Thermodynamics of Industrial Biofuels

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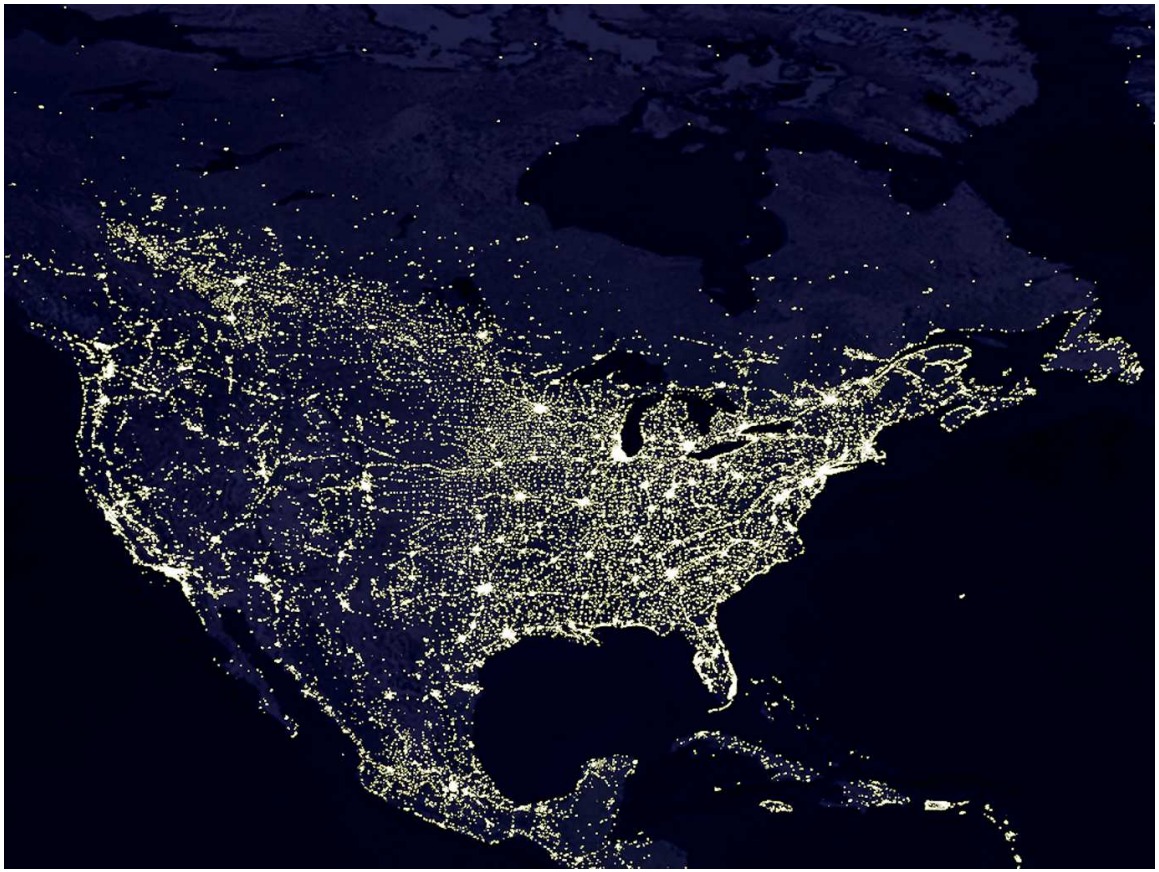
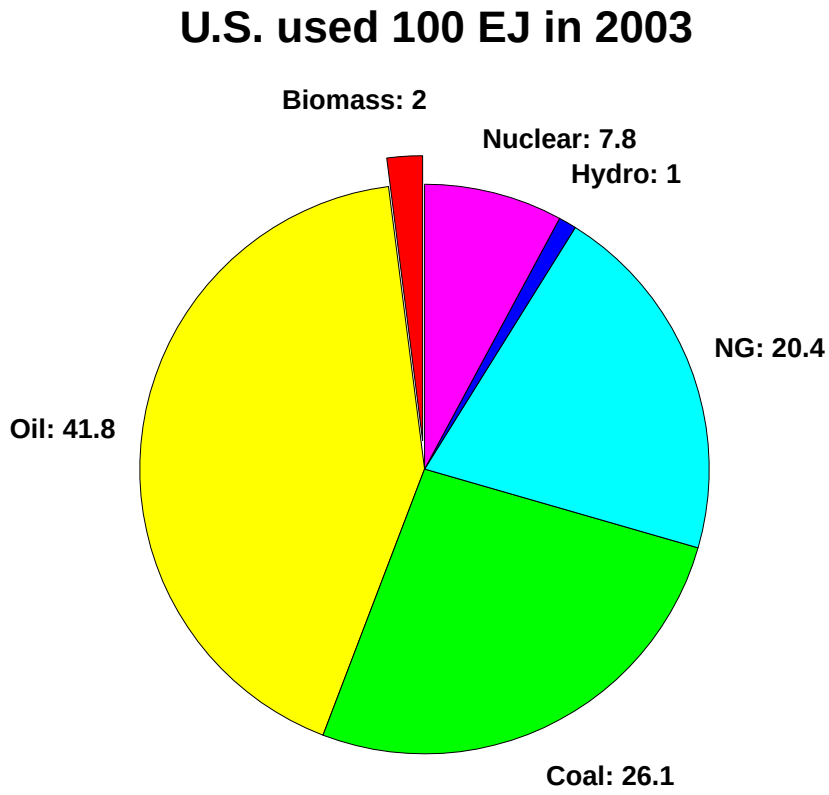
March 28, Solar to Fuel – Future Challenges and Solutions

Plan of Attack. . .

- In order to begin the Second Law analysis of a complex system, one should first master the First Law cumulative energy balance of that system
  - The linear First Law calculations are familiar to every scientist, engineer, and economist
  - The Second Law calculations require switching to the less-familiar cycles
- We start from the First Law consequences of producing ethanol from all U.S. corn. . .

Primary Energy Use by U.S.



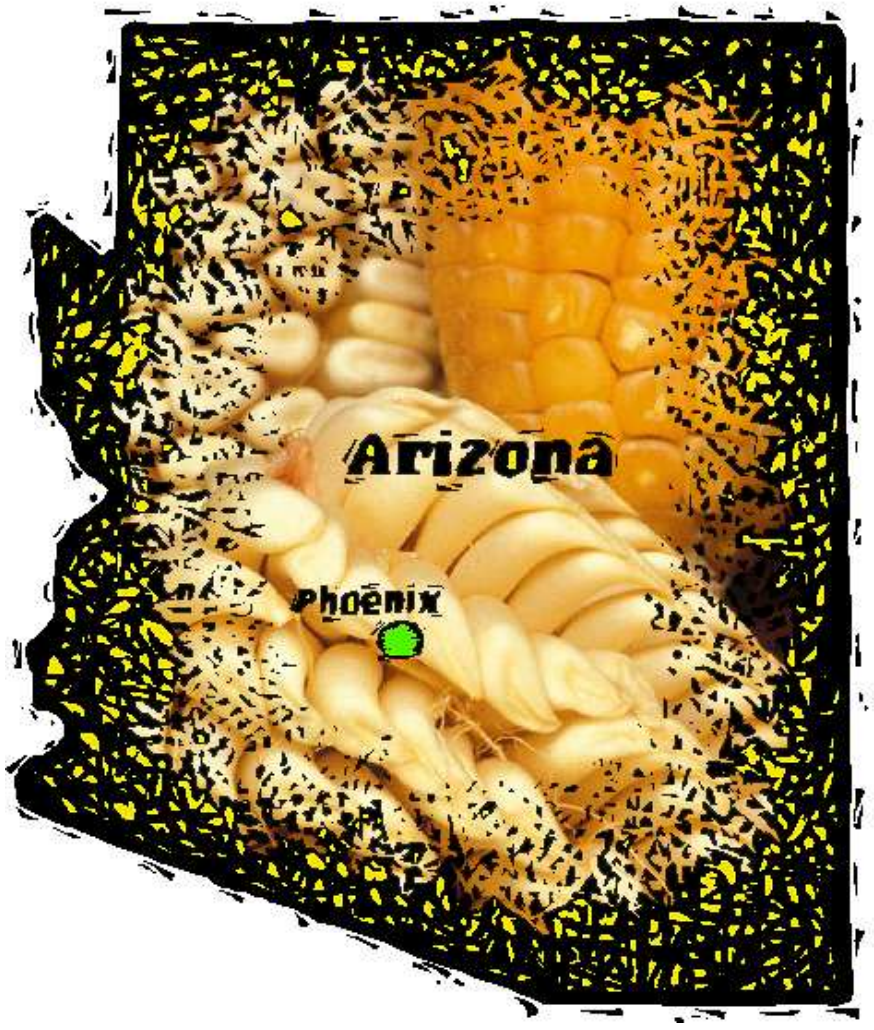


1 EJ = 1 000 000 000 000 000 000 Joules is enough to feed the U.S. population for one year

Maximum Ethanol from All Corn

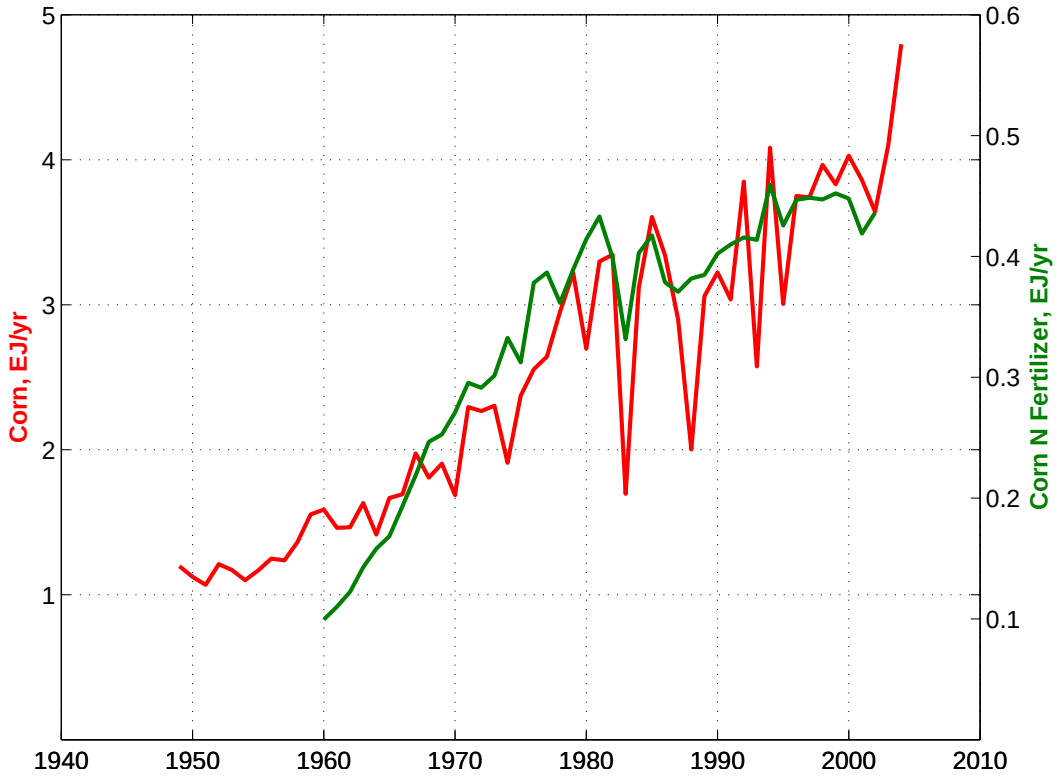
In 2004, U.S. had the best corn crop ever

- Corn grain was harvested from an area of 300 000 km^2 (equal to Arizona state)
- 300 million tonnes of grain were harvested (almost $6\times$wheat)
- As maximum ethanol, this crop would be 1/7 of the 19 EJ/year consumed as motor gasoline
- But at what cost in fossil fuels and environmental damage?



Corn Yield and N-Fertilizer

- 40% of all fertilizer in the U.S. is used to grow corn
- 100 MJ of free energy are consumed to produce 1 kg of nitrogen in fertilizer
- Huge problems with air and water pollution



Nitrogen fertilizer = methane (80% of cost in NG, 66% imported in 2003)

Sources: USDA NASS, NFI, PNAS **96**, Feb. 1999

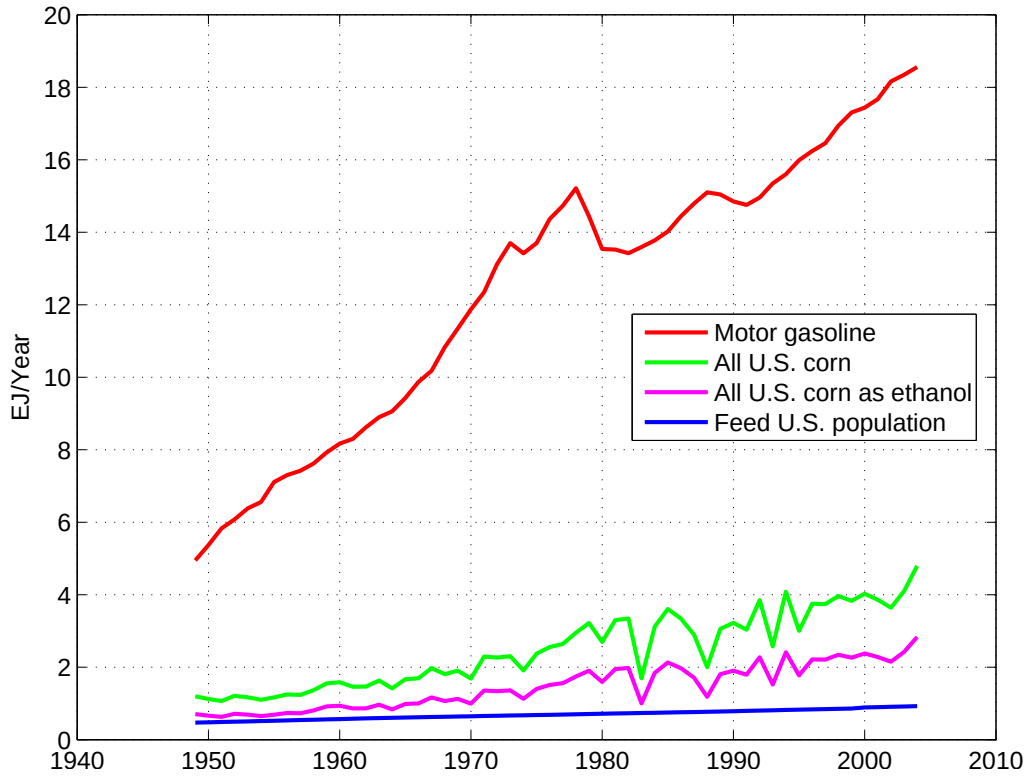
Watering U.S. Corn

480 km^3 of water in Lake Erie, 300 km^3 to water U.S. corn crop each year

15-20% in irrigation water from, e.g., the High Plains aquifer

U.S. Gasoline Consumption and Corn

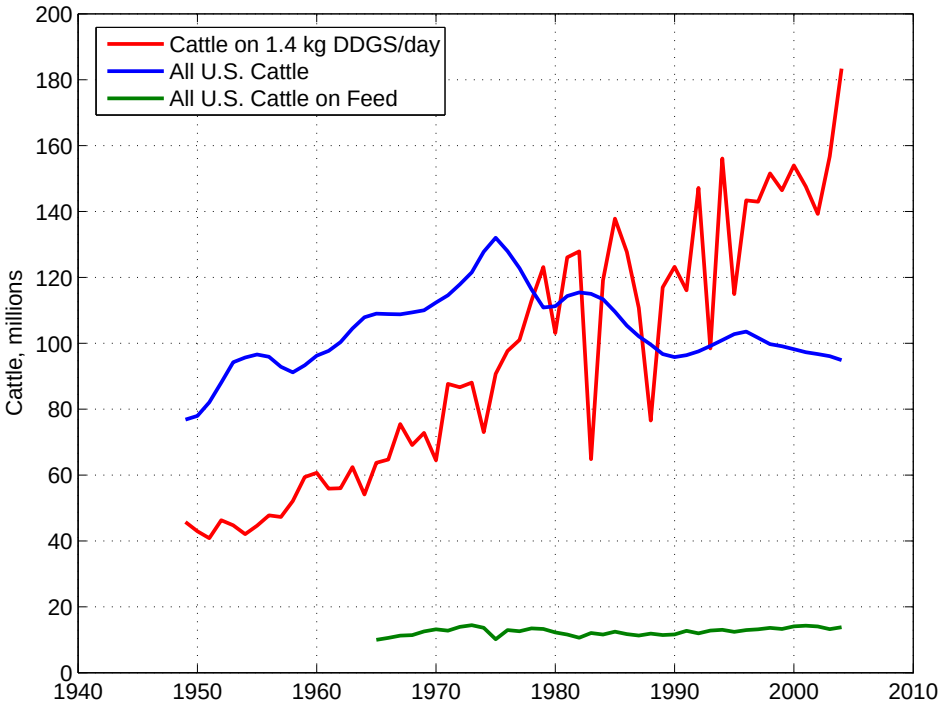
- 15% of U.S. gasoline consumption is replaceable with maximum corn grain ethanol
- To produce this maximum ethanol, we would use an equivalent of 15.5% of U.S. gasoline



Corn ethanol = methane + gasoline + diesel fuel + LPG + coal + machines + insecticides + herbicides + soil nutrients + water + corn

Sources: DOE EIA, USDA NASS, U.S. Census Bureau

Dried Distiller's Grain & Solubles

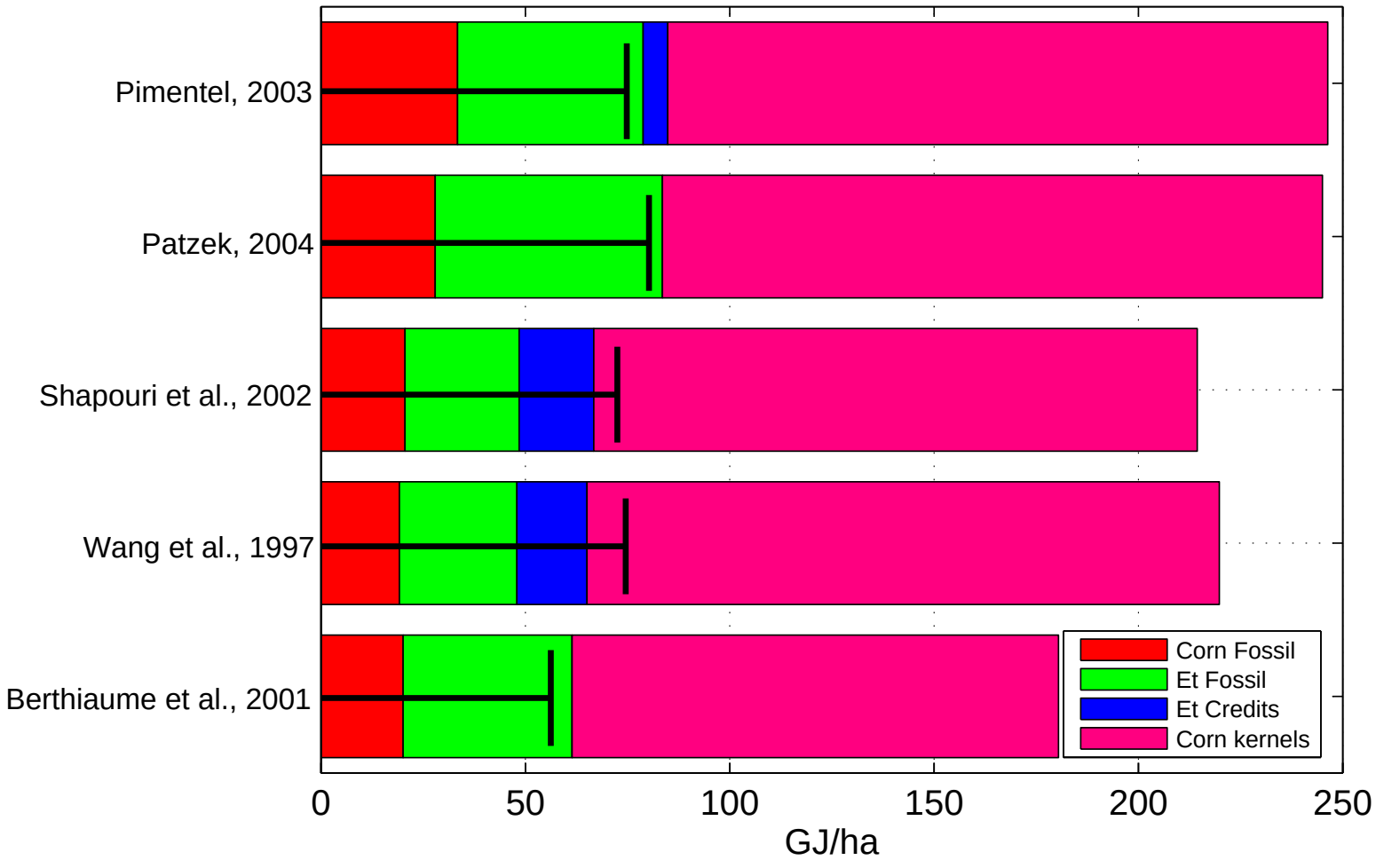


0.3 kg DDGS per 1 kg of moist corn grain is a byproduct of EtOH production

Feed 180 million cows with 90 million tonnes of DDGS, or return it to the fields

Sources: USDA NASS, Kansas State University

Overall Energy Balance…

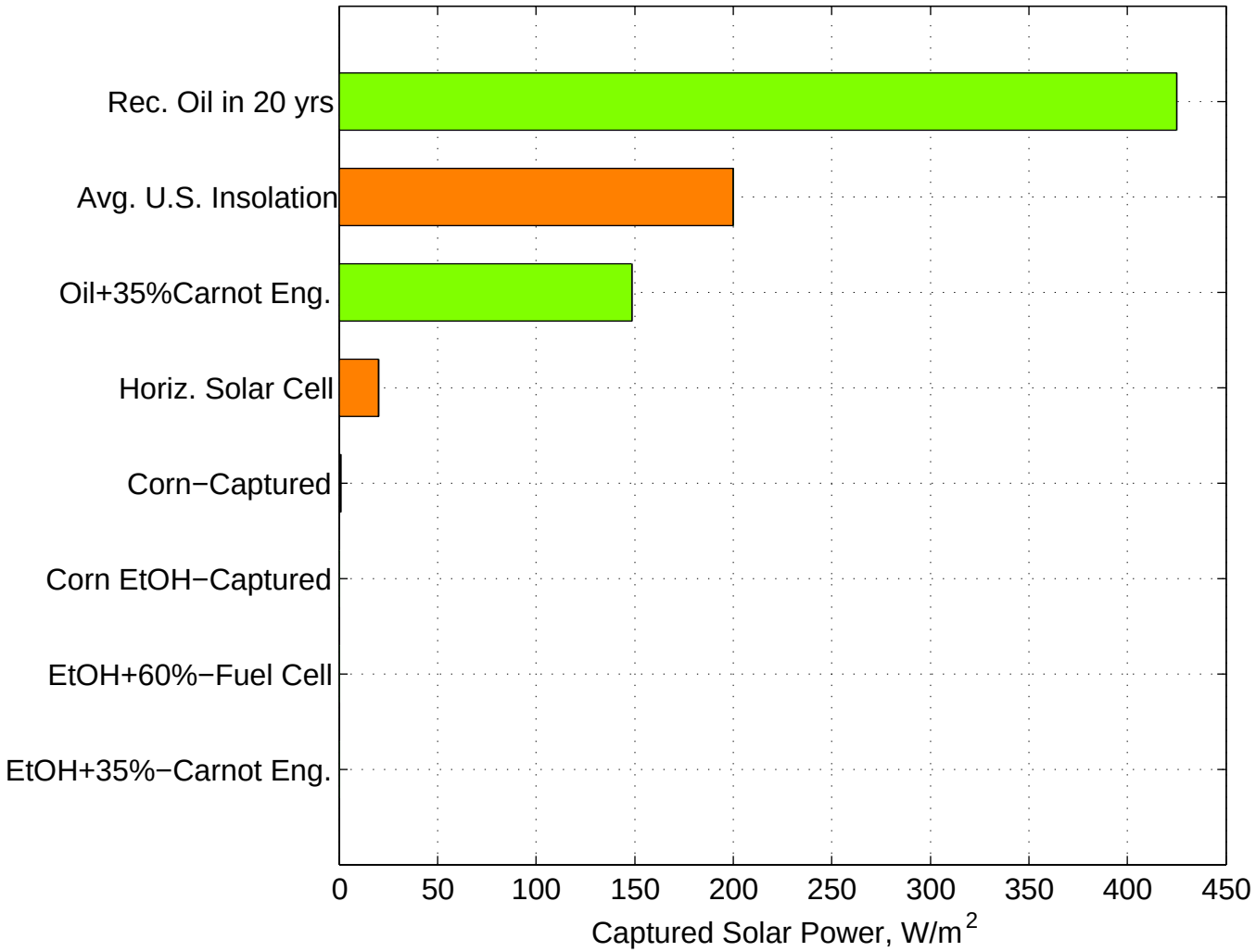


Conclusion: Drawbacks Exist!

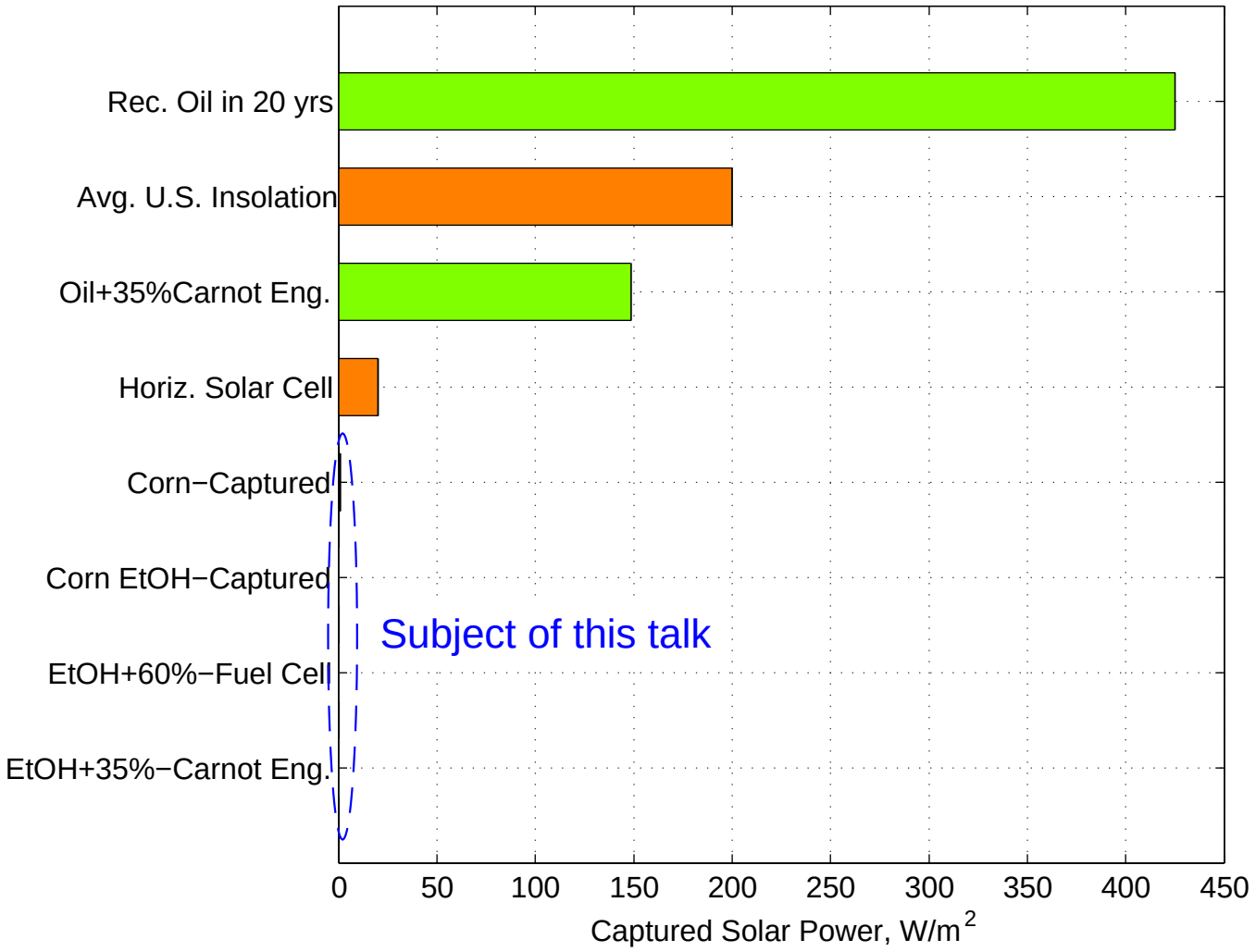
By converting the U.S. corn grain to ethanol, we have

- Denied food to the entire population of U.S. and India for one year
- Used up huge quantities of natural gas, gasoline, diesel fuel, liquified petroleum gas, coal, and also water and soil
- Energy content of these fossil fuels exceeded the energy content of corn ethanol by 5%, water was polluted, and there were large atmospheric emissions

Available Free Energy…



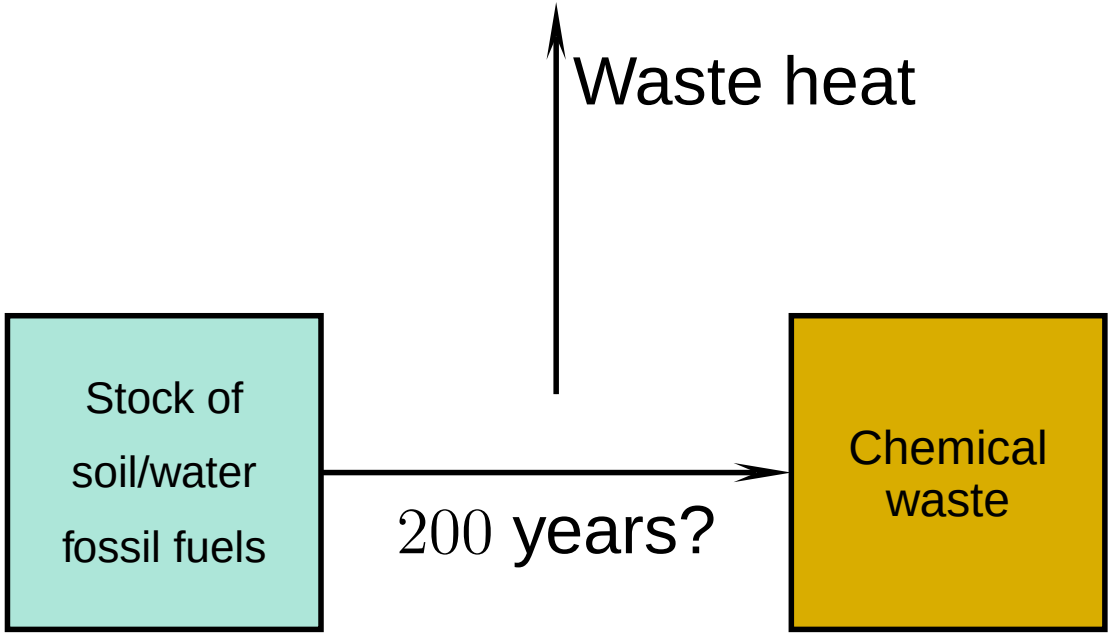
Available Free Energy…



Talk Outline. . .

- Linear process vs cycle
- Reversible and sustainable cycles
- Corn-Ethanol cycle
- Restoration work of nonrenewable resources
- Tropical Plantations
- Conclusions

Industrial Agriculture. . .



Definition of Irreversibility…

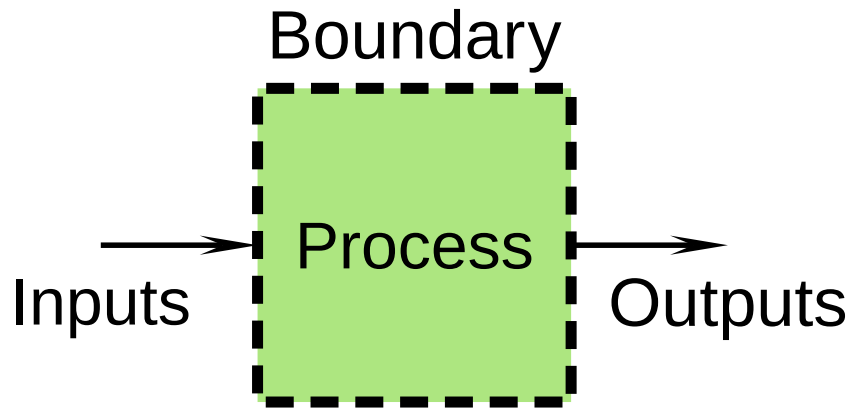
- **Max Karl Ernst Ludwig Planck**, 1926: A process is irreversible if it can in *no* way be reversed, all other processes are reversible

- It is impossible, even with the assistance of all agents in nature, to restore everywhere the exact initial state when the irreversible process has once taken place

Corrolaries. . .

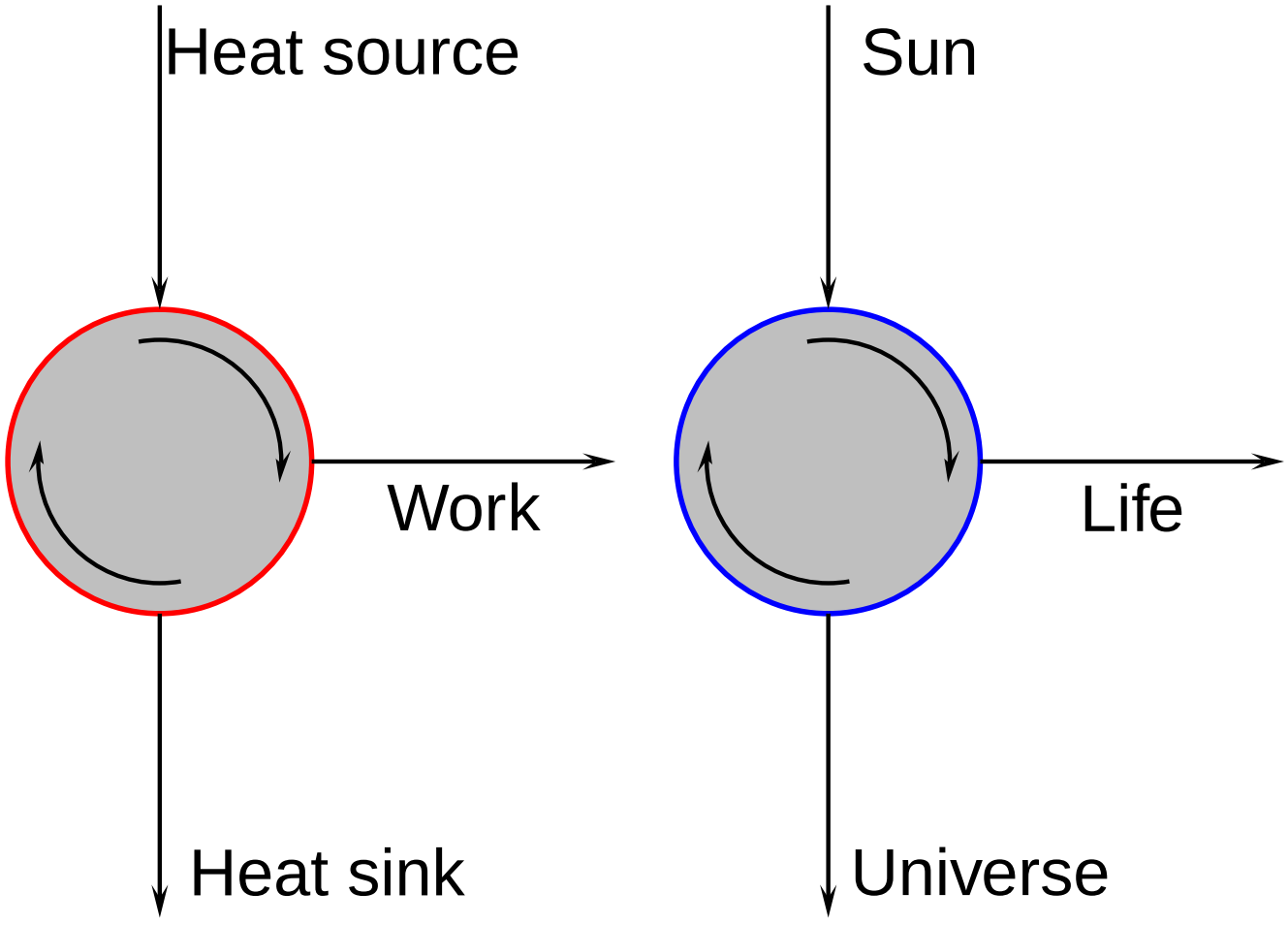
- A linear process that converts low entropy of fossil fuels into waste is irreversible and *cannot* be sustainable
- The linear fossil fuel process accumulates chemical entropy in the earth and the atmosphere, and irreversibly degrades our planet on a *time scale* of our civilization, measured in hundreds of years
- **Modern agriculture, with its reliance on mining fossil fuels, soil, water and air, is irreversible and unsustainable**

Corrolaries. . .

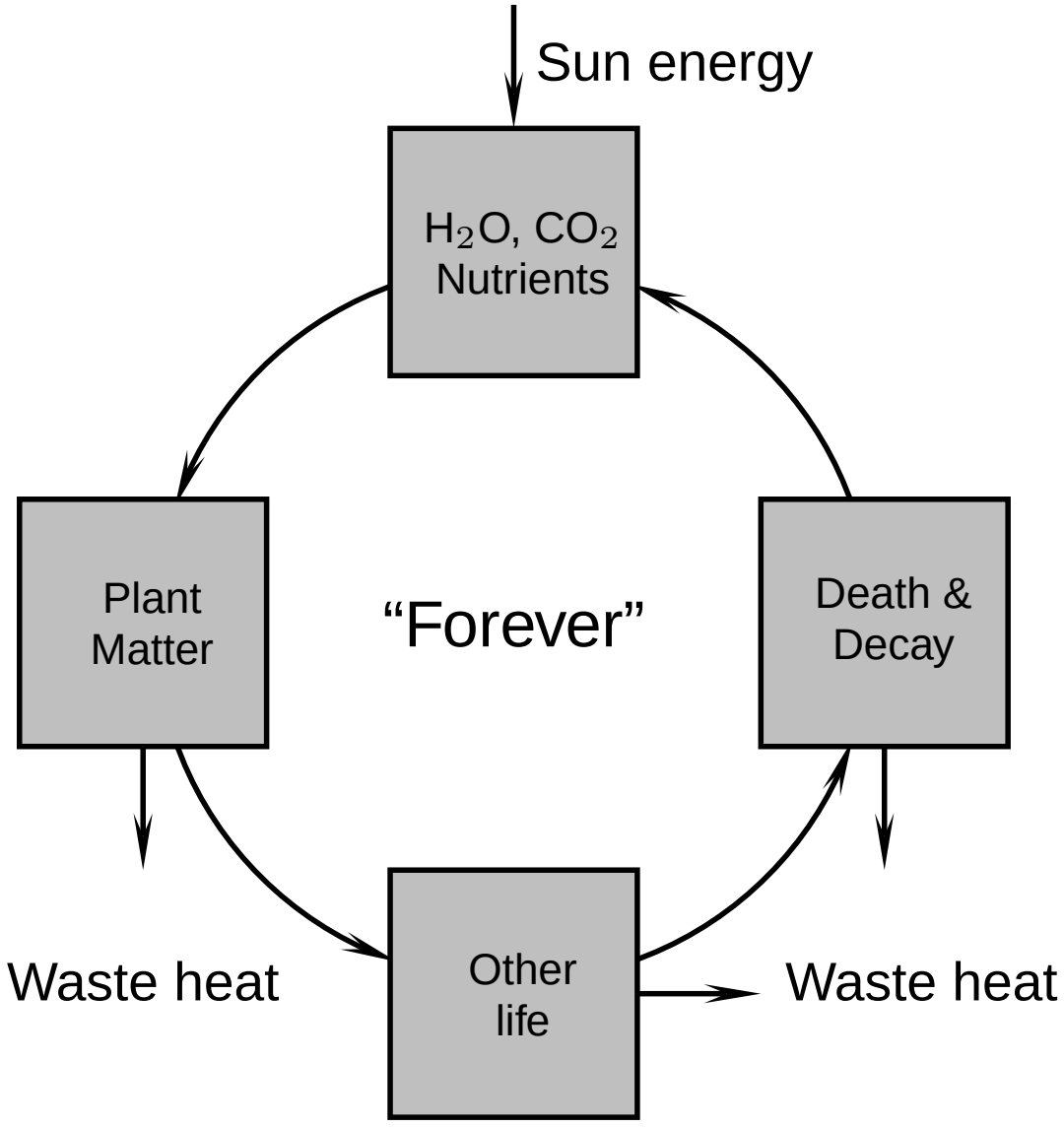


- All human processes interact with the “environment”
- A sustainable process cannot be *linear*, therefore it must be a cycle

Thermal Cycles. . .



Ecological Cycles. . .



Sustainability…

A cyclic process is sustainable if and only if

- It is capable of being *sustained*, *i.e.*, maintained without interruption, weakening or loss of quality "forever," and
- The *environment* on which this process feeds and to which it expels its waste is also sustained "forever"

Corrolaries. . .

- A sustainable cyclic process **must not** reject chemicals into the environment, *i.e.*, its net mass consumption and production must be “close” to zero “forever”

- A sustainable cyclic process must not reject heat into the environment at a rate that is too high for the earth to export this heat to the universe; otherwise, the environment properties will change

Available Energy or Exergy...

Our standard of life is maintained by the exploitation of natural resources that have accumulated in the earth over millions of years

A natural resource whose chemical composition differs most from the dead states of the elements comprising it, is most valuable

Available Energy or Exergy...

Relative to a datum environment ($T_0 = 25^0$ C, 1 atm), the quality of heat rejected by a process depends on temperature:

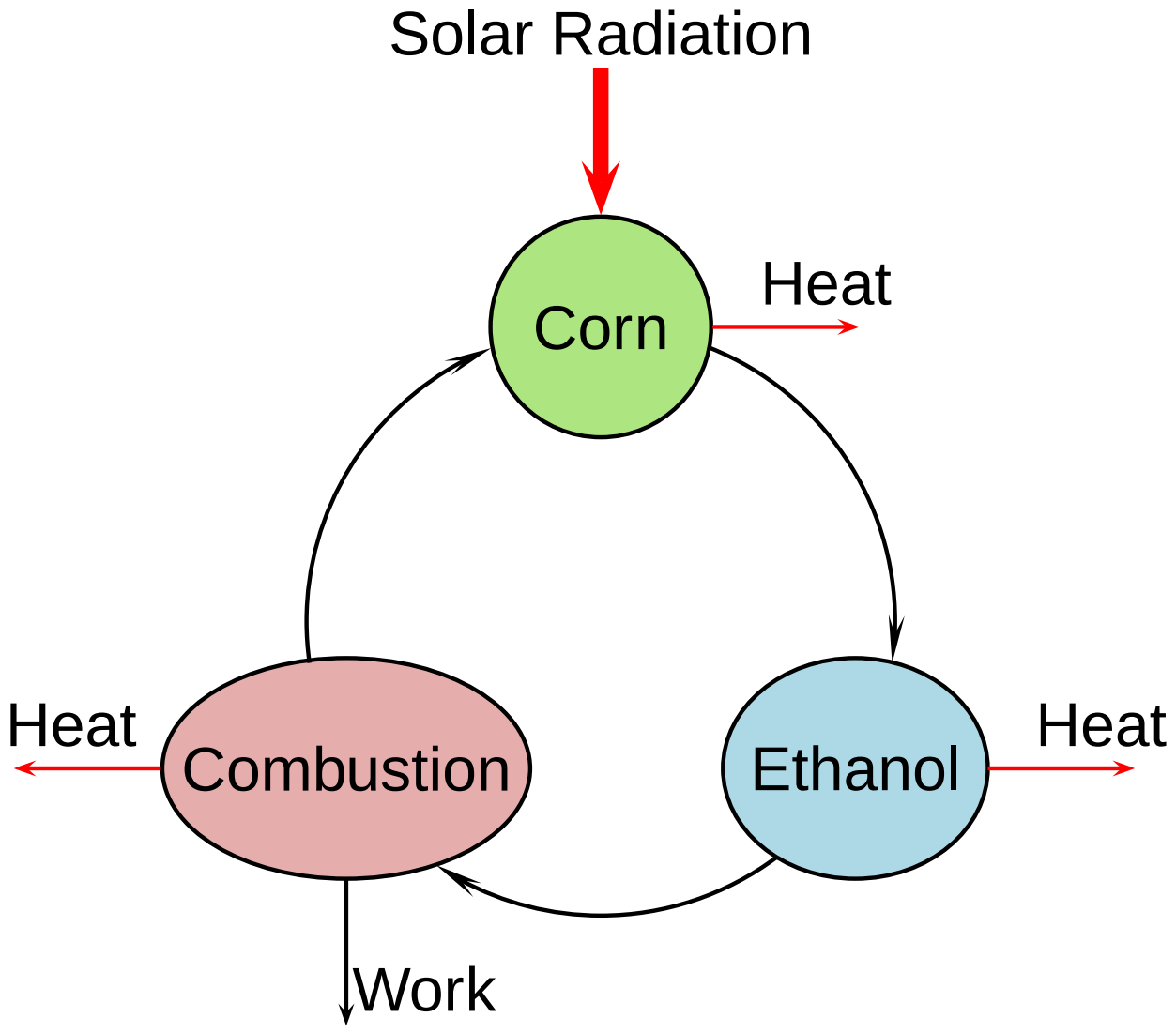
1J of heat at 500^0C $= 0.614$ J of work

1J of heat at 50^0C $= 0.077$ J of work

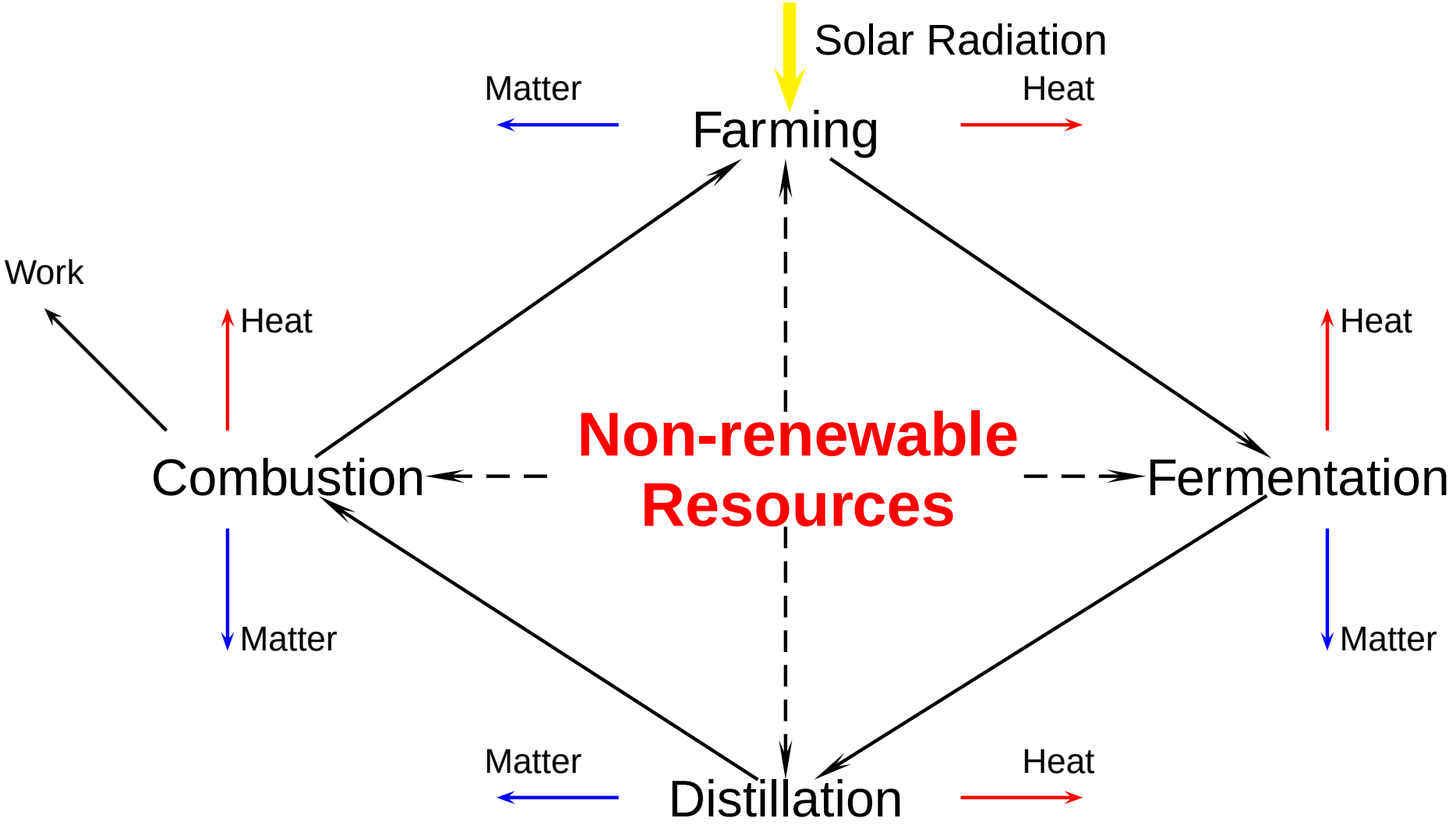
Exergy...

LUDWIG RIEKERT (1975): Exergy, B, is the shaft work or electrical energy necessary to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged with the environment at constant temperature T_0

Ideal Corn-Ethanol Cycle. . .



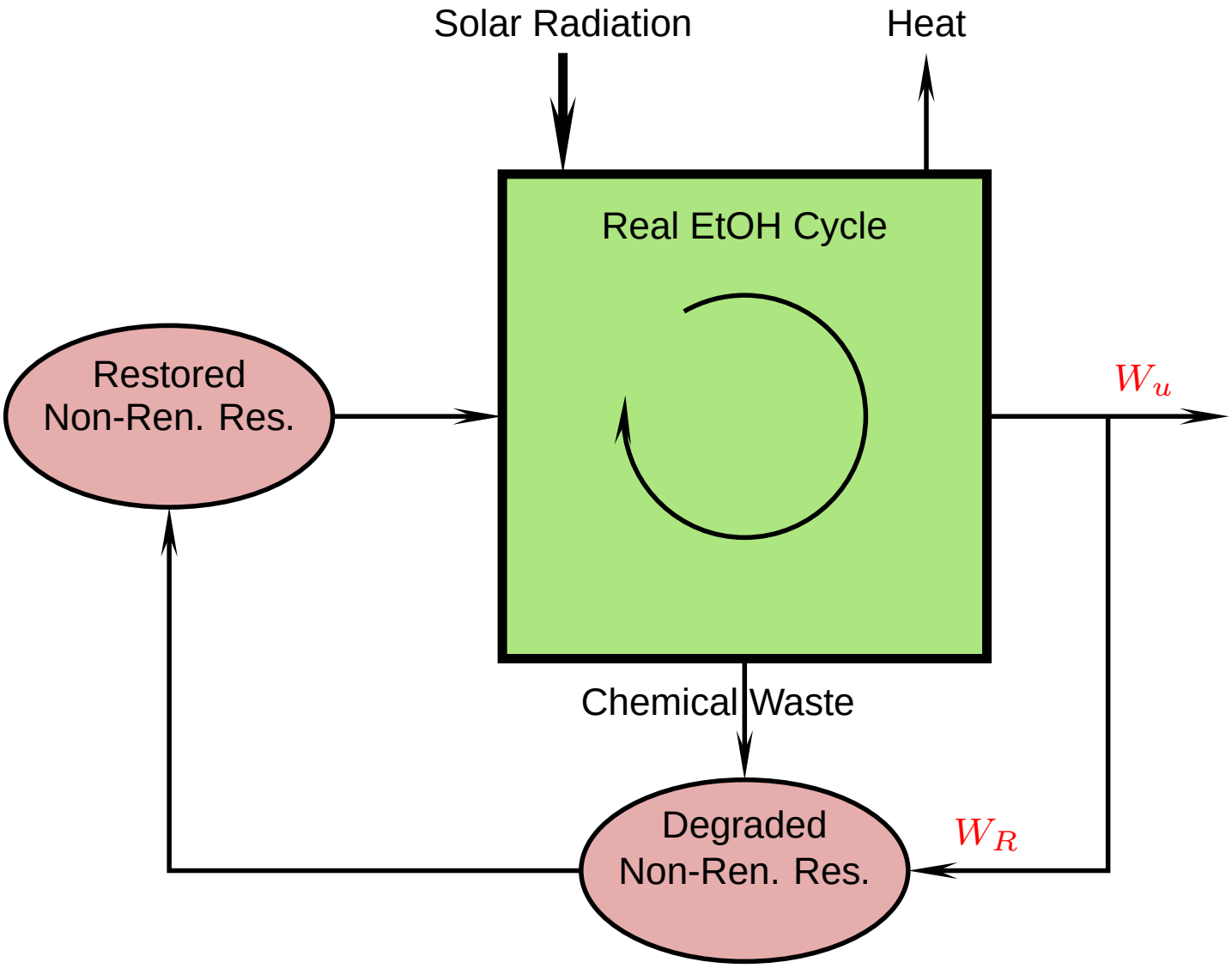
Real Corn-Ethanol Cycle. . .



CExC...

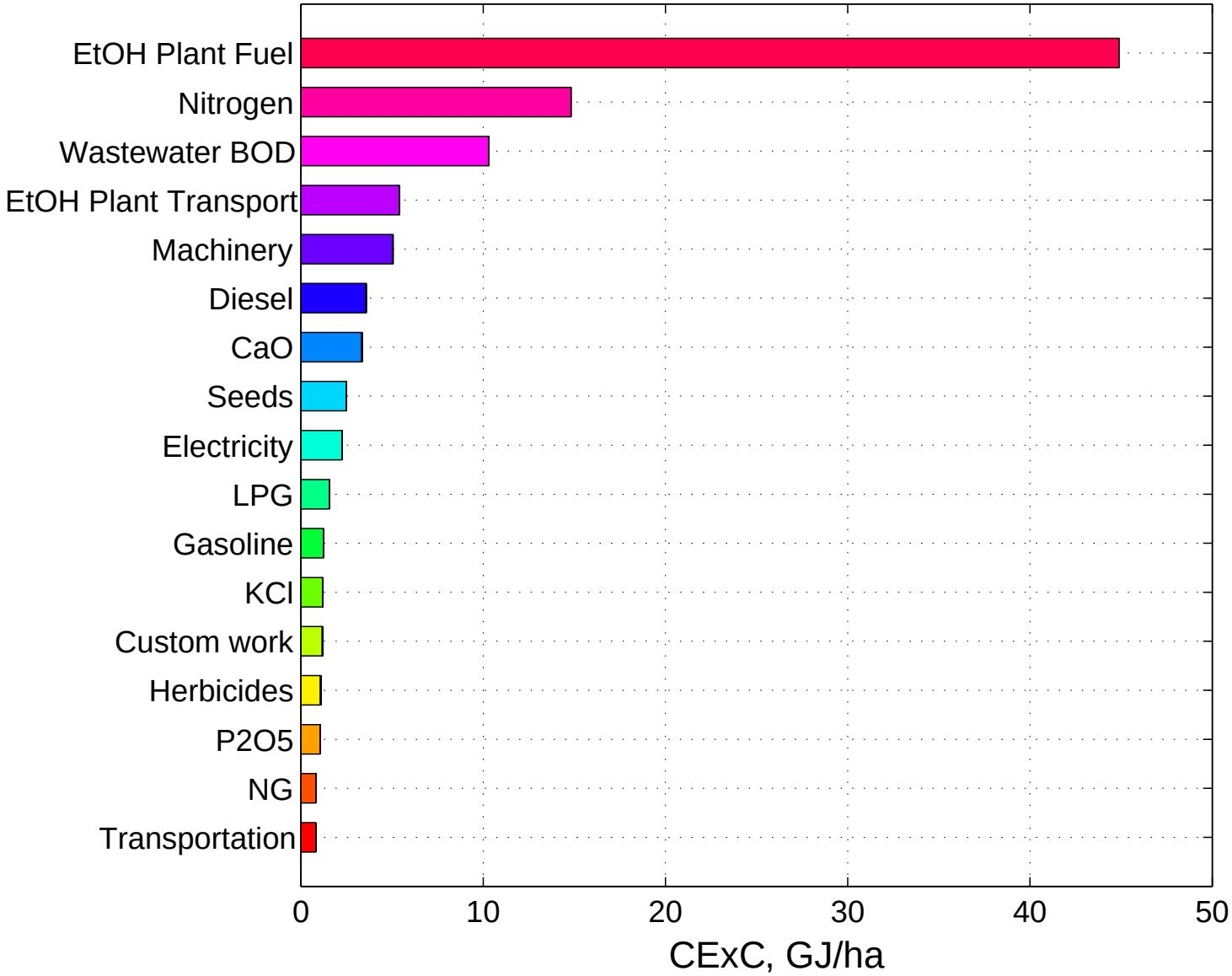
- All the steps of a production process leading from natural resources taken from the environment to the final product result in exergy losses
- The cumulative exergy consumption (CExC) is the sum of the exergy of all natural resources in all the steps of a production process
- The problem of cumulative energy consumption (CEnC) is better known, but calculation of CExC is more informative as it accounts for the exergy of non-energetic raw materials (soil, water, air) extracted from the environment

Restoration work. . .

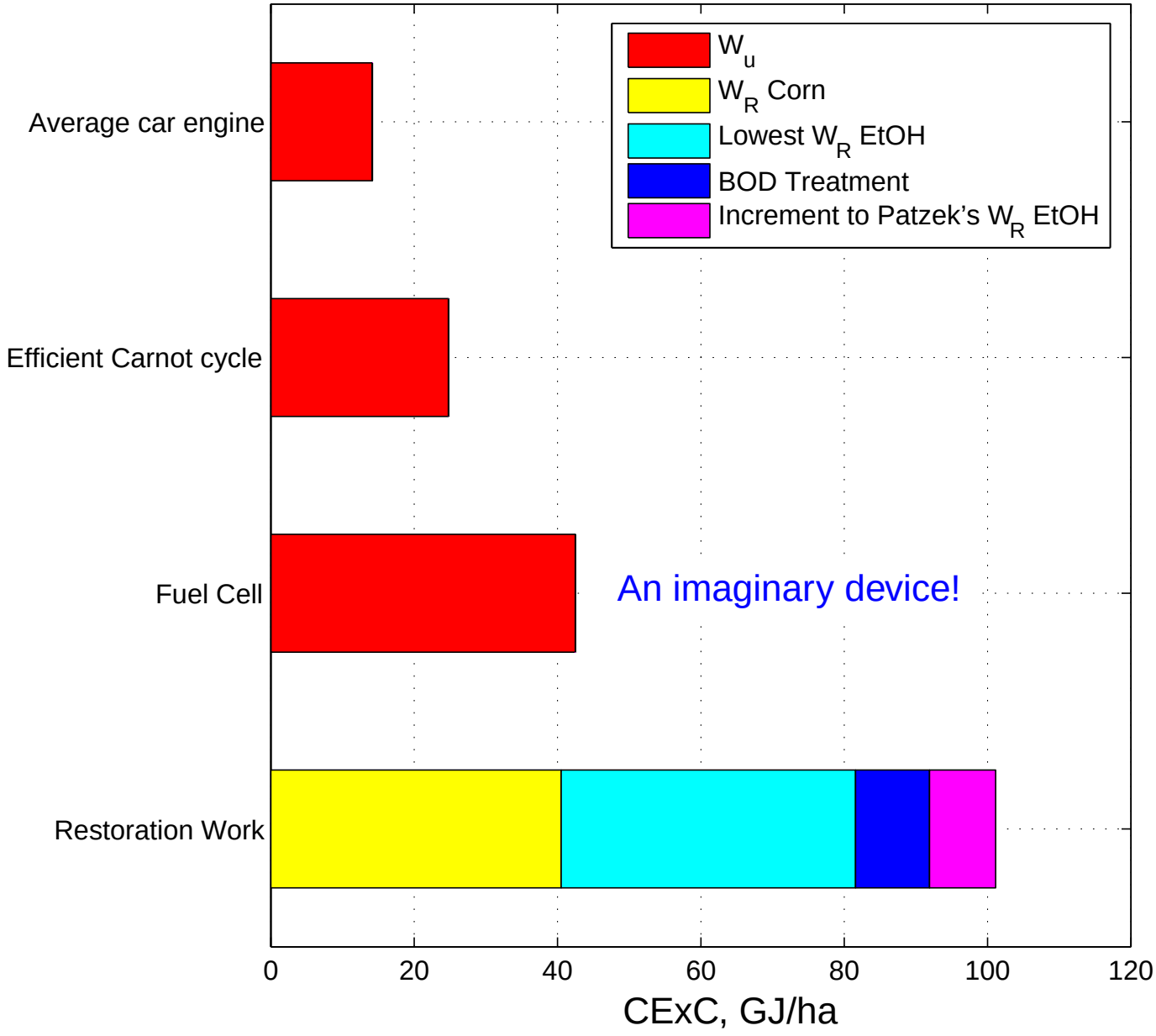


If $W_u > W_R$, there is benefit from a biofuel cycle. But is it?

Restoration Work…



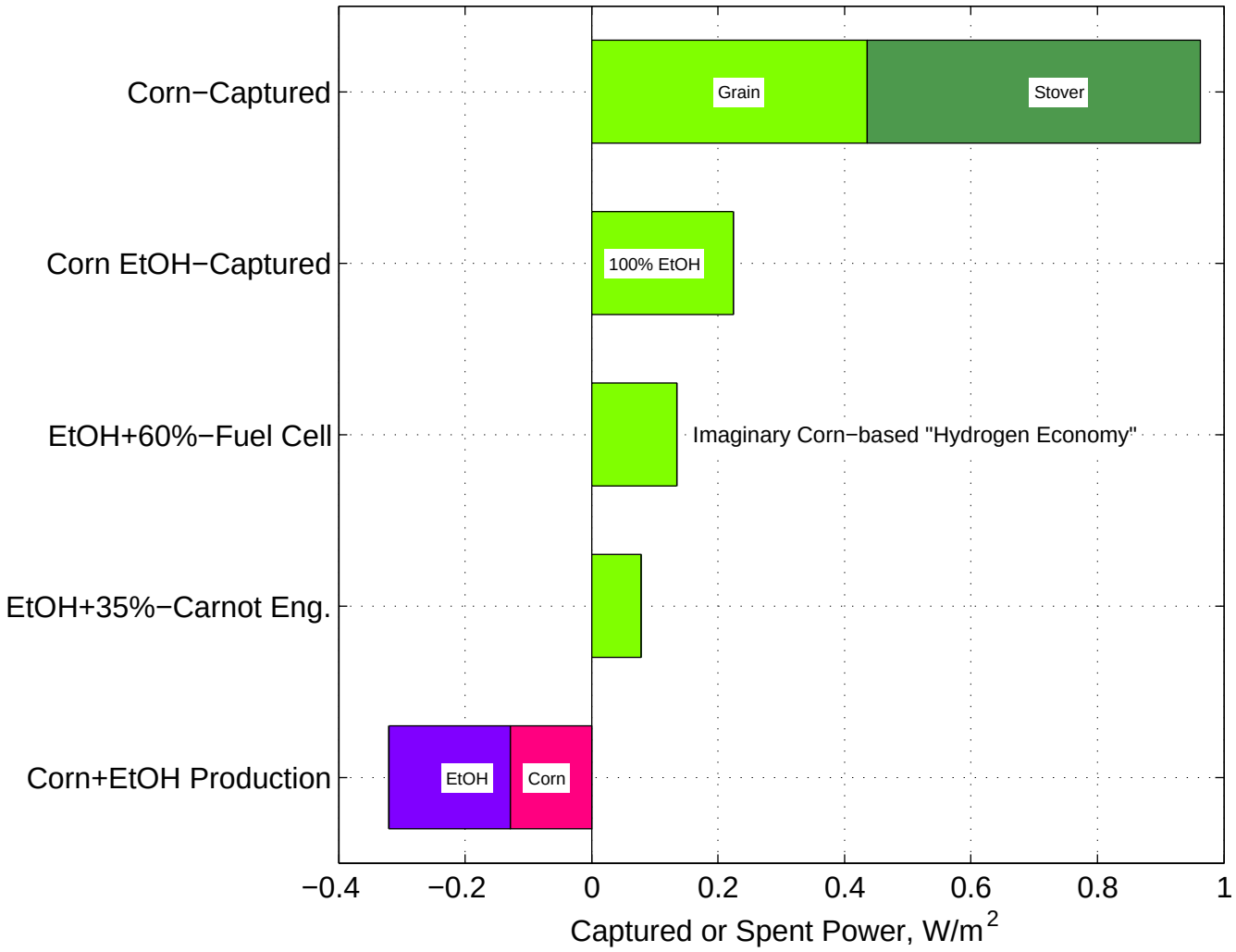
Overall Exergy Balance…



Conclusions. . .

- The *minimum* cumulative exergy consumption in restoring the environment polluted and depleted by the industrial corn-ethanol cycle is over 7 times higher than the *maximum* shaft work of a car engine burning the cycle's ethanol
- This unfavorable ratio decreases to 4, when an efficient CARNOT engine is used to burn the ethanol, and to over 2.4 when an imaginary hydrogen fuel cell is used
- The industrial corn cycle is not renewable, and is unsustainable by a wide margin (400-700%)
- No process changes can make this cycle more viable

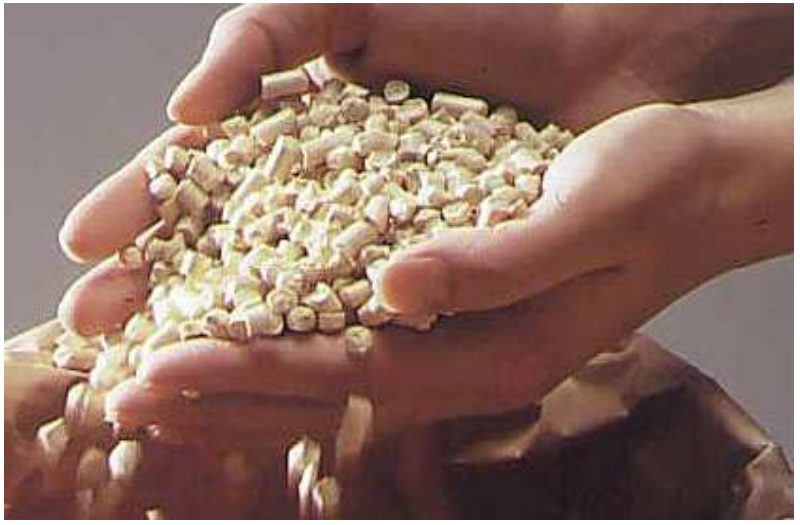
Exergy from U.S. Corn. . .



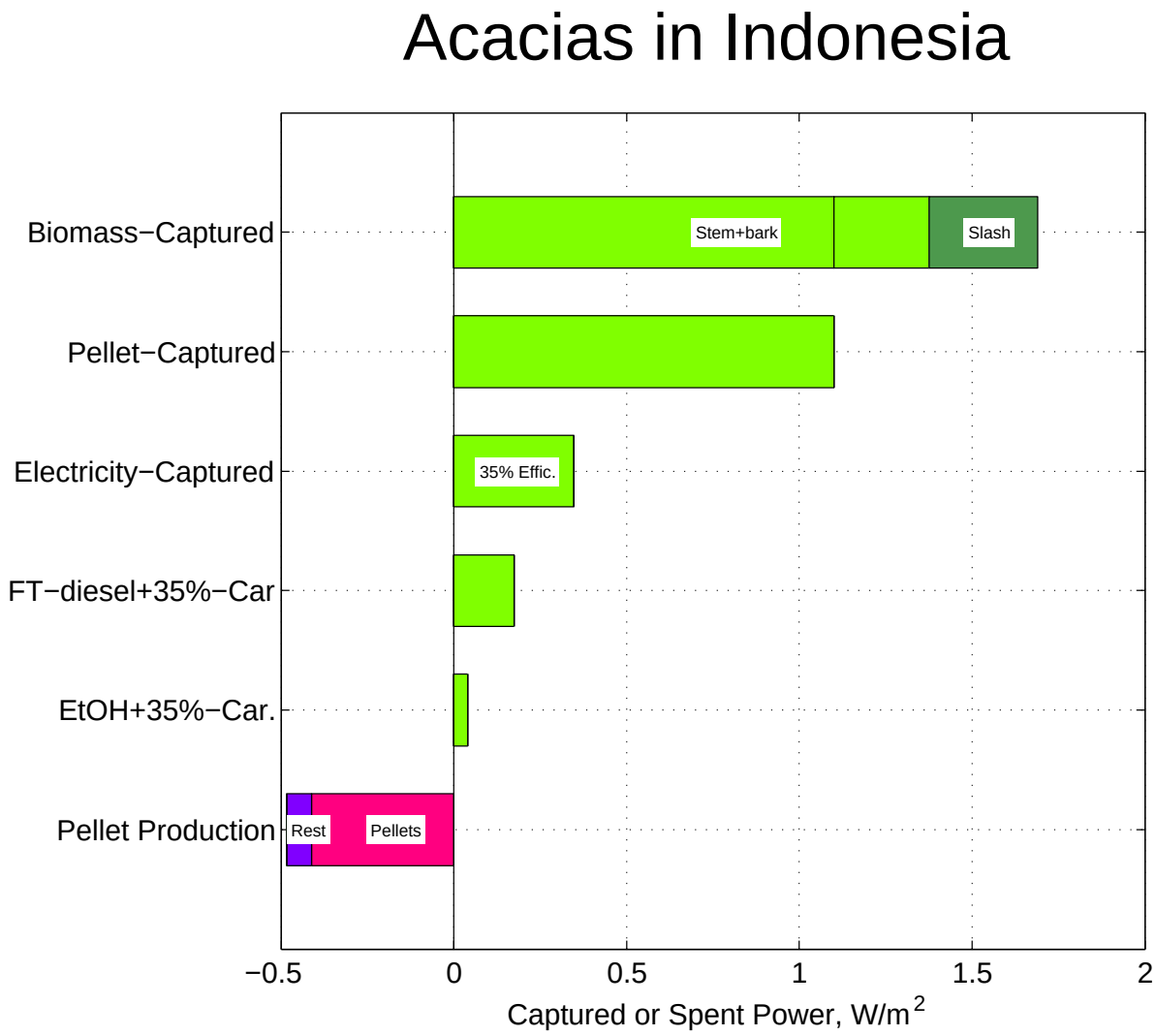
$\sim$1 W/m^2

1 m^2 of oil field delivers for 20 years $2000\times$ more car power than EtOH from 1 m^2 of corn

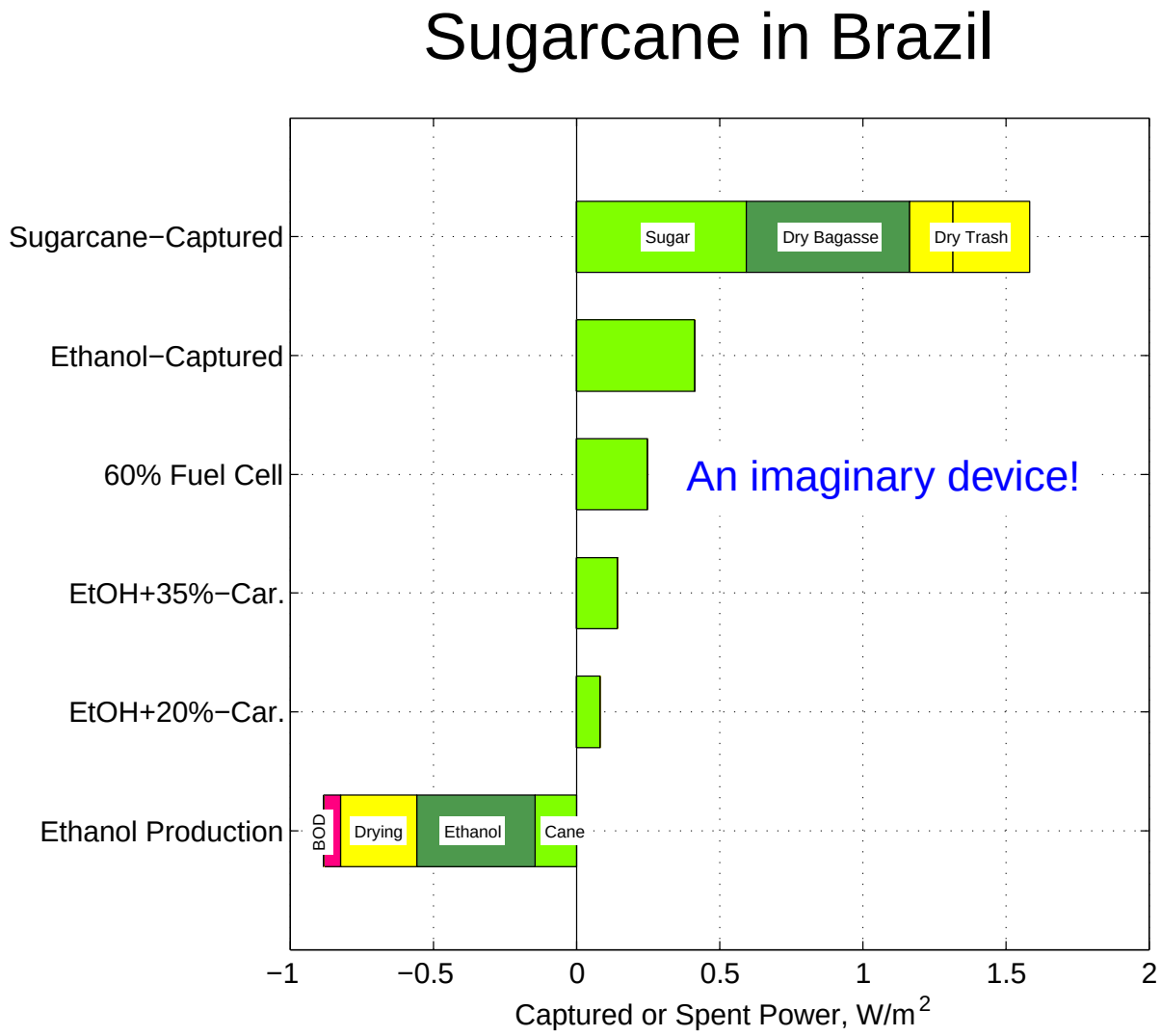
Wood Pellets from the Tropics. . .



Exergy from Tropical Plantations. . .



Exergy from Tropical Plantations. . .



Conclusions. . .

- Biofuel production is a human assault on the geologic processes and geologic time scale
- The *limiting factors*: fertilizer-rich humus and water that carries the dissolved nutrients to plant roots are augmented by chemicals obtained in linear fossil processes
- The natural processes of plant growth, soil and water renewal are accelerated many-fold by industrial mining of non-renewable resources
- The sun-light is *not* a limiting factor, and could be used to great benefit if we were in less of a hurry

Paper Links. . .

Critical Reviews in Plant Sciences, **23**(6):519-567, 2004
http://petroleum.berkeley.edu/papers/patzek/twppapers.htm

Maximum Ethanol as Gasoline %