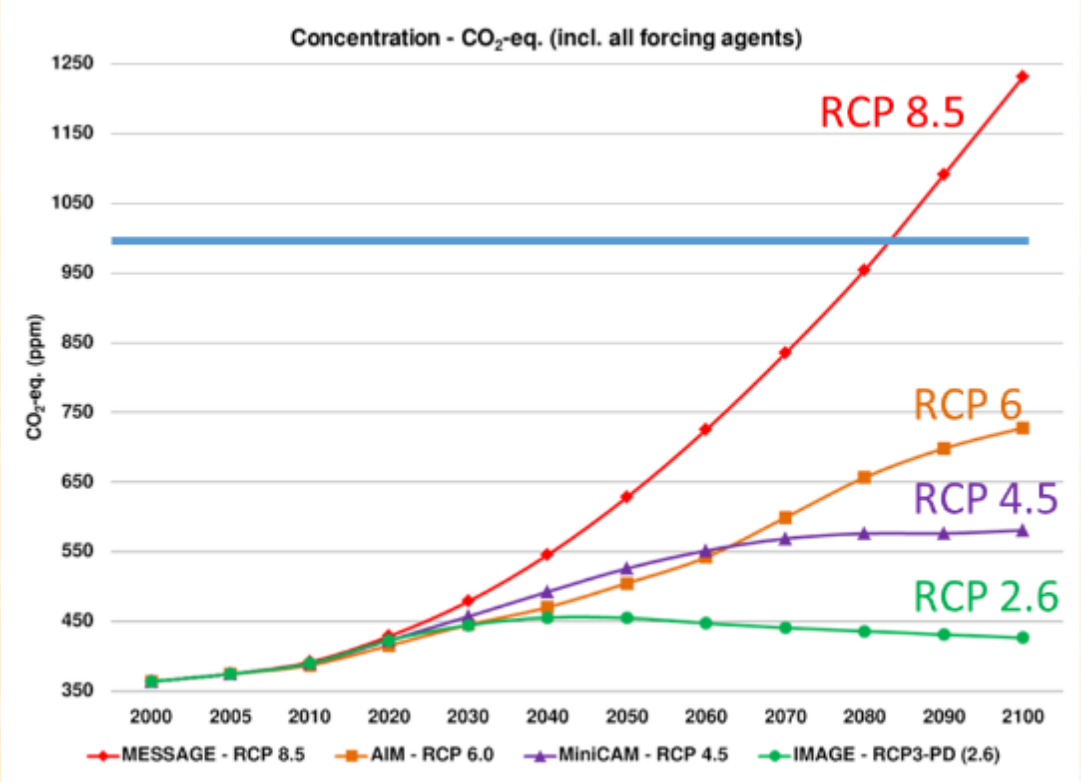
More Detail Of Assumptions

- RCP 8.5
  - 12 B global population by 2100
  - Poor Stay Poor
  - 1.5X increase in efficiency of energy use
  - Renewables/CCS 30% of world energy use
- RCP 6
  - 9 B global population by 2100
  - Poor Stay Poor
  - 2X increase in efficiency of energy use
  - Renewables 50% of world energy use
  - 50% of fossil fuel sources use CCS or recycling
  - CO_2 removal/recycling from air starting in 2100

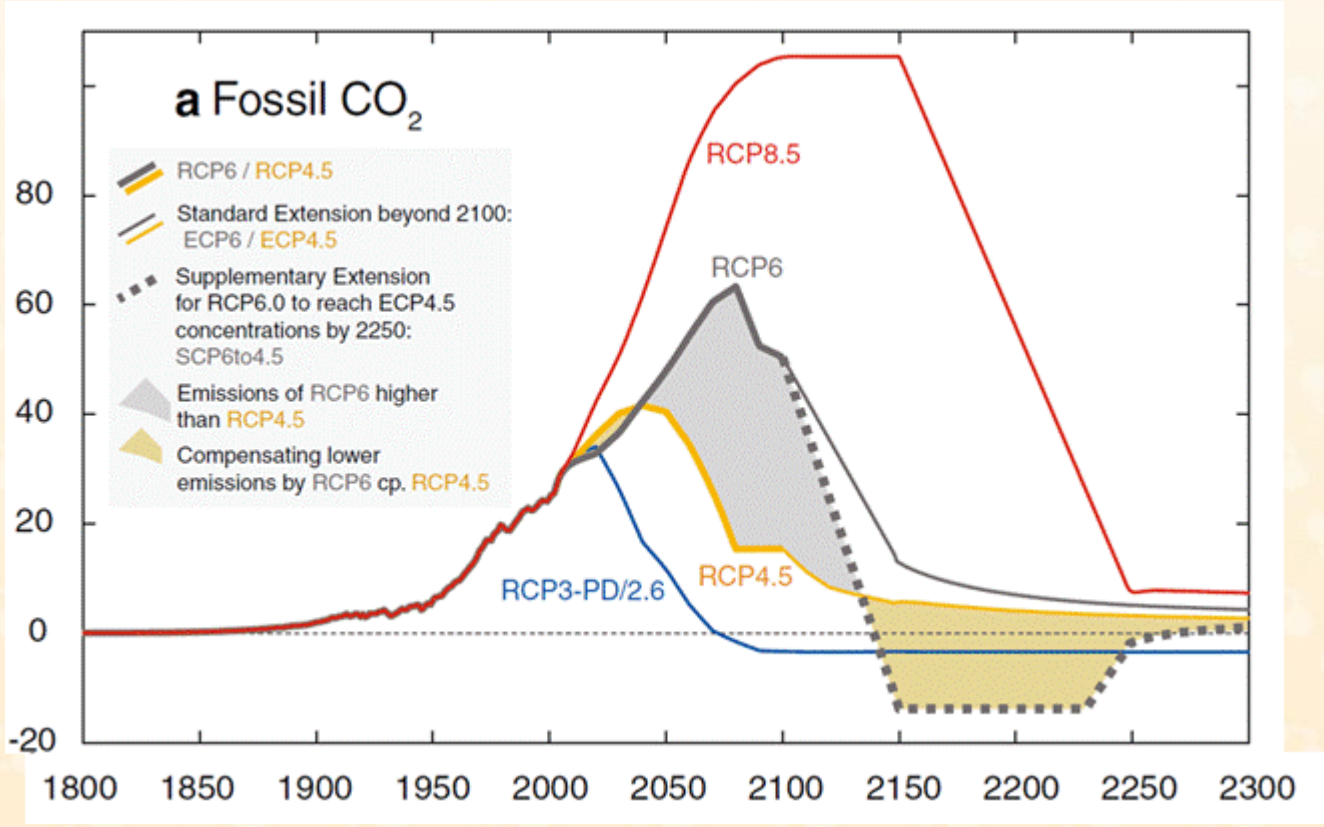


More Detail Of 2100 Assumptions

- RCP 4.5
  - 8 B global population by 2100
  - Poor Stay Poor
  - 3X increase in efficiency of energy use
  - Renewables 75% of world energy use
  - 75% of fossil fuel sources use CCS or recycling
  - CO_2 removal/recycling from air starting in 2080
- RCP 2.6
  - 8 B global population by 2100
  - West eliminates fossil fuels by 2030
  - Poor Stay Poor
  - 3.5X increase in efficiency of energy use
  - Renewables 90% of world energy use
  - 80% of fossil fuel sources use CCS or recycling
  - CO_2 removal/recycling from air starting in 2050



Need CO_2 Removal From The Air To Get To Negative CO_2 Emissions!



Meinshausen et al. Climatic Change (2011) 109:213–241

Where Are Current Plans?

- 11.5 B Global Population By 2100
- Poor in china → middle class
- Fuel Economy Standards Increase Energy Efficiency Of Cars
- CCS on power plants
- Renewables Increase

- RCP 8.5
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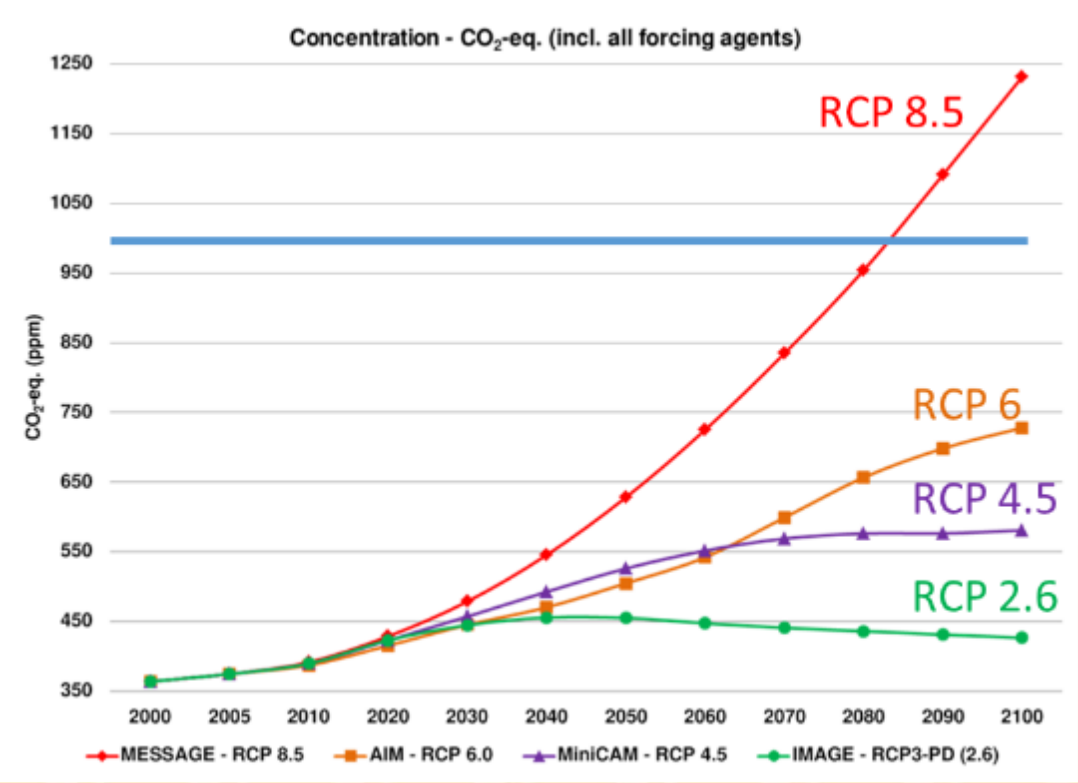
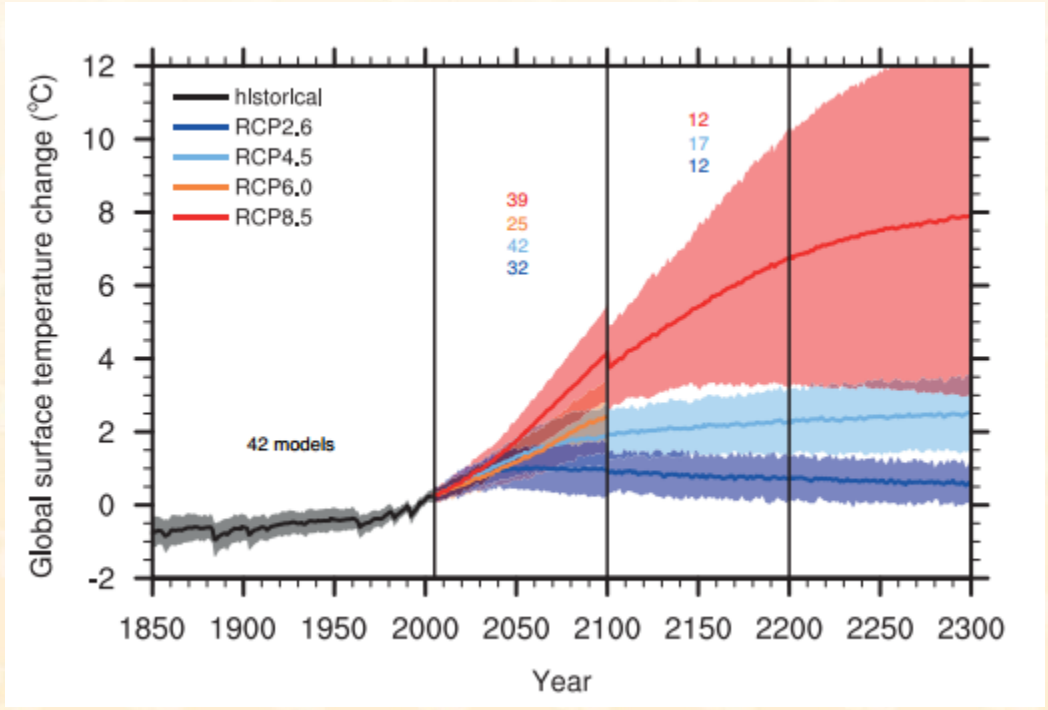
Likely Effects

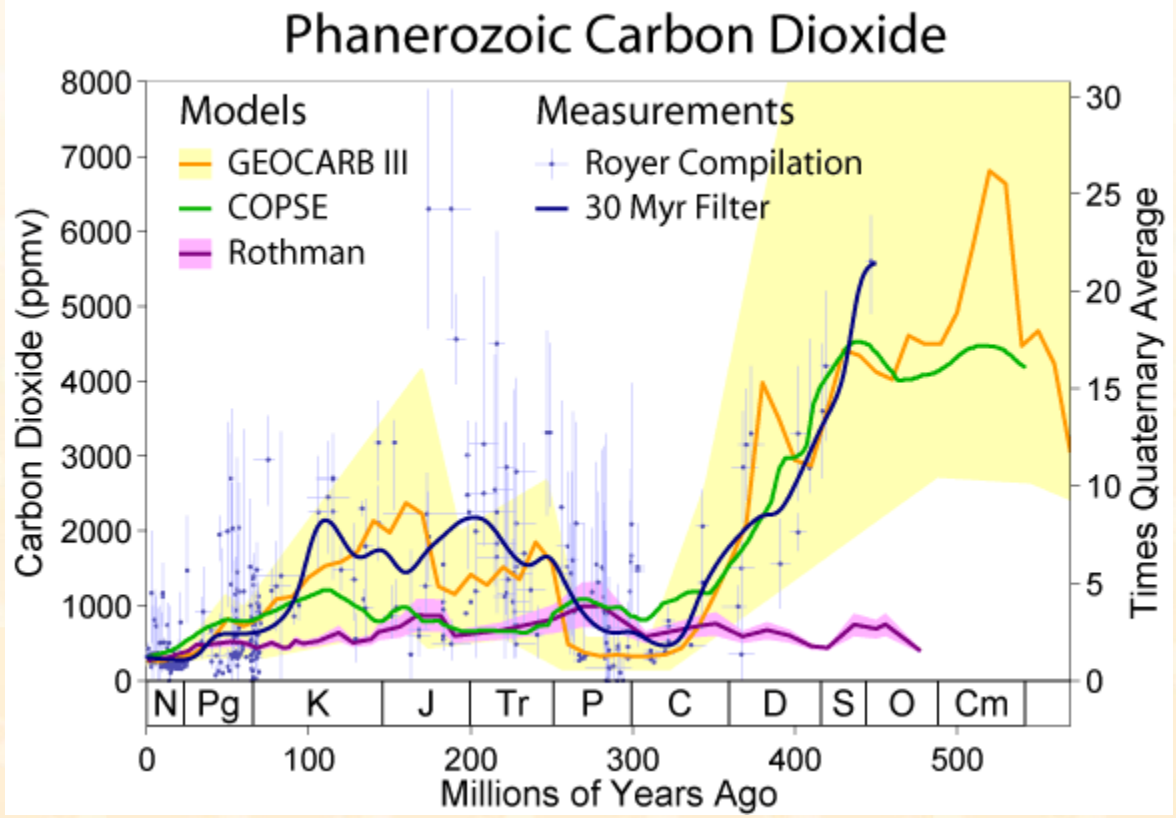




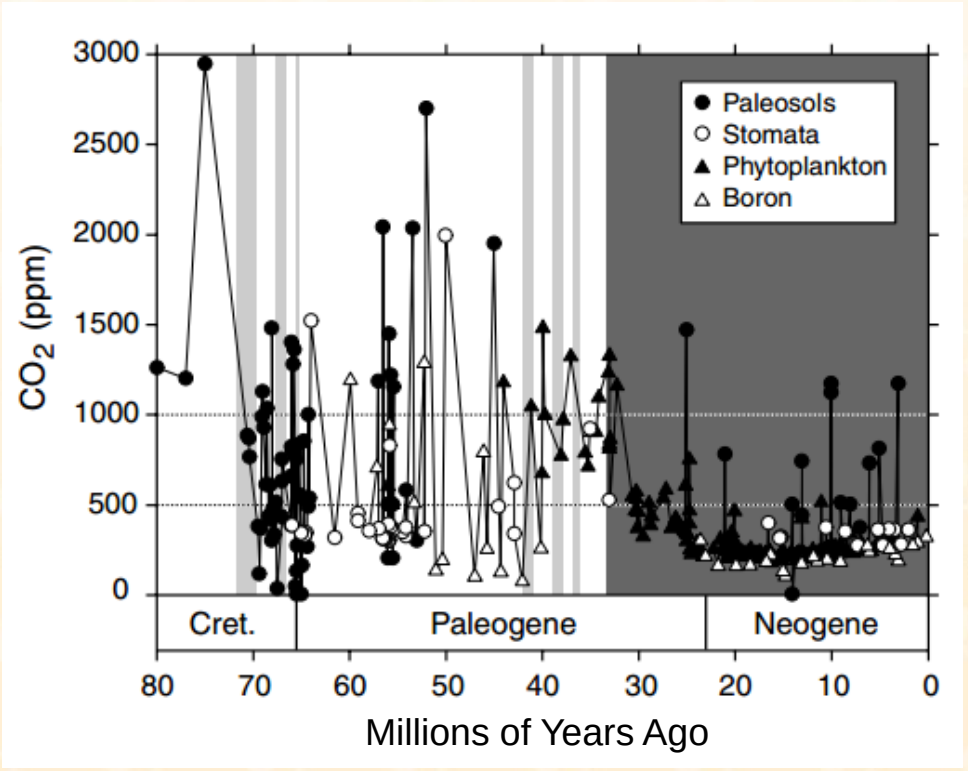
How Will Humans Be Affected By High CO_2 Concentrations?

Effects Other Than Global Warming

Humans Evolved When Global CO_2 Concentrations Were Low

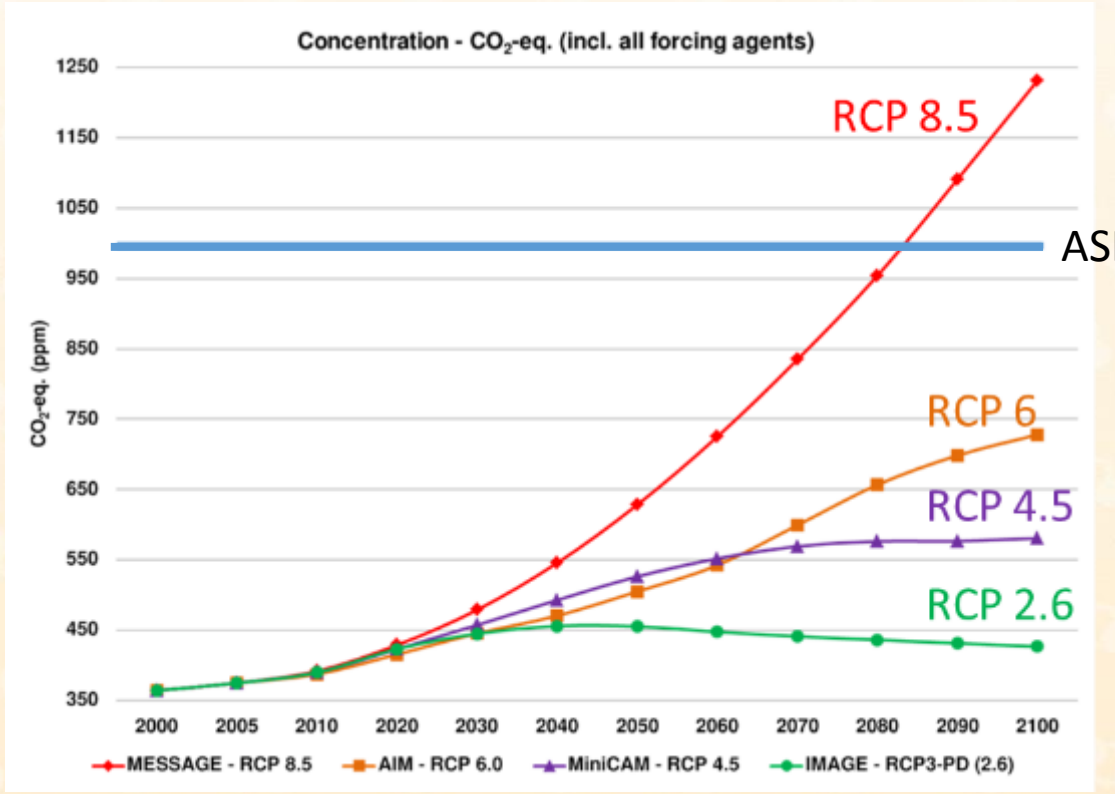


Wikipedia



Dana L. Royer, Geochimica et Cosmochimica Acta 70 (2006) 5665–5675

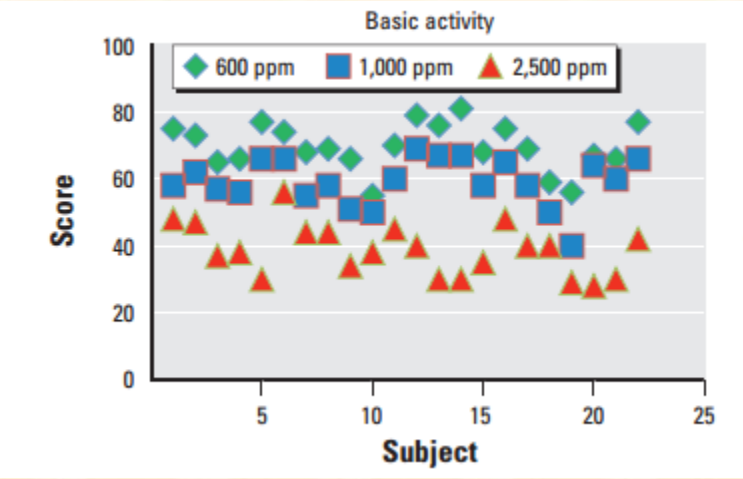
ASHRAE Limit 1000 ppm CO2 in Offices

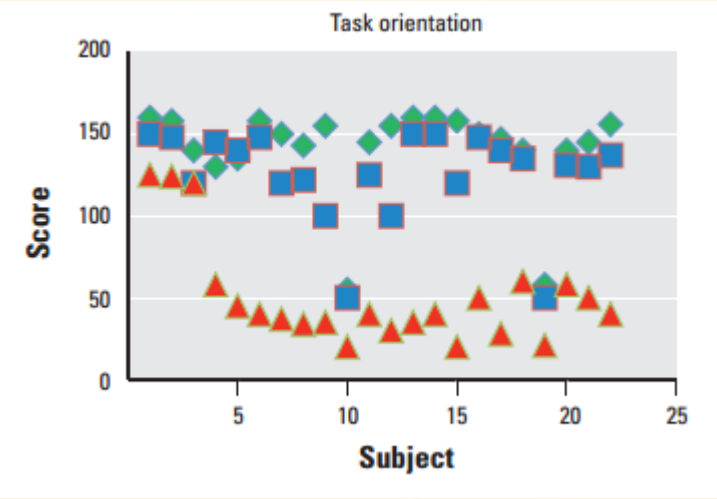


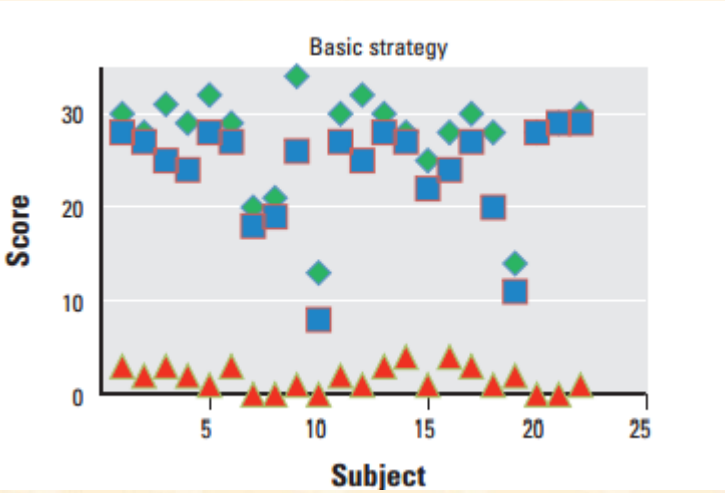
ASHRAE Limit

https://commons.wikimedia.org/wiki/File:All_forcing_agents_CO2_equivalent_concentration.png

Data On Effects Of CO_2 On Human Performance

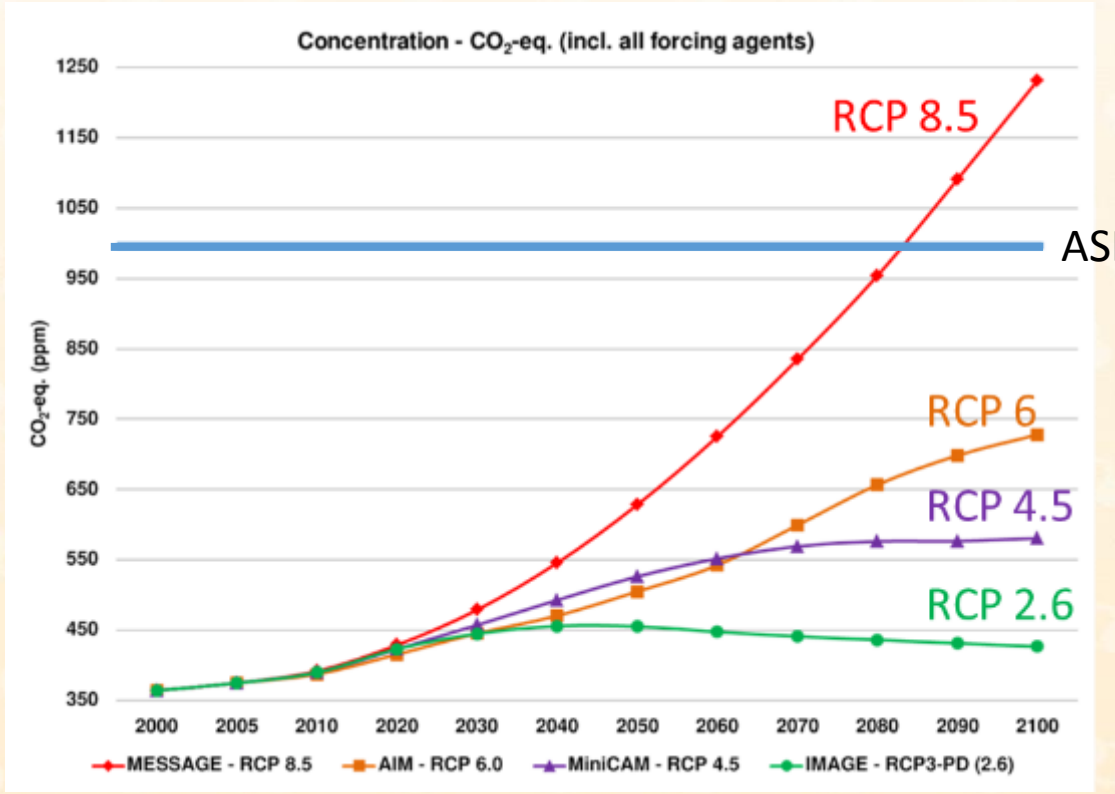






Satish, et al, Environmental Health Perspectives • volume 120 | number 12 | December 2012

Need To Avoid CO_2 Levels Getting So High That Human Health Is Affected



ASHRE Limit

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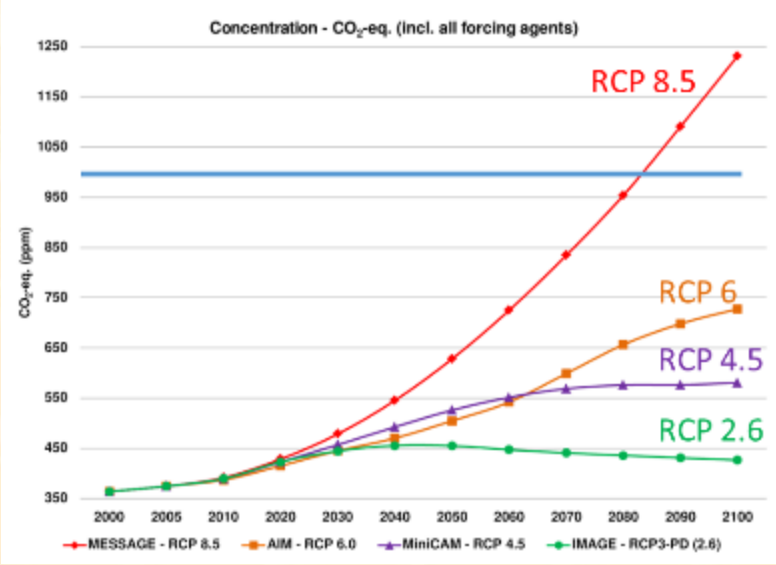
RCP 8.5 Will Result In Human Health Effects

- Fuel Economy Standards Increase Energy Efficiency Of Cars
- CCS on power plants
- Renewables Increase



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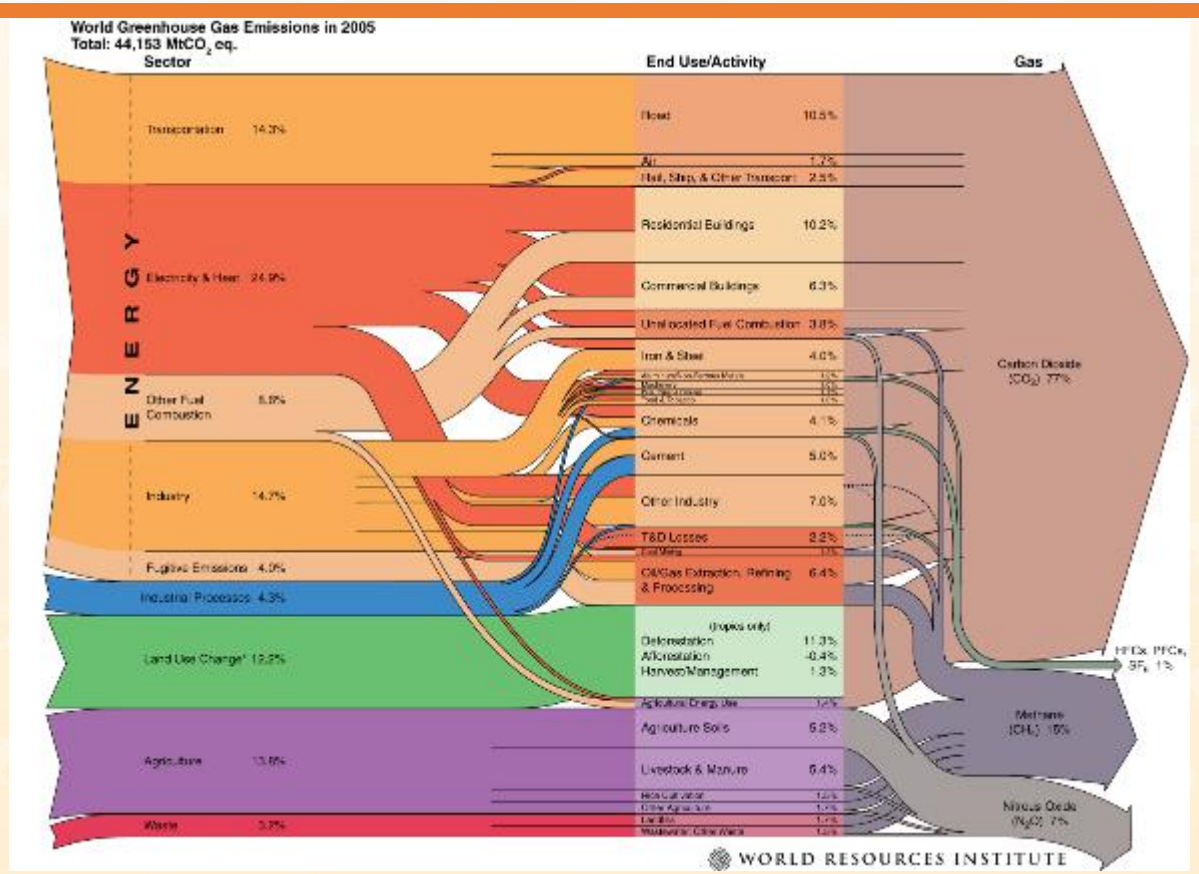
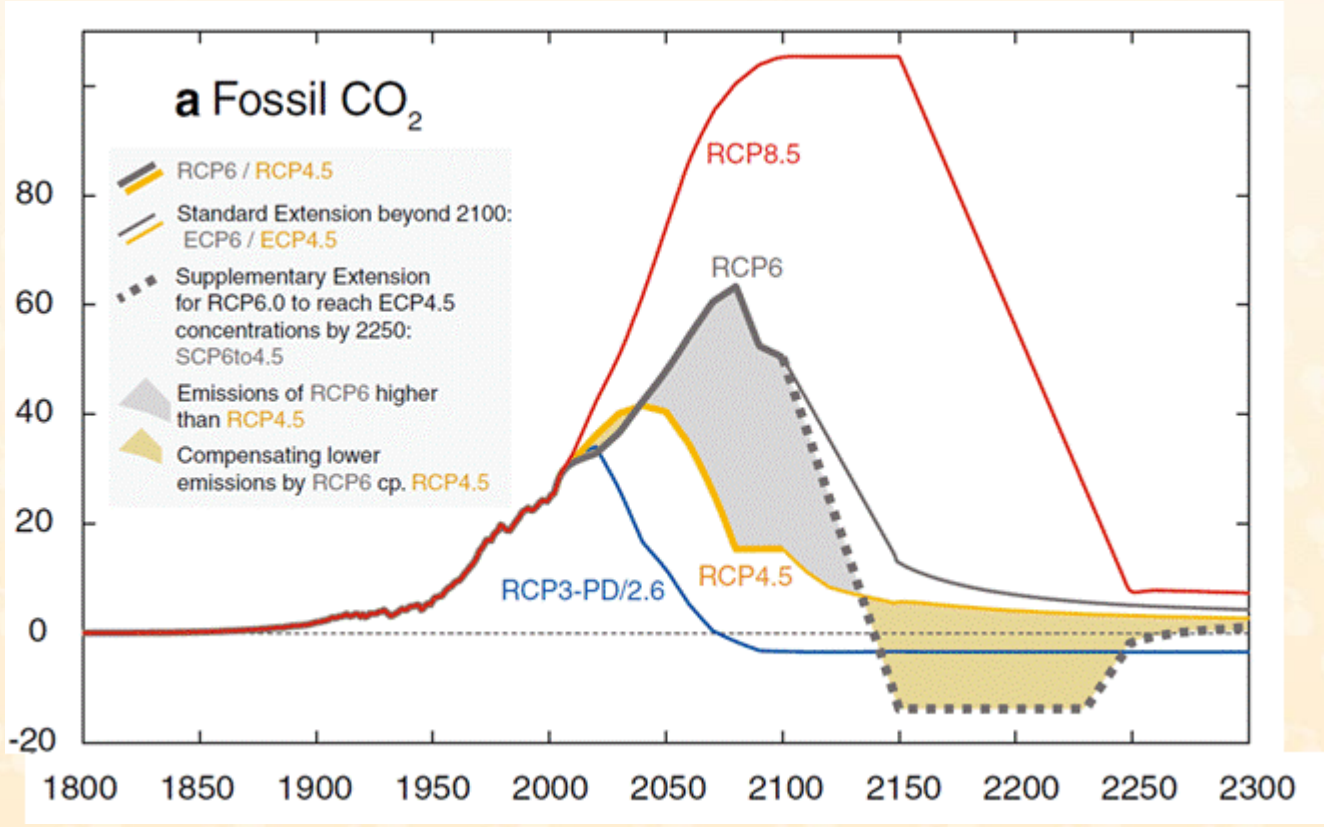
Why Are The Current Plans Insufficient?

Greenhouse Gases Come From Many Sources



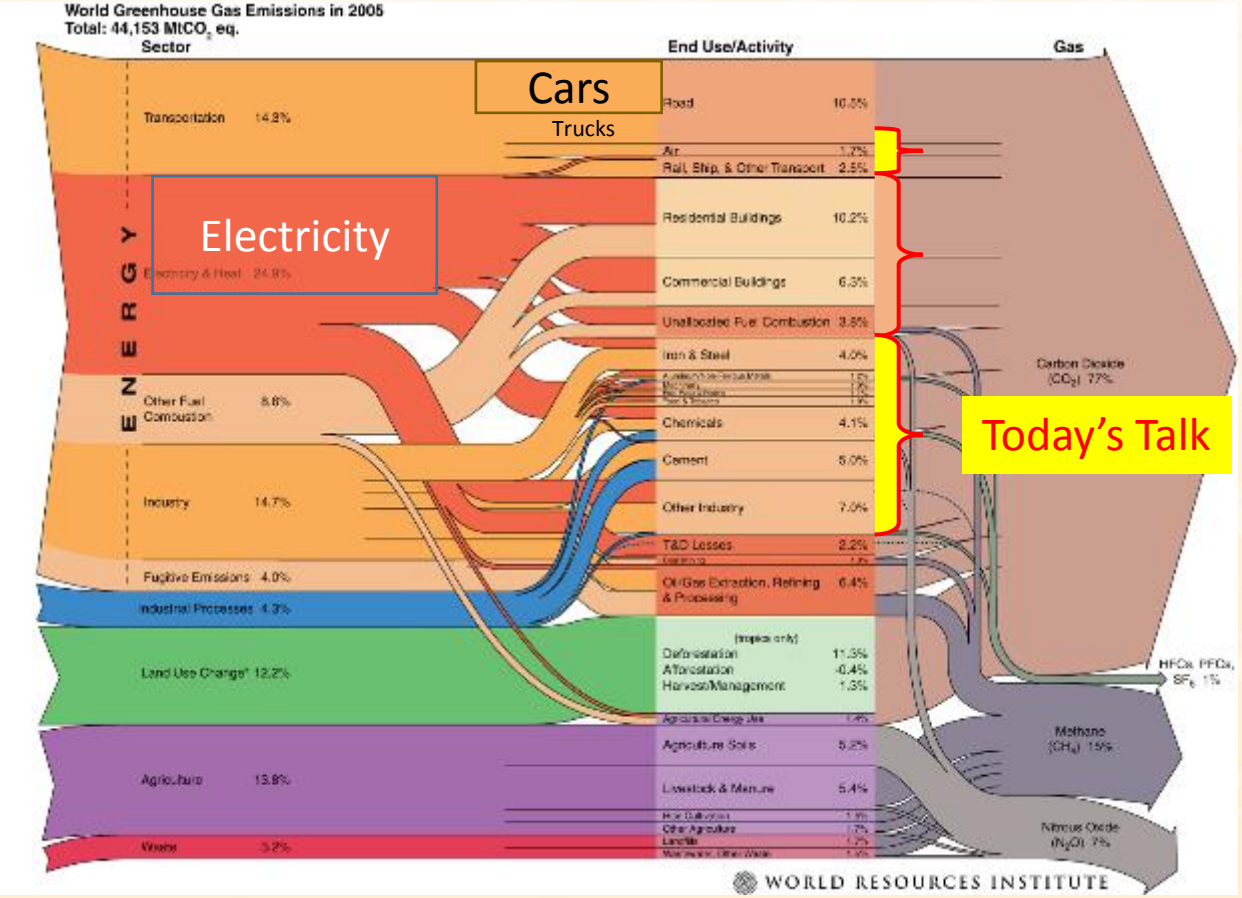
http://www.wri.org/publication/world-greenhouse-gas-emissions-2005

Net CO_2 Emissions Must Be Negative



Meinshausen et al. Climatic Change (2011) 109:213–241

Cars & Electricity Only 20% of Total Emissions

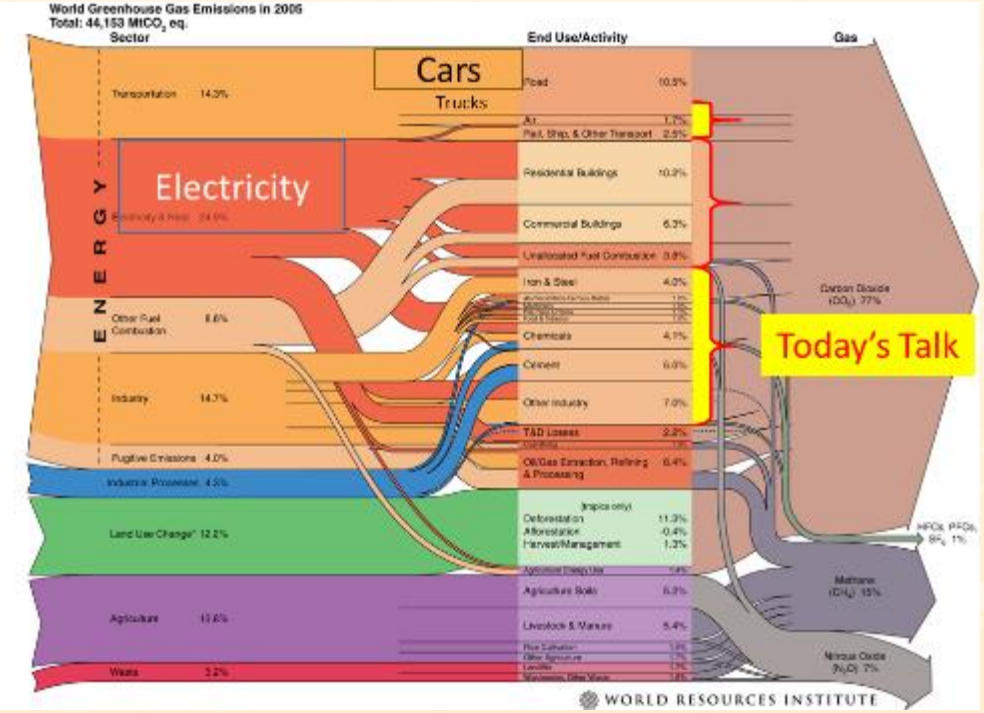


http://www.wri.org/publication/world-greenhouse-gas-emissions-2005

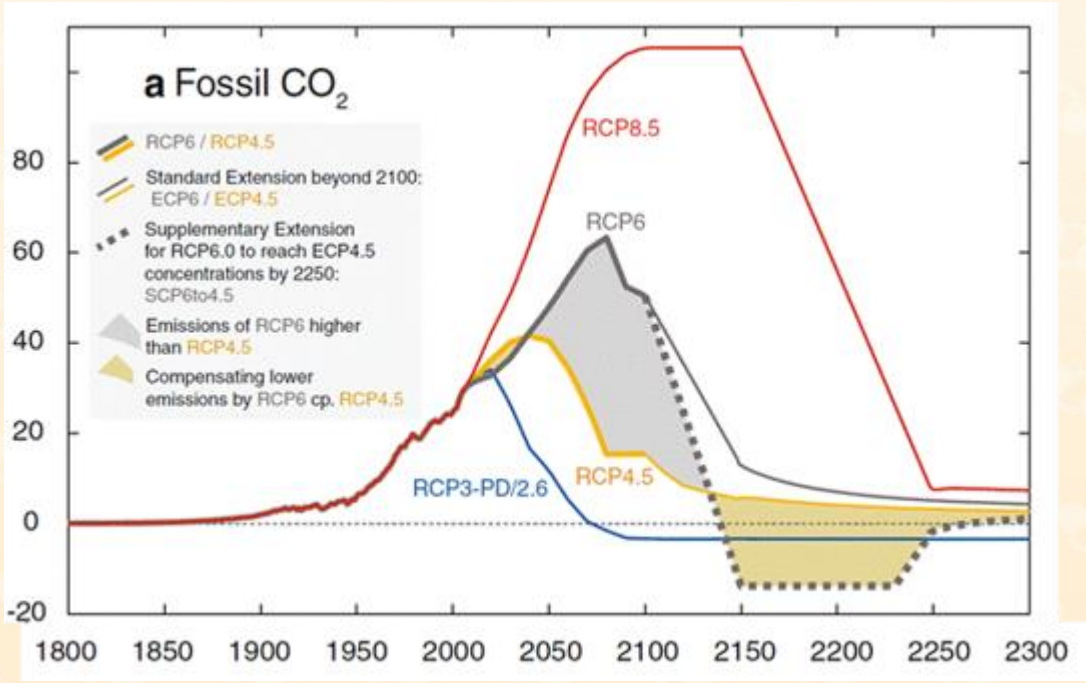
A Plan To Limit CO_2 Buildup In The Atmosphere

Plan To Limit CO_2 Buildup In Atmosphere

Use Non-Fossil Sources For All Sources Of CO_2 Emissions

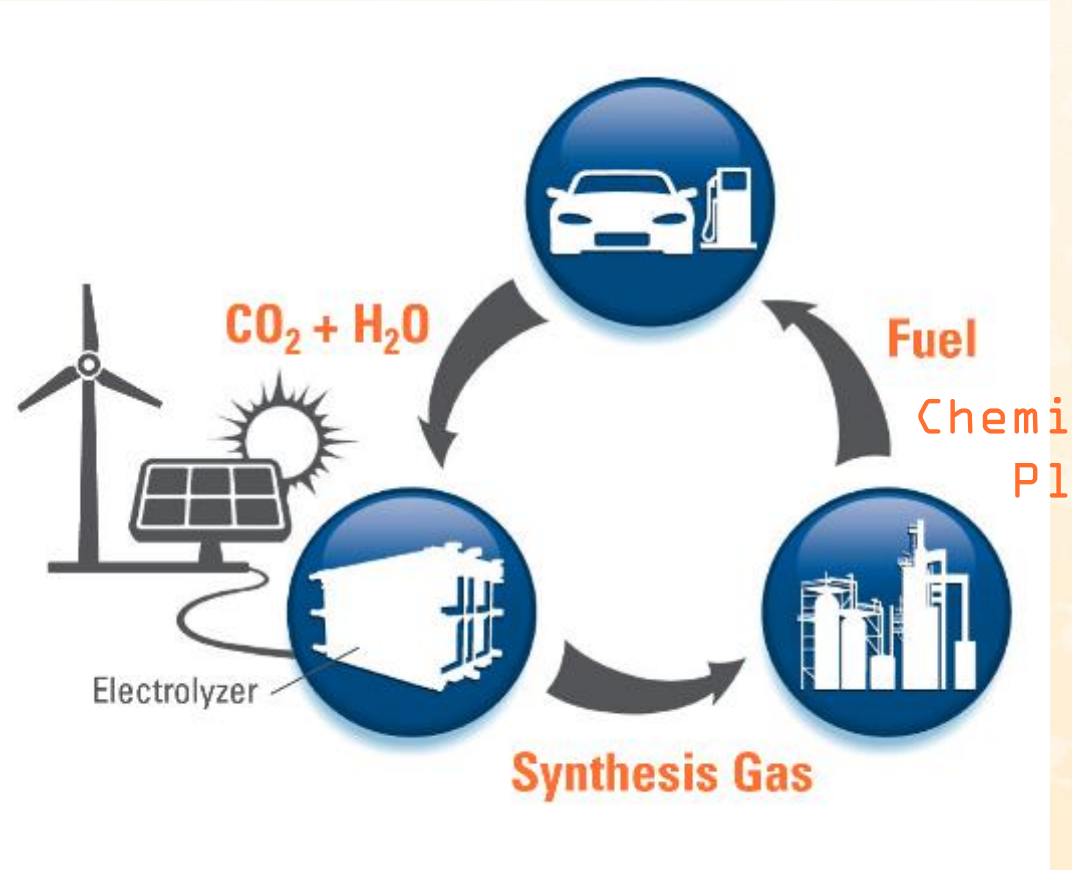


Net Negative CO_2 emissions

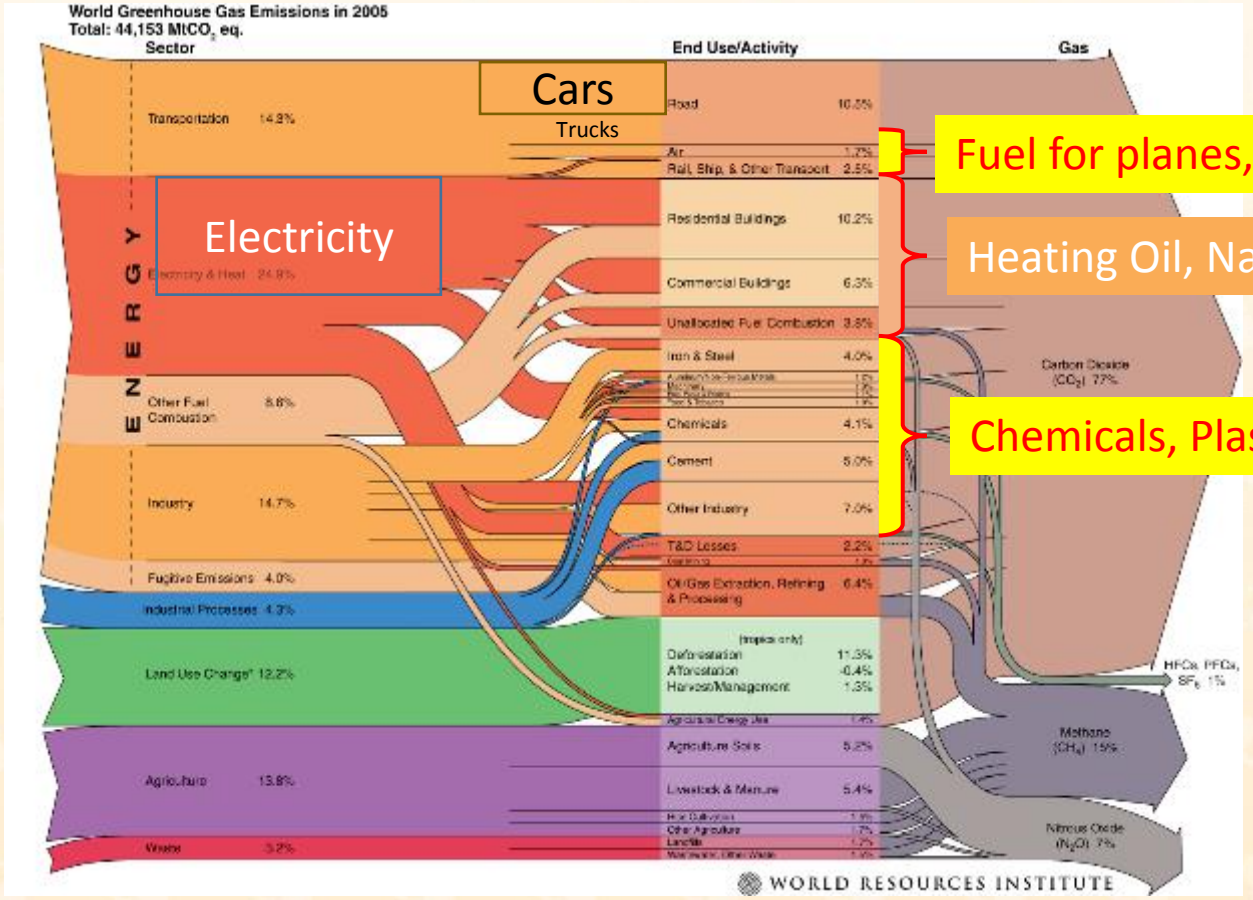


CO_2 Recycling To Get Negative CO_2 Emissions?

- Take CO_2 out of the atmosphere
- Put the CO_2 into products



Where Does The CO_2 Need To Go



Need 3 Billion Tons/yr Net Storage

- Plastics and Chemicals ~1 billion tons/yr
- Cement & Steel ~1 billion tons/yr
- Must bury ~1 billion tons/yr

Also need fuels from low carbon sources

- Fuels ex gasoline ~5 billion tons

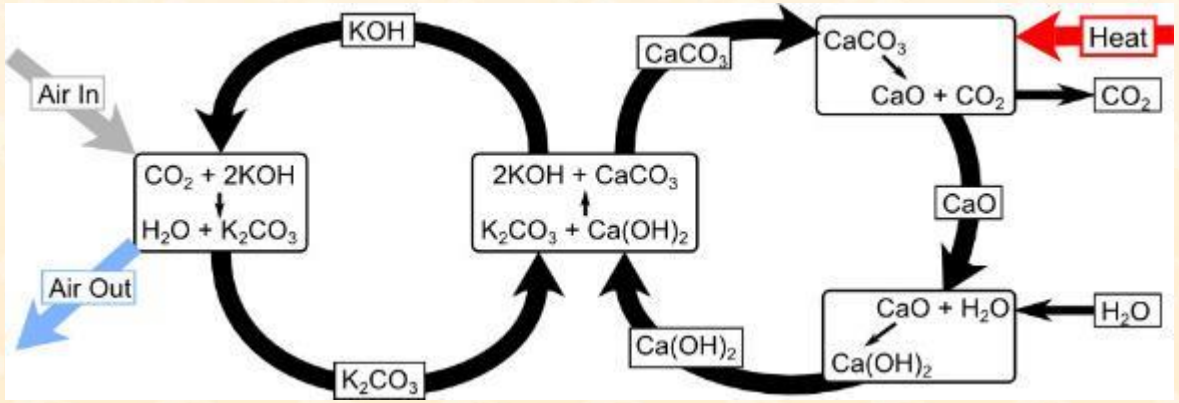
CO_2 Capture From The Atmosphere

CO_2 Capture from the Air In Route to Negative Emissions

- Three active startups in pilot stages
  - **Carbon Engineering -**
    - **Uses hydroxide capture**
  - **Global Thermostat -**
    - **Uses solid amine sorbents**
  - **Climeworks –**
    - **Uses solid amine sorbents**
- All use mainly heat to regenerate the capture material

Carbon Engineering

- In Pilot phase through 2015 with goal to build a commercial air capture plant in ~2017.
  - They plan to eventually use carbon-neutral energy, but are currently running the process on natural gas (and capturing the CO_2 from the combustion.)
  - Pellet reactor system



1. Capture CO_2 in a KOH solution to make K_2CO_3,
2. Exchange the carbonate with $Ca(OH)_2$ to make $CaCO_3$,
3. Heat the $CaCO_3$ to produce CO_2 and CaO,
4. Add water to regenerate $Ca(OH)_2$, and repeat the cycle.

Global Thermostadt

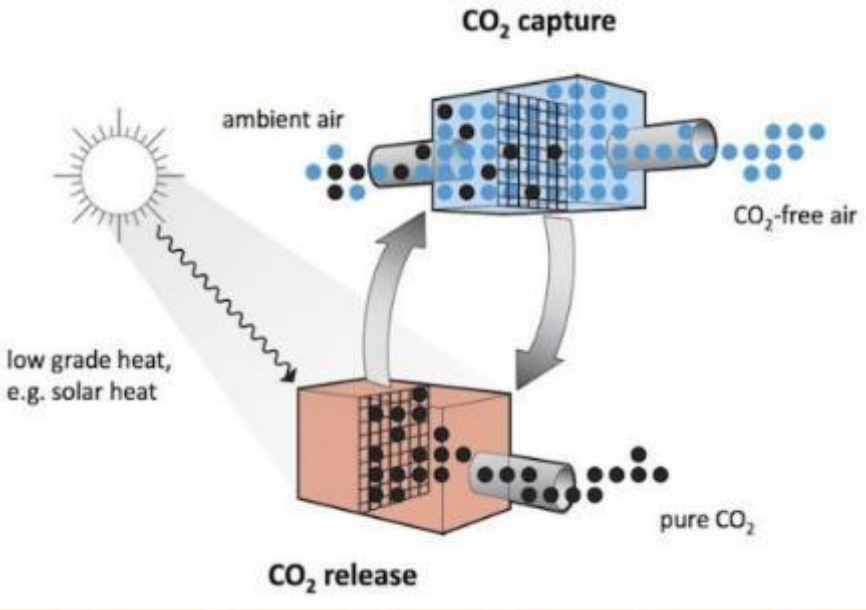
- Cost between $15 and $50 per ton of carbon dioxide captured from air, depending on how long the amine surfaces last
- Fans draw air in over alternating 10-foot-wide surfaces known as contactors that are comprised of 640 ceramic cubes embedded with the amine sorbent.
  - The tower raises one contactor as another is lowered allowing the cubes of one to collect CO2 from ambient air while the other is stripped of the gas by the application of the steam, at 85 °C.
  - For now that gas is simply vented, but depending on the customer it could be injected into the ground, shipped by pipe, or transferred to a chemical plant for industrial use.

Pilot Plant at SRI International

Source
http://www.marcgunther.com/

Climeworks

•Uses low grade heat (e.g., solar) for a CO2 adsorption/desorption cycle on a filter sorbent.



•Filter modules, fitted into standard 40-foot containers
Control module (one 40-foot container)
•>99.5% CO2 purity

CO_2 Conversion

Two opportunities

- Conversion to organics
  - Fuels (gasoline), Plastics, Fertilizers, …
- Conversion to Inorganics
  - Cement

Skyonic, Calera, Blue Planet: Produce Inorganics

Skytronic

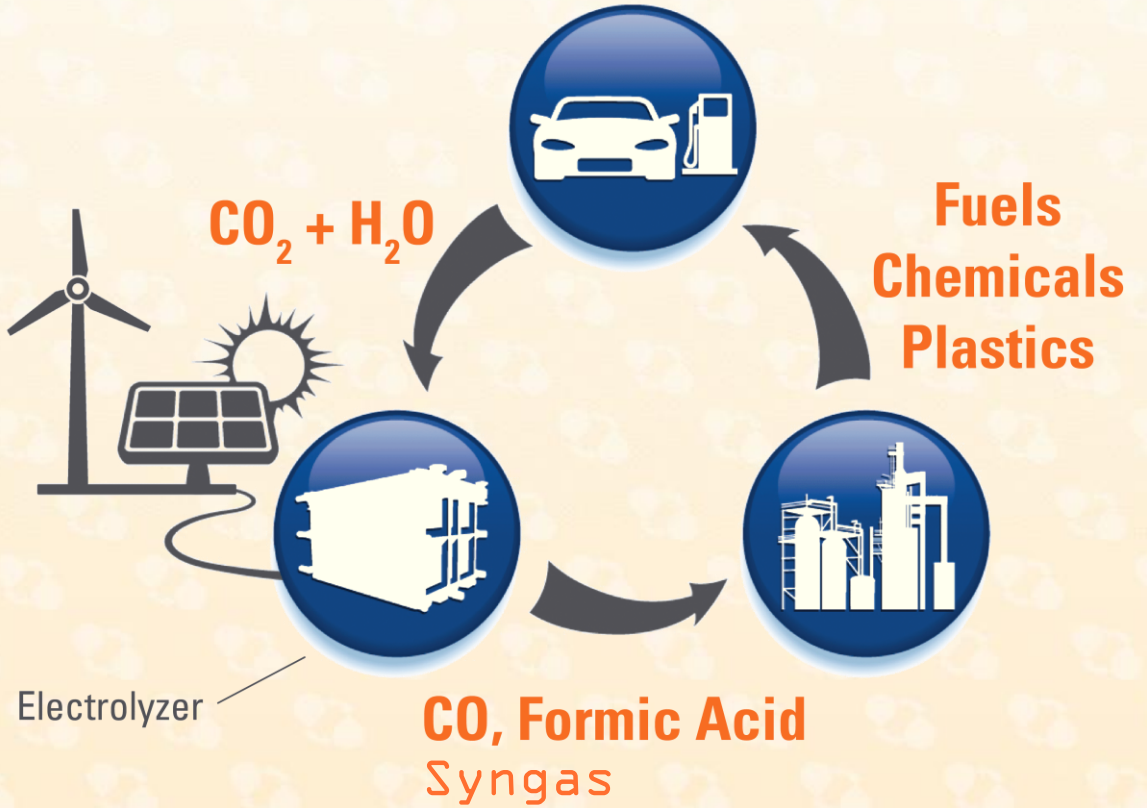
- **Skymine** - remove s carbon dioxide (CO_2), acid gases such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), and other heavy metals from industrial waste streams. Skyonic captures these harmful pollutants from flue gases and transform them into marketable products, such as sodium bicarbonate (baking soda), hydrochloric acid, and bleach.

- **Skyscraper** -post-combustion carbon-capture and scrubbing technology can remove virtually all sulfur oxides (SO_x), nitrogen oxides (NO_x), mercury, and other heavy metals emitted from flue gases (97-99 percent). Like SkyMine, it can be easily retrofitted to existing infrastructures or implemented as a new facility is being planned or built.

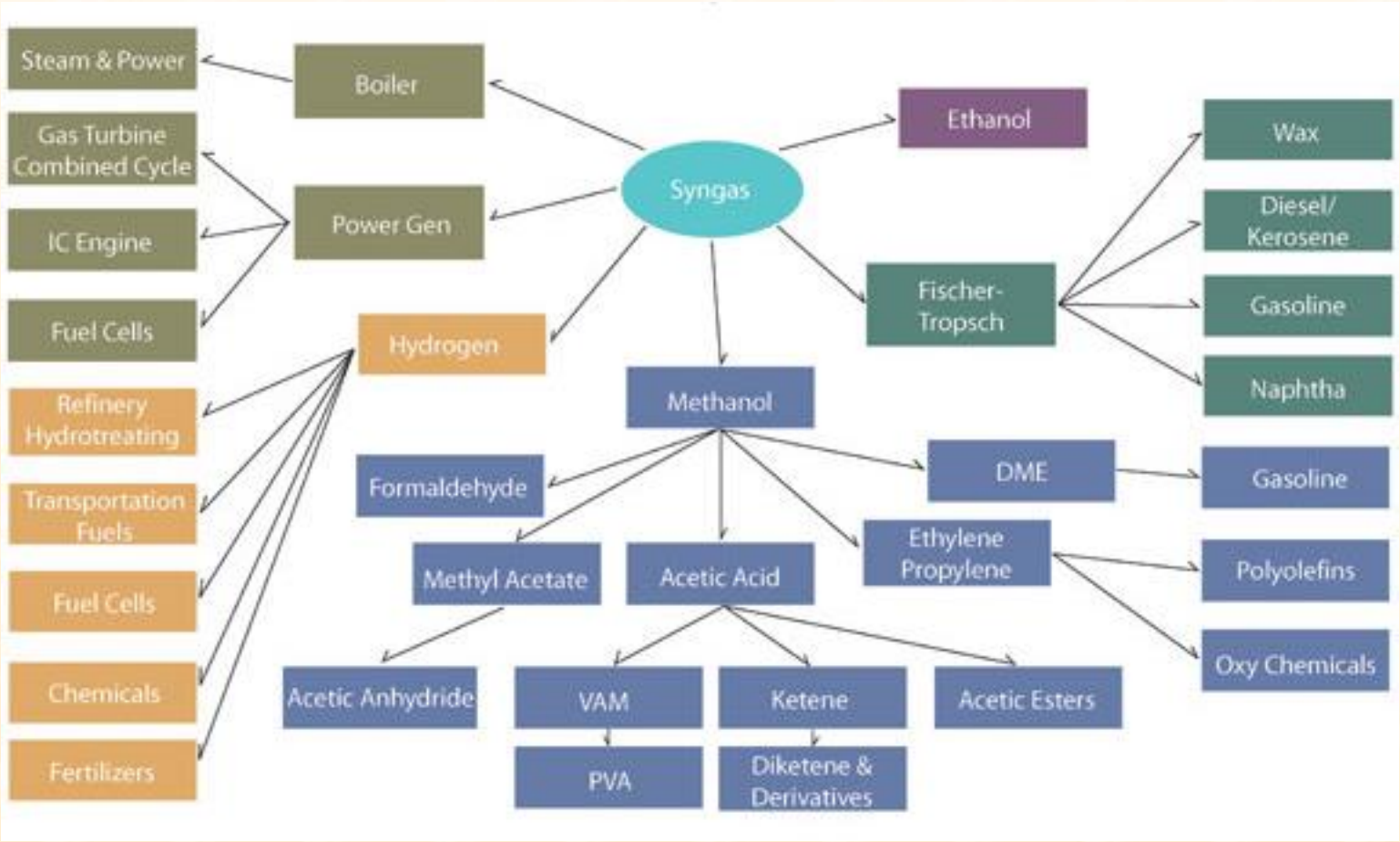
- **SkyCycle®** -thermolytic decarbonation" process, that enables Skyonic to use waste heat instead of electricity to power its carbon-capture-and-utilization process.

Converting CO_2 To Useful Products

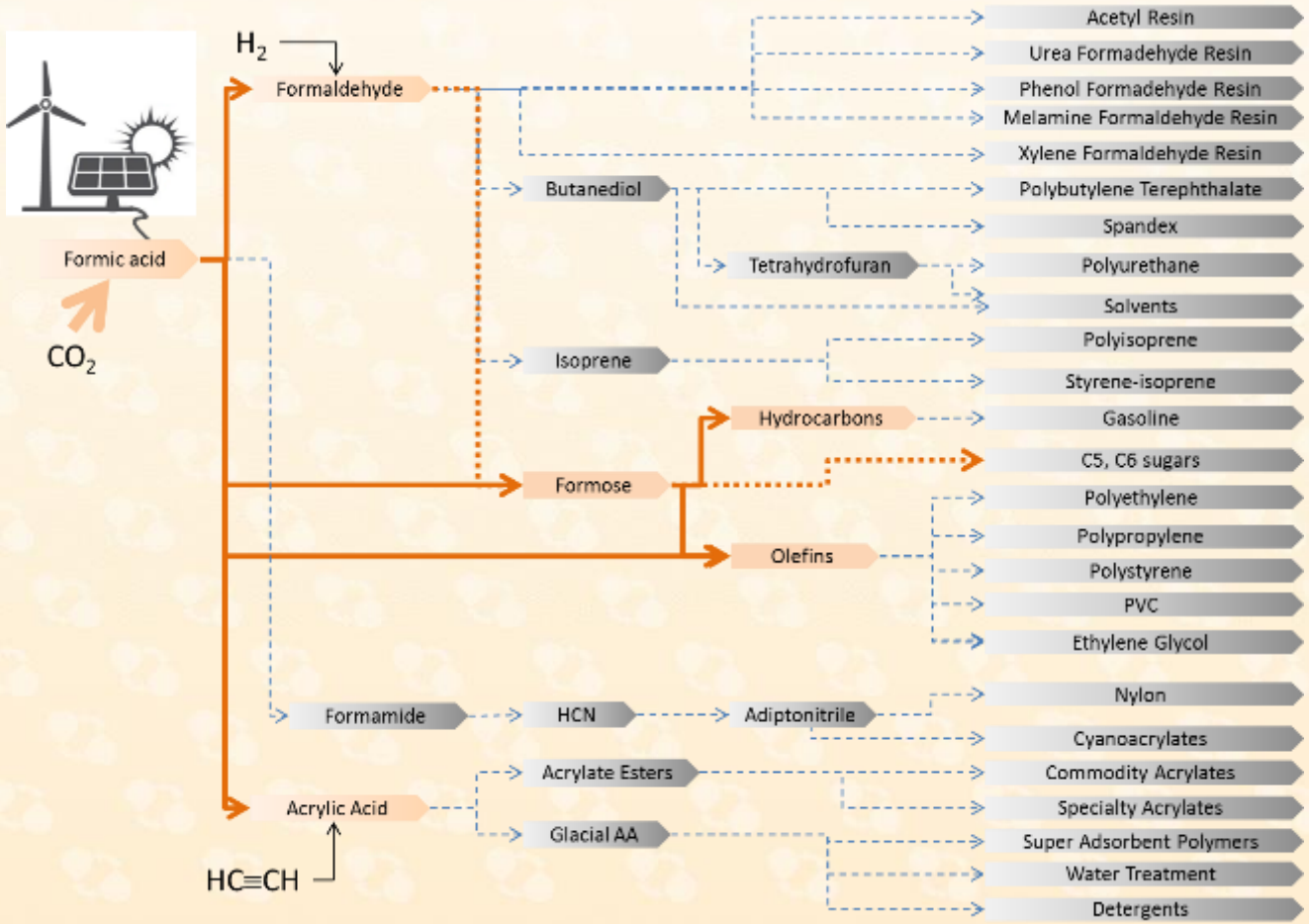
Converting $CO_2 + H_2O$ to Fuels & Chemicals



Syngas To Chemicals



Formic Acid to Chemicals (Patent Pending)



Production Of Syngas

Electrolyze H_2O to H_2 then react H_2 with CO_2

- USC (Olah)
- Carbon Recycling International
- Sunfire

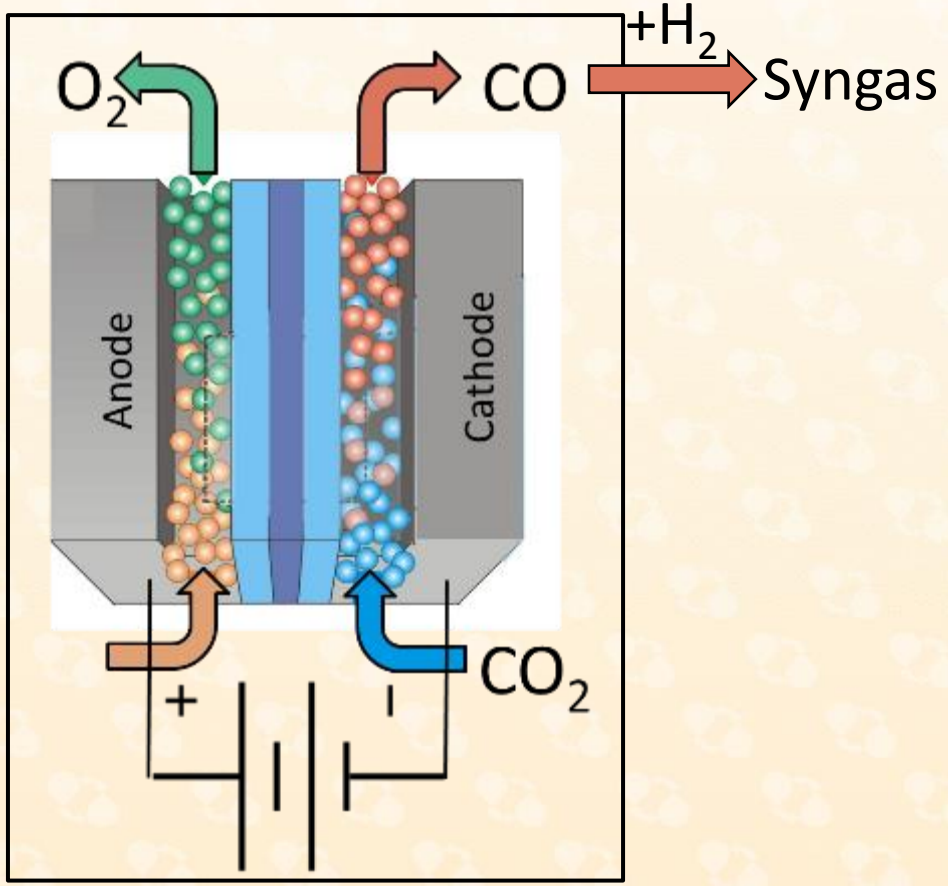
Electrolyze CO_2

- Dioxide Materials
- Liquid Light
- DNV
- Mantra Energy
- Sustainable Innovations

Thermal Decomposition

- New CO_2 Fuels
- Solar Jet

Electrolyze CO_2



Issues With CO_2 Electrolysis

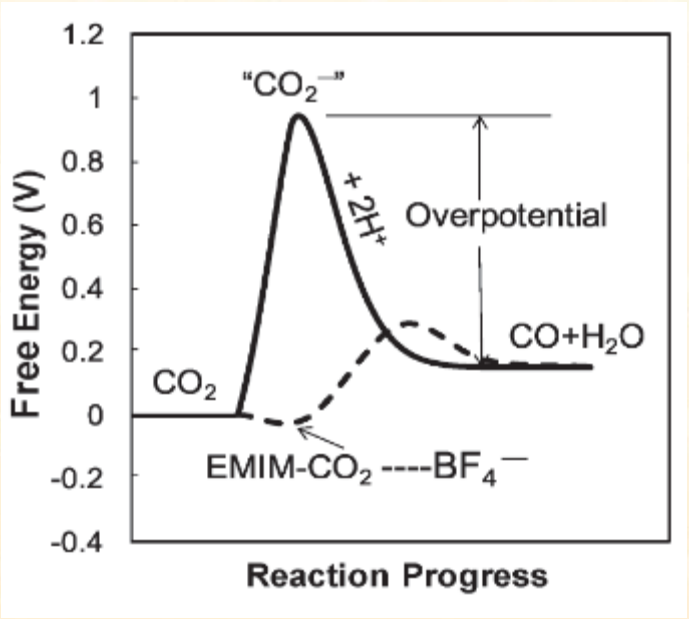
- Previous difficulty: Wastes too much energy
- Dioxide Materials patented solution: Use two catalysts to lower energy barrier

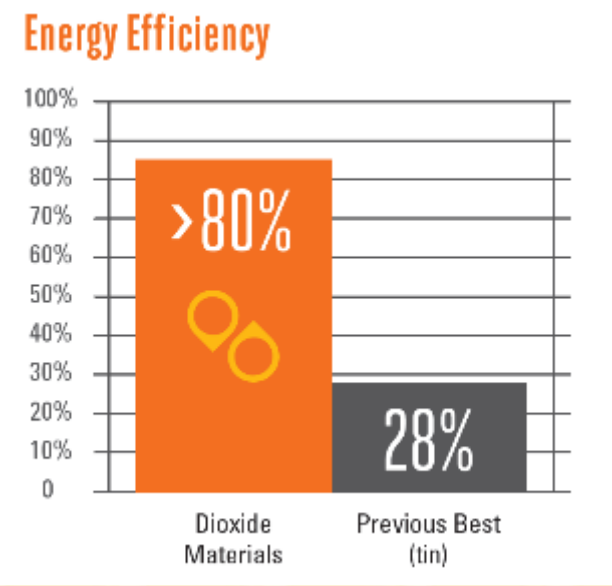
Science AAAS

Science 4 November 2011:
Vol. 334 no. 6056 pp. 643-644
DOI: 10.1126/science.1209786

Ionic Liquid Mediated Selective Conversion of CO_2 to CO at Low Overpotentials

Brian A. Rosen, Amin Salehi-Khojin, Michael R. Thorson, W. Zhu, Devin T. Whipple, Paul J. A. Kenis, Richard I. Masel





Present Situation

- Technology demonstrated in the lab
- 1000 hrs demonstrated
- Produce CO at a similar cost to CO from natural gas in Europe.
- Scale-up needed

Alternative Electrolyze Water To Hydrogen Then React Hydrogen With CO_2

Issues With Water Electrolysis

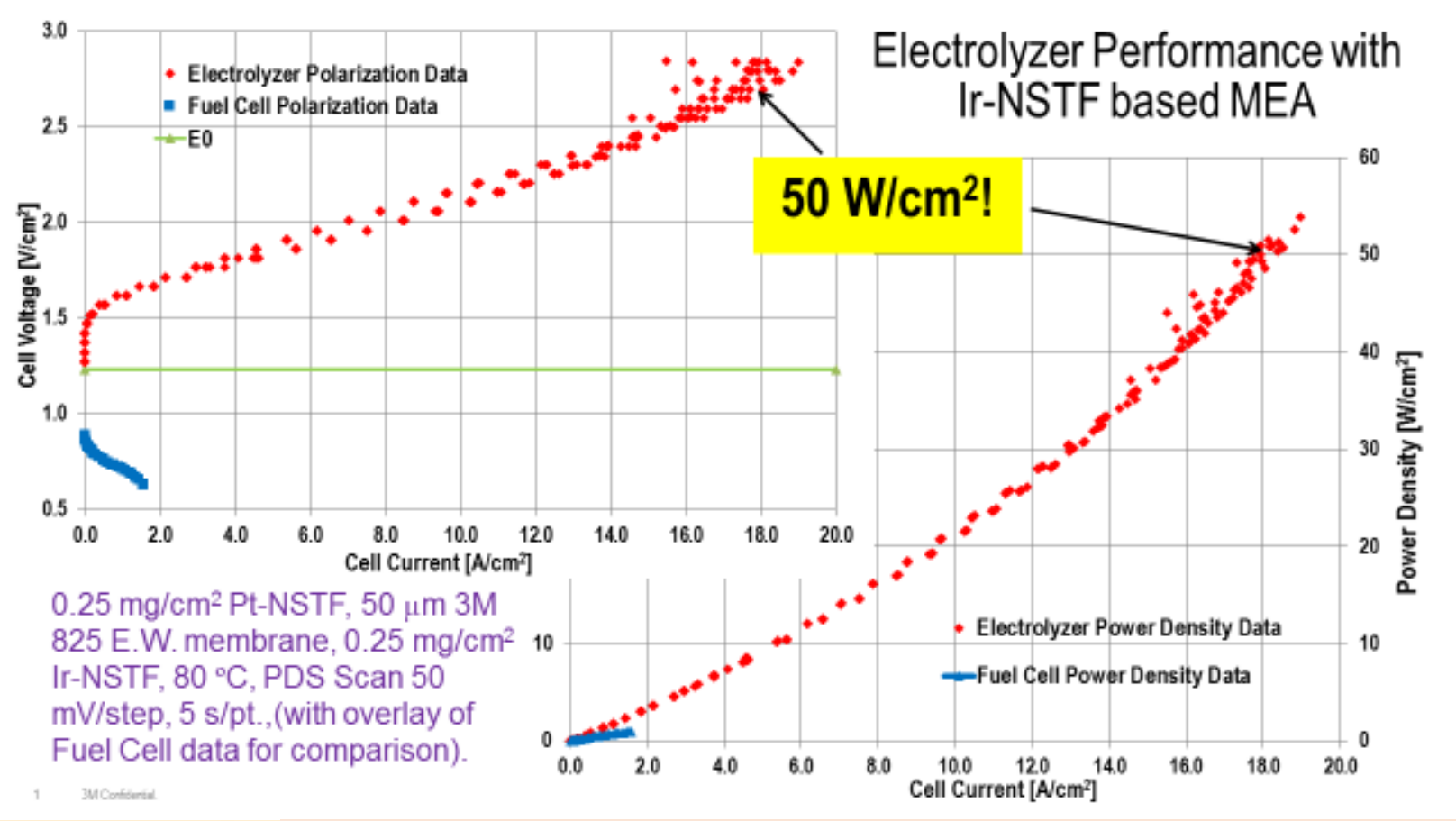
Alkaline Electrolyzers

- Well established technology
- Low current
  - Need giant device to produce significant hydrogen
- Corrosion issues

PEM Electrolyzers

- New Technology
- High currents
- Needs copious amounts of platinum

3M Advance: PEM Electrolyzers With Much Less Platinum



- Low PGM electrodes
  - Factor of 10x improvement over the state of the art
- Much higher potential for power and current density
  - Again, factor of 10x above the existing state of the art demonstrated
  - 100 x more than alkaline
- The two advancement are independent, that is, high power using low catalyst loading.

Courtesy of Krzysztof Lewinski, Sean Luopa and Dennis van der Vliet, 3M

CO_2 Based Syngas To Fuels & Chemicals

Carbon Recycling International

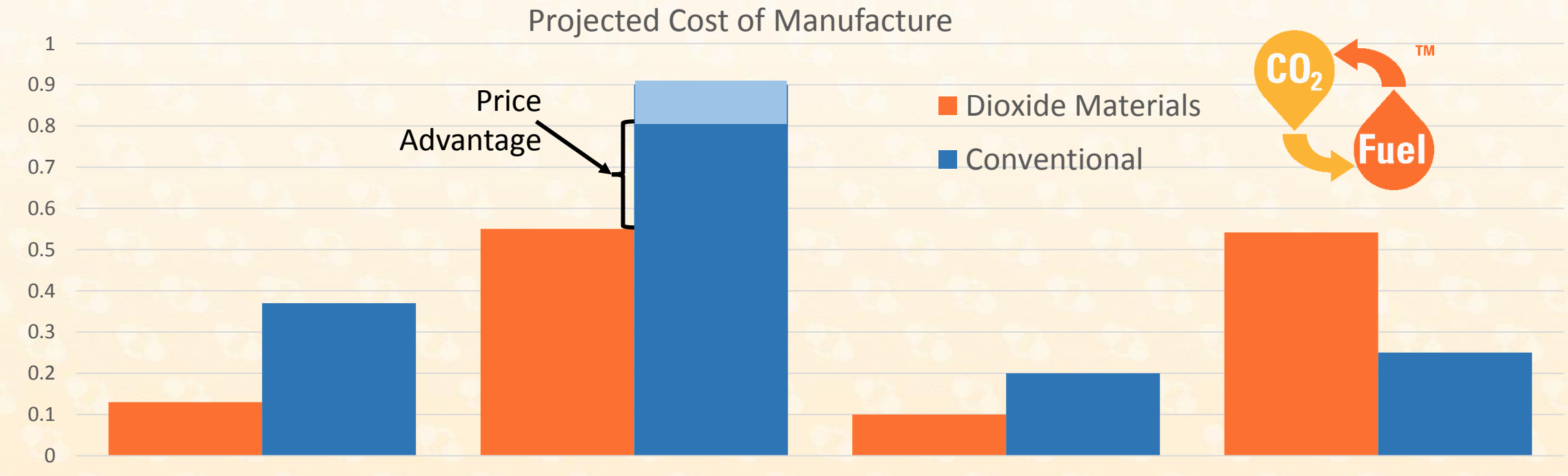
$CO_2 + H_2 \rightarrow CO + H_2$ (Syngas) $\rightarrow$ methanol

Syngas to methanol already large scale process

Primus Green Energy

Syngas → Gasoline

Economics Of Low Cost Chemical Production Using Inexpensive CO_2



	Formic Acid	Acrylic Acid	37% Formaldehyde	Gasoline
Market	$0.8B	$12B	$30B	$3T
	Animal Feed Grain Drying/Preservation	Diapers Adhesives Paints	Building materials Foams	

CO_2 @ $0.02/lb

Government Support Needed

Present govt support

- DOE/Fossil Energy has $1M/yr specifically targeting CO_2 reuse – focused on CO2 flooding for enhanced oil recovery
  - Total budget is $711M/yr.
- NETL CO_2 capture program focused on capture and underground storage of CO_2 from coal fired power plants
  - CO_2 to useful products outside their mandate
- Dioxide Materials has received funding from SBIR's and ARPA-E
- Need a more substantial government program to move technology forward

Summary

Summary

- Present plans to reduce CO_2 emissions are insufficient to limit CO_2 buildup in the atmosphere
  - Human health/performance affected by 2080
- Air capture & CO_2 recycling needed to meet Intergovernmental Panel On Climate Change (IPCC) goals
- Technology is being developed but needs govt support toward commercialization

Questions

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