Energy for Climate Stabilization

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REVIEW: ENGINEERING

Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet

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Stabilizing the carbon dioxide–induced component of climate change is an energy problem. Establishment of a course toward such stabilization will require the development within the coming decades of primary energy sources that do not emit carbon dioxide to the atmosphere, in addition to efforts to reduce end-use energy demand. Mid-century primary power requirements that are free of carbon dioxide emissions could be several times what we now derive from fossil fuels (~10^{13} watts), even with improvements in energy efficiency. Here we survey possible future energy sources, evaluated for their capability to supply massive amounts of carbon emission–free energy and for their potential for large-scale commercialization. Possible candidates for primary energy sources include terrestrial solar and wind energy, solar power satellites, biomass, nuclear fission, nuclear fusion, fission-fusion hybrids, and fossil fuels from which carbon has been sequestered. Non–primary power technologies that could contribute to climate stabilization include efficiency improvements, hydrogen production, storage and transport, superconducting global electric grids, and geoengineering. All of these approaches currently have severe deficiencies that limit their ability to stabilize global climate. We conclude that a broad range of intensive research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development.

More than a century ago, Arrhenius put … sil f… red opacity … warm Earth… human pop…

fossil fuel burning, climate change, and en-…

effort. Even holding at 550 ppm is a major challenge.

Primary power consumption today is ~12 TW, of which 85% is fossil-fueled. Stabilization at 550, 450, and 350 ppm CO_2 by Wigley *et al.* scenarios require emission-free power by mid-century of 15, 25, and >30 TW, respectively (*8*). Attaining this goal is not easy. CO_2 is a combustion product vital to how civilization is powered; it cannot be regulated away. CO_2 stabilization could prevent developing nations from basing their energy supply on fossil fuels (*9*). Hansen *et al.* call for reductions in methane and black soot, which also cause warming (*10*). Such reductions are desirable but do not address fossil fuel greenhouse warming. The Kyoto Protocol calls for greenhouse gas emission reductions by developed nations that are 5% below 1990 levels by 2008 to 2012. Paradoxically, Kyoto is too weak and too strong: Too …

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$$GDP = C \times (E/C) \times (GDP/E)$$

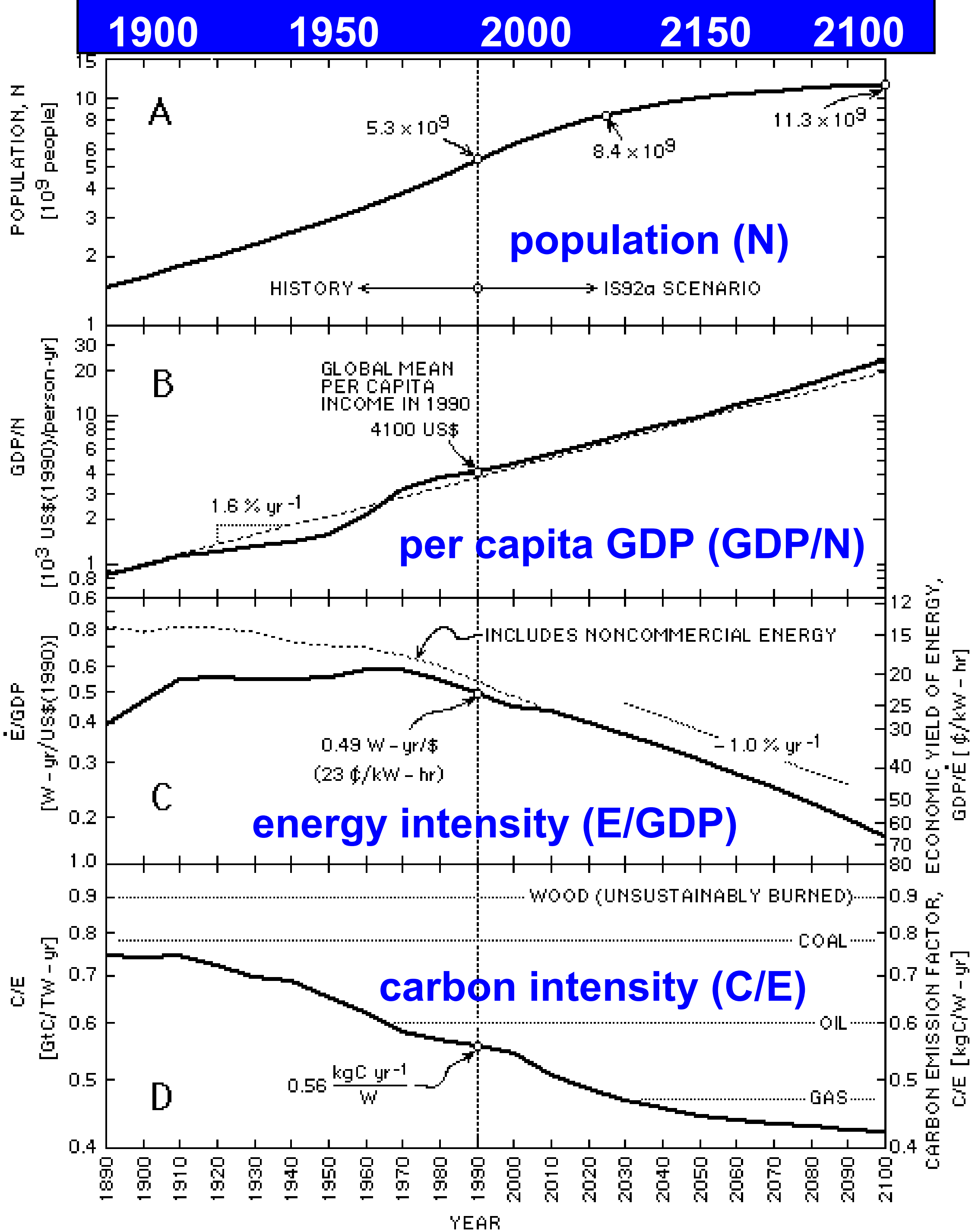
- To increase economic productivity (GDP) without increasing carbon emissions (C), we must increase
  - The amount of energy produced per unit carbon emitted (E/C)
  - The economic productivity of energy (GDP/E)
    - We need a research and development program aimed at increasing GDP in a carbon-constrained world

CO_2 volumes

- In year 2000, we produced
  - ~25,000 km^3 of gaseous CO_2 per year (at STP)
  - ~25 km^3 per year compressed to liquid CO_2 density
- By 2100, perhaps
  - ~100,000 km^3 gaseous CO_2 per year
  - ~100 km^3 liquid CO_2 per year

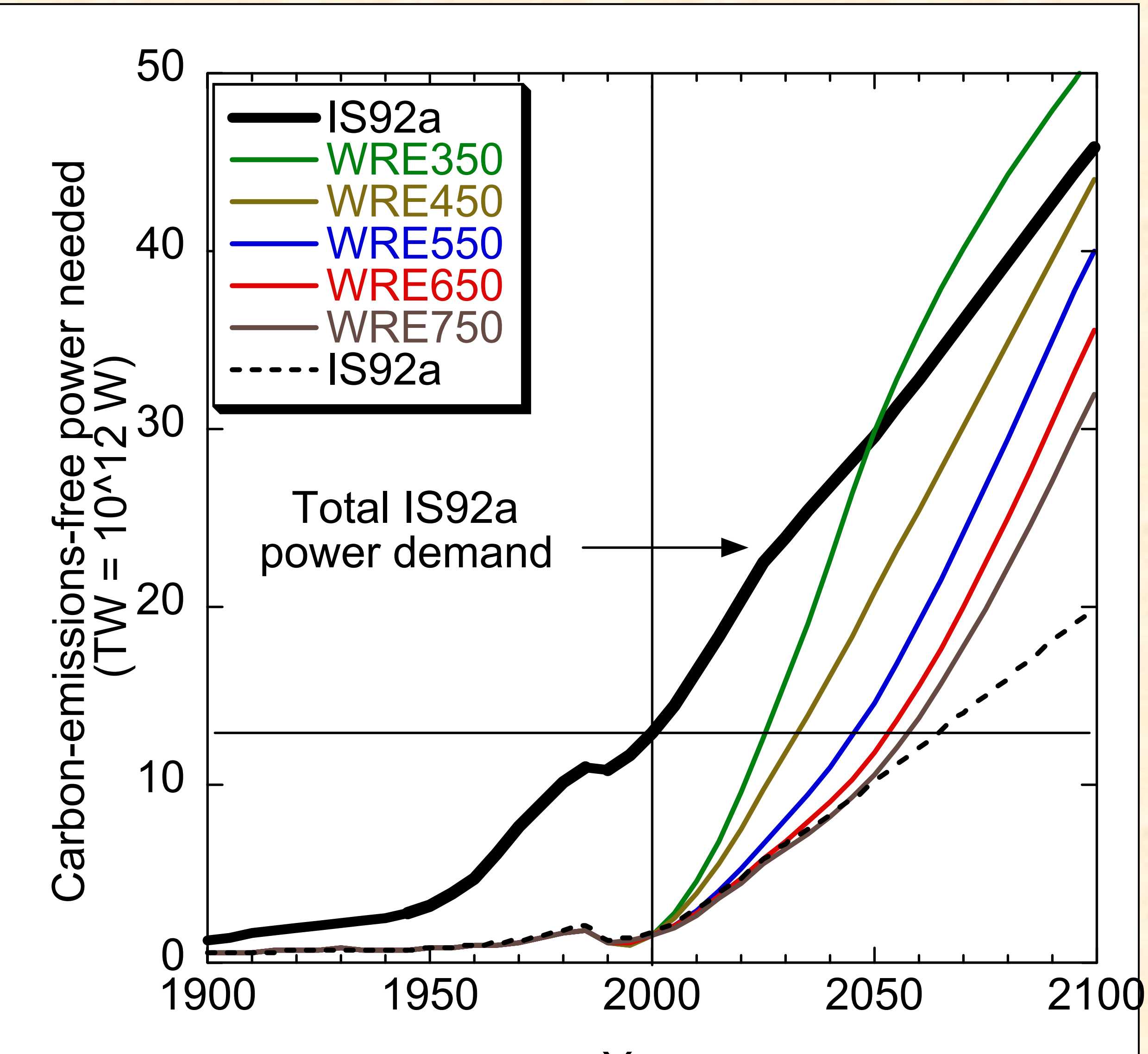
CO_2 emissions =

N x (GDP/N) x (E/GDP) x (C/E)



IPCC IS92a
“Business as usual”
scenario assumptions

Carbon-emissions-free primary power required for CO_2 stabilization



Adding 1 GW_t / day, would yield 20 TW_t in ~55 years

IPCC IS92a "Business as Usual" economic assumptions

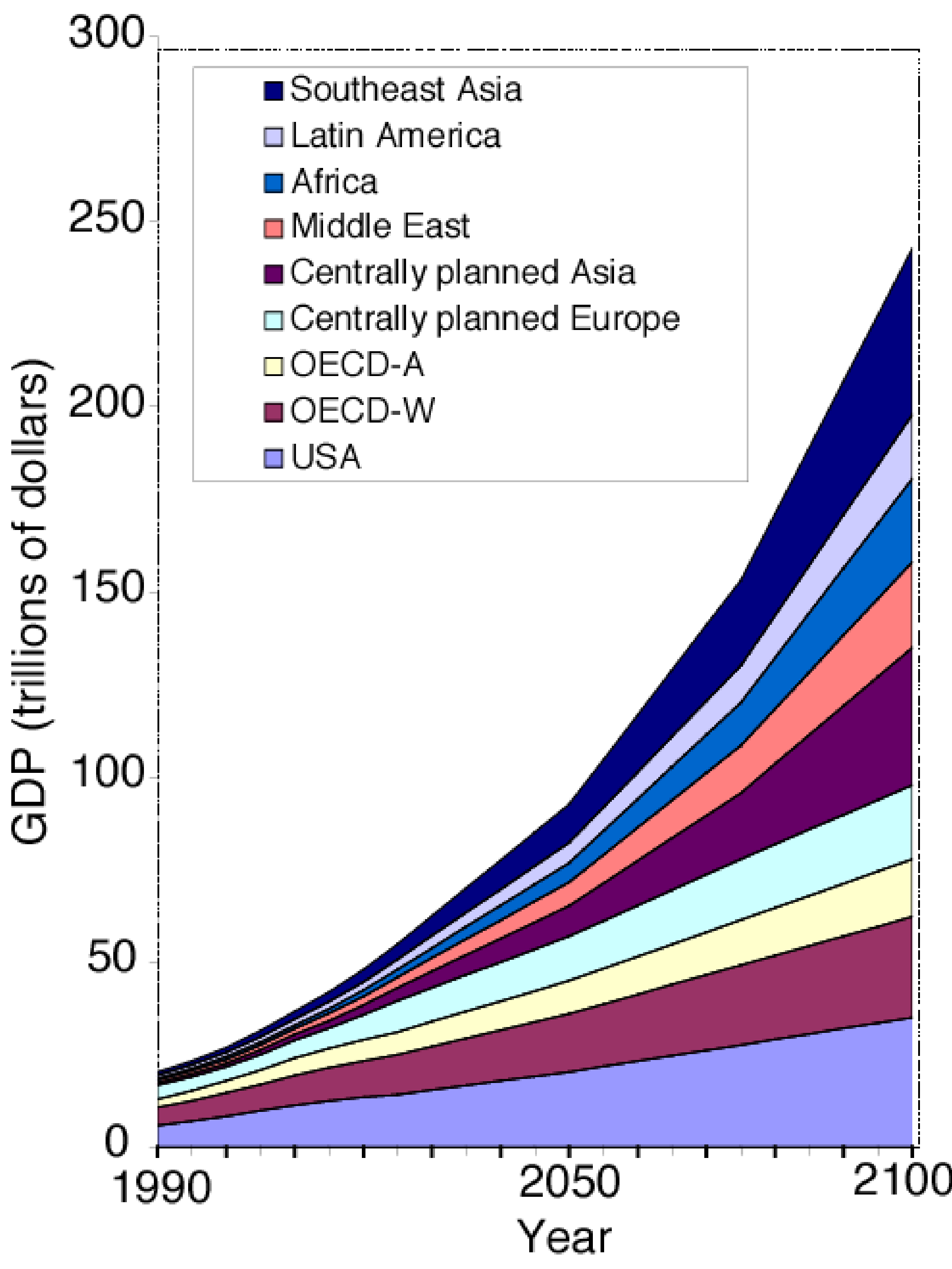
Solutions must work for the developing wo

Per capita GDP in developing world is expected to lag USA

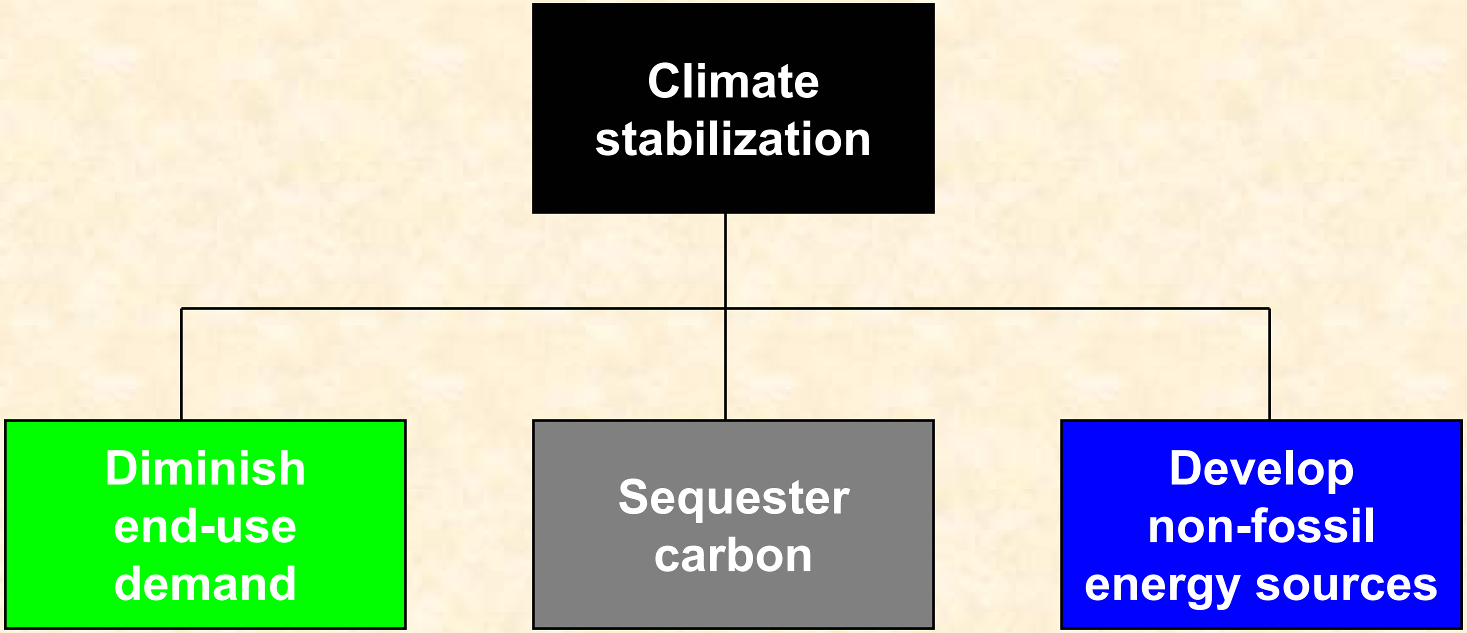
Year	USA (k$)	South -east Asia (k$)	Africa (k$)
1990	23	0.9	0.7
2050	68	10	2.3
2100	119	45	7.6

Yet, GDP growth in devel world is expected to exce that in USA, OECD

IS92a economic assumptions



Three strategies to climate stabilization



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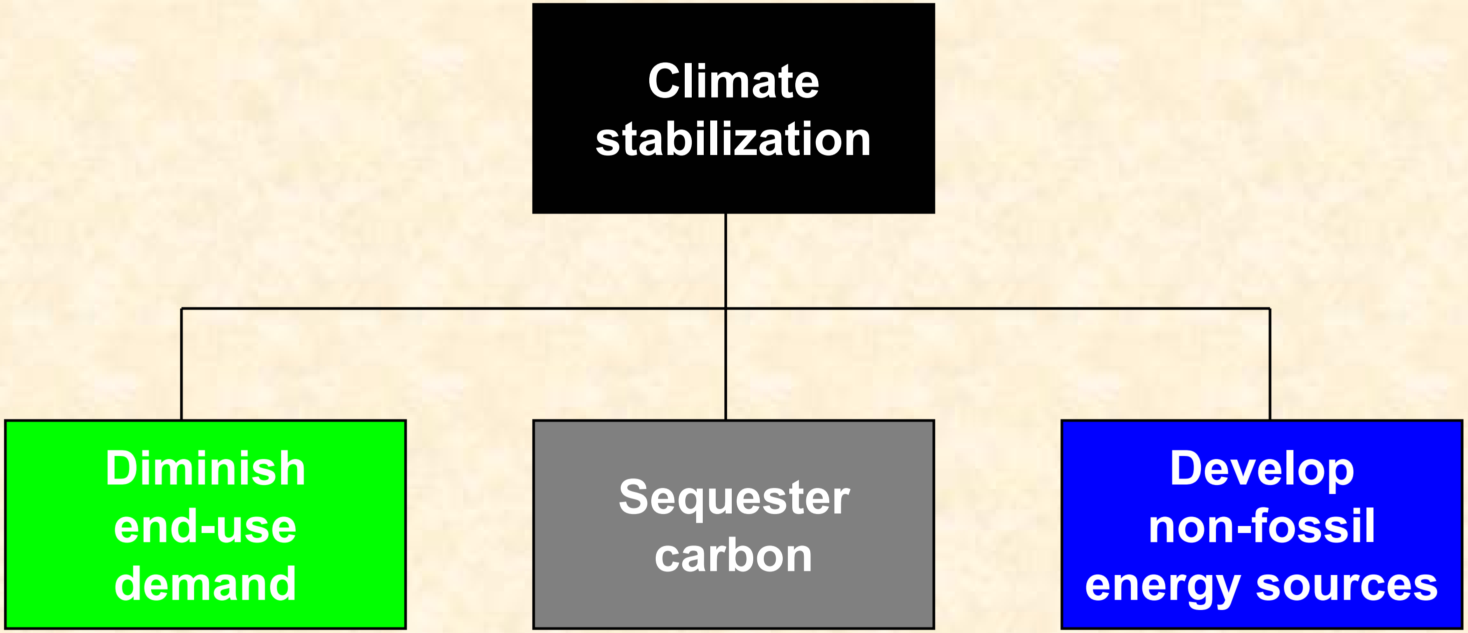
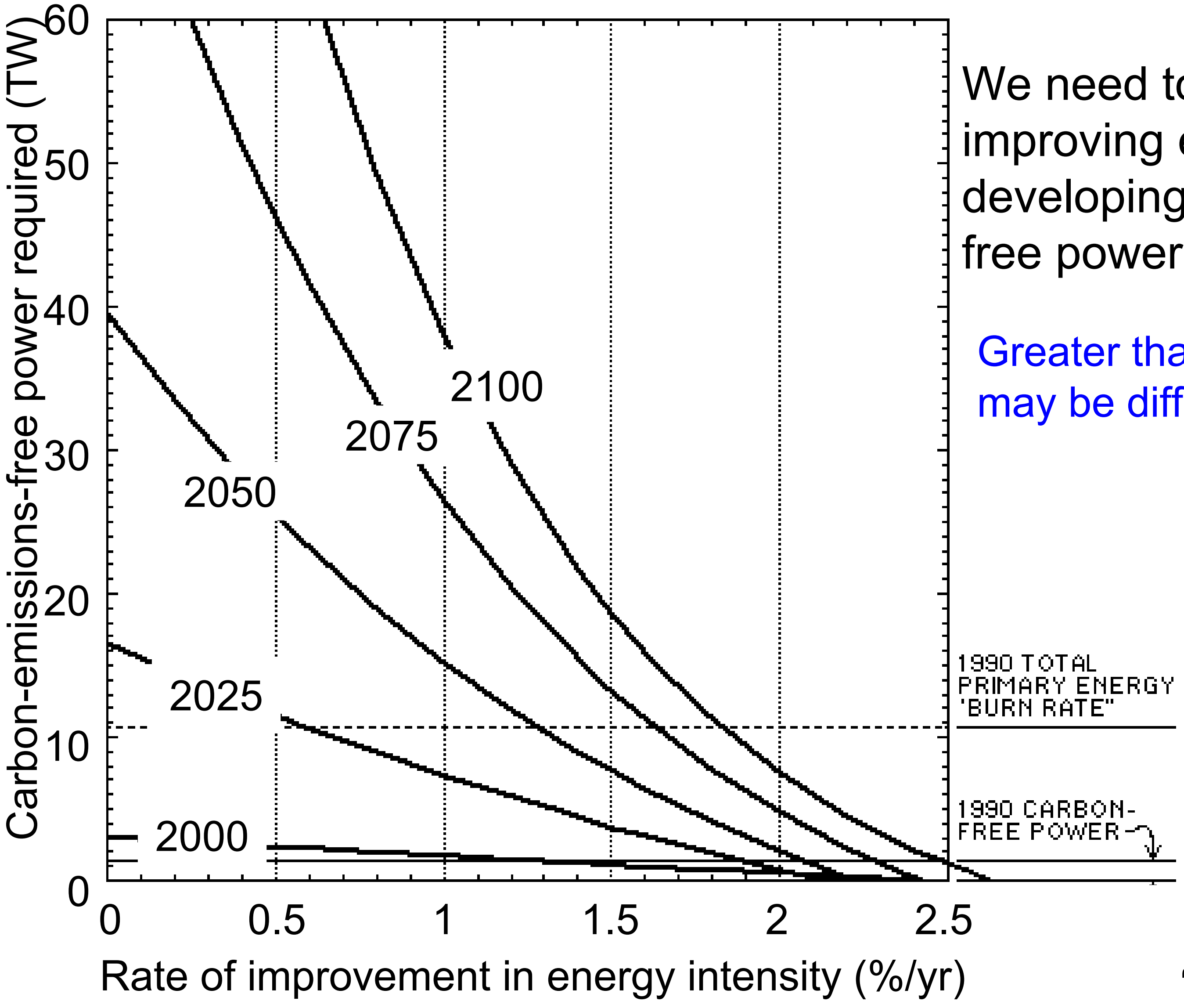


We need to work hard on all three strategies

Energy intensity decline and carbon-emissions-free power required to stabilize at 2 x CO_2



We need to push hard on both improving energy intensity and developing carbon-emissions-free power sources

Greater than 1%/yr improvement may be difficult to sustain

Over 100 years,
1% / yr = 2.7
2% / yr = 7.2
2.5% / yr = 11.8

IPCC IS92a "Business as usual" scenario assumptions

The transportation sector

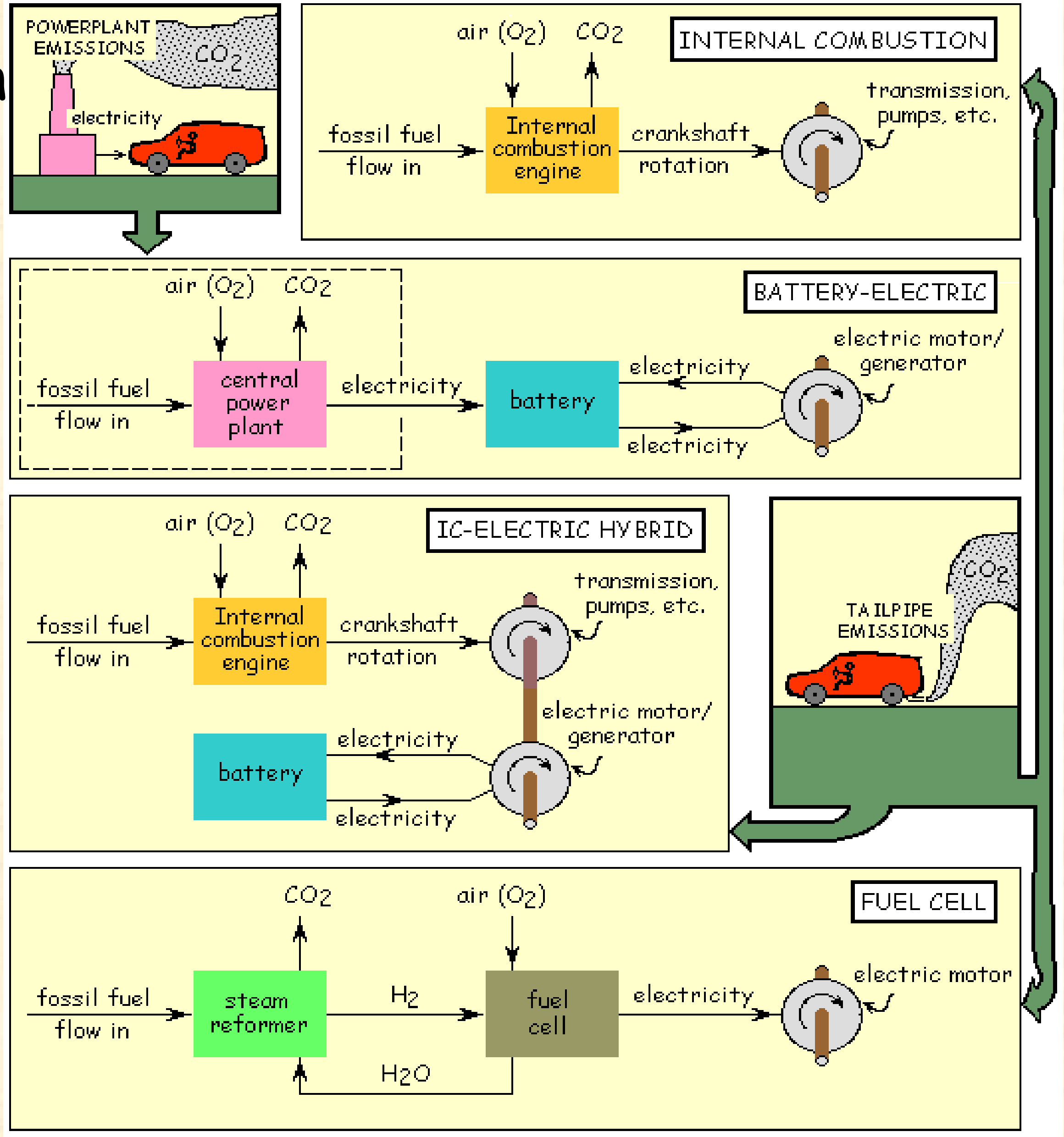
Without structural changes, we can only obtain a factor of 2 improvement in the transportation sector

Internal combustion
18-23% efficiency

Battery-electric
21-27% efficiency

IC-Hybrid electric
30-35% efficiency

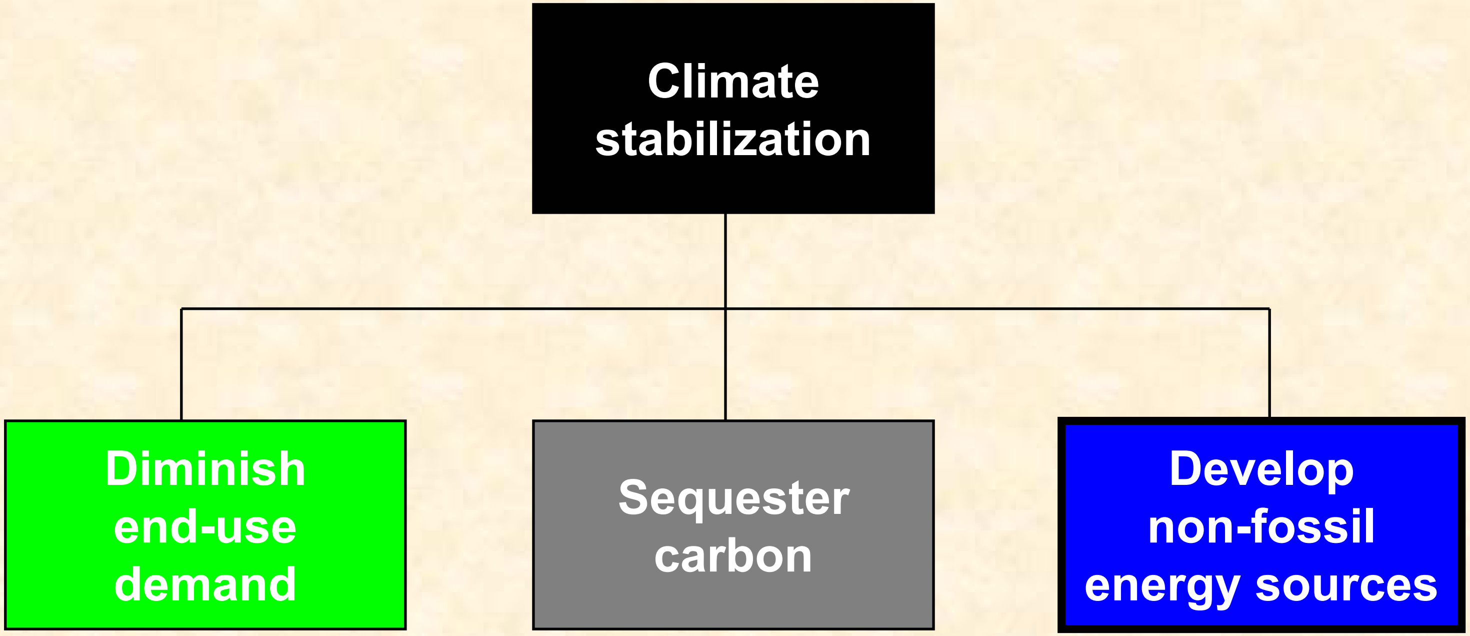
Fuel cell
30-37% efficiency



Economic productivity of energy use (GDP/E)

- Improve efficiency of cars, homes, power plants, etc (device efficiency)
- Improve economic value generated per unit energy consumed (system efficiency)

Three strategies to climate stabilization



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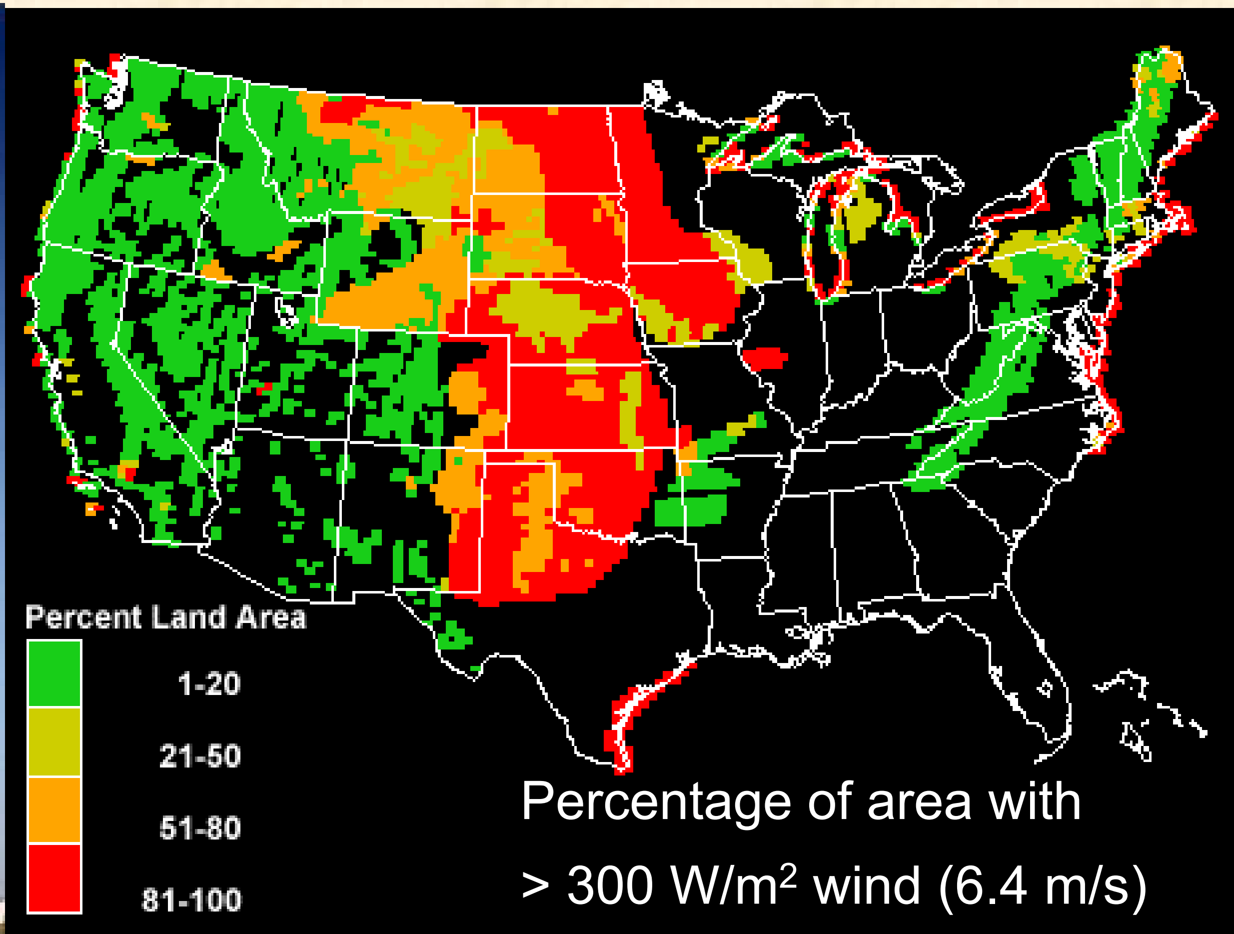
Renewable Energy densities and rates for 10 TW_t

- Wind energy
  - 4 W/m^2 = 800,000 $km^2/(10\ TW_t)$
  - Add ~20 km^2 / day for 100 years
    - 1% coverage with turbines
    - 100 turbines averaging 1 MW delivered per day
- Solar photovoltaic
  - ~200 W/m^2 @ ~20% efficiency = 80,000 $km^2/(10\ TW_t)$
  - Add ~ 2 km^2 / day for 100 years
- Biomass energy
  - ~200 W/m^2 @ 2% efficiency = 2,500,000 $km^2/(10\ TW_t)$
  - Add ~70 km^2 / day for 100 years

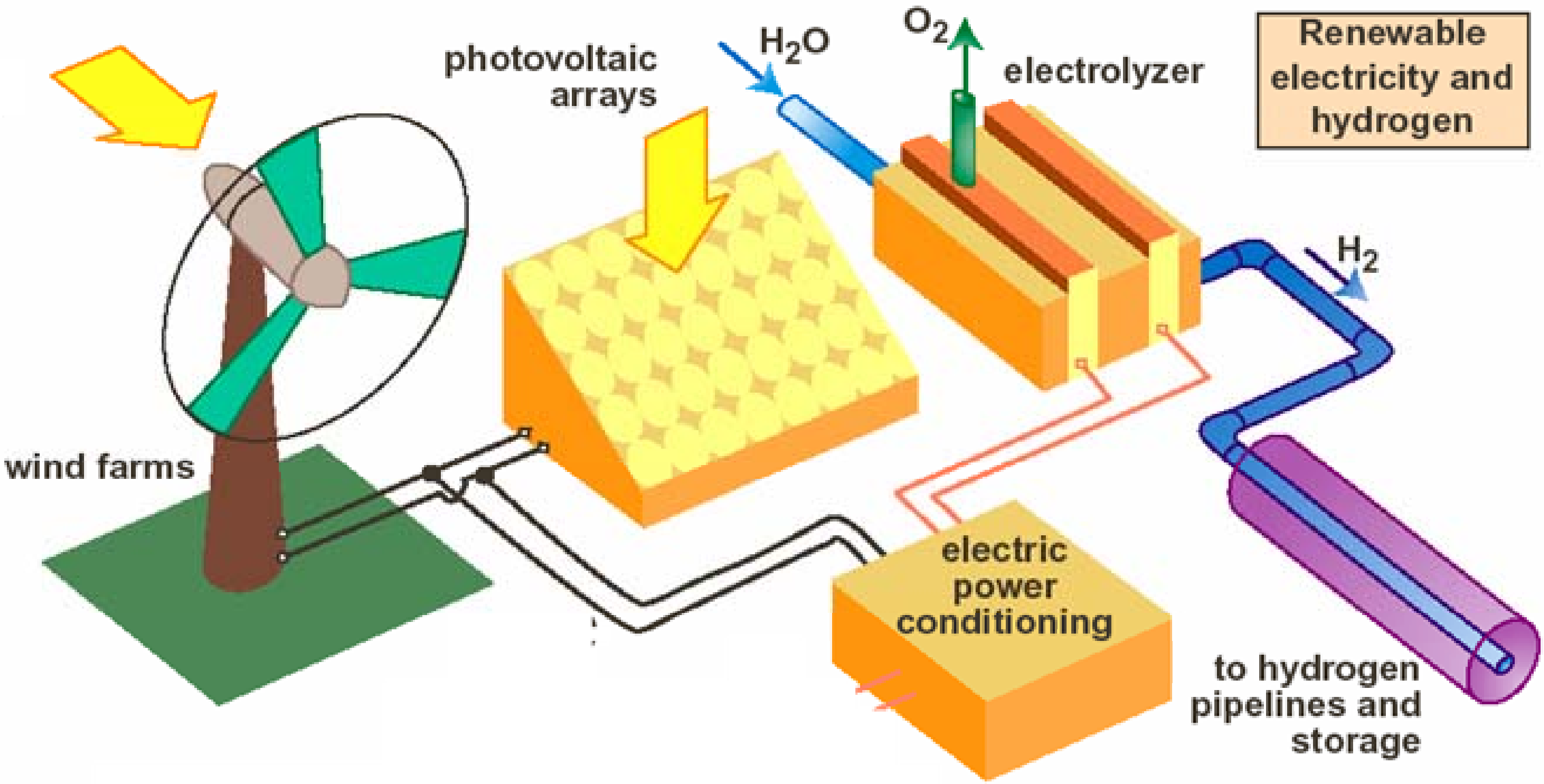
Wind power

- Need >3 million mega-wind-turbines for 10 TW_t
  - 100 per day added for next 100 years
- Intermittancy, Storage, Distribution



Renewables:
Storage and distribution remain challenges

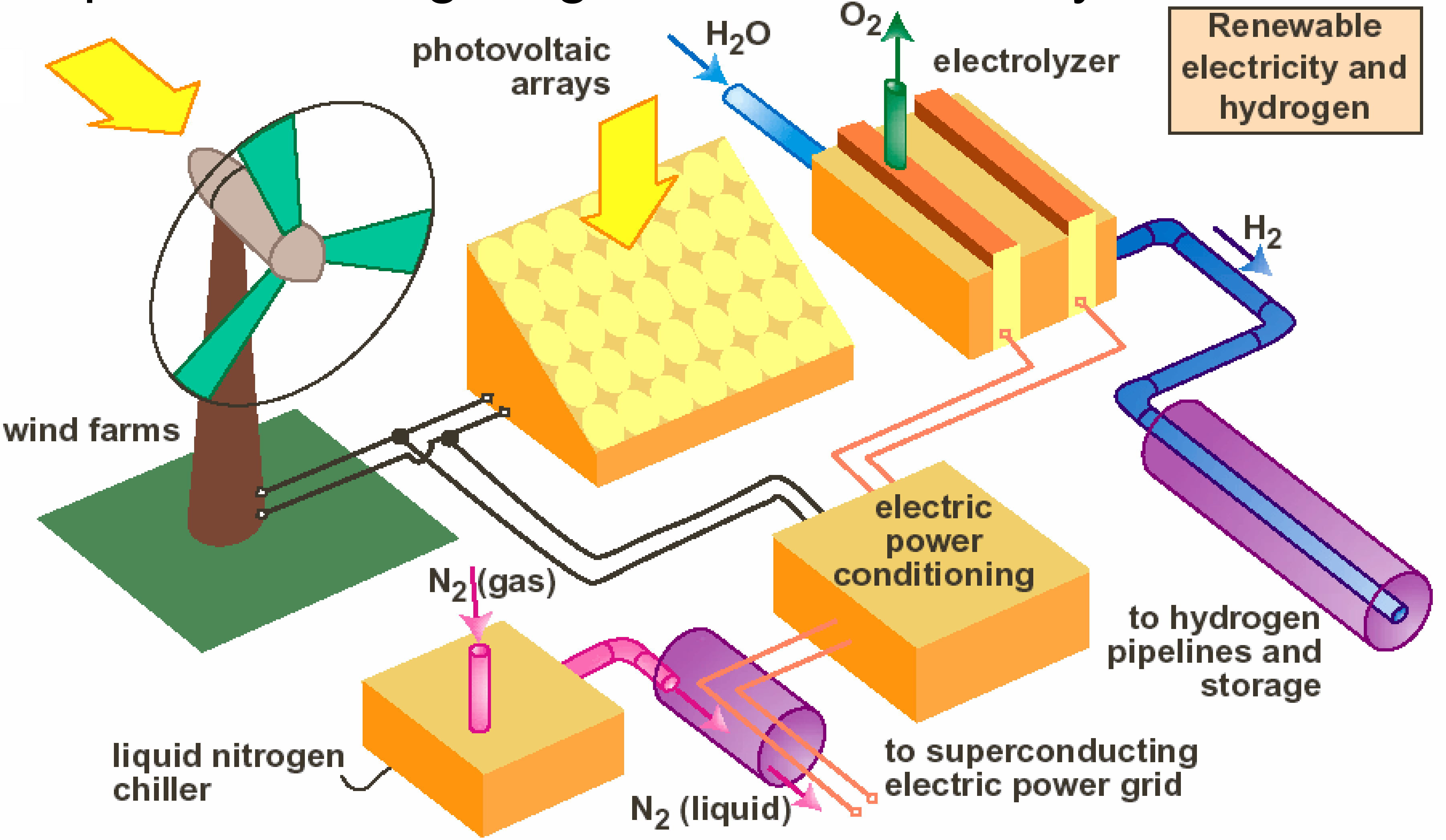
Hydrogen energy storage and distribution



Platinum requirement for high-density electrolyzers / fuel cells to produce 10 TW = 30 x today's global platinum mining rate

Renewables:
Storage and distribution remain challenges

Hydrogen energy storage and distribution
Superconducting long-distance electricity transmission



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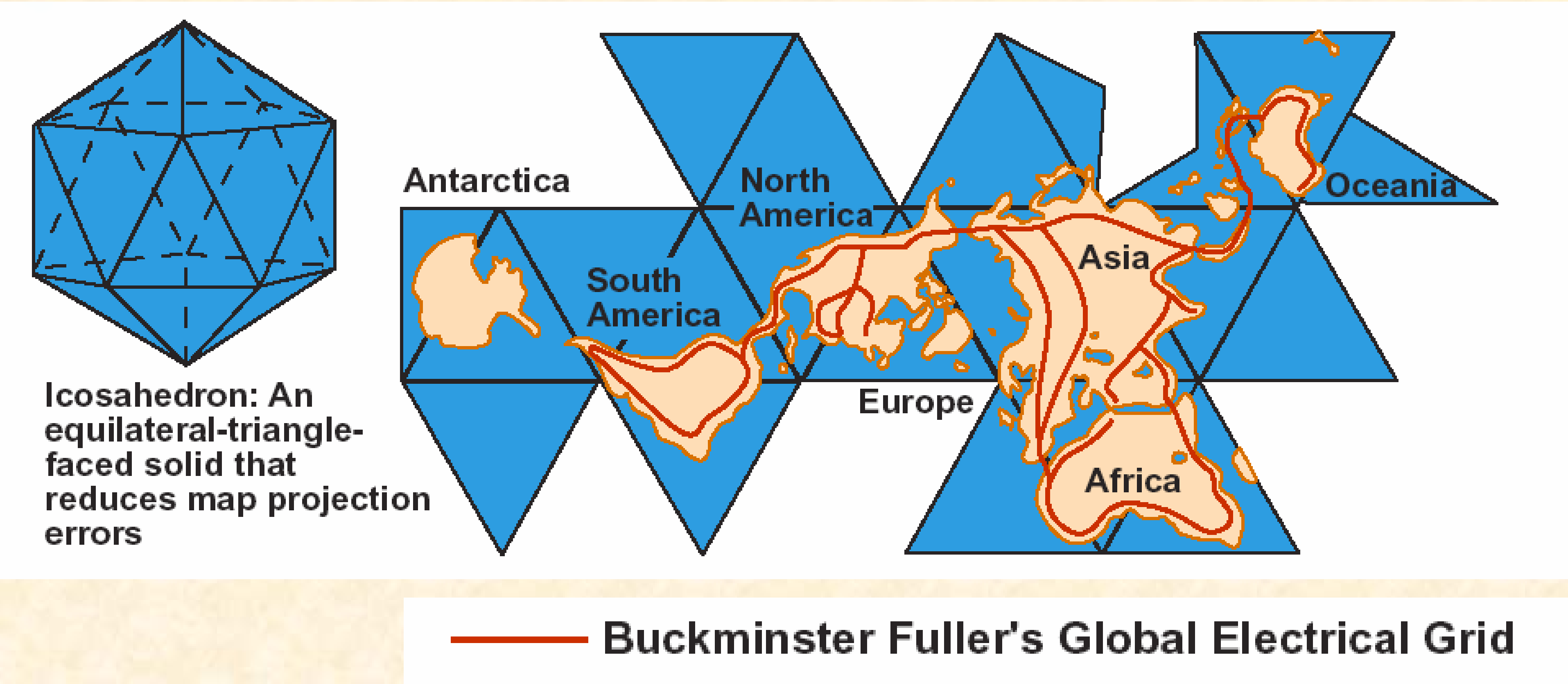
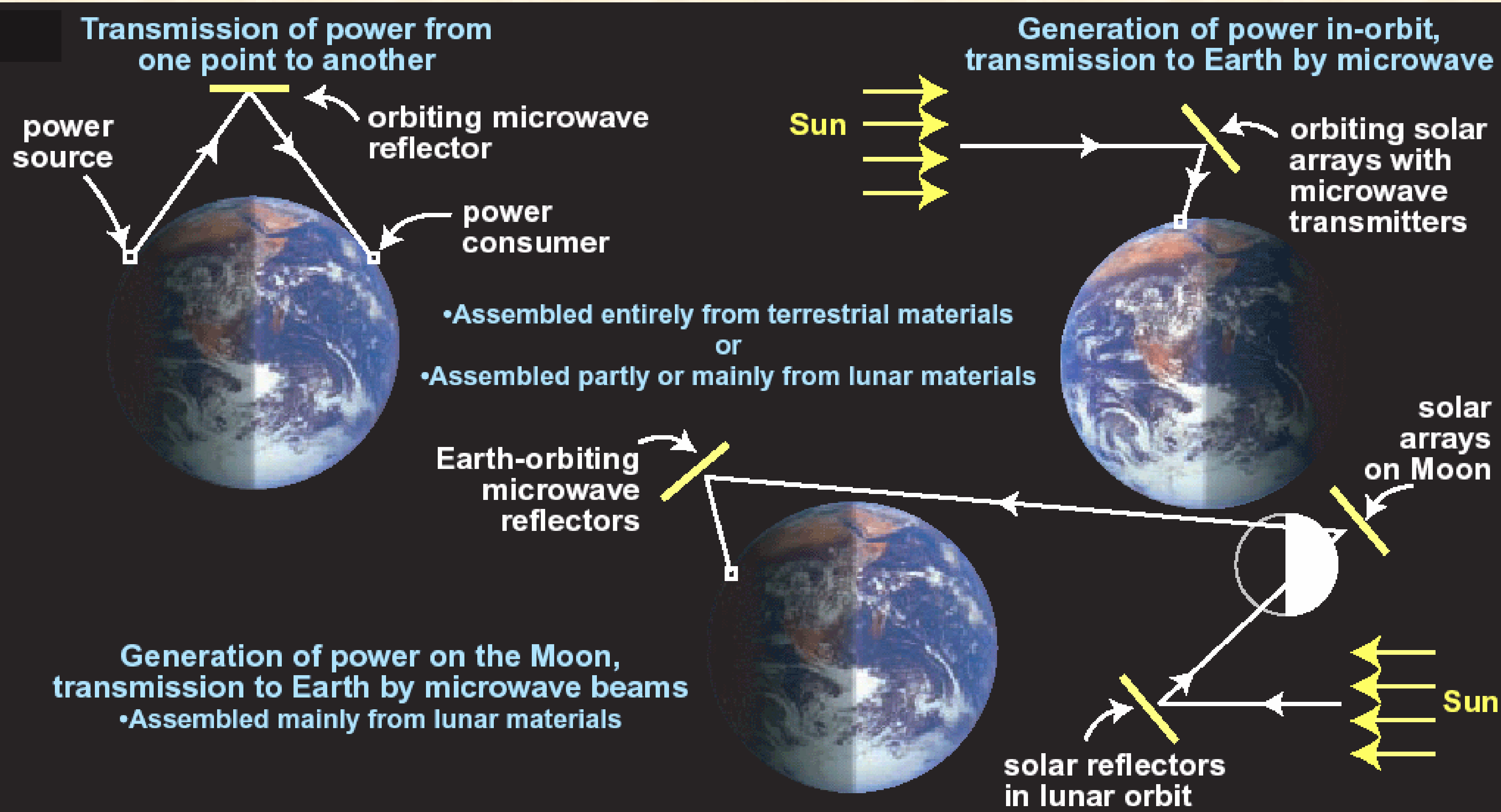


Electricity transmission and production in space



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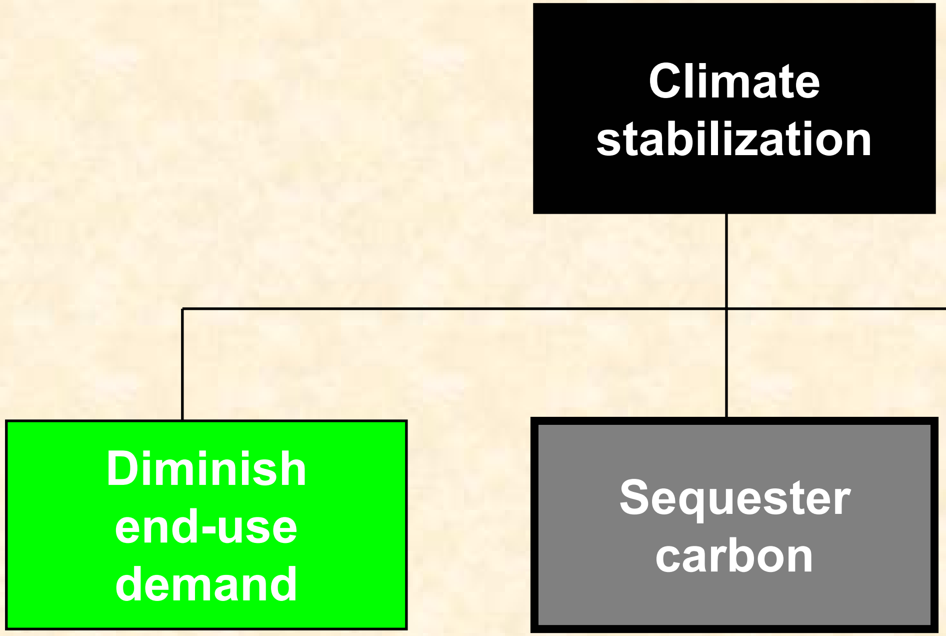

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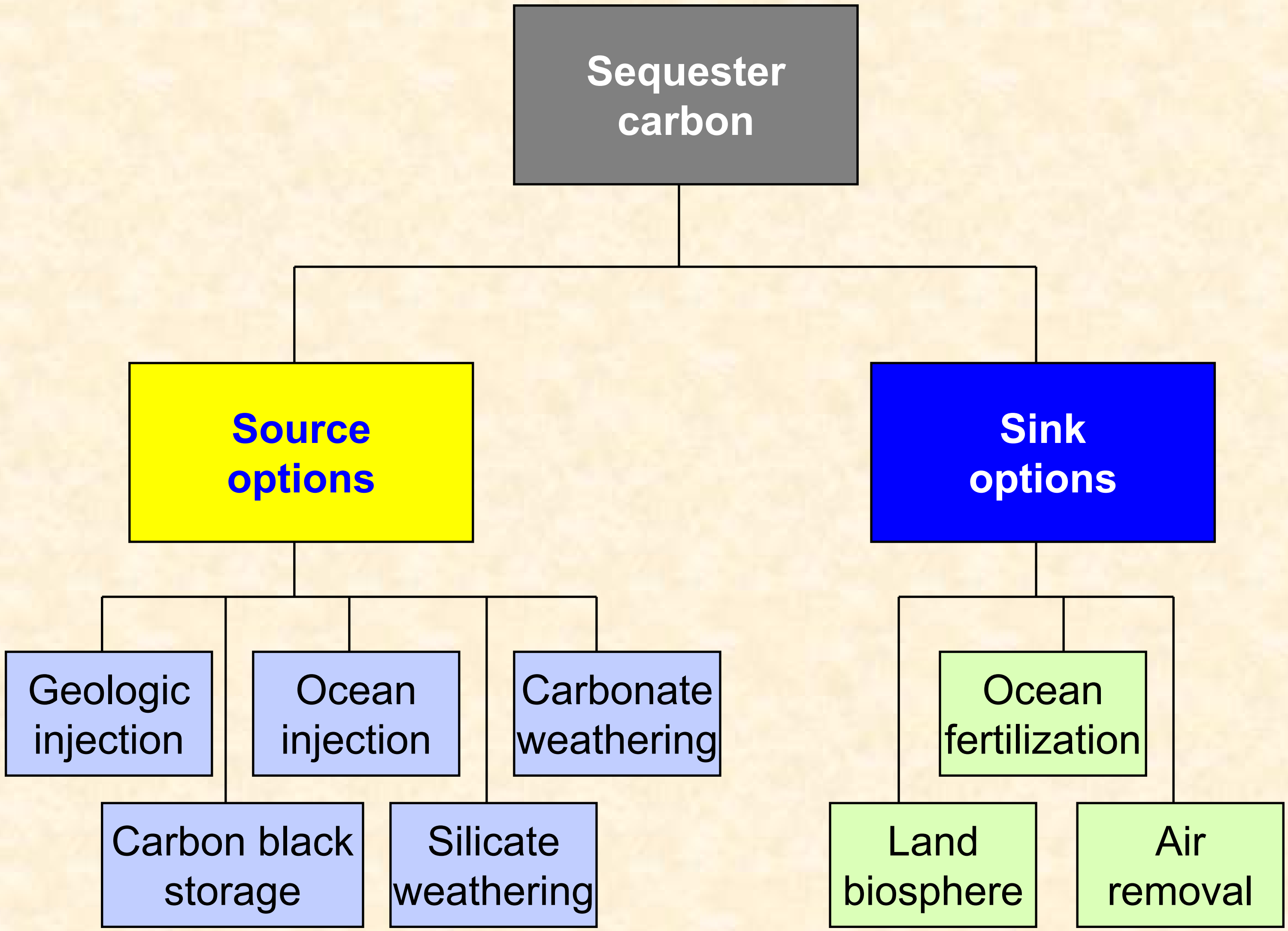
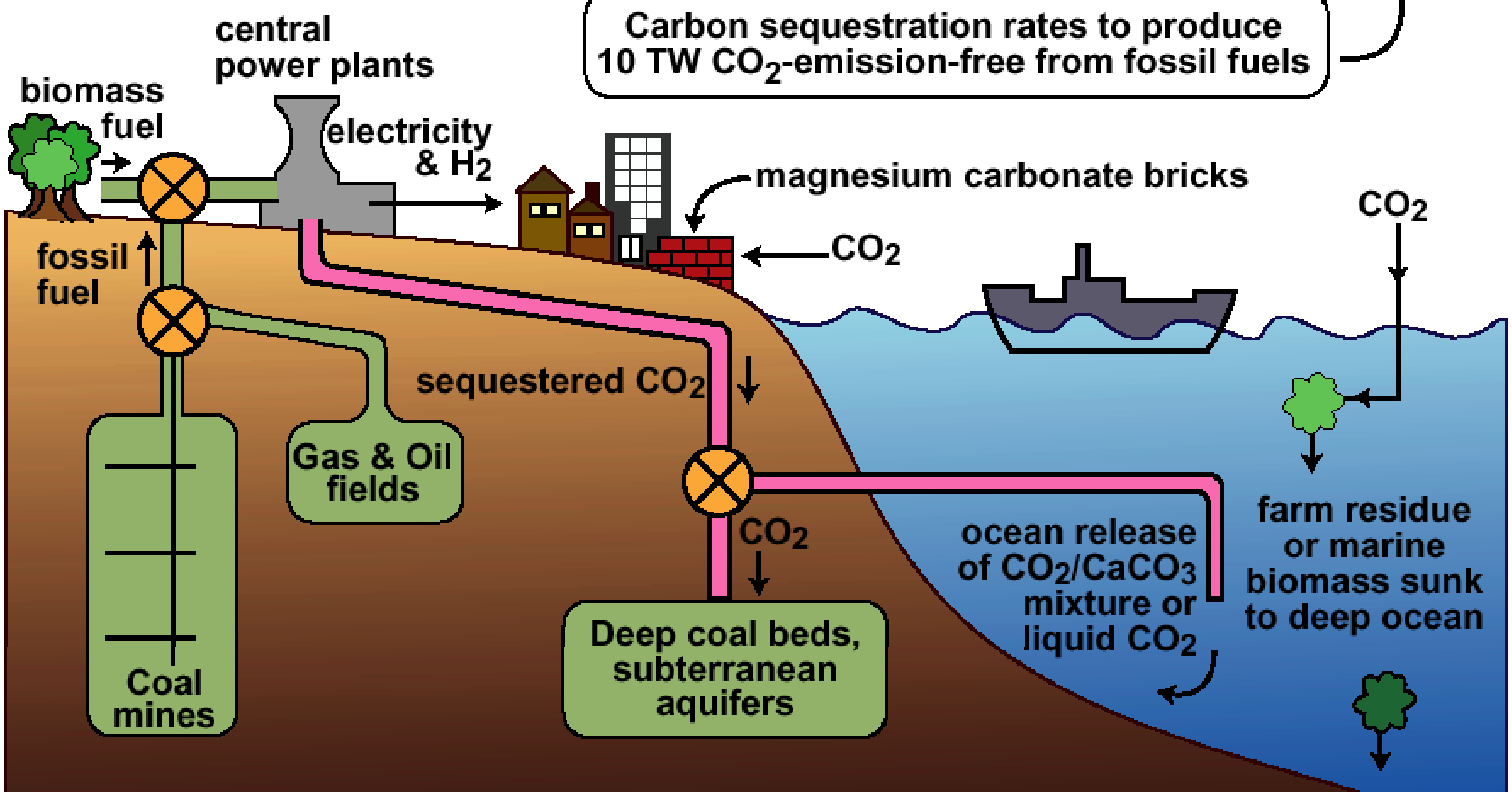
Carbon sequestration strategies



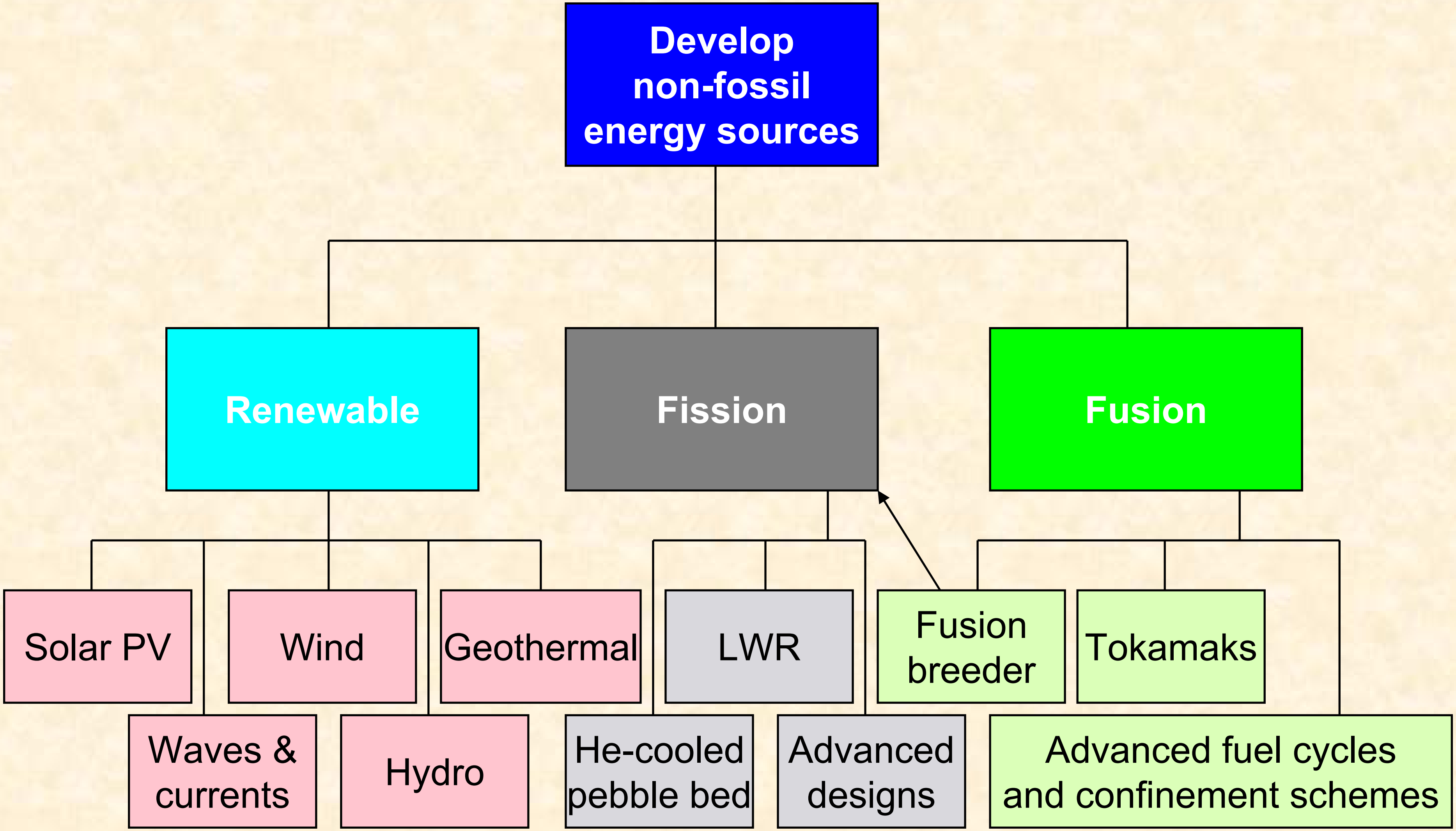
Carbon sequestration:
A carbon-emission-free fossil-fuel economy

Fossil fuel	Energy content [TW-yr]	Carbon content [GTC]	(E_{fuel}/C) [TW-yr/GtC]	(E/C) [TW-yr/GtC]	Sequestration rate [GtC/yr]
Gas	1200	570	2.1	1.9 - 1.6	5 - 6
Oil	1200	750	1.6	1.4 - 1.2	7 - 8
Coal	4800	3690	1.3	1.2 - 1.0	9 - 10

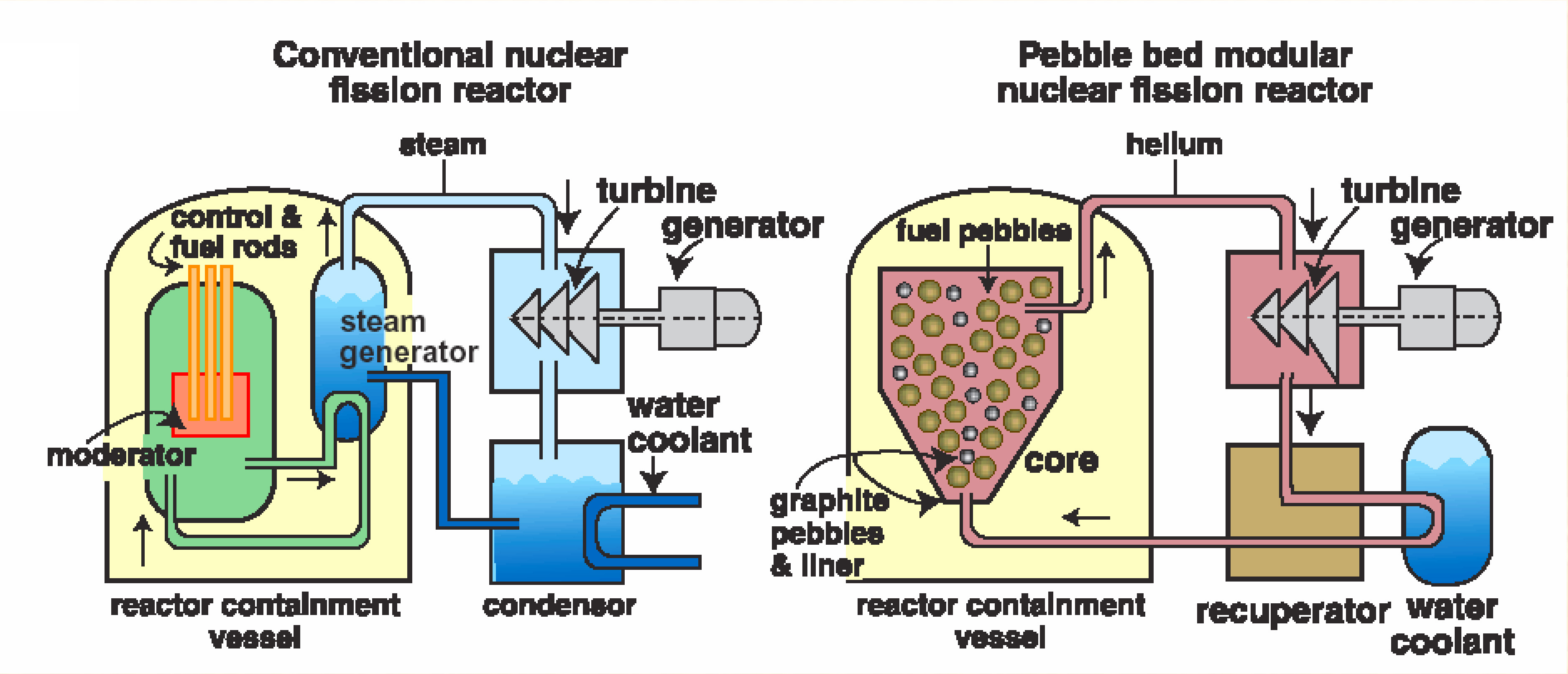
Carbon sequestration rates to produce 10 TW CO_2-emission-free from fossil fuels



Non-fossil energy strategies



Fission power



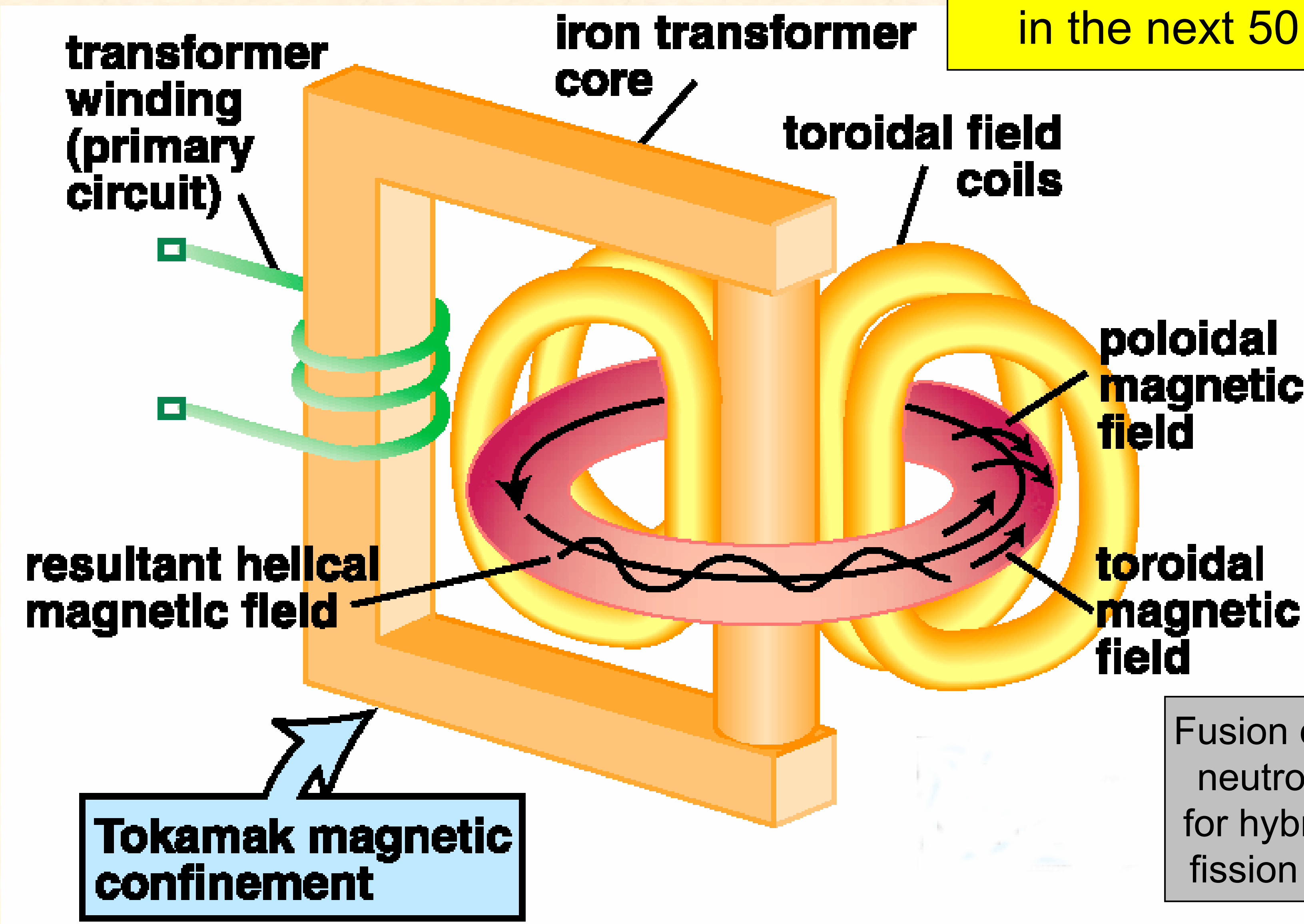
Known uranium reserves can provide 10 TW of power for less than 30 years
--> breeder reactors

Inherently safe reactor designs
Waste disposal
Recovery of ^{235}U from low-grade ores or seawater

Proliferation
Advanced breeding concepts

Fusion

Despite recent advances, fusion is unlikely to be a power source in the next 50 years



Fusion could be a neutron source for hybrid fusion/ fission breeders

Conclusions

- Very large amounts of carbon-emissions-free power will be needed to stabilize climate

- Only a portfolio of technologies and approaches can produce the tens of terawatts (TW_t) of carbon-emissions-free primary power needed in the next decades for economic growth

- We must research and develop ways to —

  - Improve the economic productivity of our energy use
  - Get more energy from renewable resources
  - Store energy and transmit it over long distances
  - Sequester carbon from fossil-fuels
  - Have safe and environmentally acceptable fission power
  - Get energy from fusion, and other advanced energy sources