# ELI Presentation: Energy is everything

by Robert Ayres

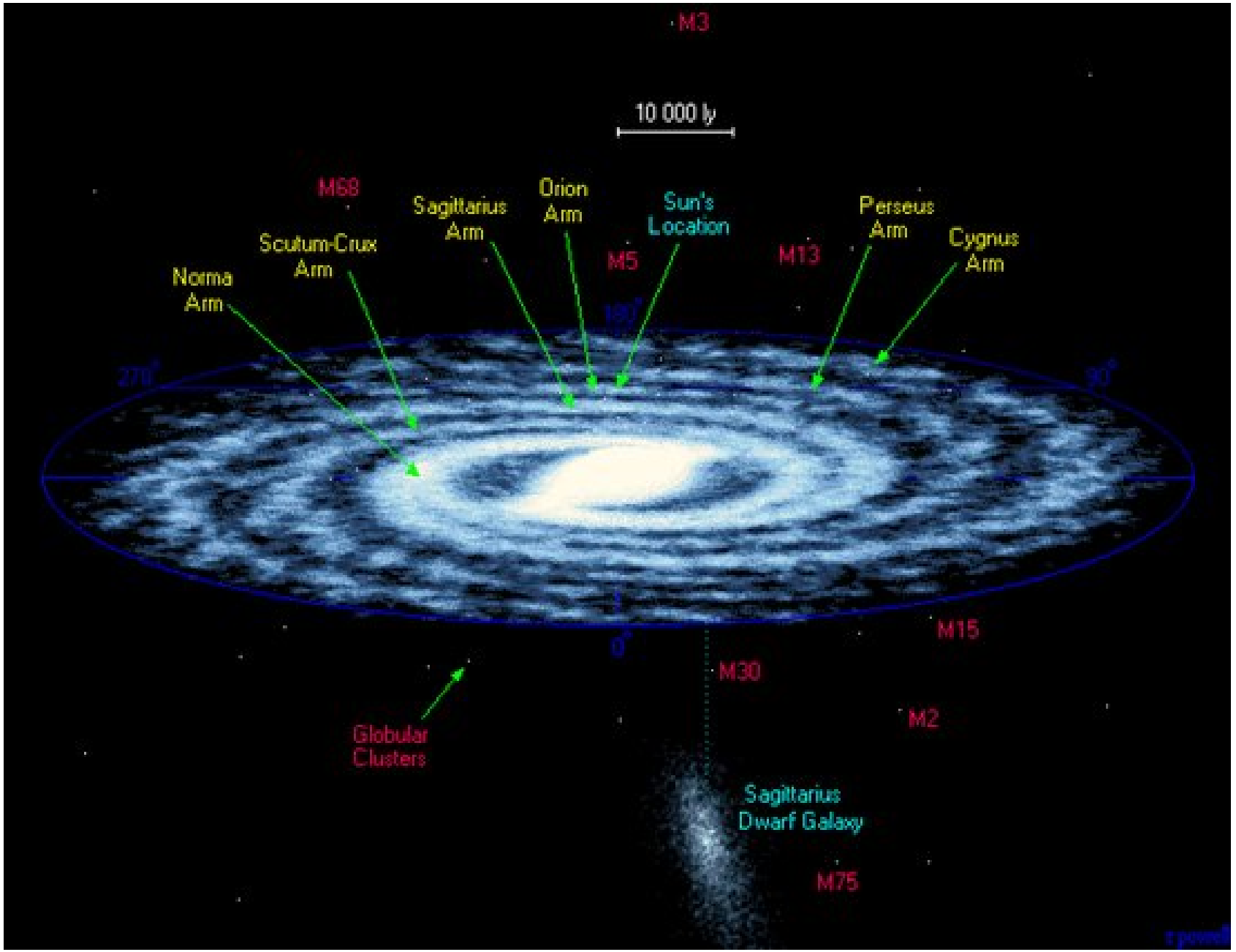
November 18-19 2021

# ELI Workshop, Nov. 18-19, 2021

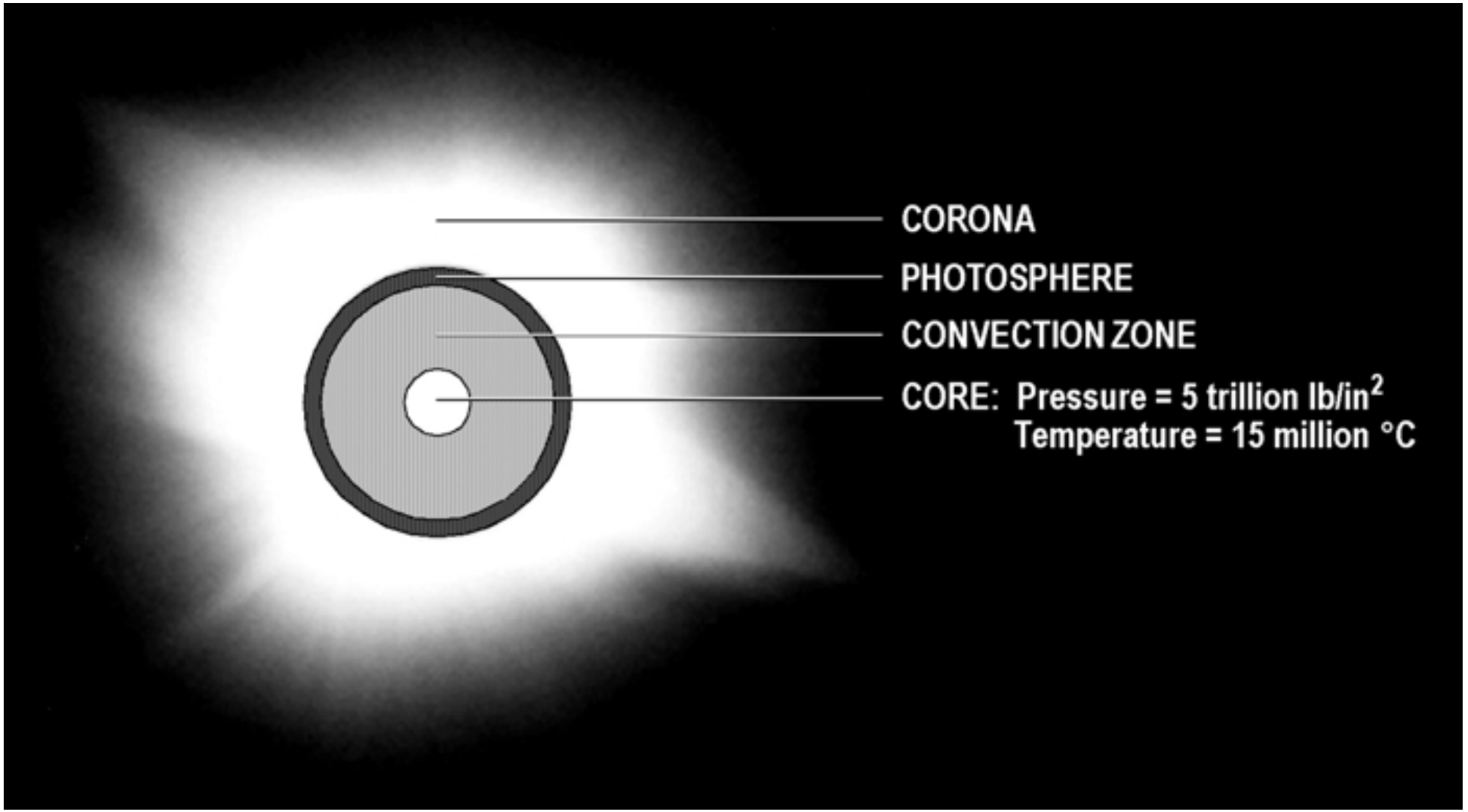
- This talk has two major messages.

- The first (Part I) is that capital and thermodynamic work are the only factors of production, and both are composed of the same substance – the substance of the universe -- namely Energy (Exergy). Energy can neither be created nor destroyed by human activity, so it makes no sense to think of energy as a product of capital or labor, or of any other sectoral outputs. Therefore, energy cannot be considered an intermediate product.

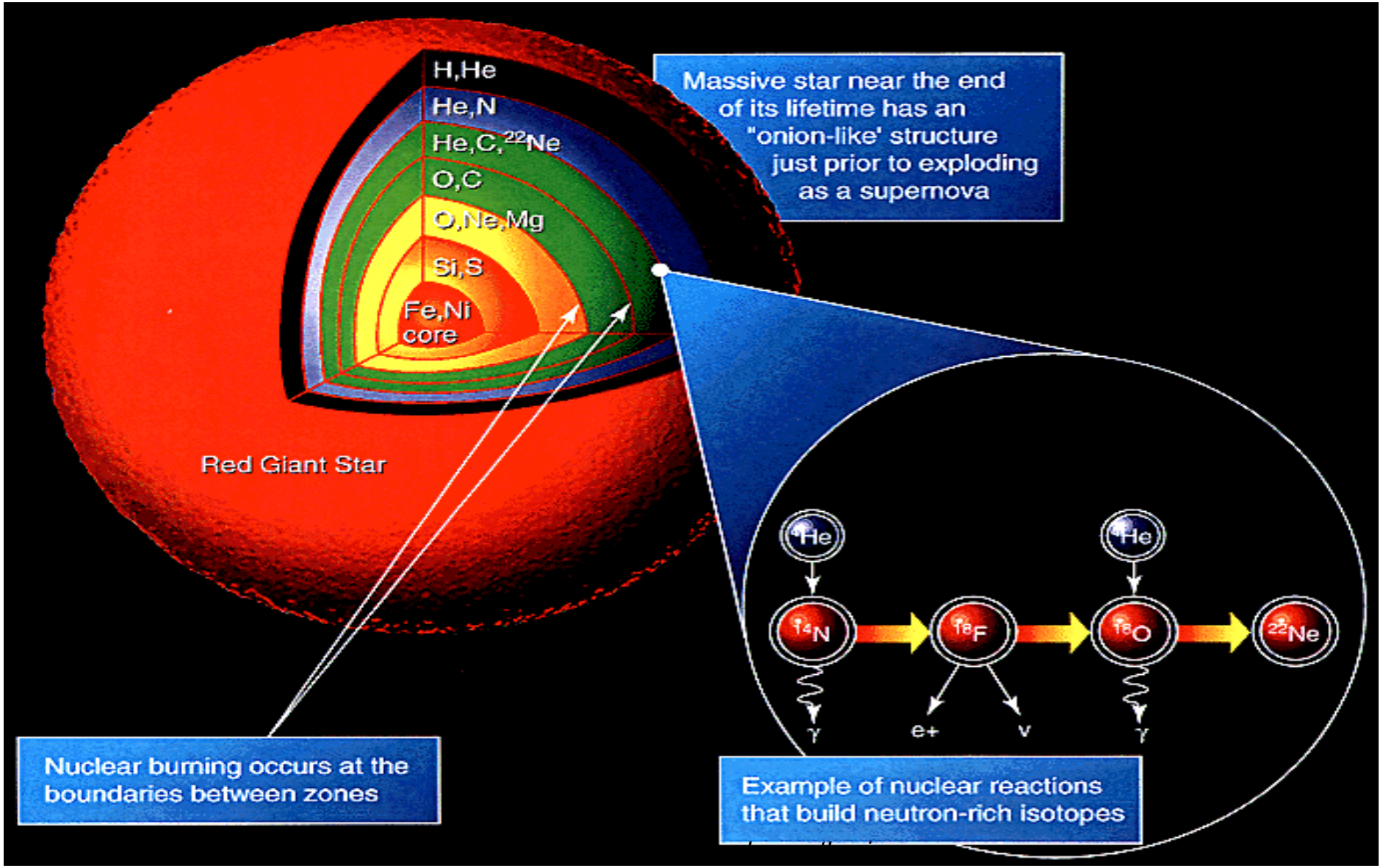
- The second message (Part II) is that the key to stopping global climate change due to the accumulation of greenhouse gases (GHGs) in the atmosphere, is to increase the energy (exergy) efficiency (the ratio of useful output to input) of our economy. There is a lot of room for improvement.


M3
10 000 ly
M68
Sagittarius Arm
Orion Arm
Sun's Location
Perseus Arm
Cygnus Arm
Scutum-Crux Arm
Norma Arm
M5
M13
M92
270°
90°
0°
M15
M30
M2
Globular Clusters
Sagittarius Dwarf Galaxy
M75

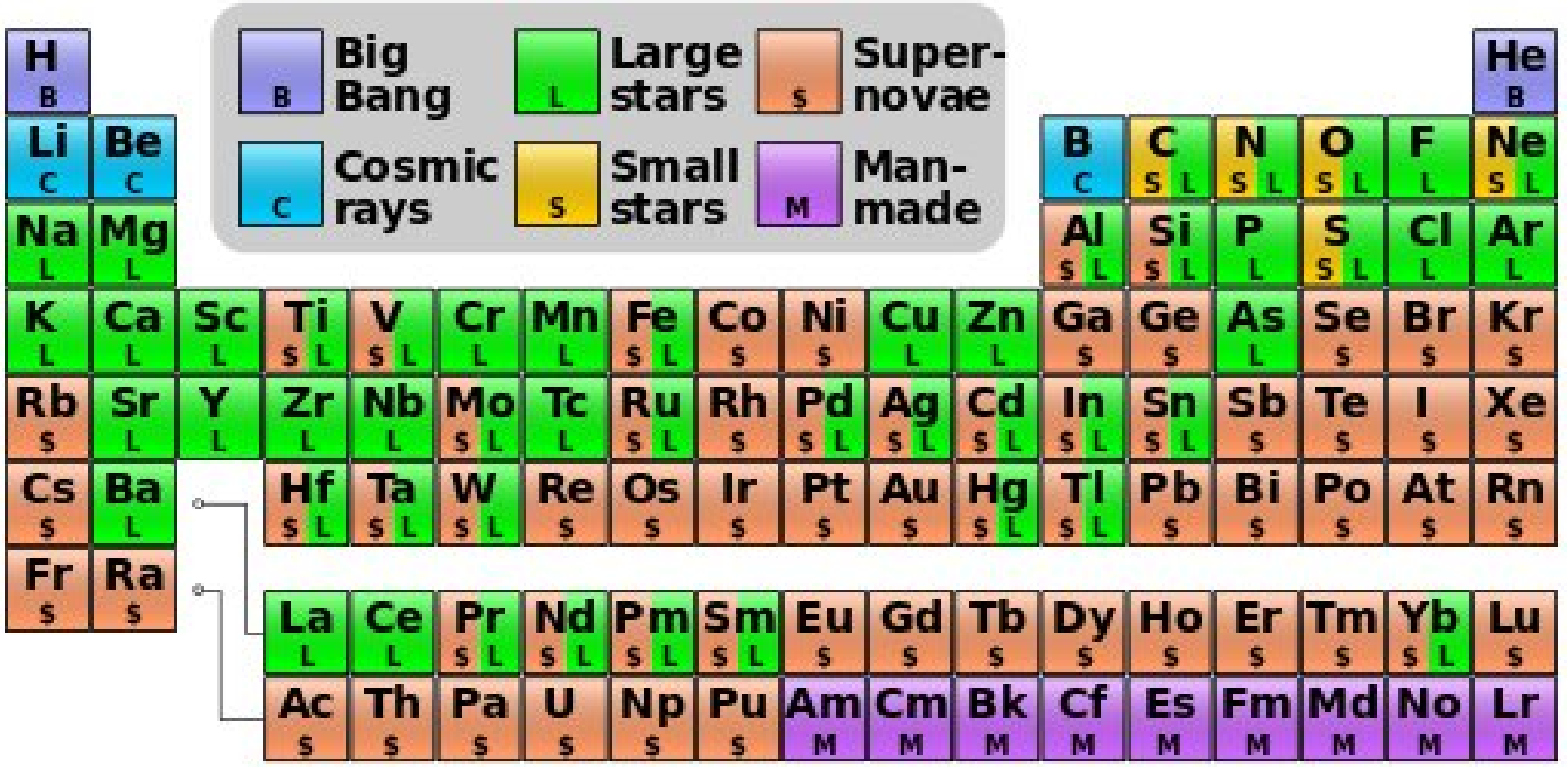
# Schematic of a star structure



# The structure of an "old" red giant before exploding as a supernova

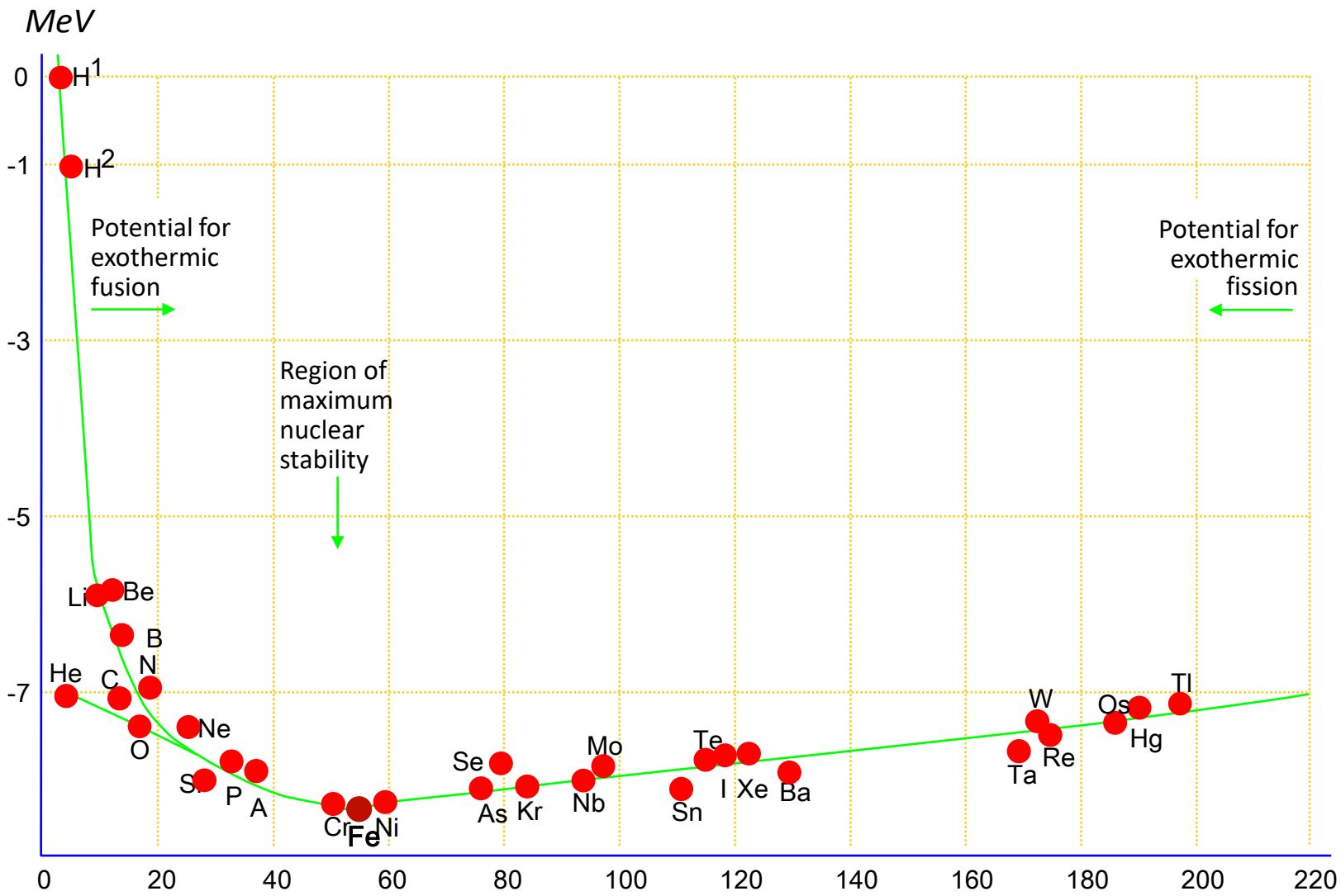


# Periodic Table showing origin of elements




*Source: https://en.wikipedia.org/wiki/Stellar_nucleosynthesis*

# Nuclear binding energy (potential) per nucleon (MeV)



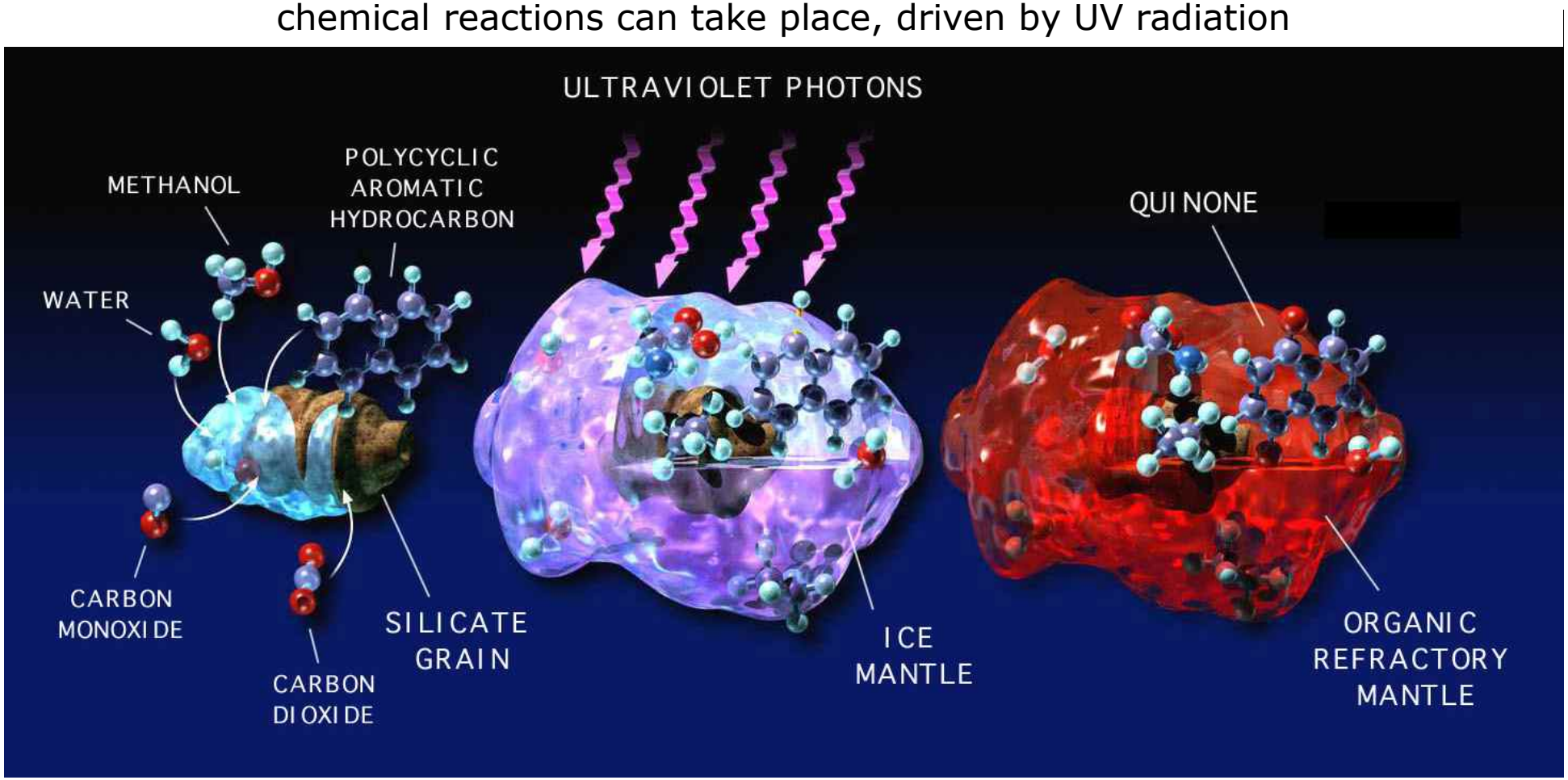

*Source: [adapted from Aston 35,36; Bainbridge 32,33]*

# A gas cloud giving birth to new stars

*A gas cloud in Casieopeia, 7000 light years from Earth. The red color indicates that organic compounds are present.*
*http://photojournal.jpl.nasa.gov/catalog/PIA03096.*

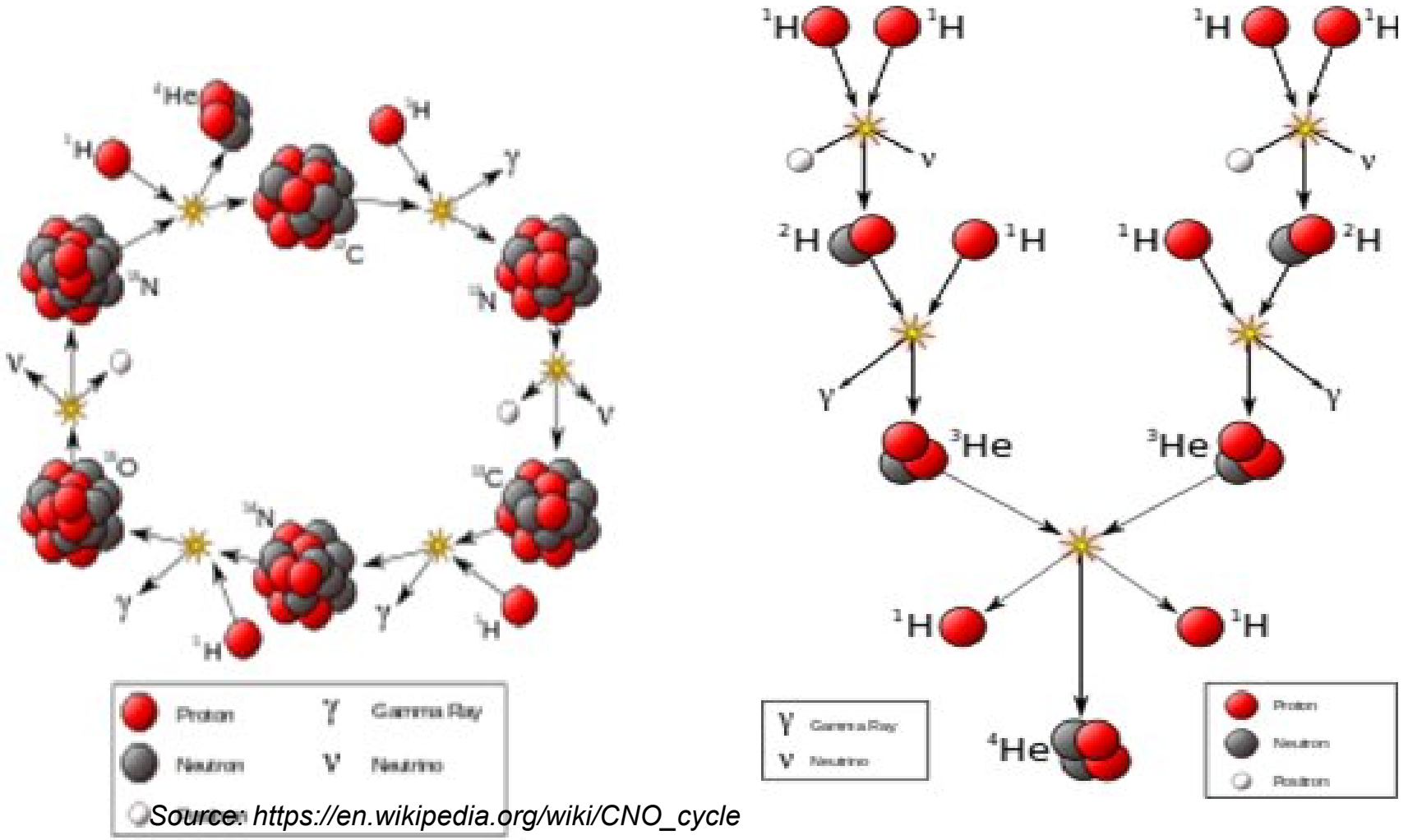
# Dust particles as chemical factories

Illustrations of ice-covered silica grains in dust clouds where chemical reactions can take place, driven by UV radiation



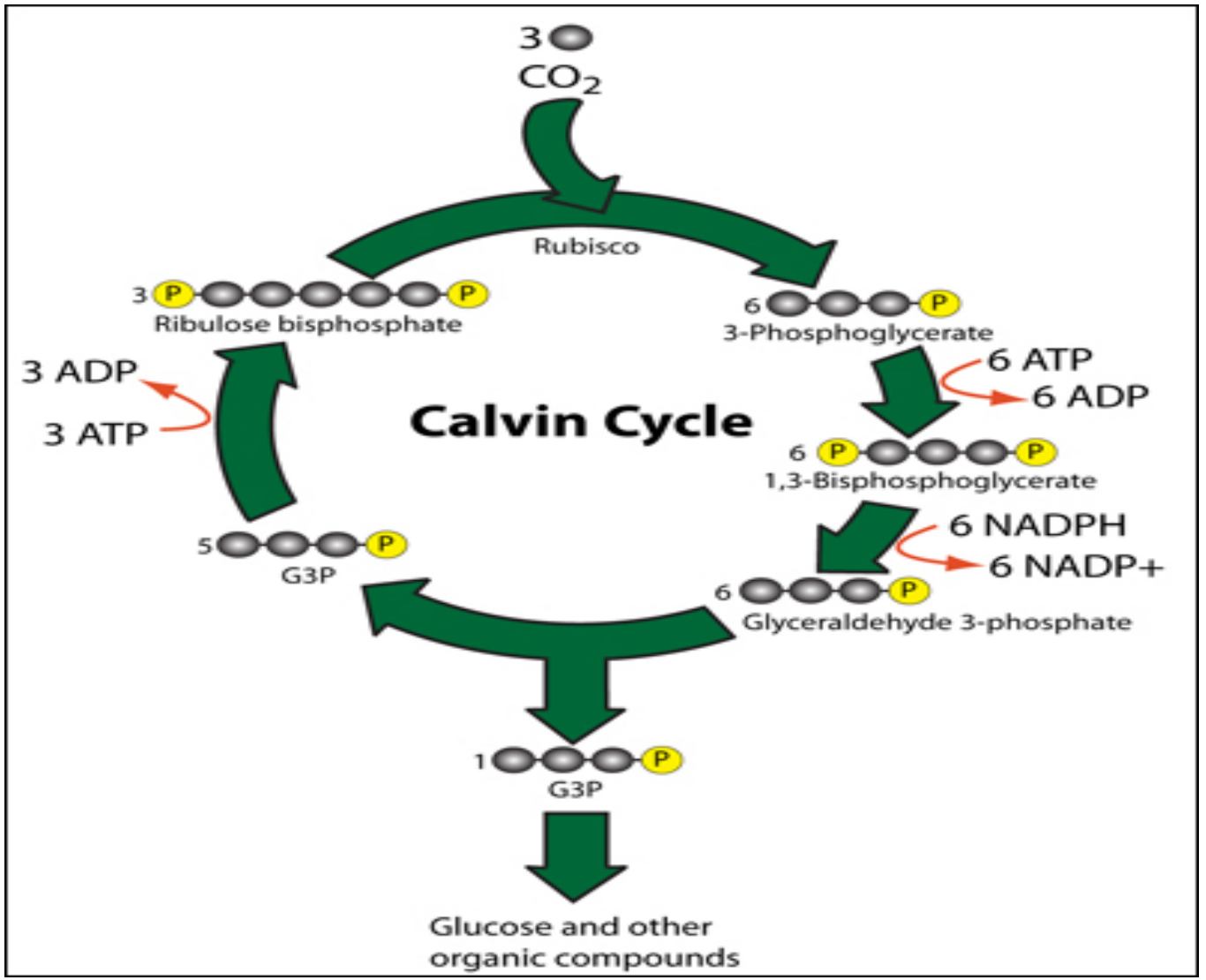

*Source http://www.astrochem.org/sci_img/icegrain.jpg*

# The carbon-nitrogen cycle and the proton-proton chain



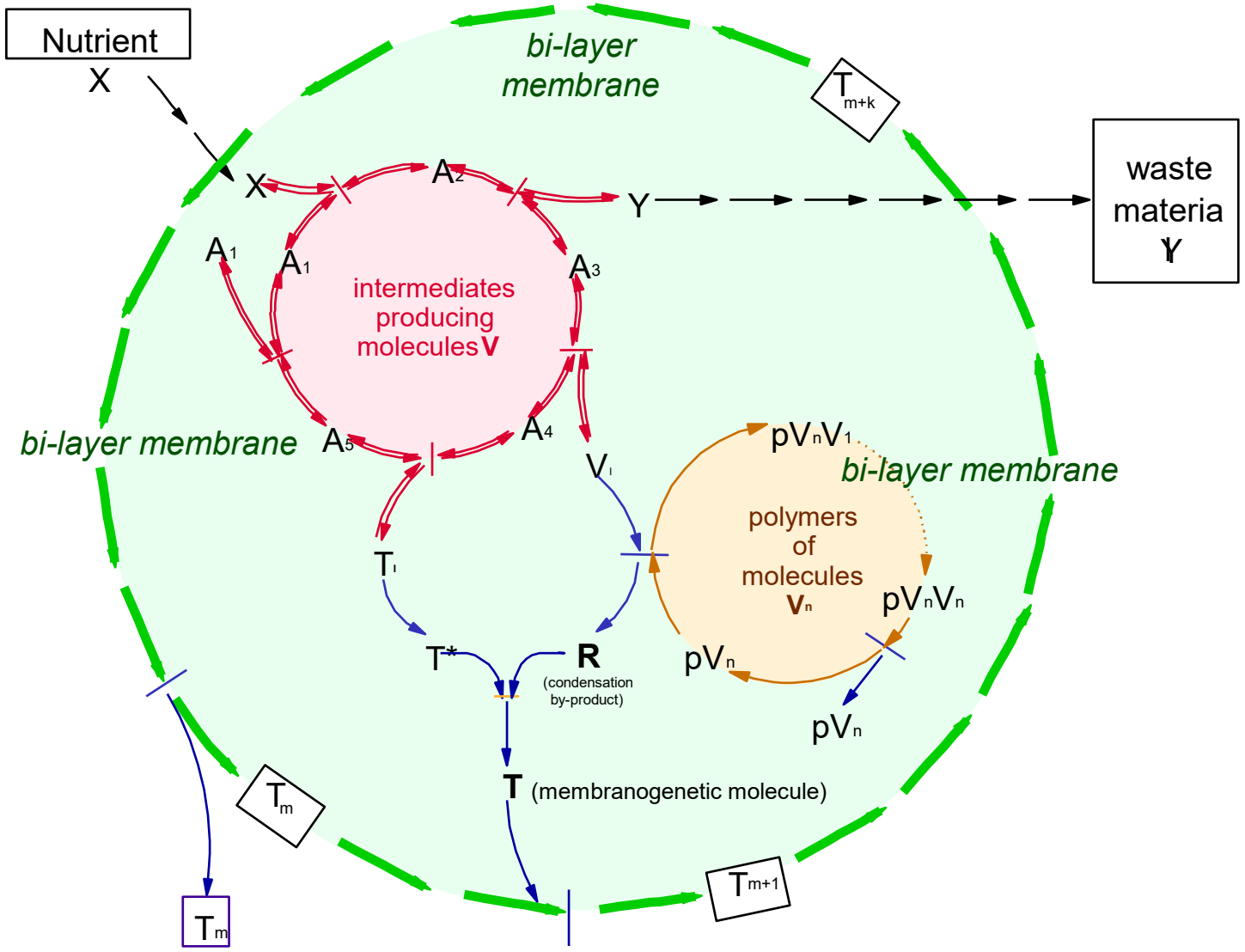

*Source: https://en.wikipedia.org/wiki/CNO_cycle*

# Calvin Cycle for photosythesis

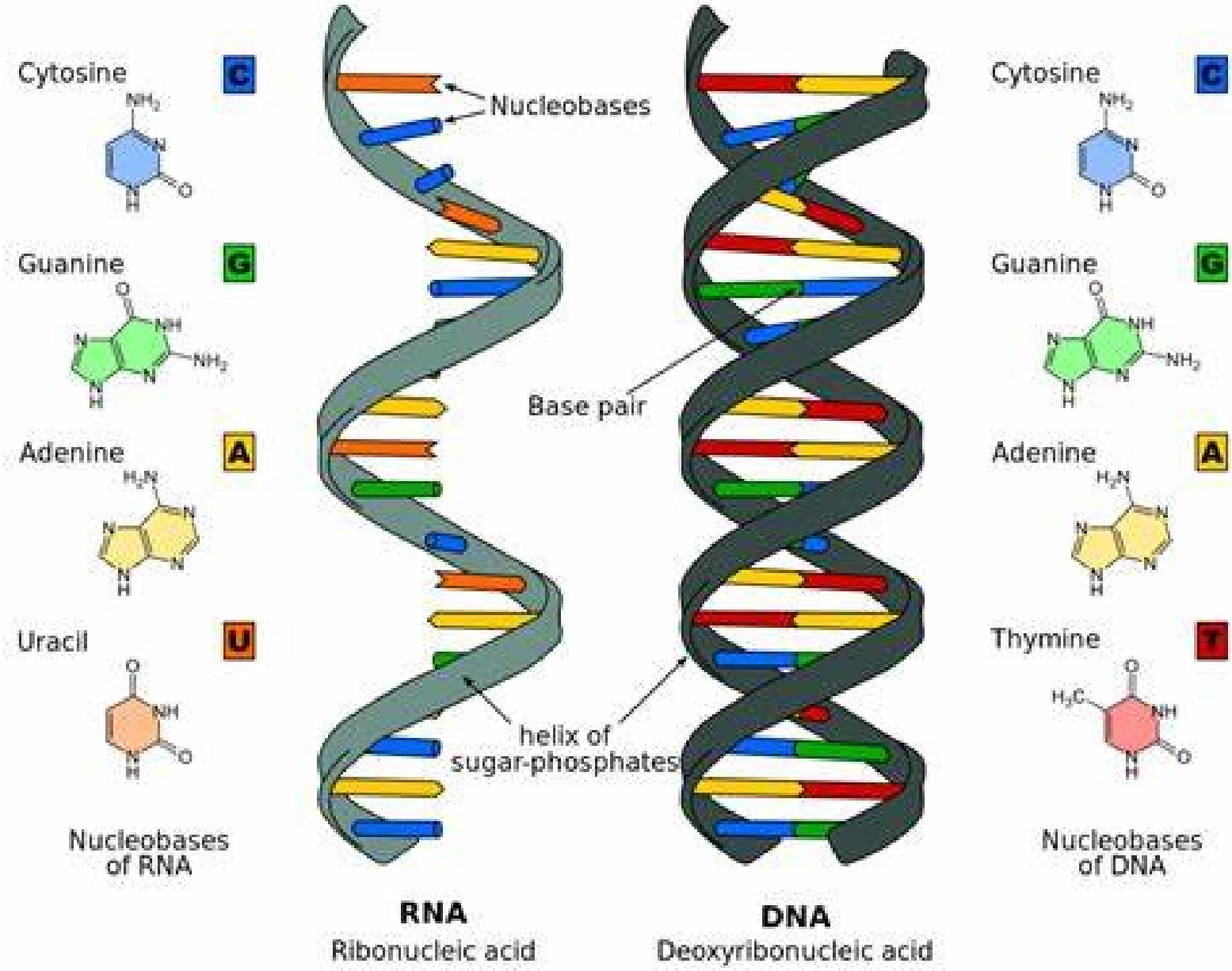



*Source: https://roboplant.files.wordpress.com/2013/06/calvincycle.jpg*

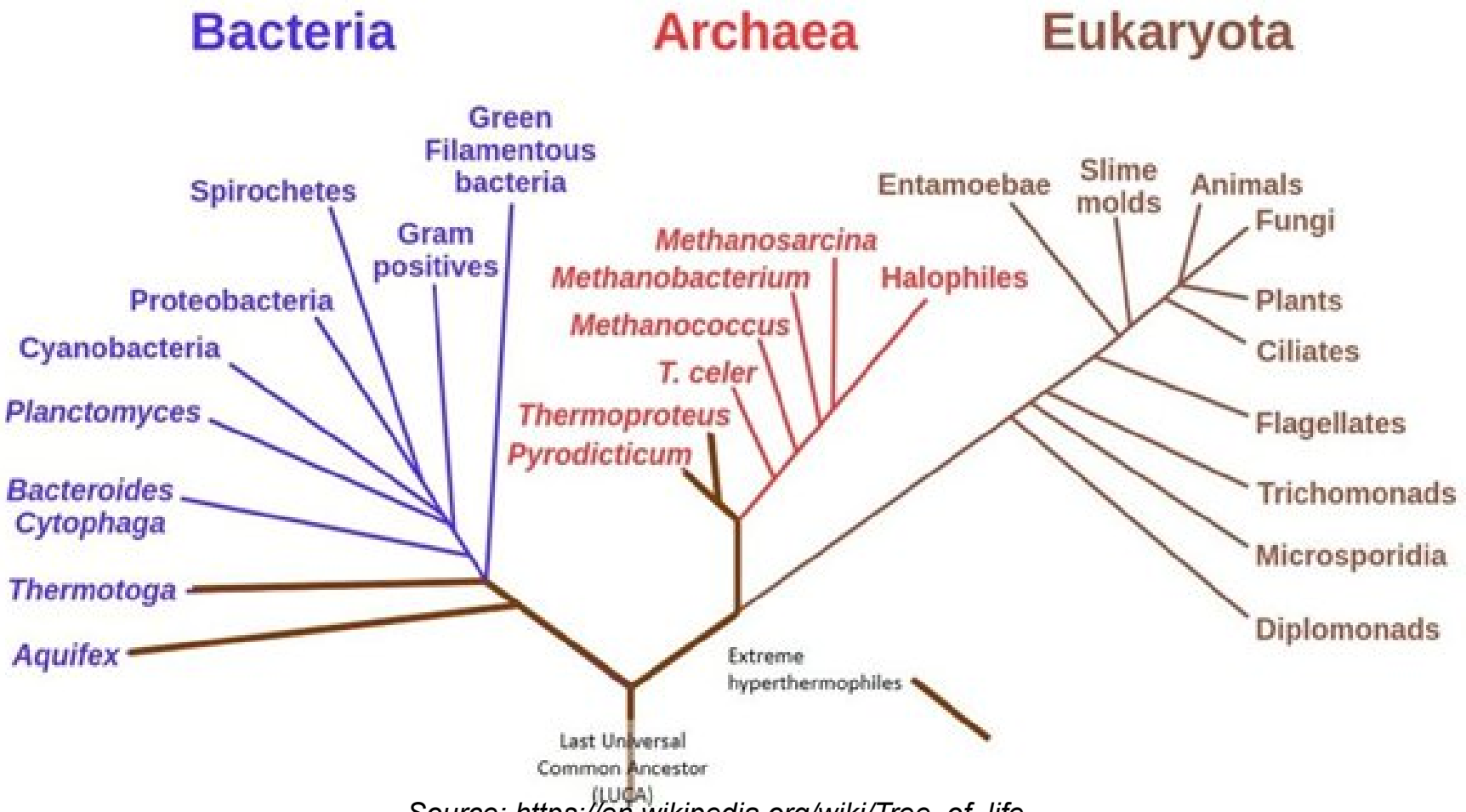
# Schematic model of the Chemoton: A self-replicating chemical system




*Source: adapted from (Smith and Szathmary 1995, Figure 2.2 p. 21)*


Cytosine
C
Guanine
G
Adenine
A
Uracil
U
Nucleobases of RNA
Nucleobases
Base pair
helix of sugar-phosphates
RNA
Ribonucleic acid
DNA
Deoxyribonucleic acid
Cytosine
C
Guanine
G
Adenine
A
Thymine
T
Nucleobases of DNA

# Phylogenetic "Tree of Life" (J. D. Crofts)

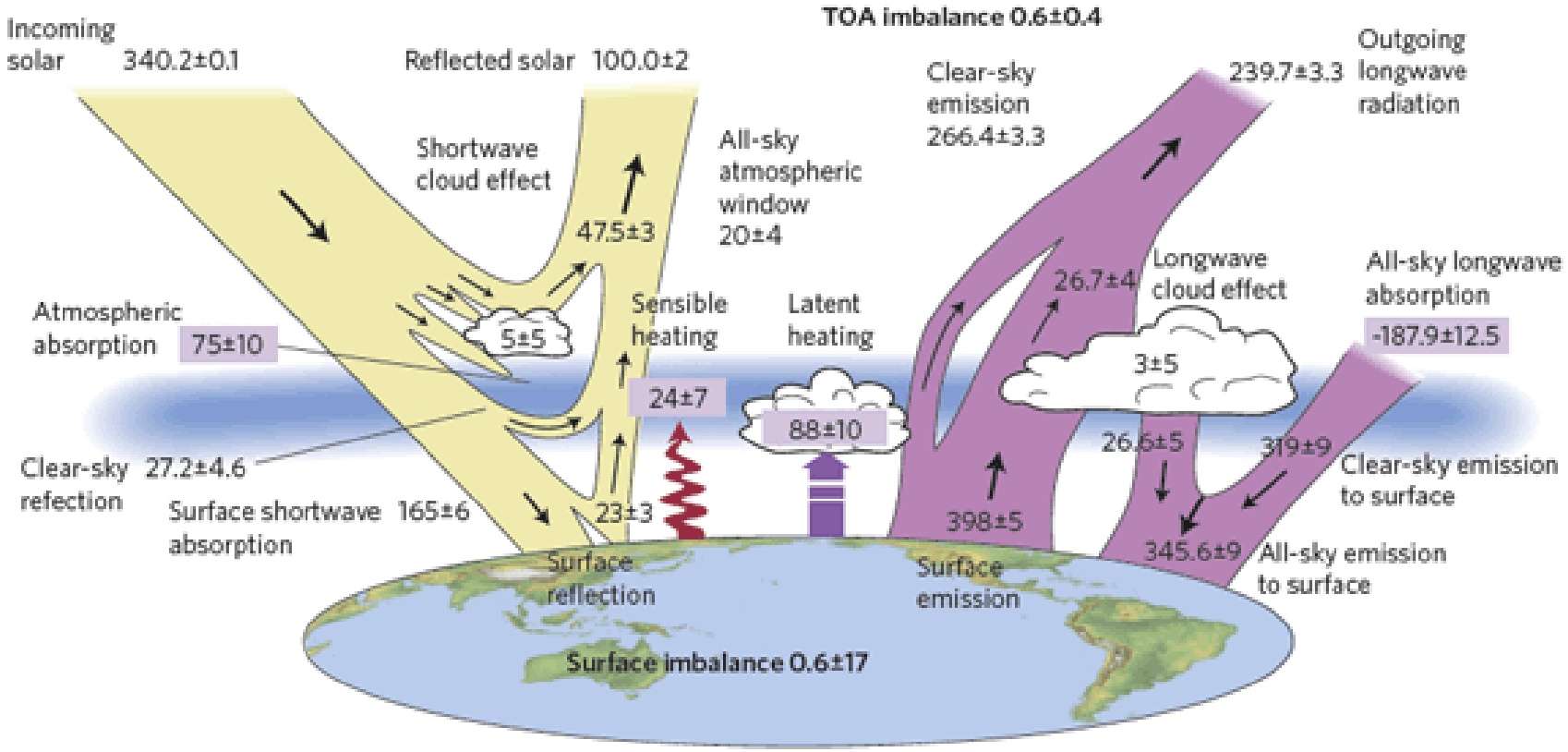



*Source: https://en.wikipedia.org/wiki/Tree_of_life*

# Biodiversity

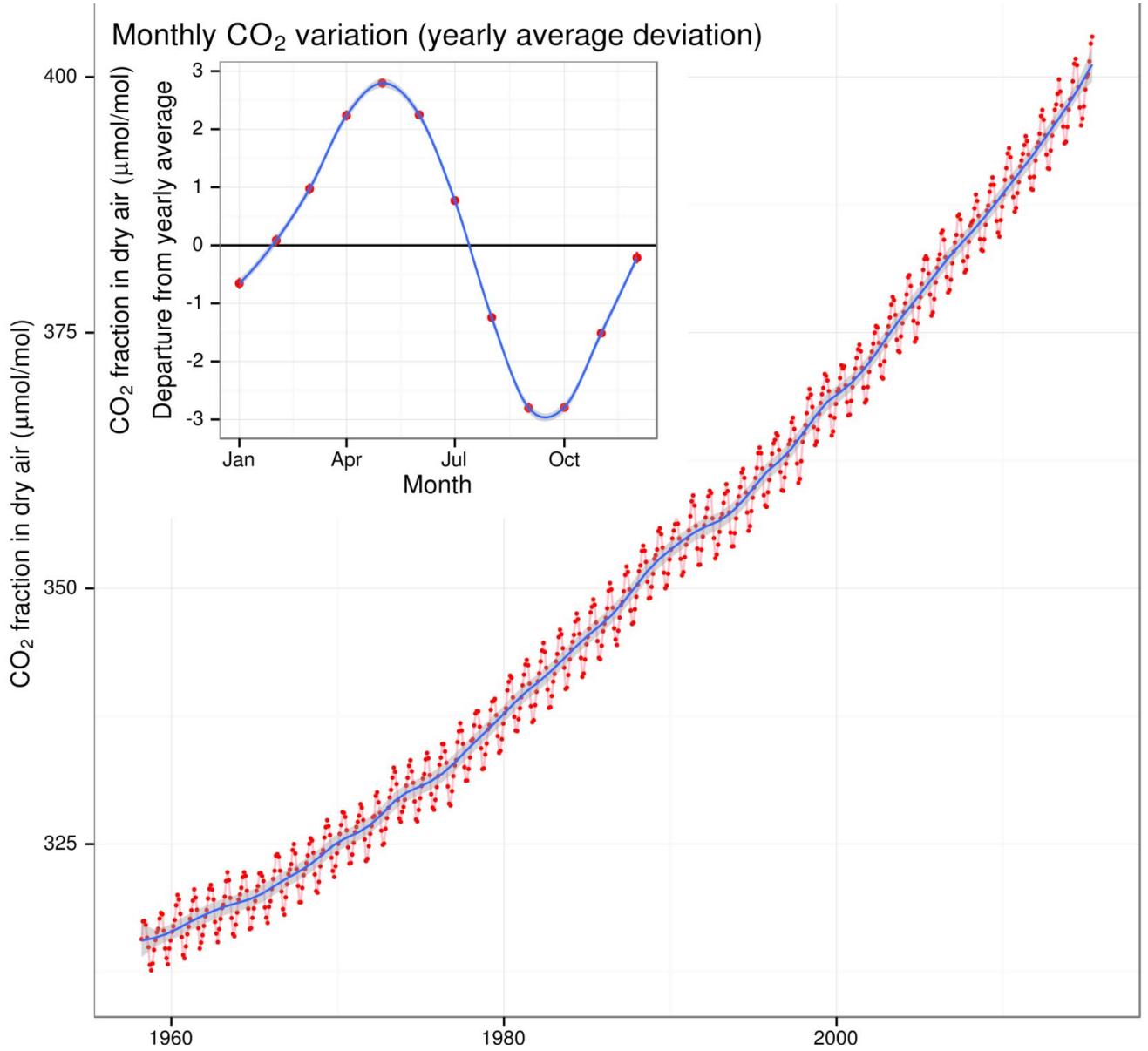
We have seen how the universe evolved after the Big Bang (assuming it did happen while the universe expanded and cooled). From a thermodynamic perspective, all the wonderful complexity of life and of civilization, has been driven by dissipating fluxes of exergy. As the exergy is dissipated – some say “destroyed” – both the entropy of the universe, and its complexity, increase. We have both disorder from order and “order from disorder” The next slides explain how we can learn to use those fluxes better.

# Solar and infrared radiation fluxes



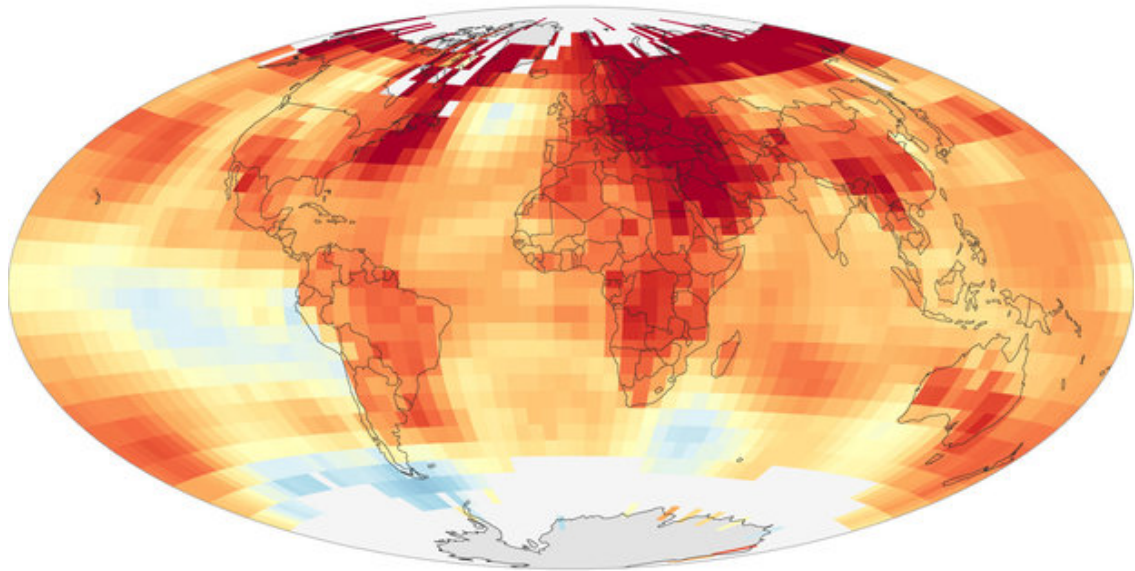

https://curryja.files.wordpress.com/2012/11/stephens2.gif

# Monthly $CO_2$ concentrations on Mauna Loa (NOAA) 1958 - 2015




*Source:https://upload.wikimedia.org/wikipedia/commons/thumb/c/c5/Mauna_Loa_CO2_monthly_mean_concentration.svg/*

# RECENT TEMPERATURE TRENDS (1990-2020)

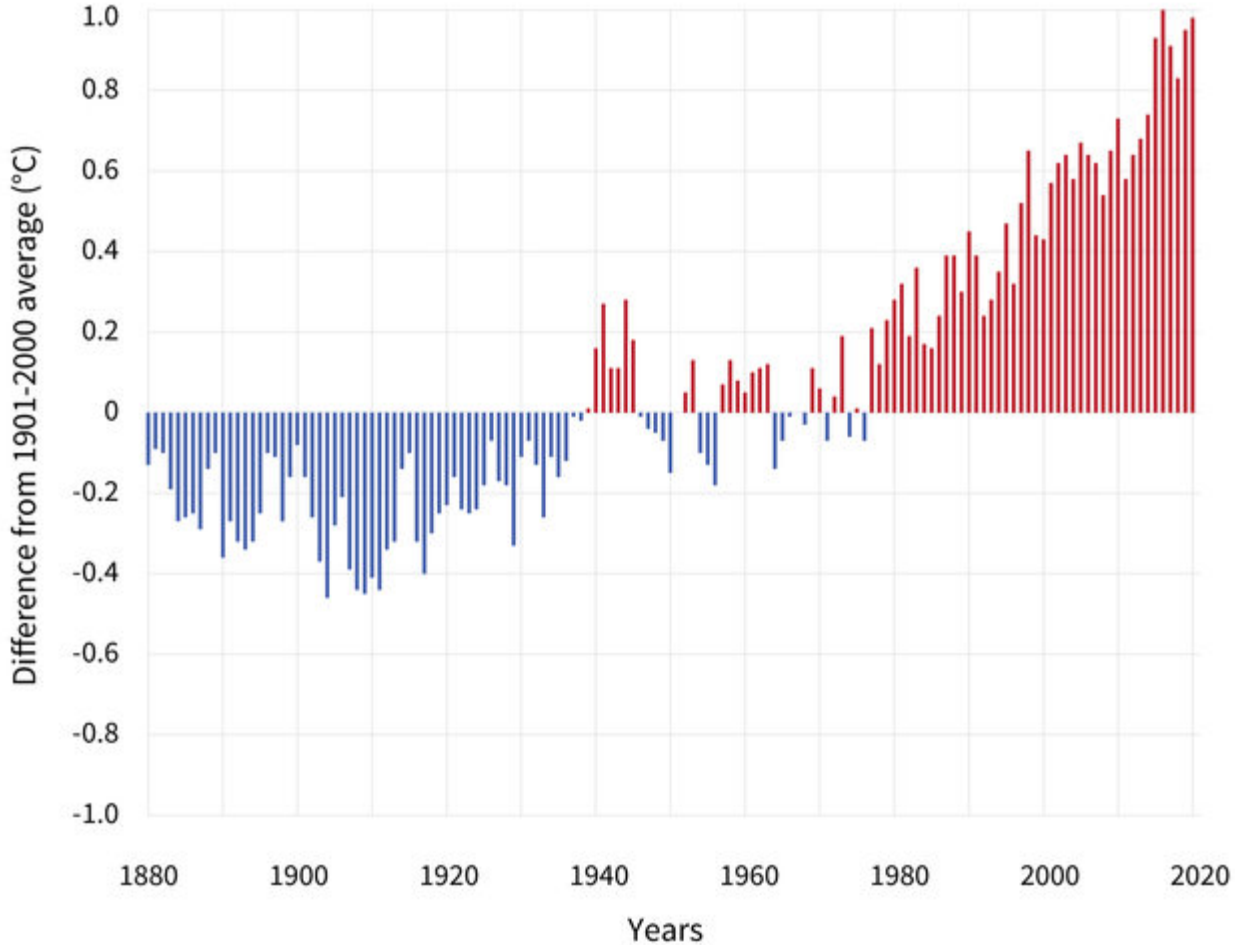


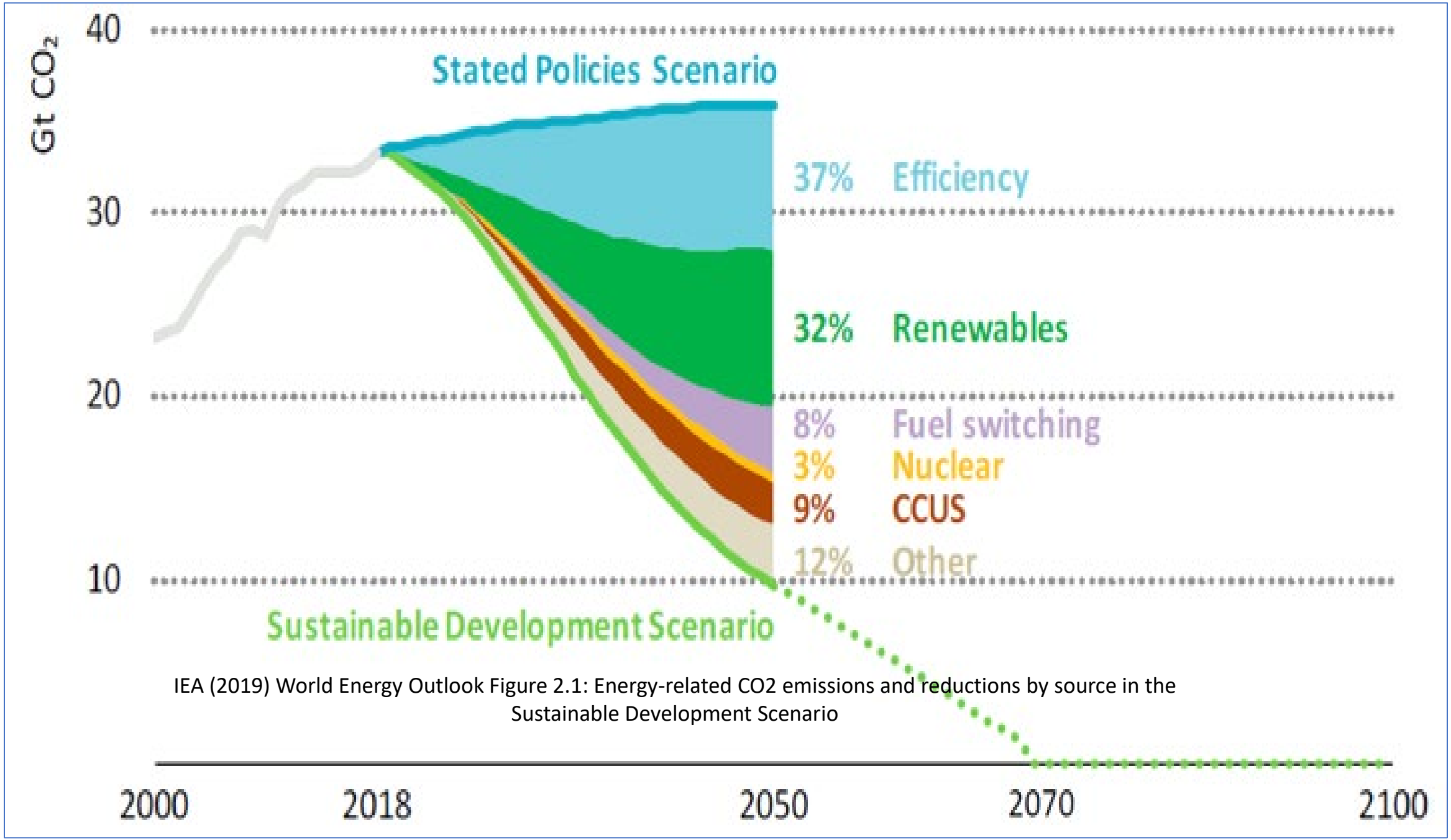
Change in temperature (˚F/decade)

-1 0 1

NOAA Climate.gov
Data: NCEI

# GLOBAL AVERAGE SURFACE TEMPERATURE



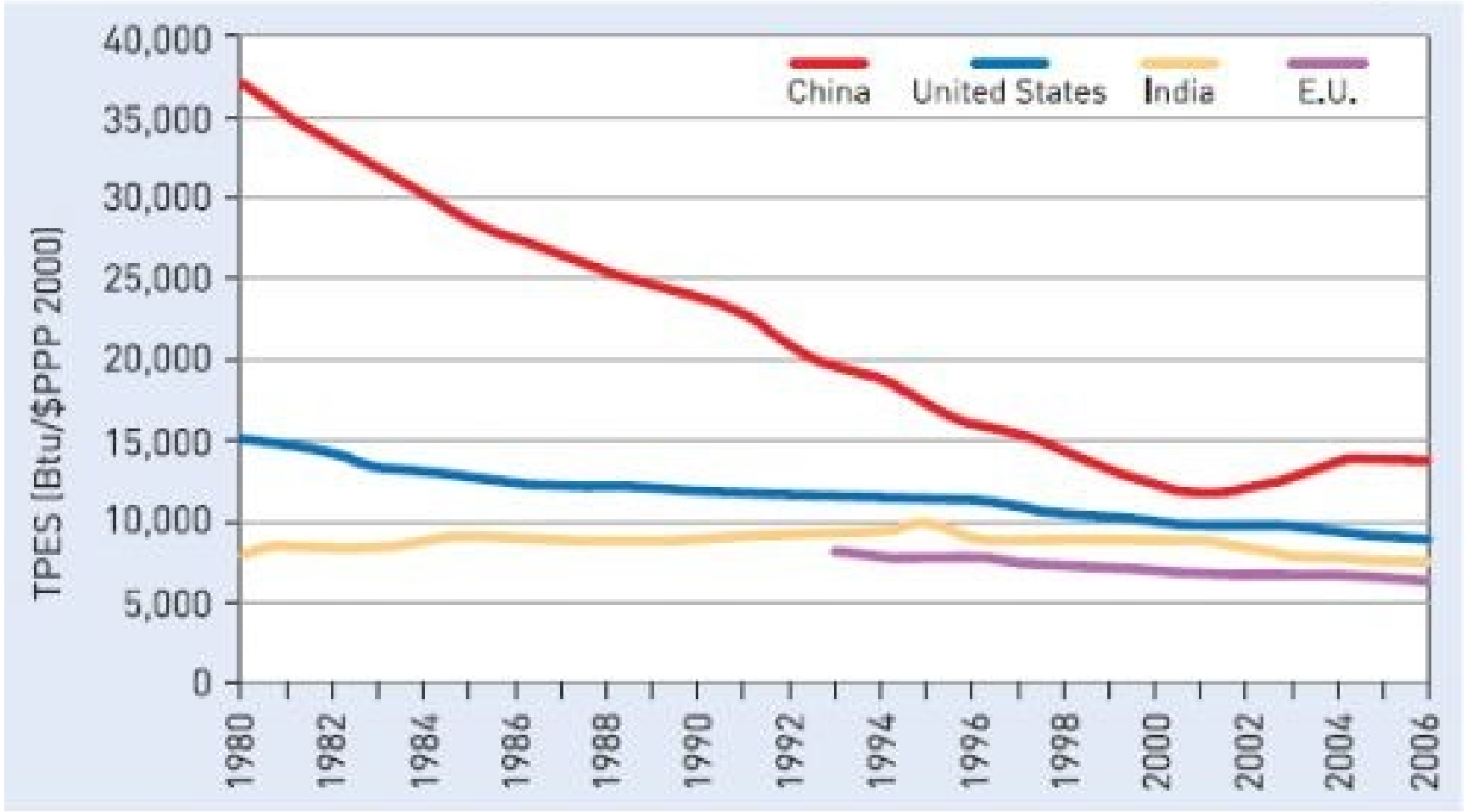



IEA (2019) World Energy Outlook Figure 2.1: Energy-related CO2 emissions and reductions by source in the Sustainable Development Scenario

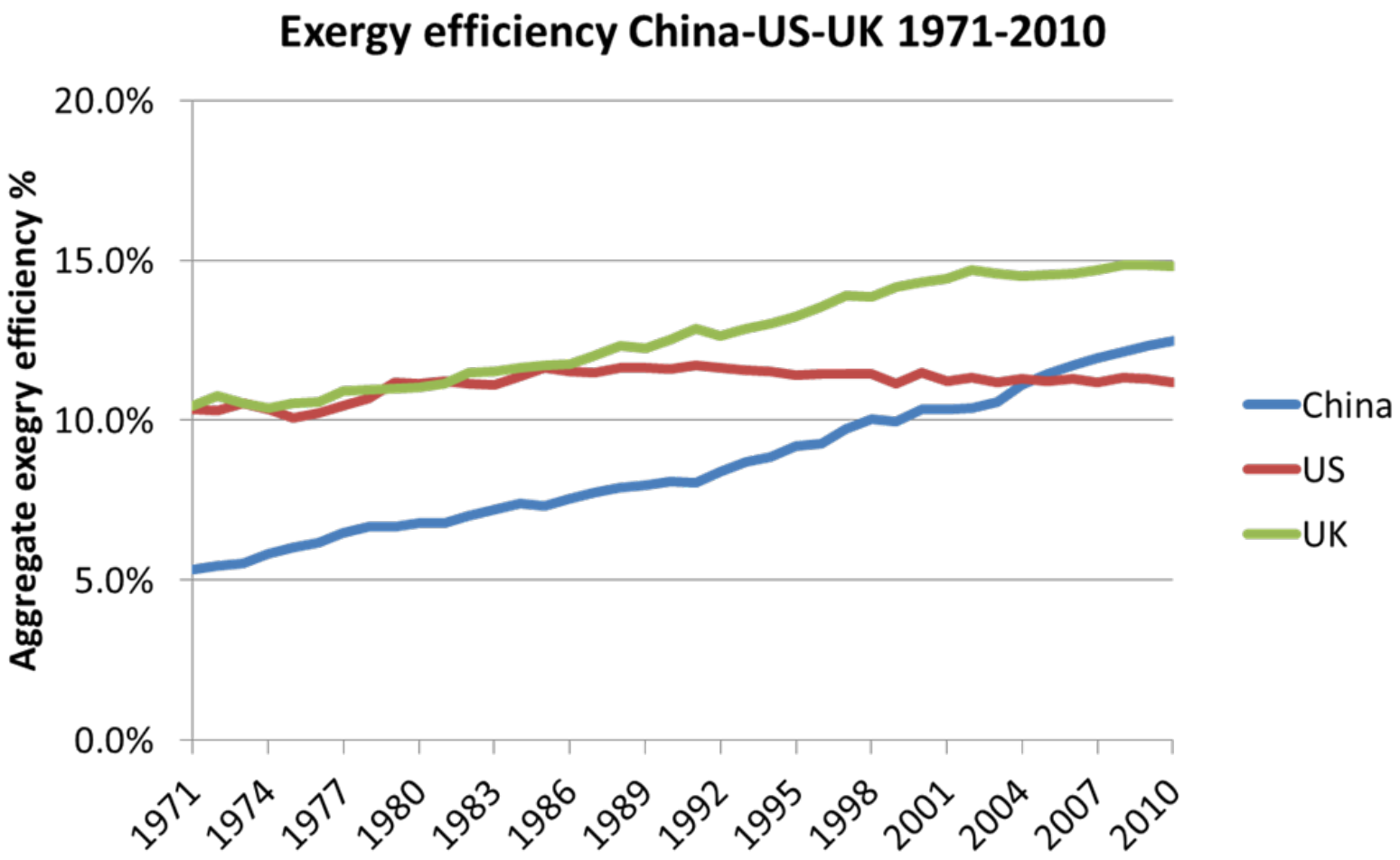
## Economy-wide energy intensity

(Total primary energy supply (Btu/$PPP 2000)

Figure 1

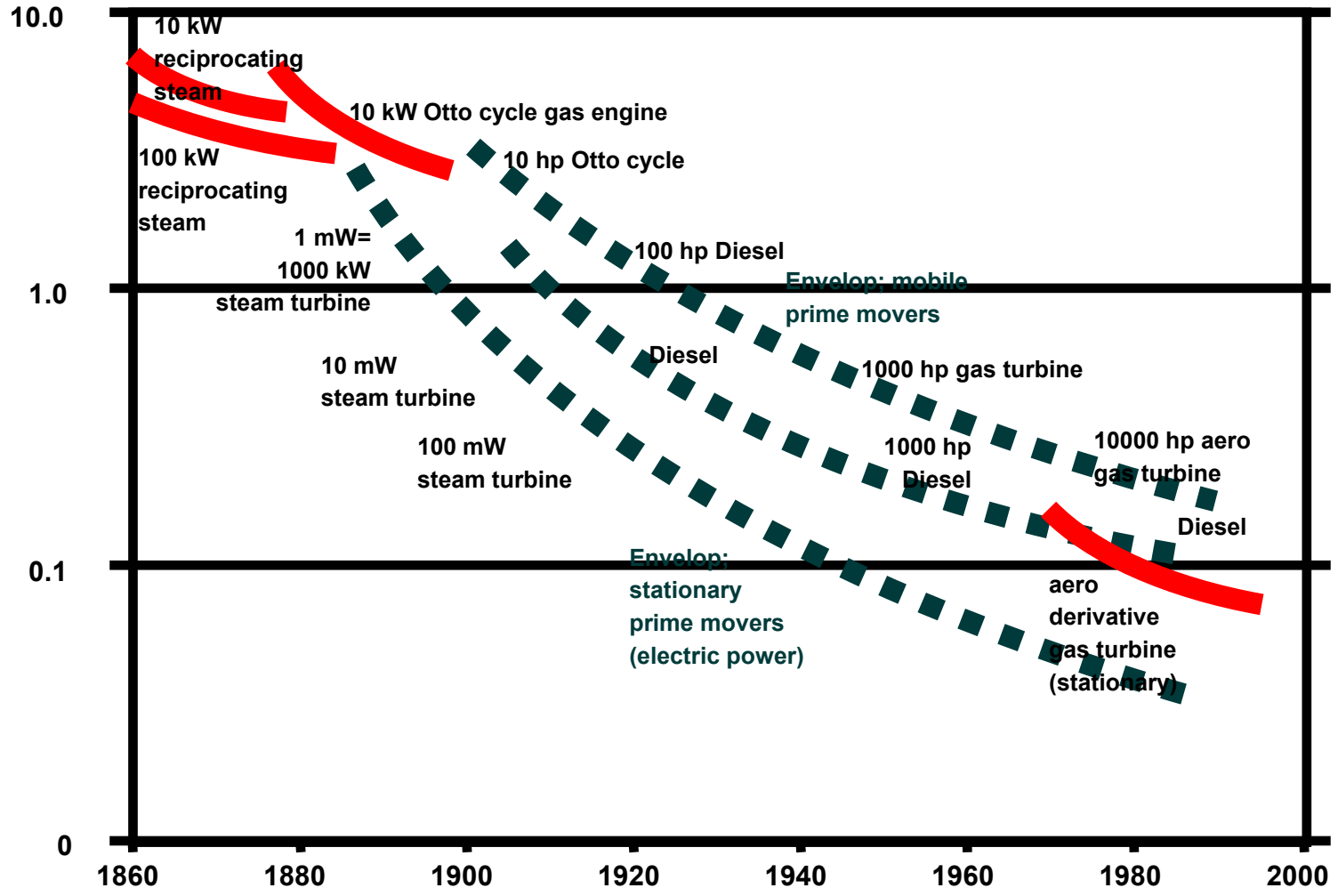


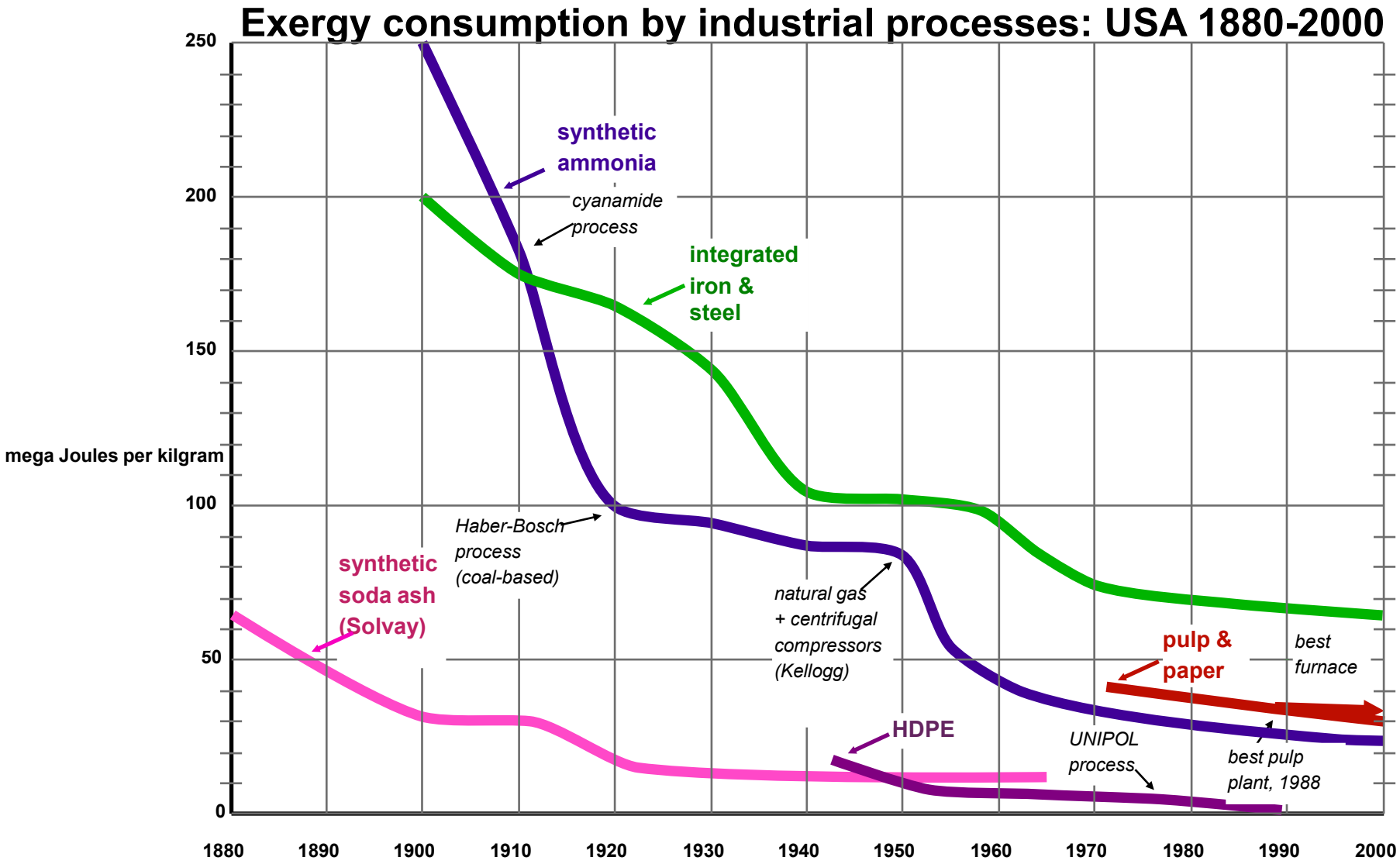

Source: Energy Information Administration, U.S. Department of Energy
(data for a few countries from E.U. unavailable before 1993)



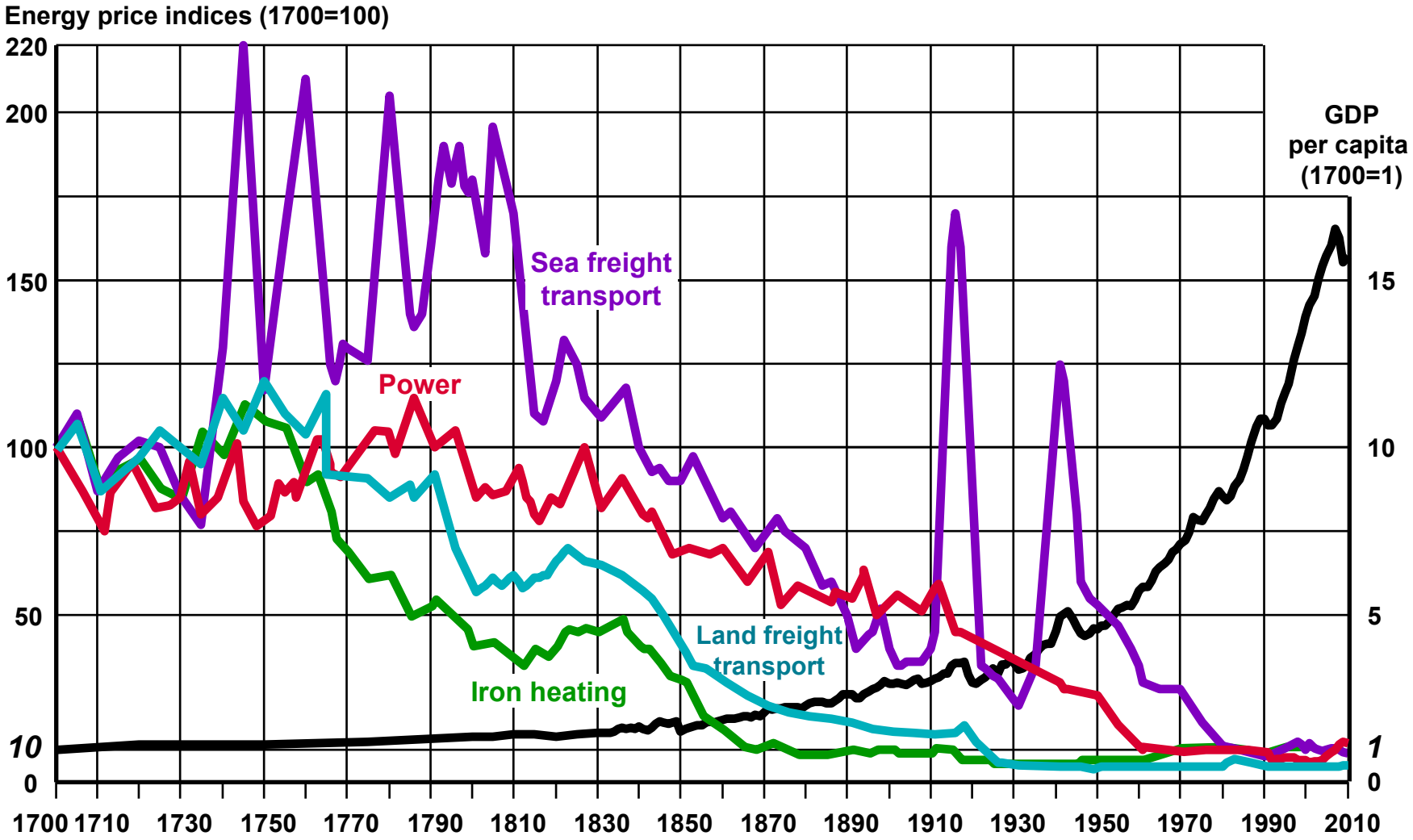

Sources: Brockway et al (2014); Brockway et al (2015)

# Cost of power per hour as multiple of hourly wage



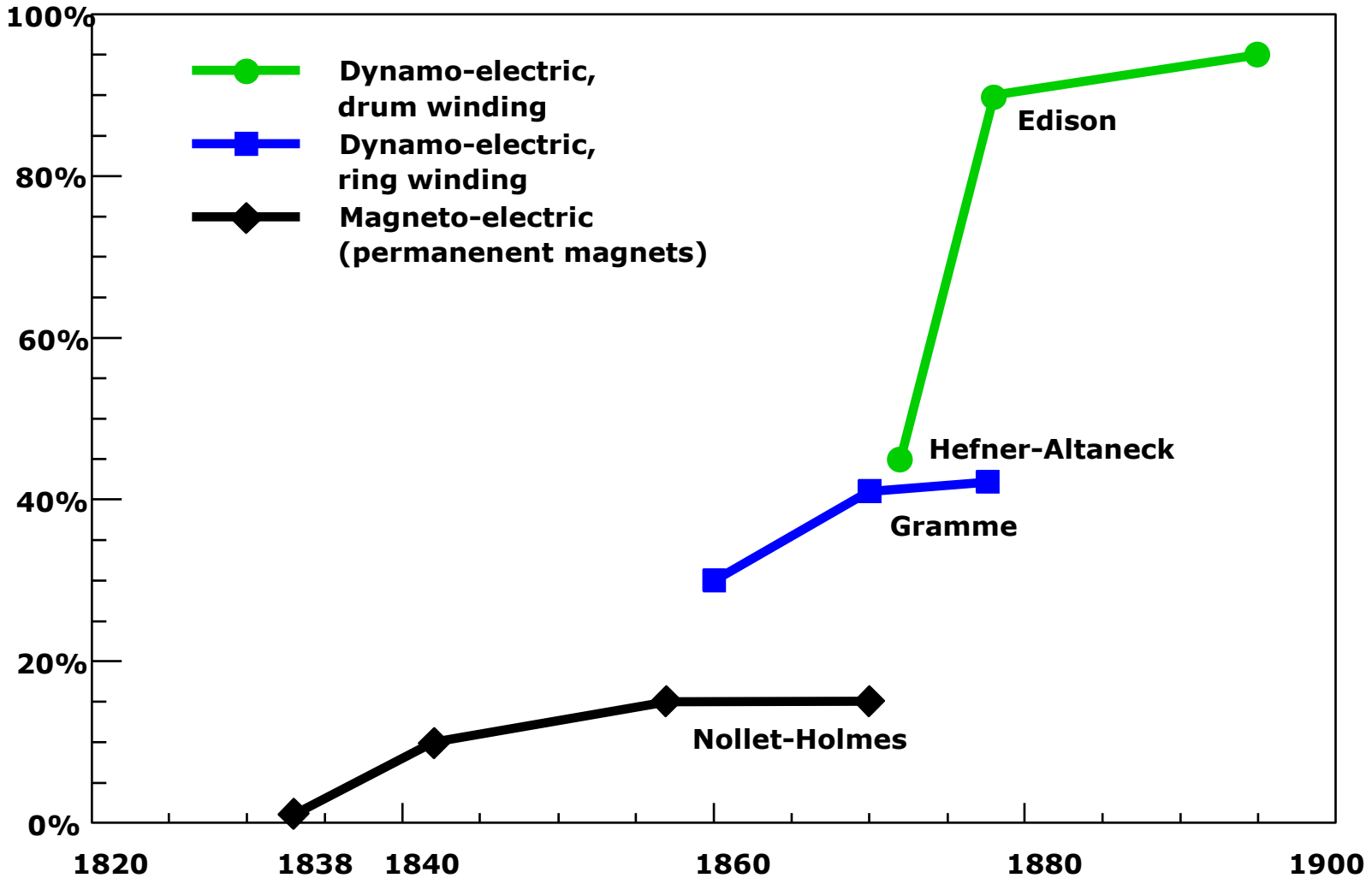

Exergy consumption by industrial processes: USA 1880-2000
mega Joules per kilgram
250
200
150
100
50
0
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
synthetic ammonia
cyanamide process
integrated iron & steel
Haber-Bosch process (coal-based)
natural gas + centrifugal compressors (Kellogg)
synthetic soda ash (Solvay)
HDPE
UNIPOL process
pulp & paper
best furnace
best pulp plant, 1988

# Energy price indices vs GDP index for the UK 1700-2010

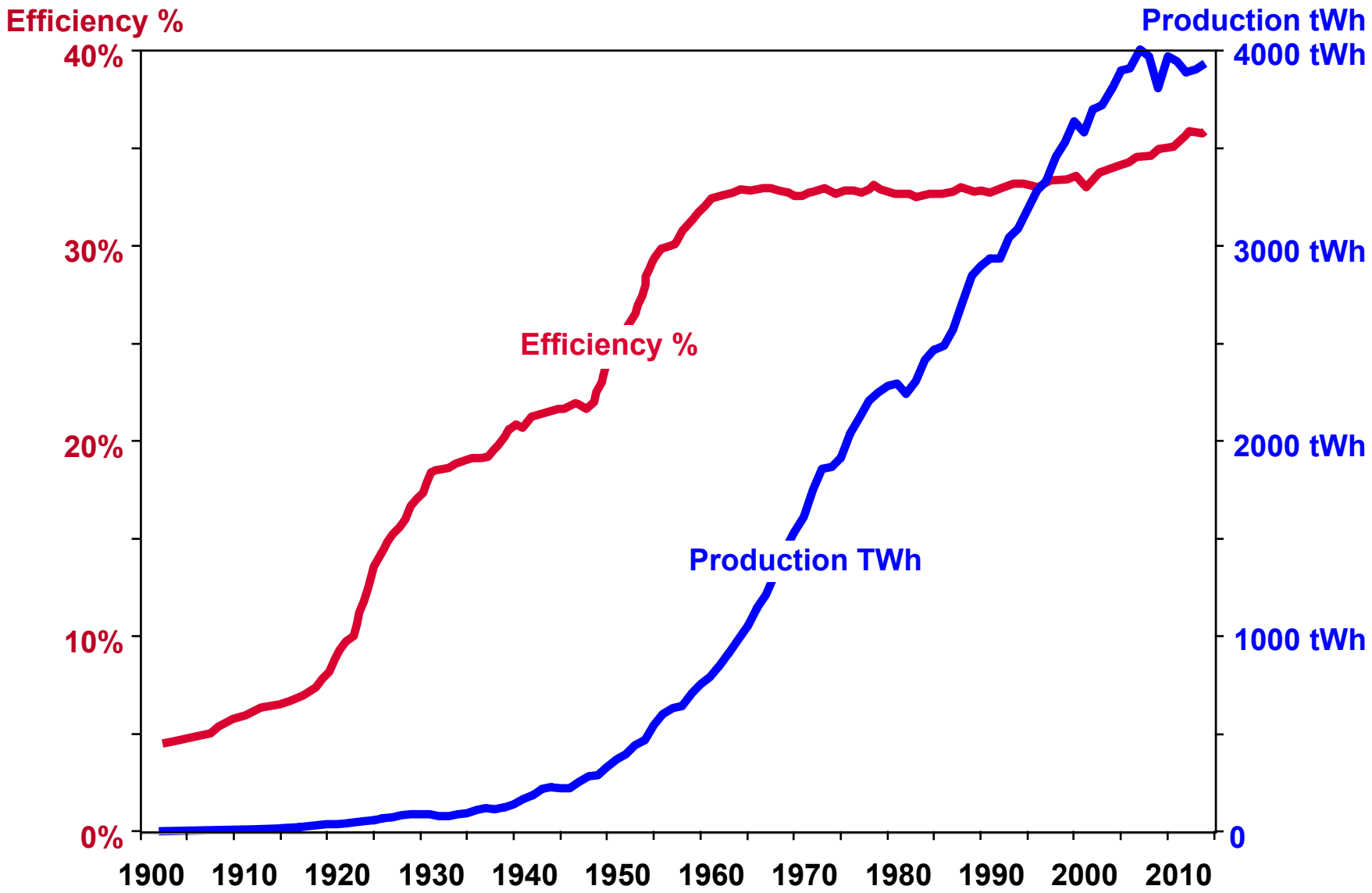



Source: **Fouquet (2011), Broadberry et al (2013)** updated and indexed by Ayres 2000-2010

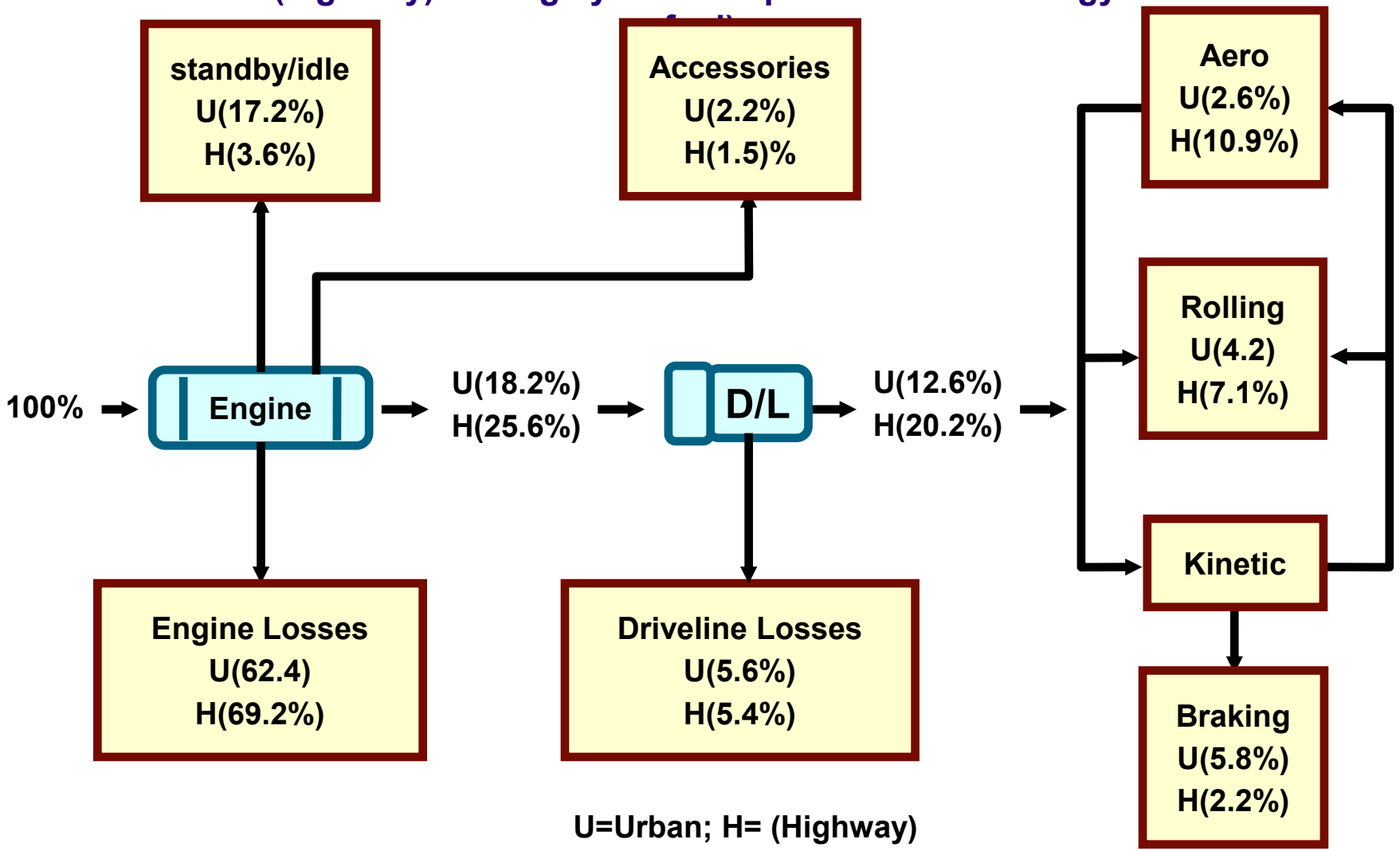
# Generator efficiency:
# Electric power output per unit mechanical power output



# Electricity production by electric utilities and average energy conversion efficiency USA 1900-1998

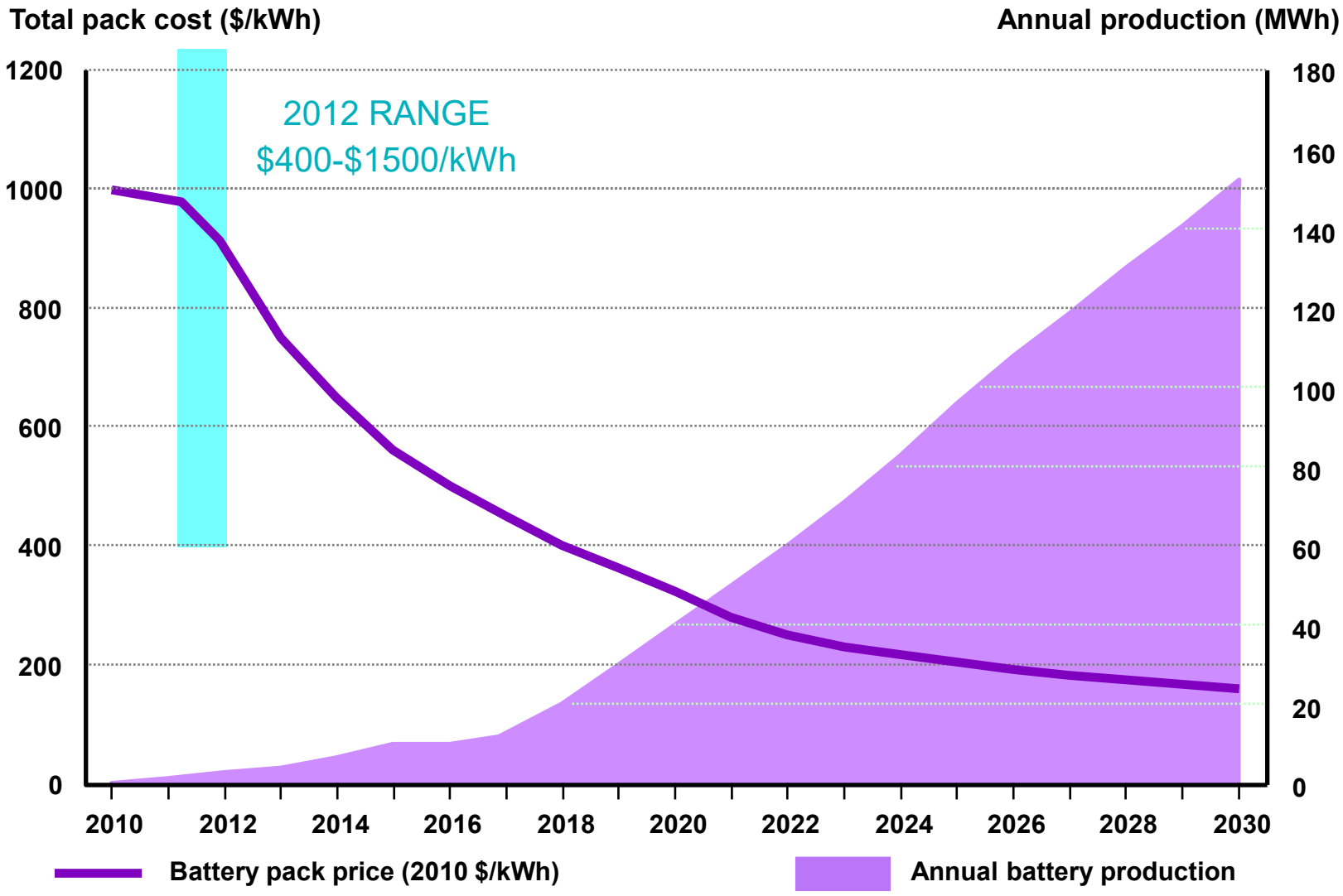


## Breakdown of energy requirements for a typical mid-size automobile (shown for US federal urban (highway) driving cycles as a percent of the energy content of the



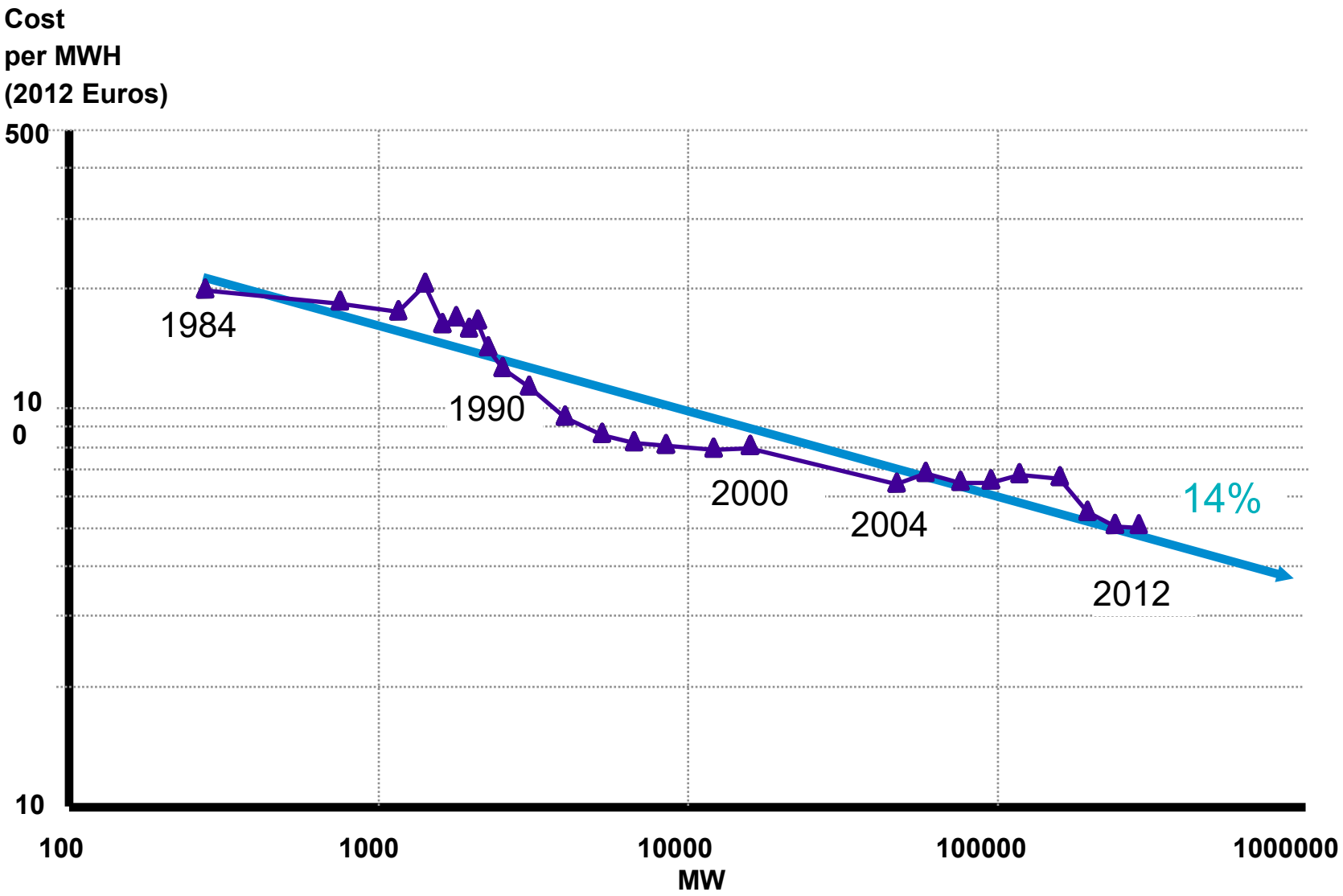

*Source: adapted from [Green 1994]*

# Lithium-ion battery pack cost & production 2010-2030




*Source: Bloomberg New Energy Finance*

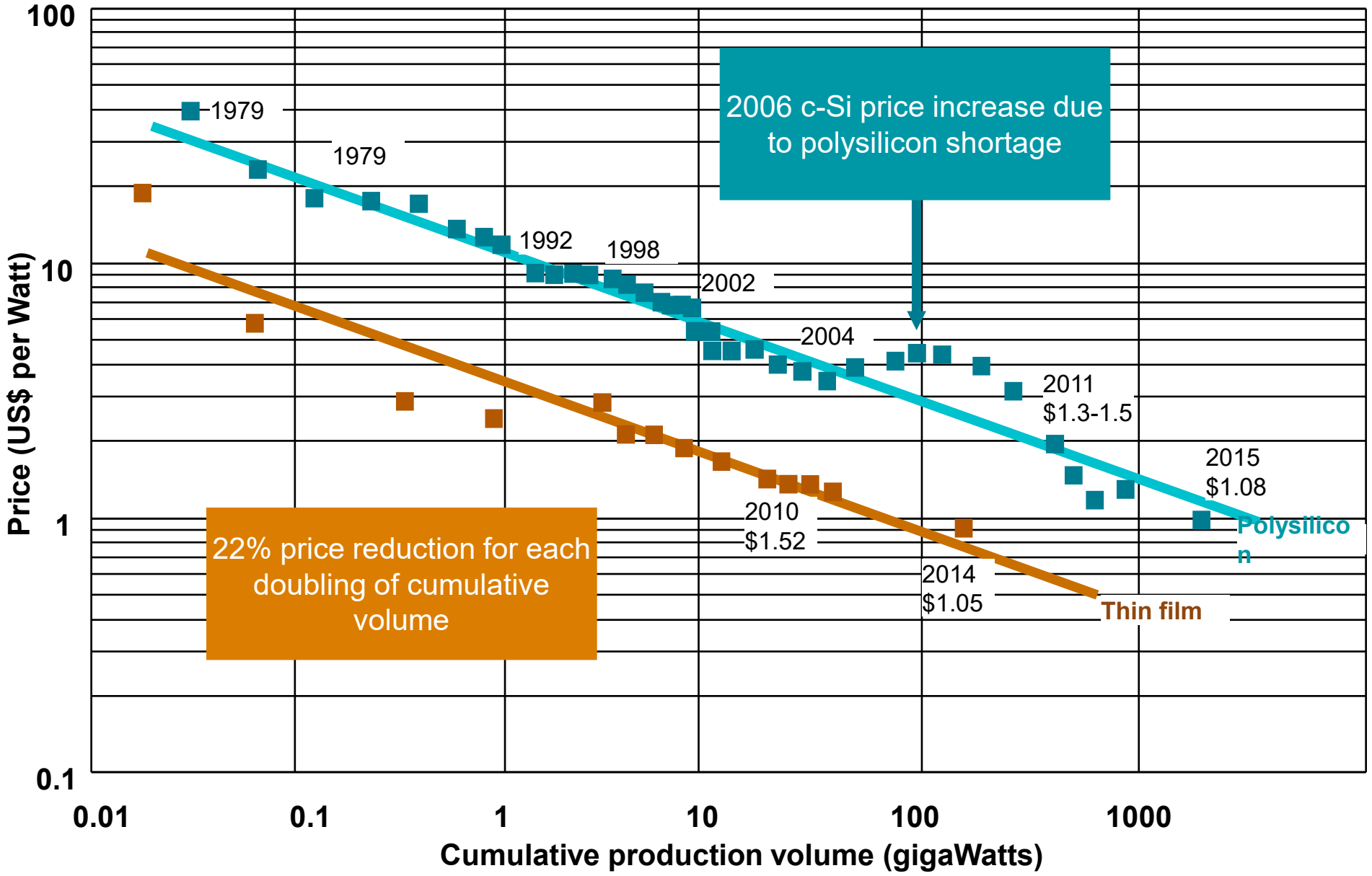
# Average levelized cost of onshore wind, 1984-2012



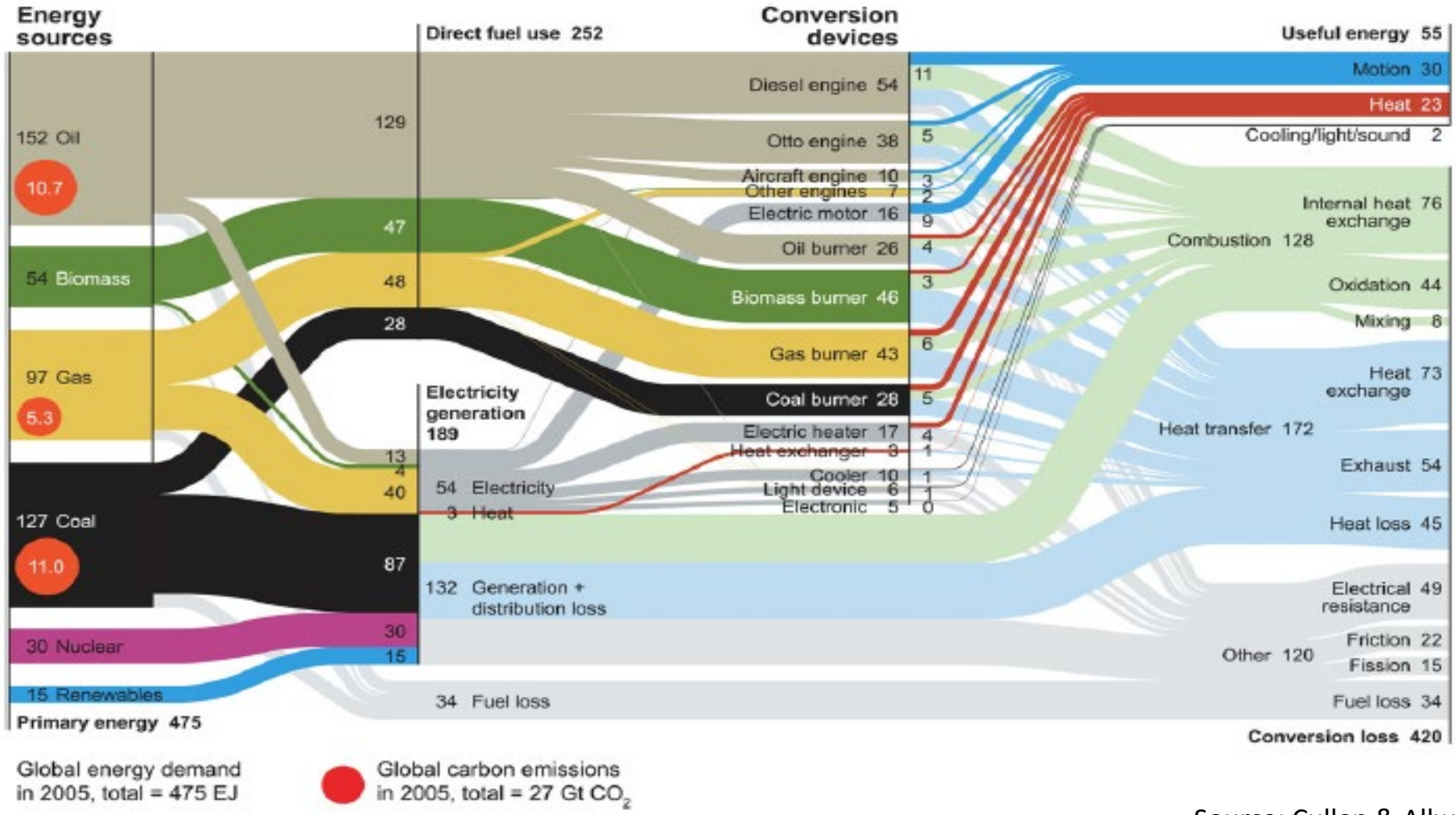

Note: Learning curve (blue line) is least square regressions: $R^2$=0.88 and 14% learning rate

***Source: Bloomberg New Energy Finance, January 2013***

# Global cumulative installed PV capacity and price, 1977-2015




*SOURCE: IRENA (2012), "RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES"; IEA (2011), "SOLAR ENERGY PERSPECTIVES"*




Source: Cullen & Allwood (2010)

**Fig. 3.** The global map of energy conversion efficiency.

At this point we come to an intellectual dichotomy. On one side (my side) energy is the substance and the essence of the universe. It cannot be created or destroyed by human activities. What we can do is to capture and utilize it for our purposes, as fluxes of exergy from nature (the sun) or from nuclear fissions in the center of the earth. On the other side are economists who divide the economy into “sectors” – picture the Input-Output table – of which most do not use exergy from nature but only as embodied indirectly in other products or services. The result of this alternative view is to exaggerate the productivity of human labor (i.e. people who are employed and create “value added” in the sectors) while greatly under-estimating the productivity of energy (exergy).