Energy Intensity, Efficiency and Economics

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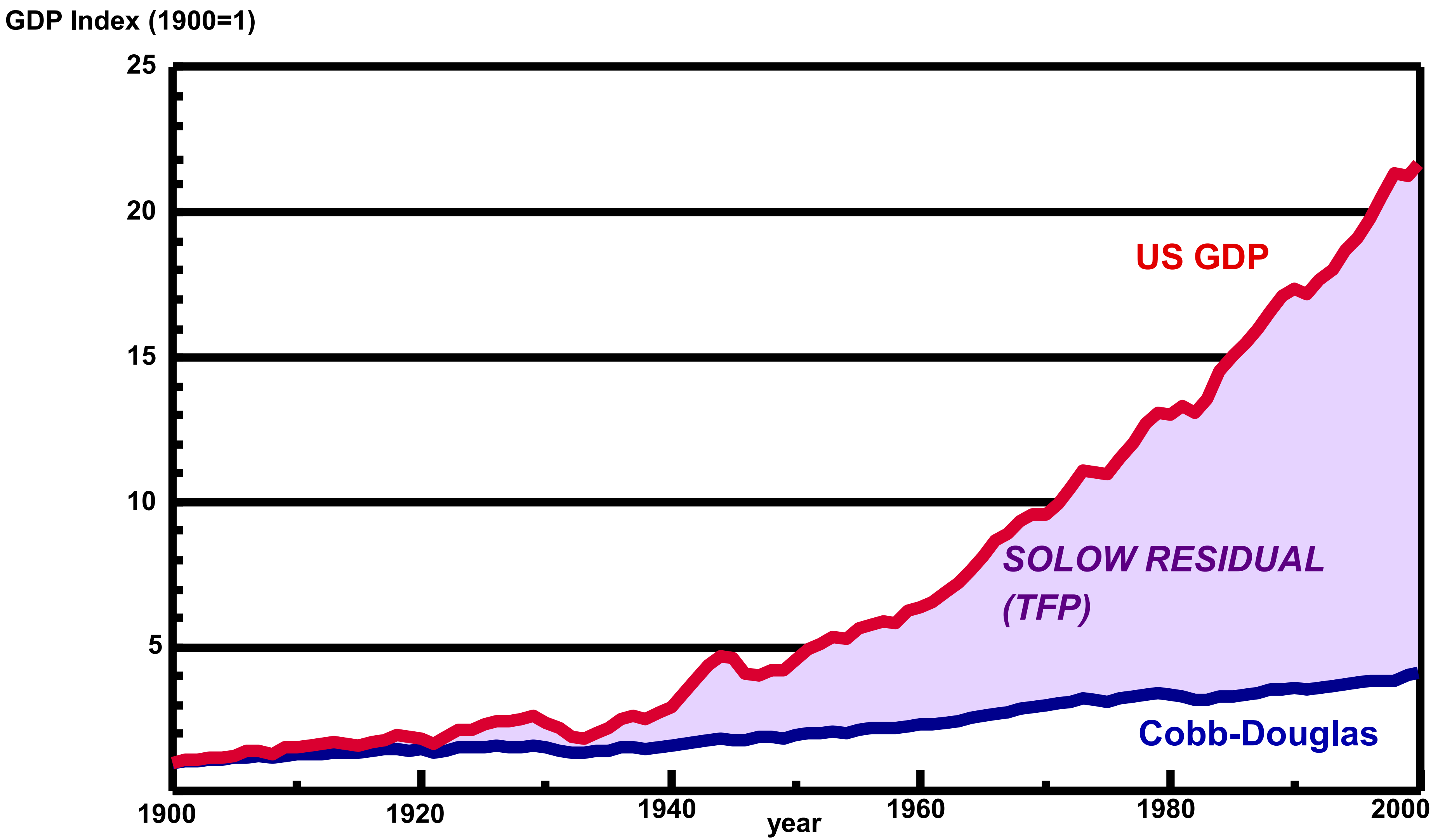
Outline of Presentation

- The conceptual Problem: the Role of energy
- Thermodynamic Intervention
- Intensity vs efficiency
- Implications for Growth Theory
- Mathematical Appendix
- Empirical results
- Forecasting tools

The Role of Energy in Economics

- Endogenous economic growth theory since Solow assumes that energy is an intermediate good produced by capital and human labor, plus knowledge embodied in "human capital".
- The energy sector is small, a few percent of GDP (depending on prices) and cannot explain growth
- An old income allocation theorem says that the output elasticity of energy must be equal to its cost share. But the cost share is too small to matter.

US GDP 1900-2000; Actual vs. 3-Factor Cobb-Douglas Production Function L(0.70), K(0.26), E(0.04)



The underlying physics

- Energy is the building block of the universe
- Energy is neither created nor destroyed (the First Law of thermodynamics).
- But not all energy can do work. The useful part is called **exergy**. The other part is called **anergy**.
- Exergy is not conserved. Doing work destroys exergy and increases entropy.
- Exergy is productive; anergy is not.

EXERGY - DEFINITION

MAXIMUM WORK OBTAINABLE FROM
A SUBSYSTEM APPROACHING
THERMODYNAMIC EQUILIBRIUM

EFFICIENCY - DEFINITION

RATIO OF ACTUAL WORK PERFORMED
TO MAXIMUM WORK (EXERGY)

A Critical Perspective: Energy, Exergy and Useful Work

- **Energy** is conserved. The energy input to a process or transformation is always equal to the energy output. This is the **First Law of thermodynamics**.
- However the output energy is always less available to do useful work than the input. This is the **Second Law of thermodynamics**, sometimes called the **entropy law**.
- Energy available to do useful work is **exergy**.
- Exergy is a **factor of production**.

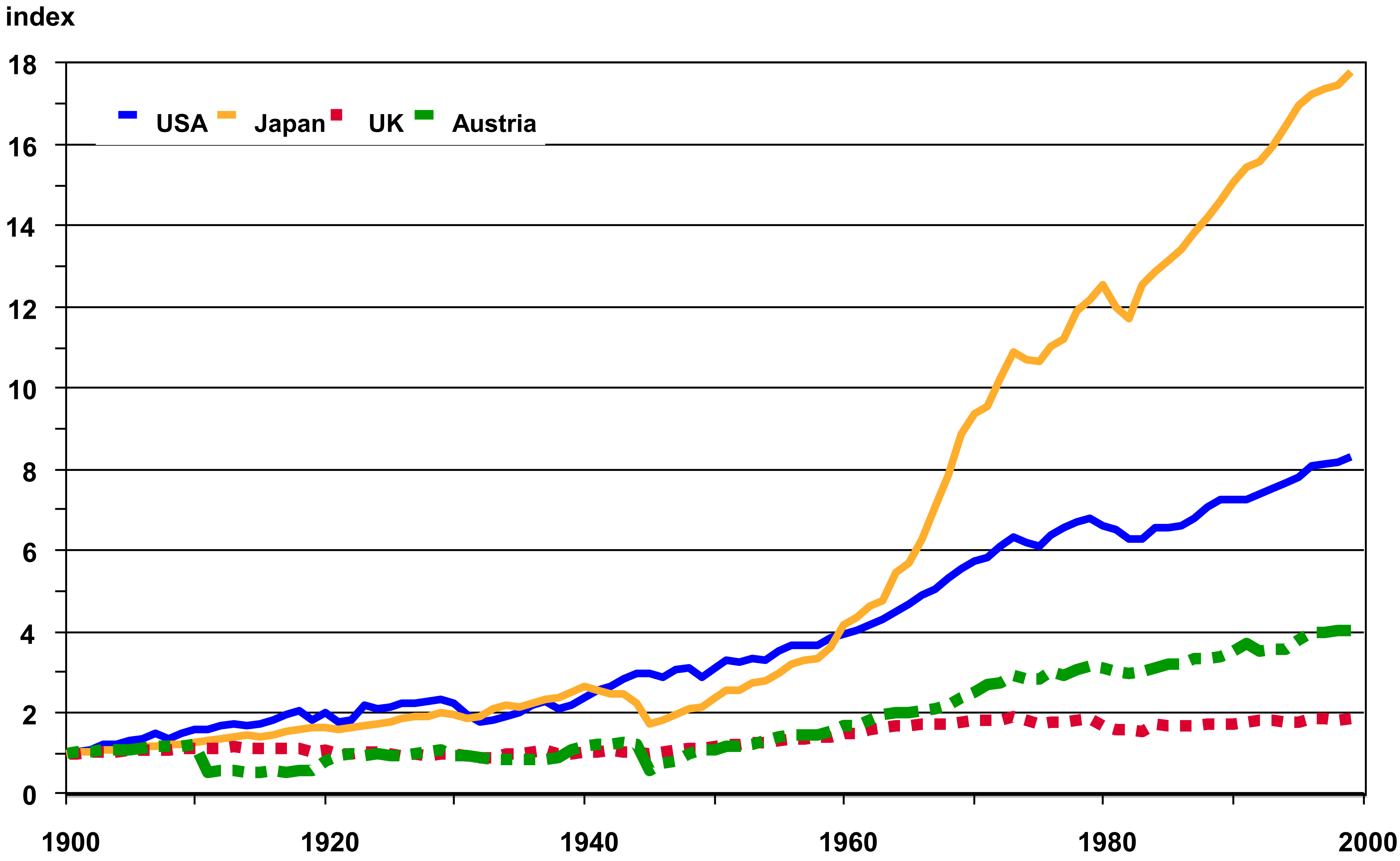
Exergy and Useful Work, Con't

- **Capital** is inert. It must be activated. Most economists regard **labor** as the activating agent. Labor (by humans and/or animals) was once the only source of **useful work** in the economy.
- But machines (and computers) require a different activating agent, **exergy** that can be converted to **useful work** (in the thermodynamic sense).
- For economic growth models, useful work can be considered as a **factor of production**.

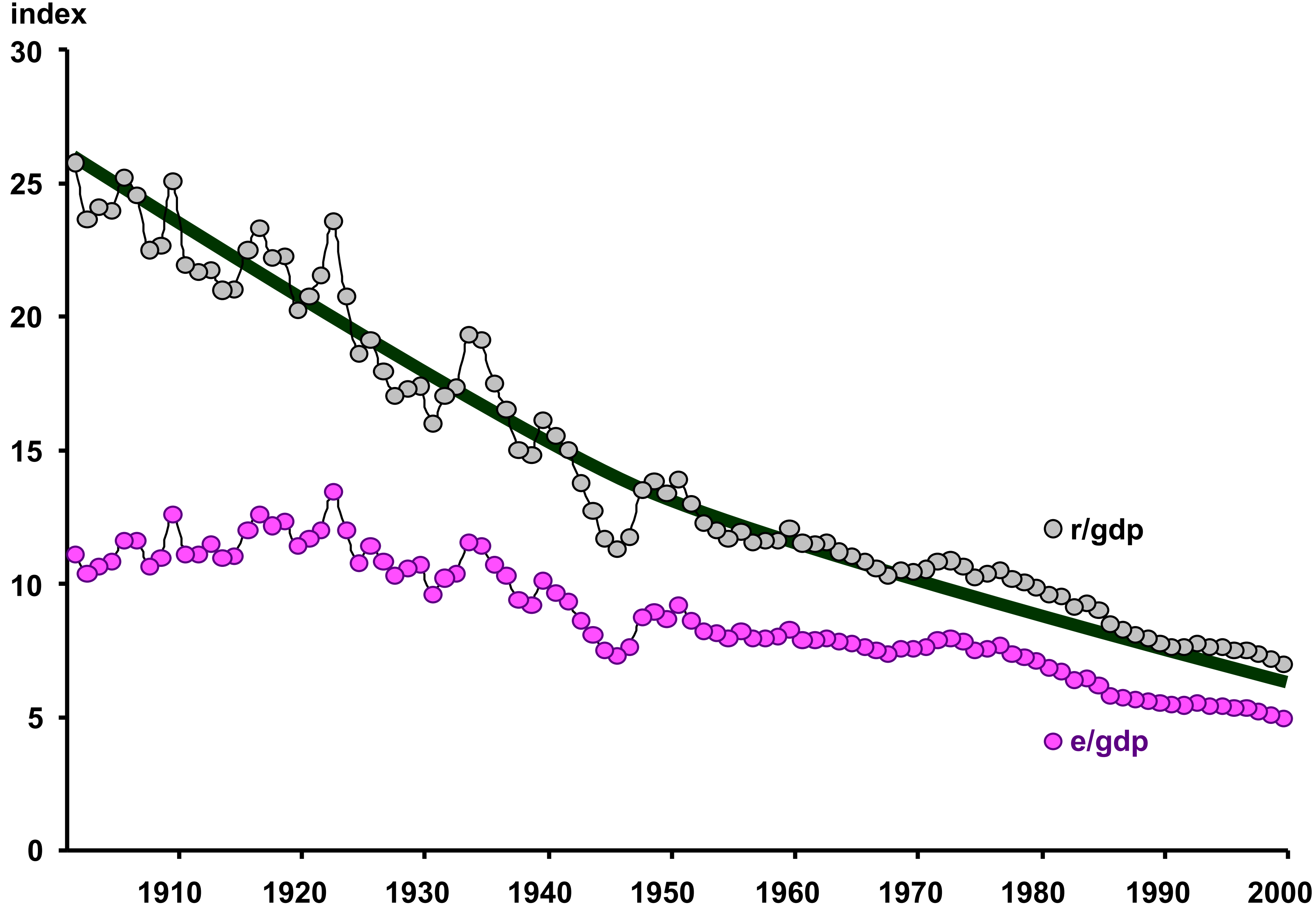
Energy Intensity and Work Intensity

- Energy intensity is defined as the energy required to produce a unit (dollar) of GDP, or E/GDP.
- E is in physical units, such as Exajoules, GDP in $
- Work intensity is the work required to produce a dollar of GDP. Notice that work intensity continued to increase untilt he early 1970s.

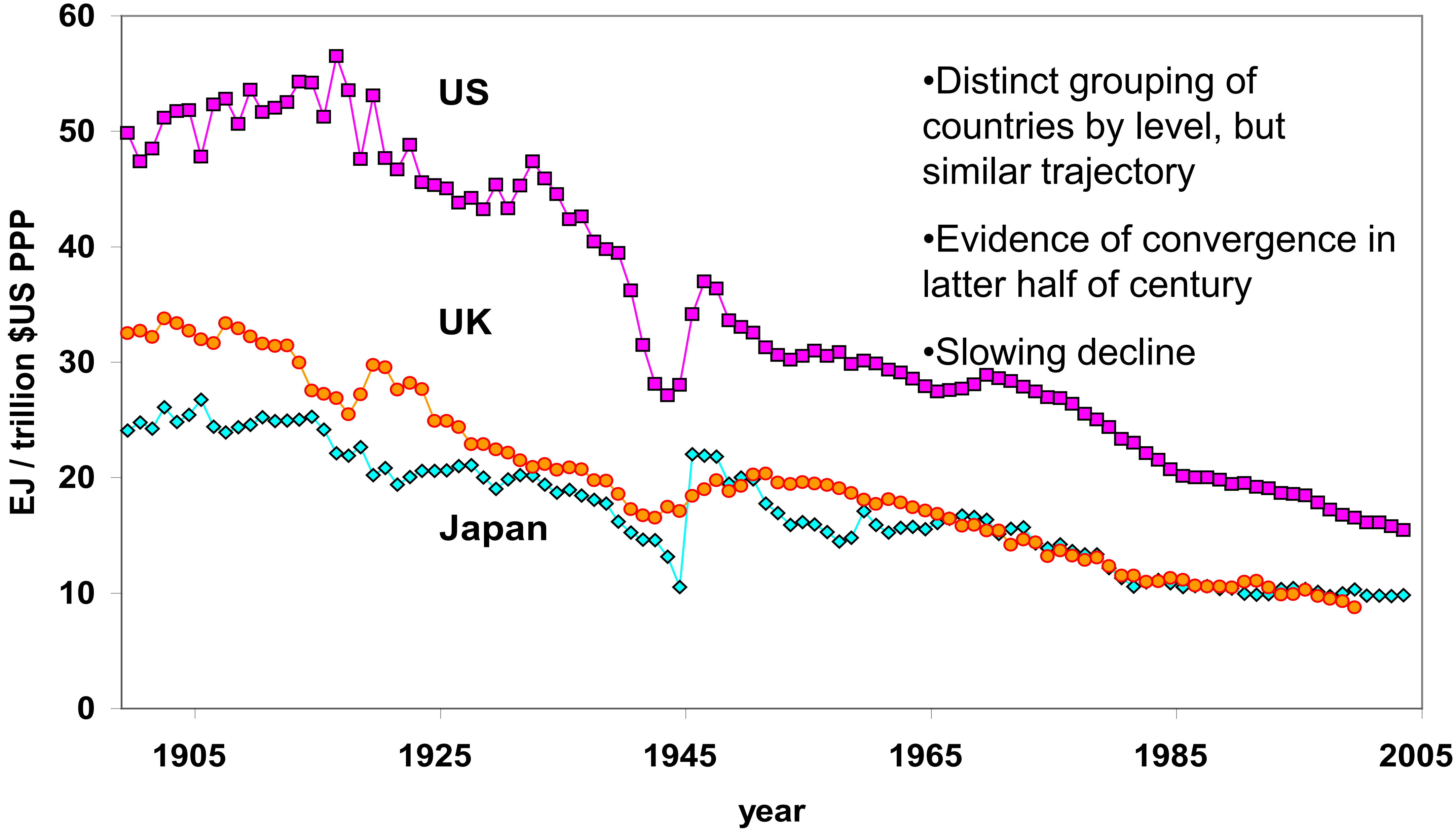
Exergy (E) Austria, Japan, UK & US: 1900-2005 (1900=1)



Model - Energy Intensity of GDP, USA 1900-2000

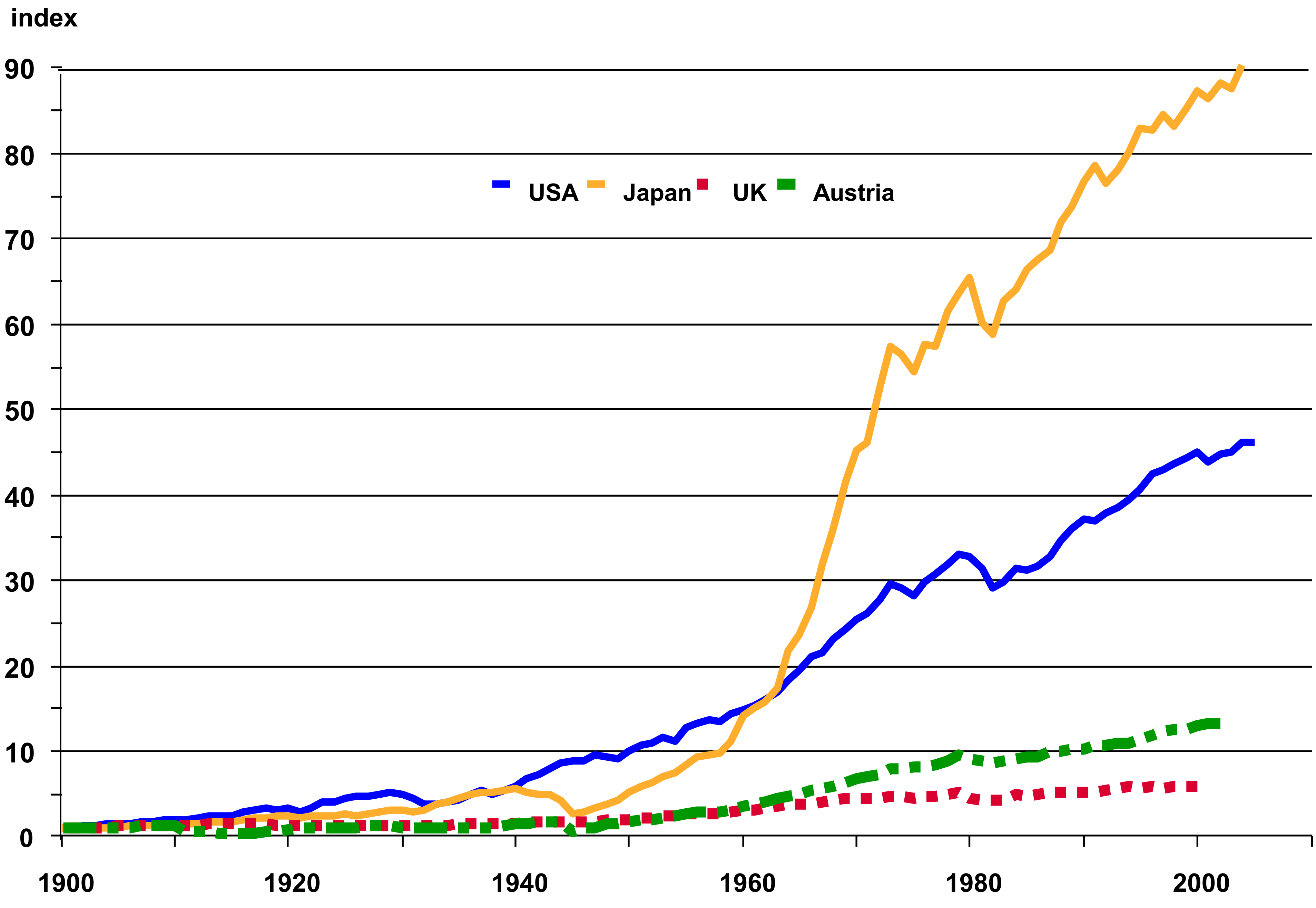


Exergy Intensity of GDP Indicator

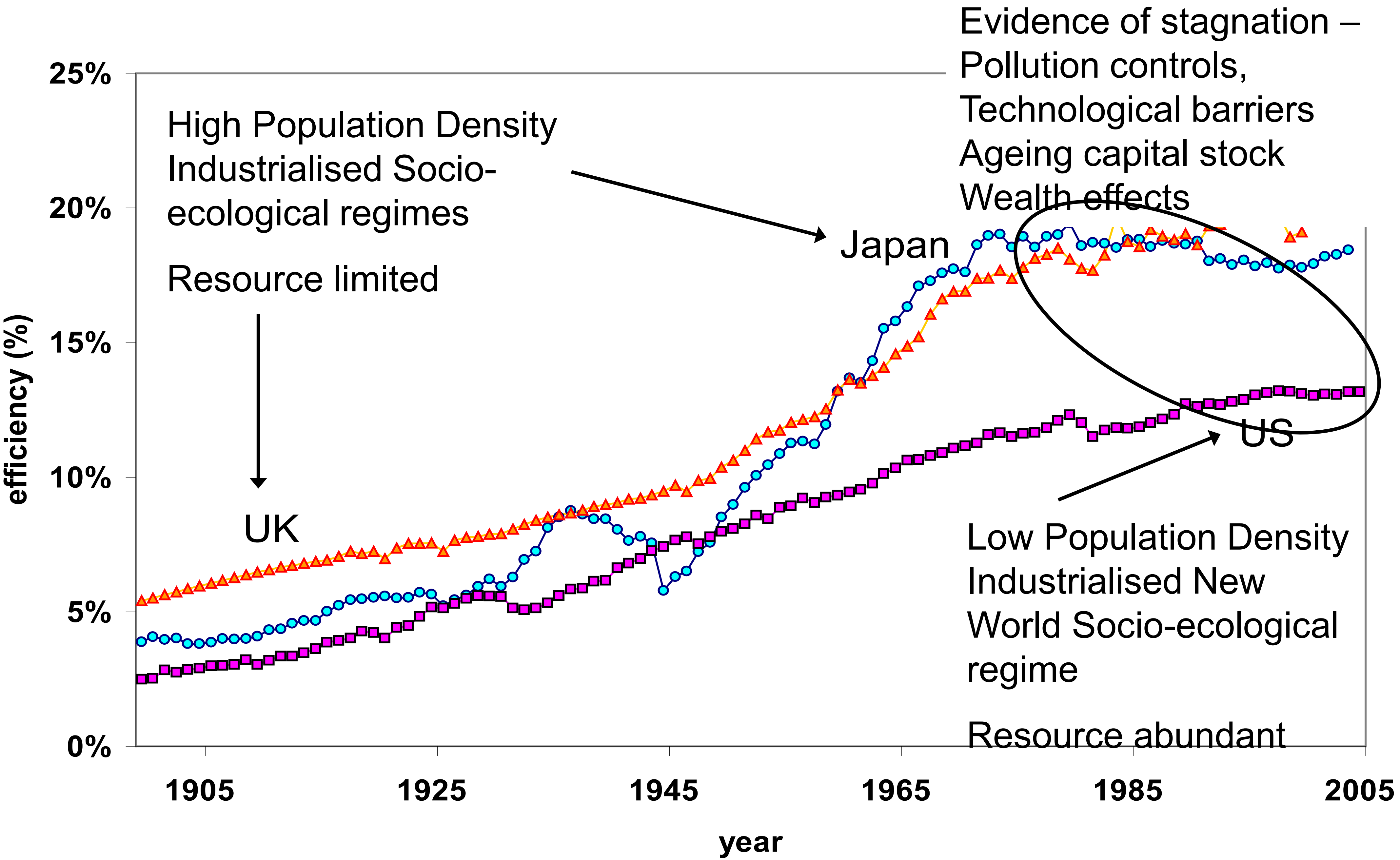


- Distinct grouping of countries by level, but similar trajectory
- Evidence of convergence in latter half of century
- Slowing decline

Useful Work (U) Austria, Japan, US, UK: 1900-2000

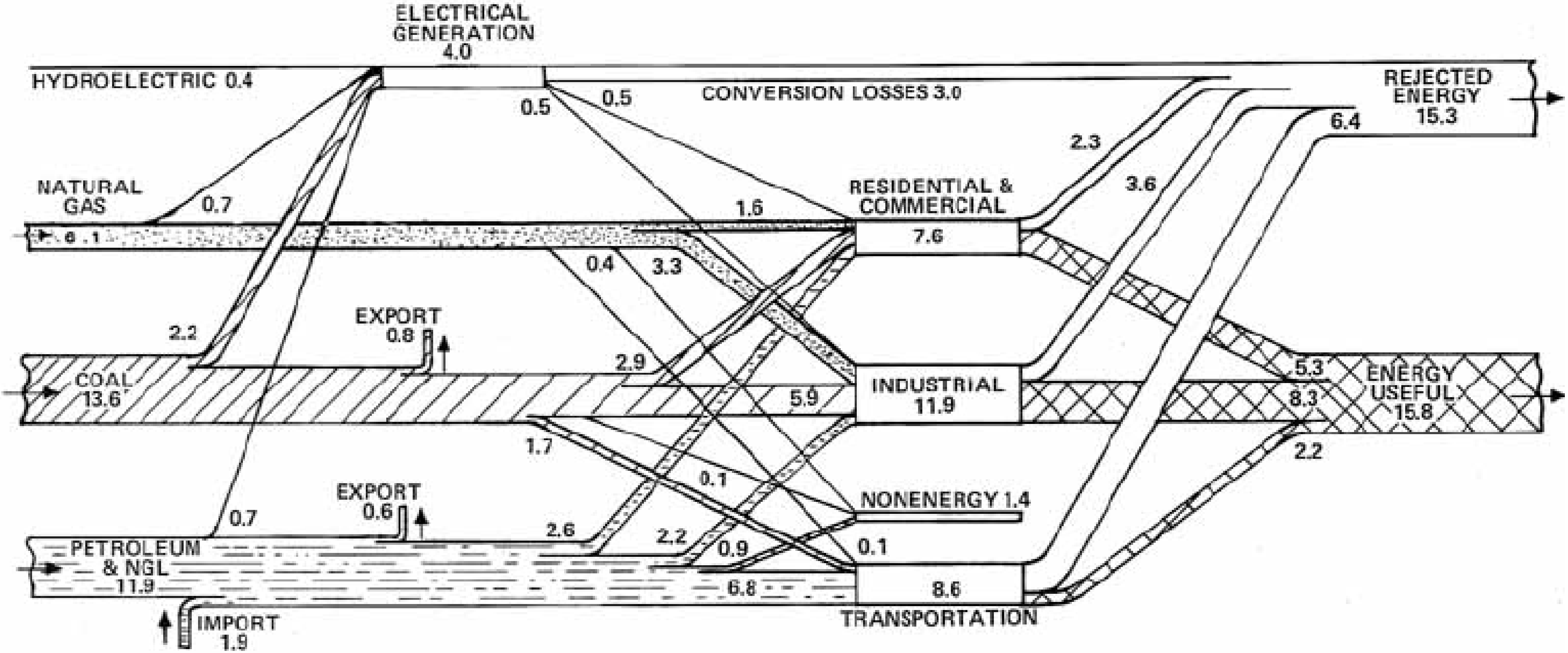


Exergy to Useful Work Conversion Efficiency



Efficiency: Two kinds

- **Energy efficiency** (First Law) is "useful output" divided by total input (of energy as fuel or feedstock). This measure is quite deceptive, but common. (See slides following)
- **Exergy efficiency** (Second Law) is a different ratio. The numerator is work actually done in the process. The denominator is the potential work (exergy) that could have been done in an ideal process allowing only for irreversibilities.

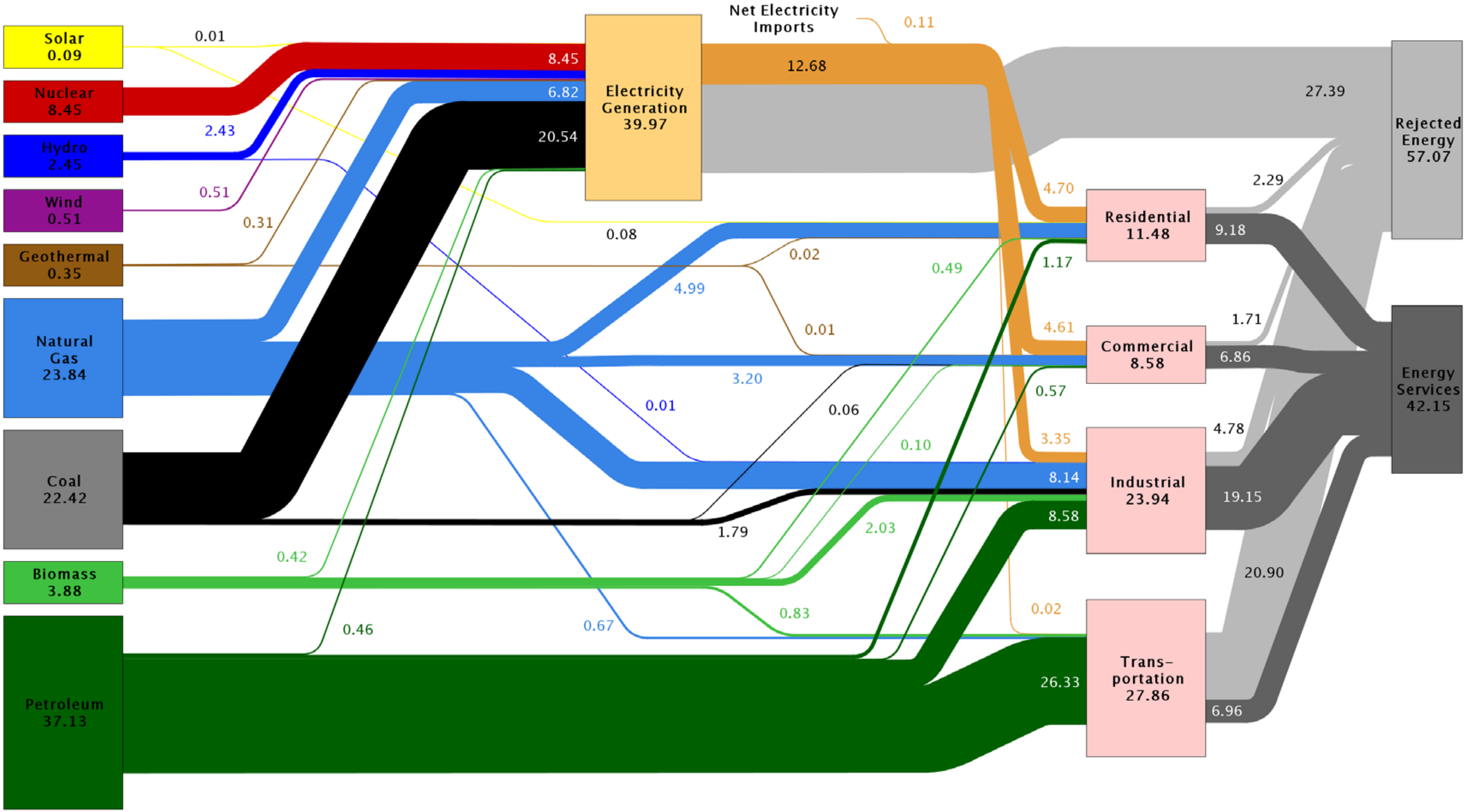


U.S. Energy Flow — 1950

All values in 10^{15} Btu (2.12×10^{15} Btu = 10^6 bbl/day oil)

Total energy consumption = 33.9×10^{15} Btu.

Estimated U.S. Energy Use in 2008: ~99.2 Quads



Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

US Estimated Energy "Efficiencies" (LLNL, Based on DOE)

Sector	1950	1970	1990	2000	2008
Electricity Generation	0.25	0.36	0.33	0.31	0.32
Residential & Commercial	0.73	0.75	0.75	0.75	0.80
Industrial	0.72	0.75	0.75	0.80	0.80
Transport	0.26	0.25	0.25	0.20	0.24
Aggregate	0.50	0.50	0.44	0.38	0.42

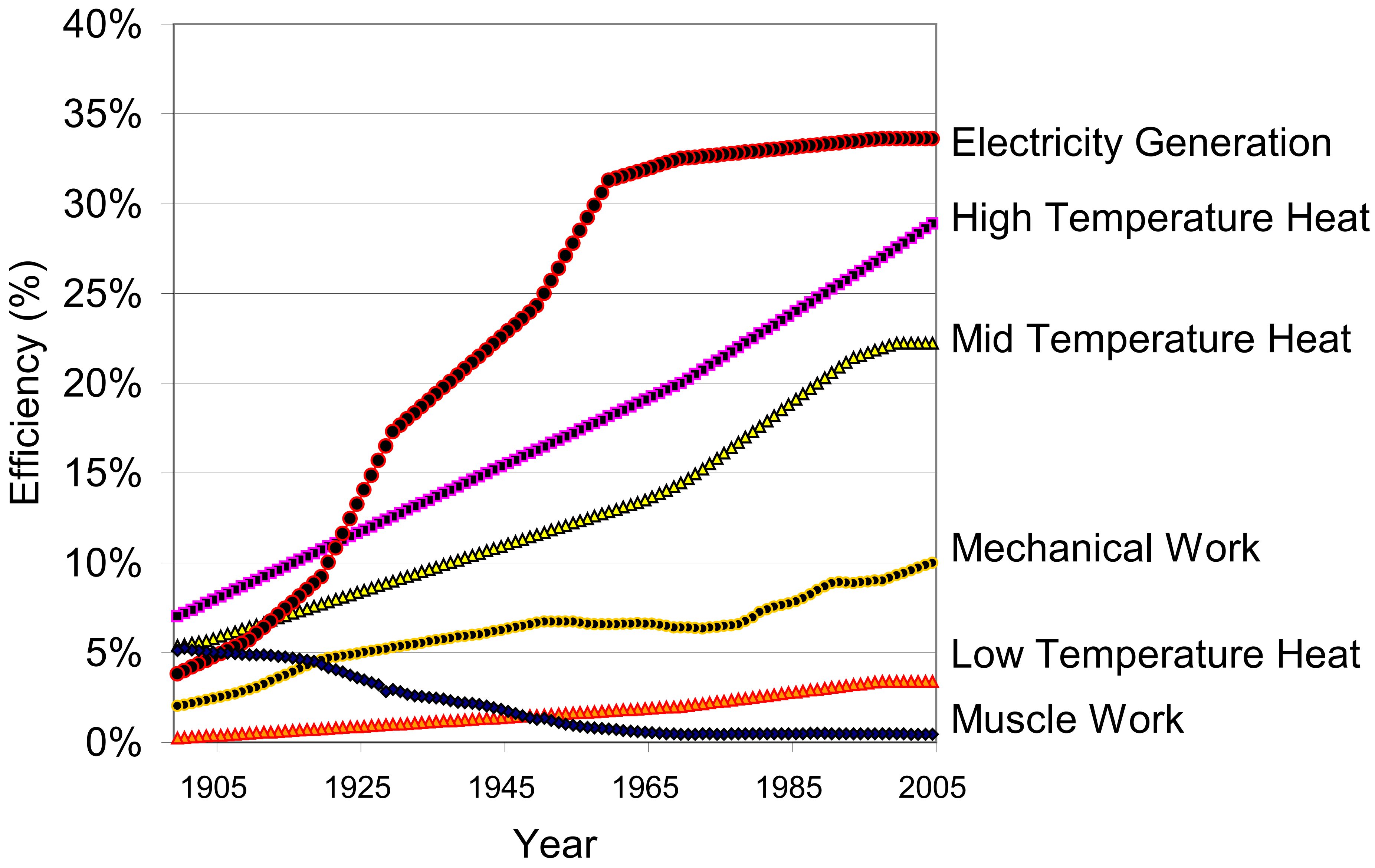
A dangerous deception

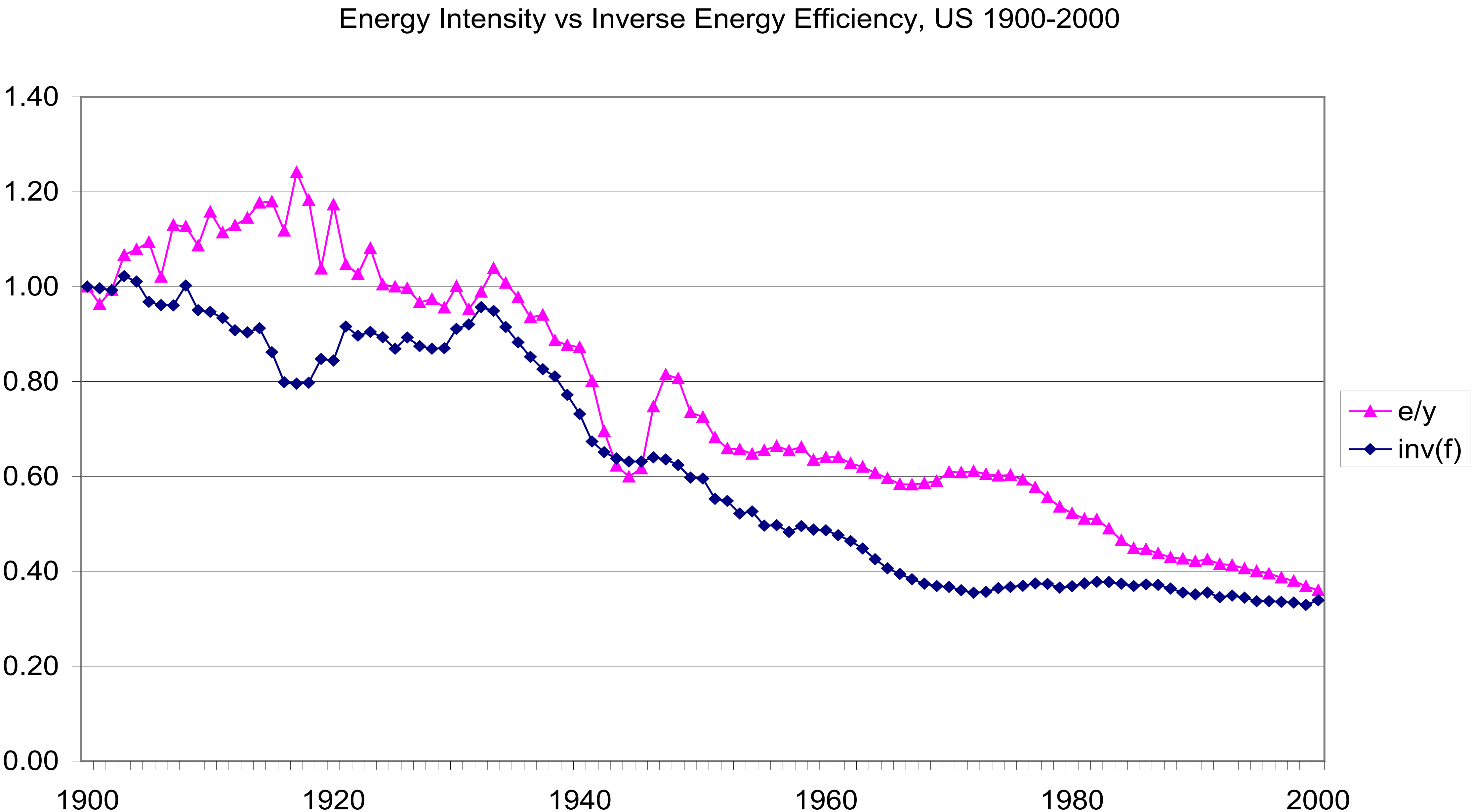
- Even the “first law” efficiency (useful output divided by total input) of the industry and buildings sectors cannot be 80%. But the energy department has been publishing this nonsense since the early 70s (and back-dated to 1950) mainly to “prove” that US energy efficiency is high, so conservation is a waste of effort and new (nuclear) supply is needed.
- In reality, the opportunities for energy efficiency are the most cost-effective source of new supply today.

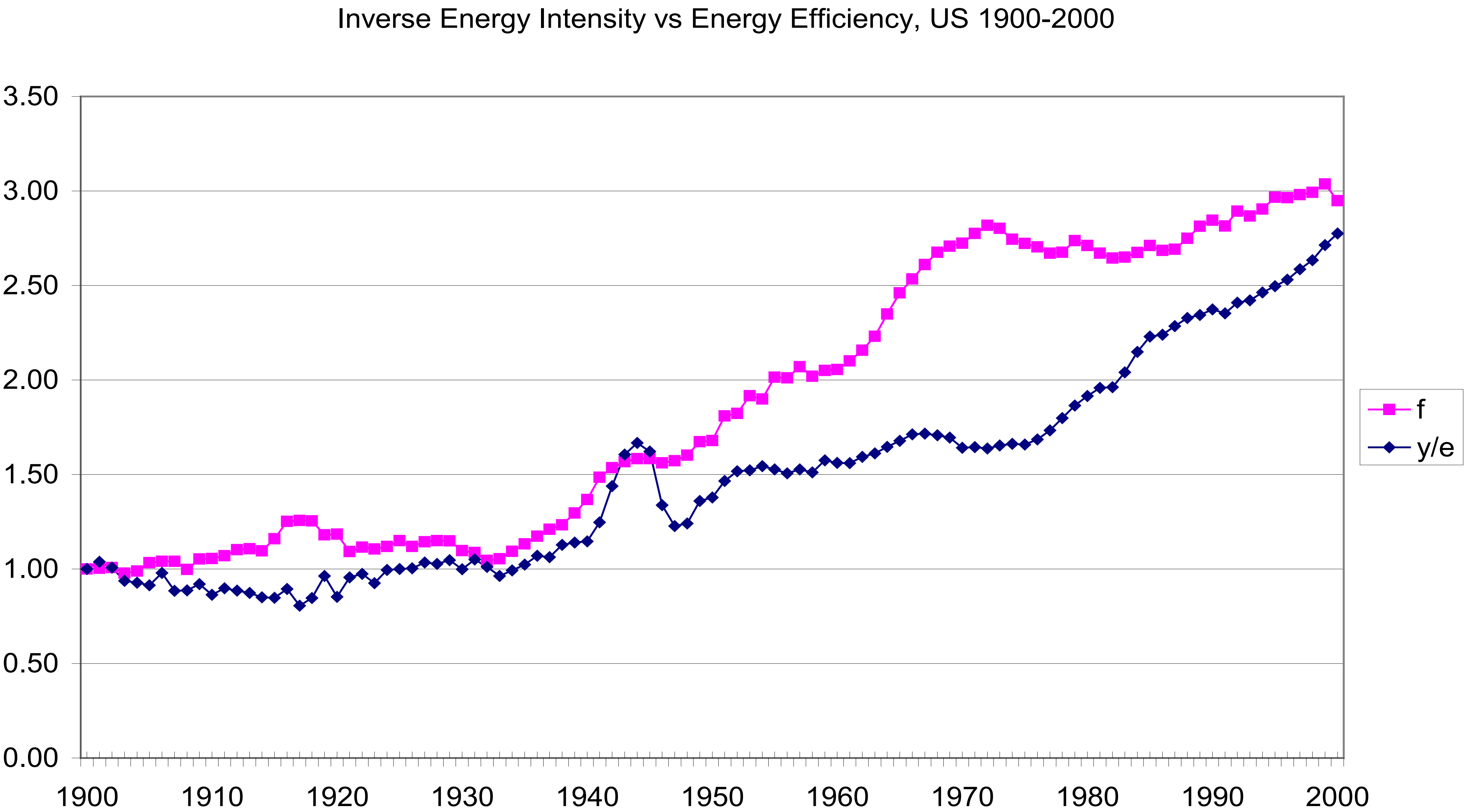
Energy Intensity vs Energy Efficiency

- A great many analysts try to use energy intensity (inverted) as a proxy for energy efficiency.
- They use decomposition analysis to allow for structural change over time (the changing mix of outputs). However, the residual is not a good measure of changing efficiency.
- Because energy intensity will decline anyhow for other reasons (the Solow residual term) :
- Calculate E/Y using the Cobb-Douglas P.F.

Conversion Efficiencies




Energy Intensity vs Inverse Energy Efficiency, US 1900-2000
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1900
1920
1940
1960
1980
2000
e/y
inv(f)



Inverse Energy Intensity vs Energy Efficiency, US 1900-2000
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
f
y/e

Useful Work and Economic Growth

- Since the industrial revolution, human and animal labor have been increasingly replaced by machines.
- Some tried to include energy in growth theory (1970s) but there is a theorem that energy output elasticity equals cost share in the national accounts.
- The theorem does not apply to a multi-sector economy with three factors of production, with physical constraints on the input ratios. Either too much or too little exergy per machine doesn't work.

Economic Production Functions

Common practice: Cobb-Douglas

$$Y_t = A_t (H_t K_t)^{\alpha} (G_t L_t)^{\beta} (F_t R_t)^{\gamma}$$

Y_t is output at time *t*, a function of,

- **K_t, L_t, R_t inputs of *capital, labor* and *natural resource services*.**
- **α, + β + γ = 1, (constant returns to scale assumption)**
- **A_t is *total factor productivity***
- **H_t, G_t and F_t coefficients of *factor quality***

Economic Production Functions: II

The linear-exponential (LINEX) production function

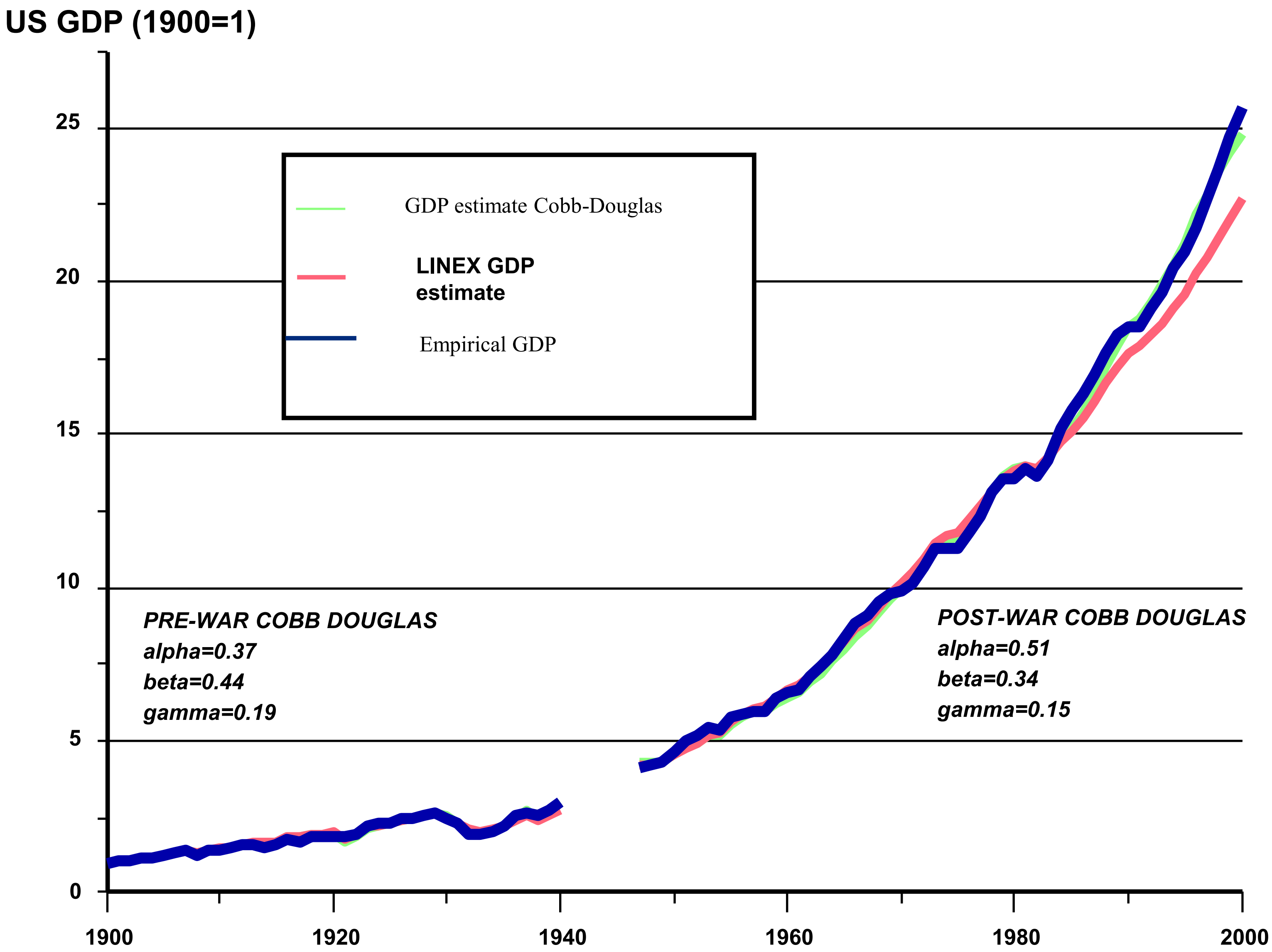
$$Y_t = U \exp\left\{ a\left(2 - \left(\frac{L+U}{K}\right)\right) + ab\left(\frac{L}{U} - 1\right)\right\}$$

For the USA, a = 0.12, b = 3.4 (2.7 for Japan)

Corresponds to $Y = K^{0.38} L^{0.08} U^{0.56}$

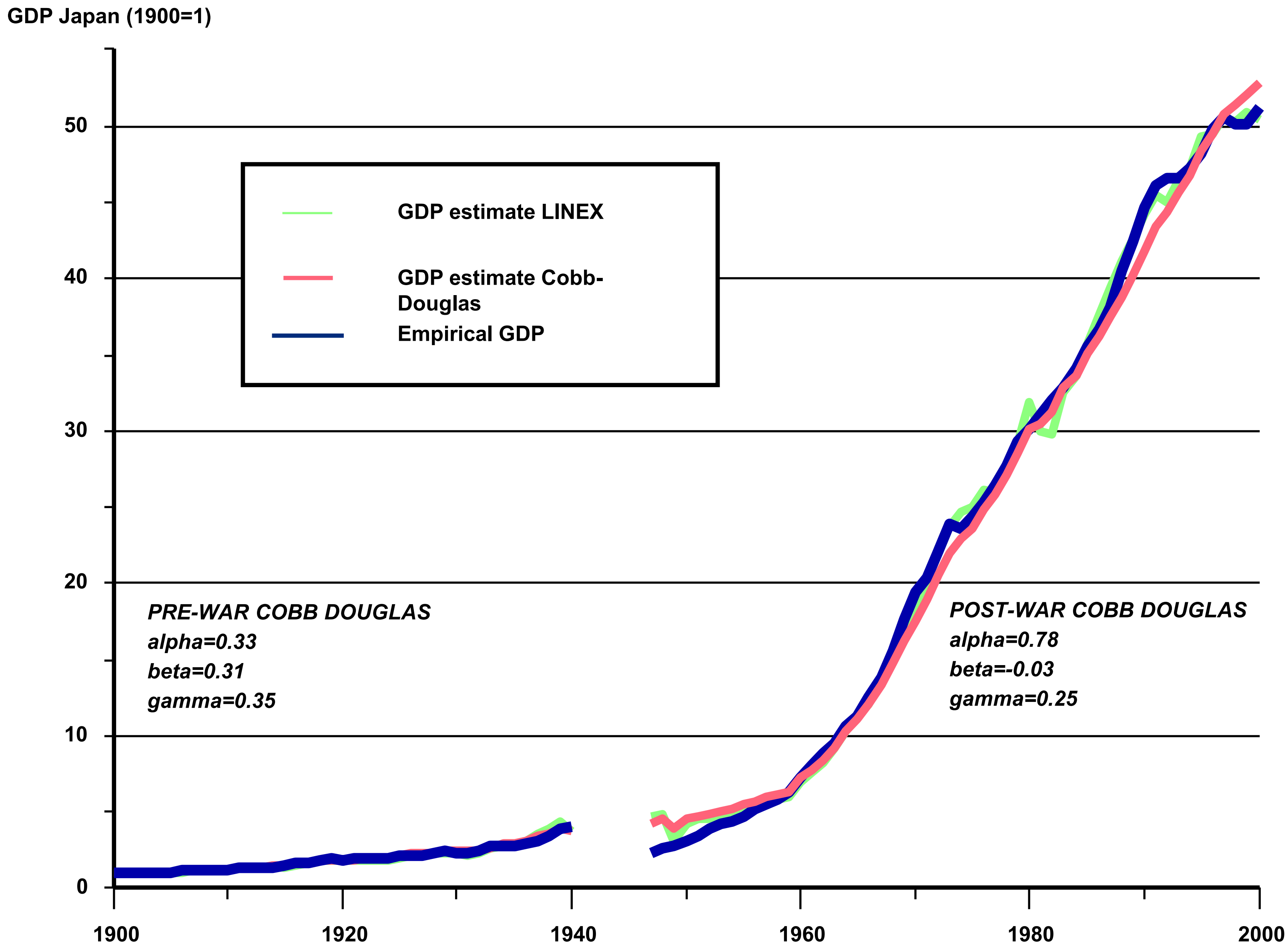
- ***A_t , 'total factor productivity', is REMOVED***
- ***Resources (Energy & Materials) replaced by WORK***
- ***F_t = energy-to-work conversion efficiency***
- ***Factors ARE MUTUALLY DEPENDENT***
- ***Empirical elasticities DO NOT EQUAL COST SHARE***

Empirical and Estimated US GDP: 1900-2000



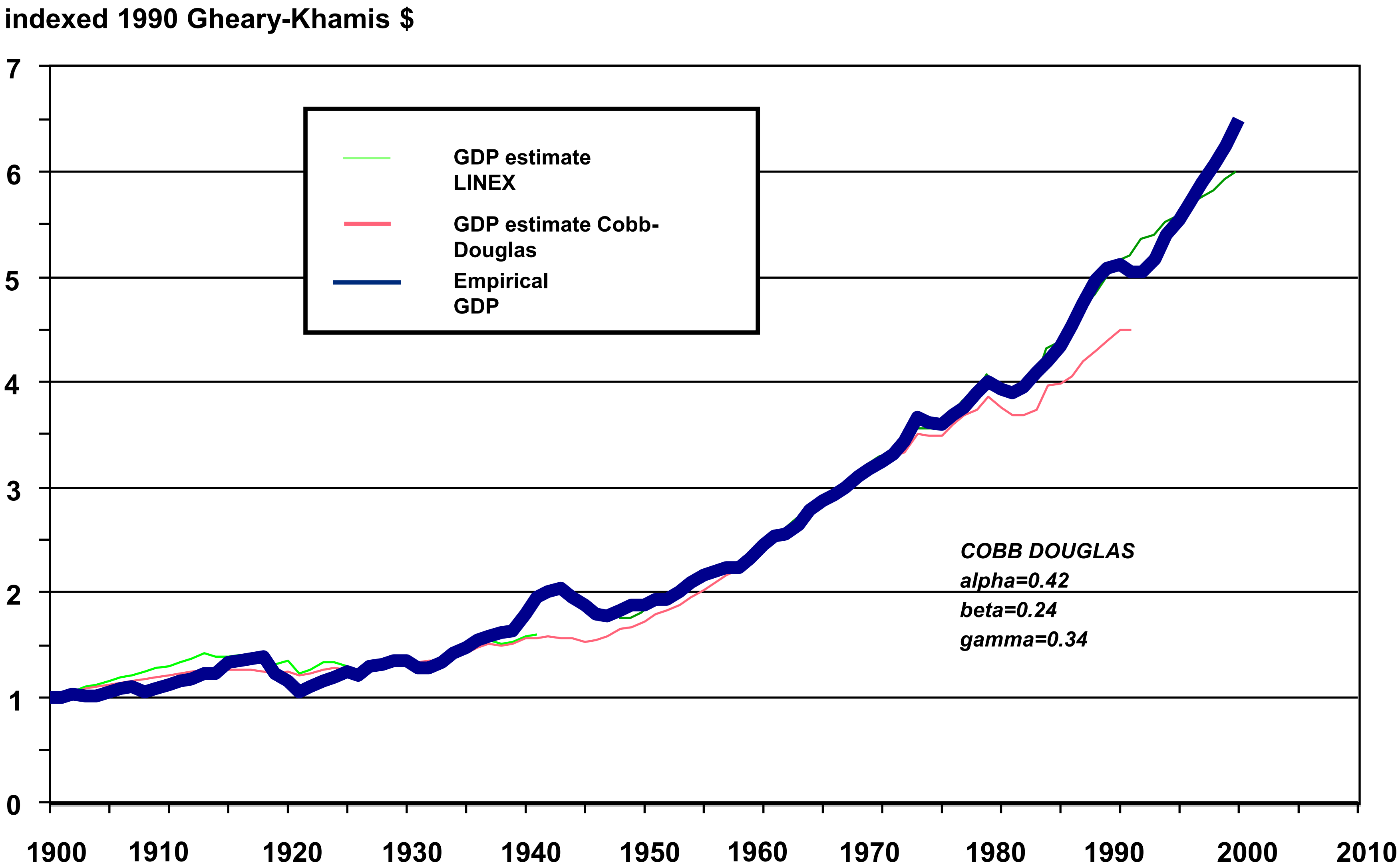
Empirical GDP from Groningen GGDC Total Economy Growth Accounting Database: Marcel P. Timmer, Gerard Ypma and Bart van Ark (2003), *IT in the European Union: Driving Productivity Divergence?*, GGDC Research Memorandum GD-67 (October 2003), University of Groningen, Appendix Tables, updated June 2005

Empirical and estimated GDP Japan; 1900-2000



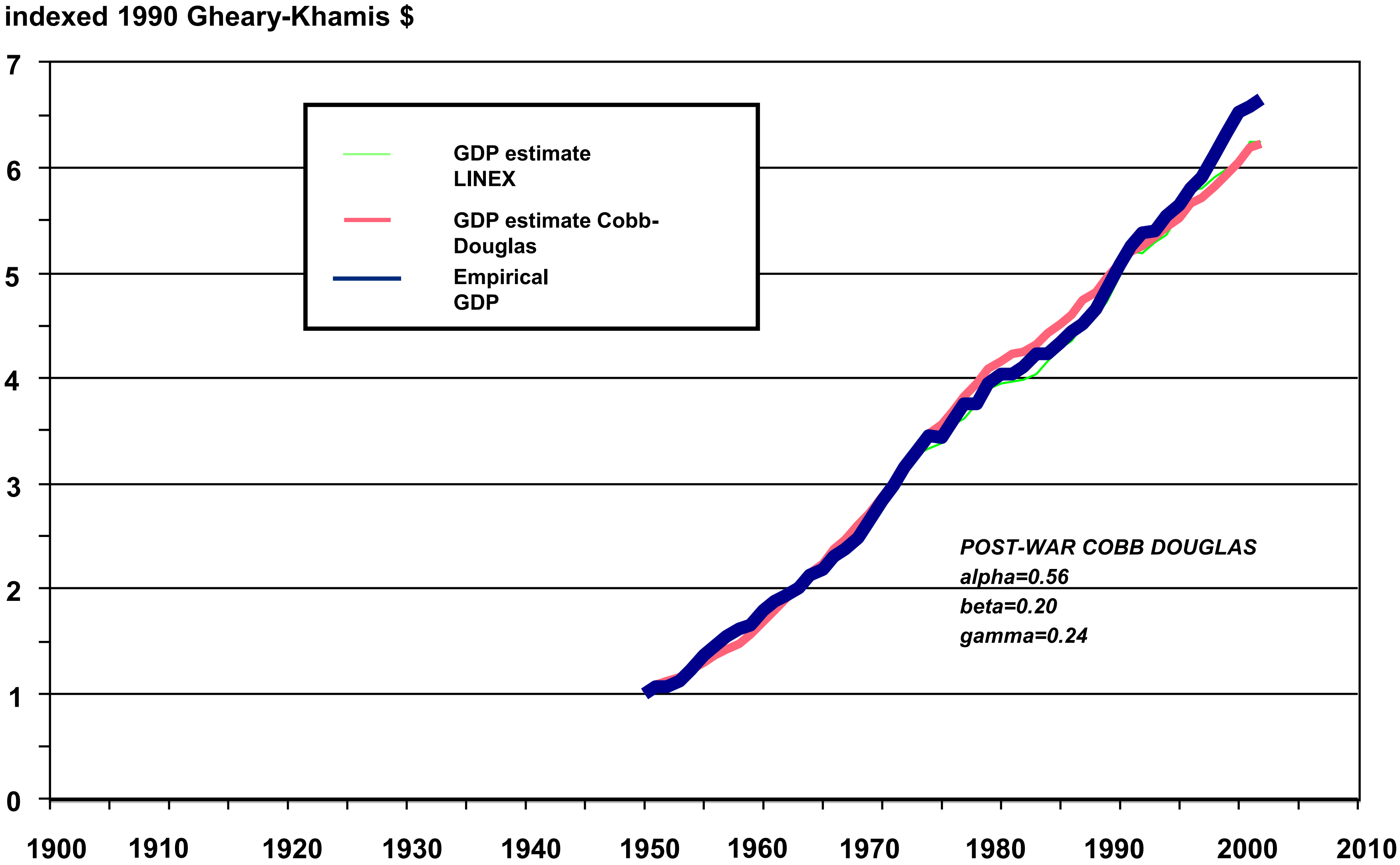
Empirical GDP from Groningen GGDC Total Economy Growth Accounting Database: Marcel P. Timmer, Gerard Ypma and Bart van Ark (2003), *IT in the European Union: Driving Productivity Divergence?*, GGDC Research Memorandum GD-67 (October 2003), University of Groningen, Appendix Tables, updated June 2005

Empirical & Estimated GDP, UK 1900-2005 (1900=1)



Empirical GDP from Groningen GGDC Total Economy Growth Accounting Database: Marcel P. Timmer, Gerard Ypma and Bart van Ark (2003), *IT in the European Union: Driving Productivity Divergence?*, GGDC Research Memorandum GD-67 (October 2003), University of Groningen, Appendix Tables, updated June 2005

Empirical & Estimated GDP, Austria 1950-2005 (1950=1)



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ICT adjusted LINEX

$$y = q * u \exp\left\{ f - a\left(\frac{u + l}{k - \delta} \right) + ab\frac{l}{u} + c\frac{\delta}{l} \right\}$$

$y = GDP$

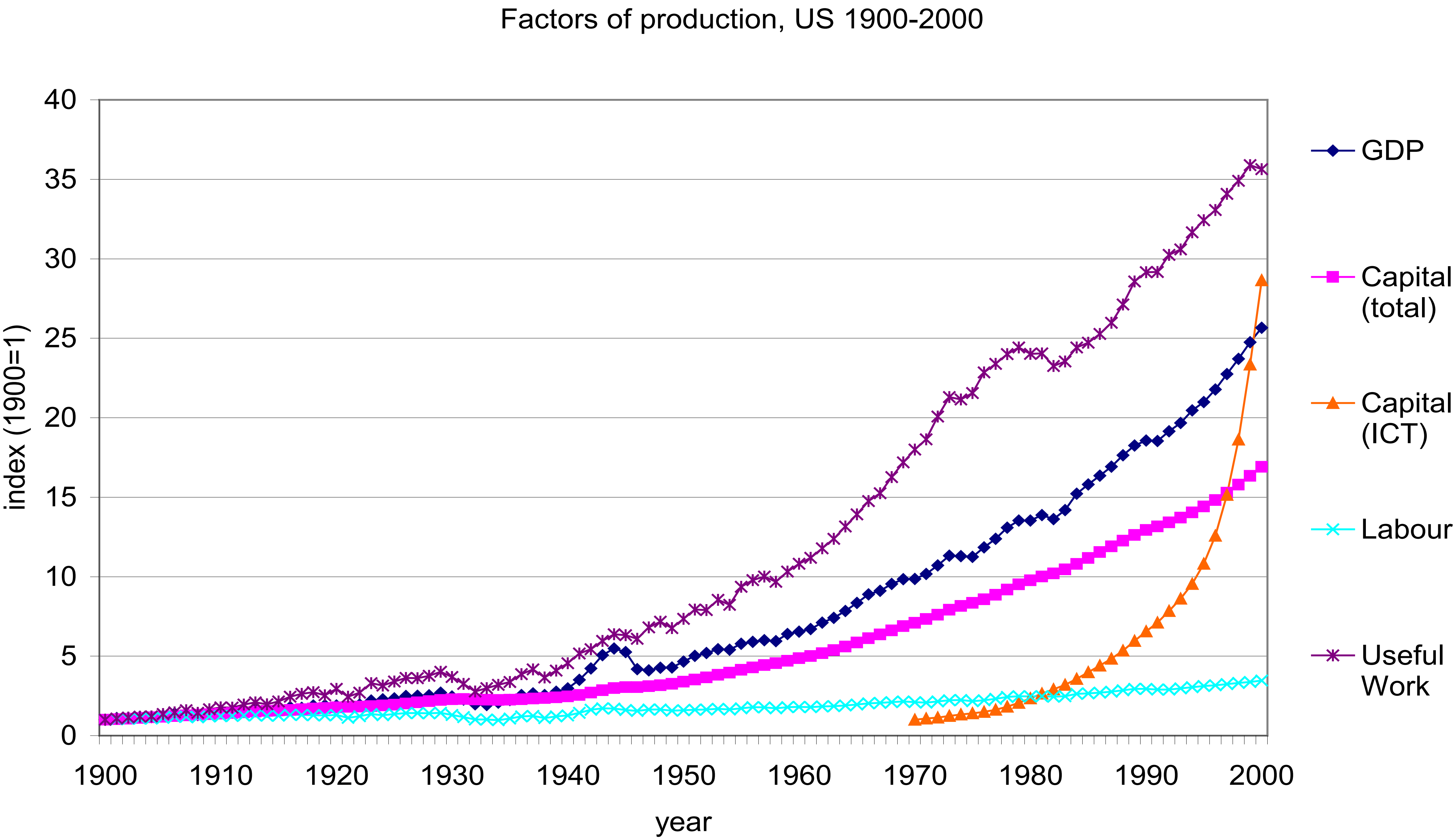
$u = useful\ work$

$l = labour$

$k = capital\ stocks\ (total)$

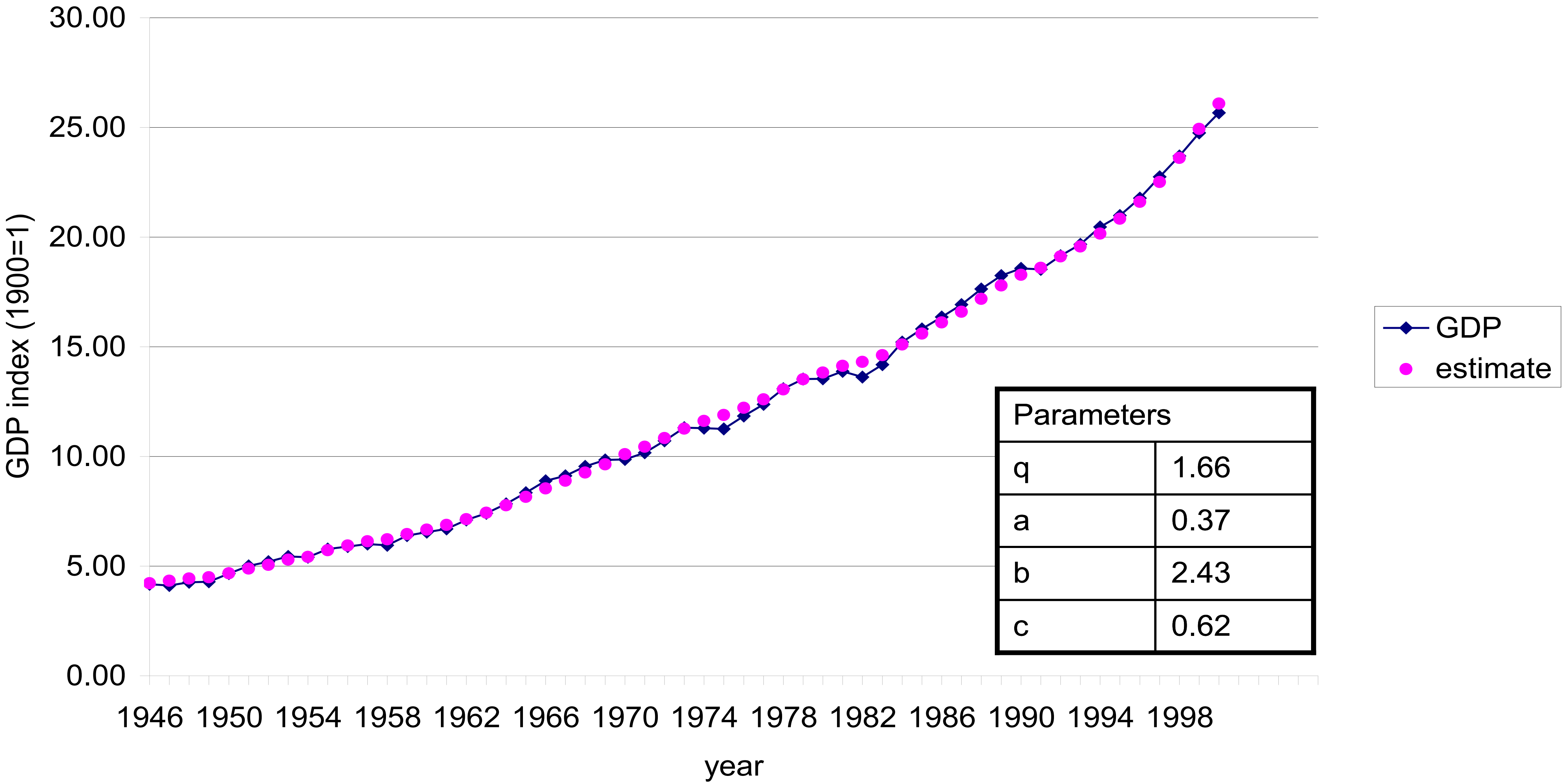
$\delta = ICT\ capital\ stocks$

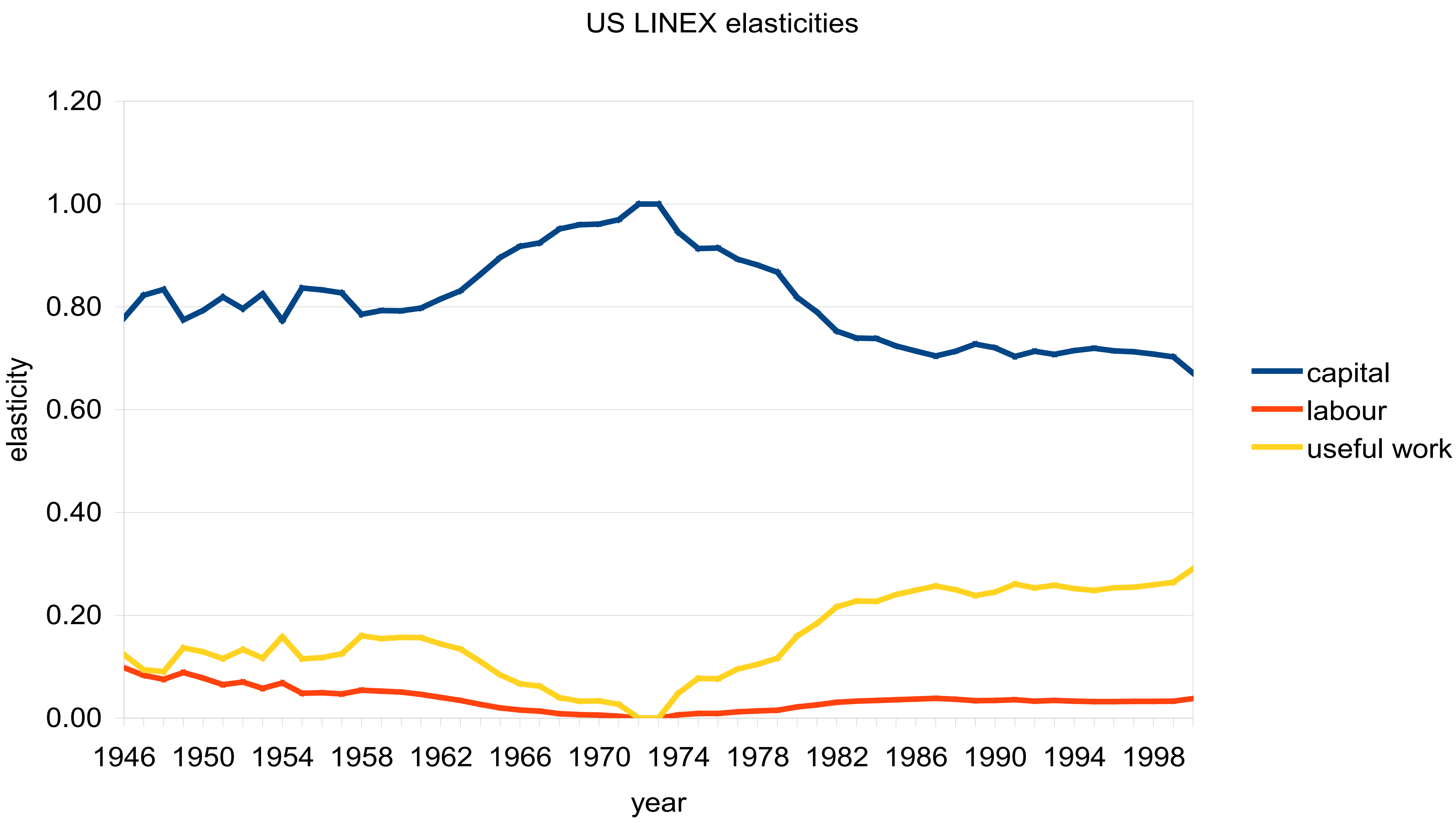
$[q, a, b, c] = fitting\ parameters$



Factors of production, US 1900-2000
index (1900=1)
40
35
30
25
20
15
10
5
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
year
GDP
Capital (total)
Capital (ICT)
Labour
Useful Work

US GDP 1946-2000

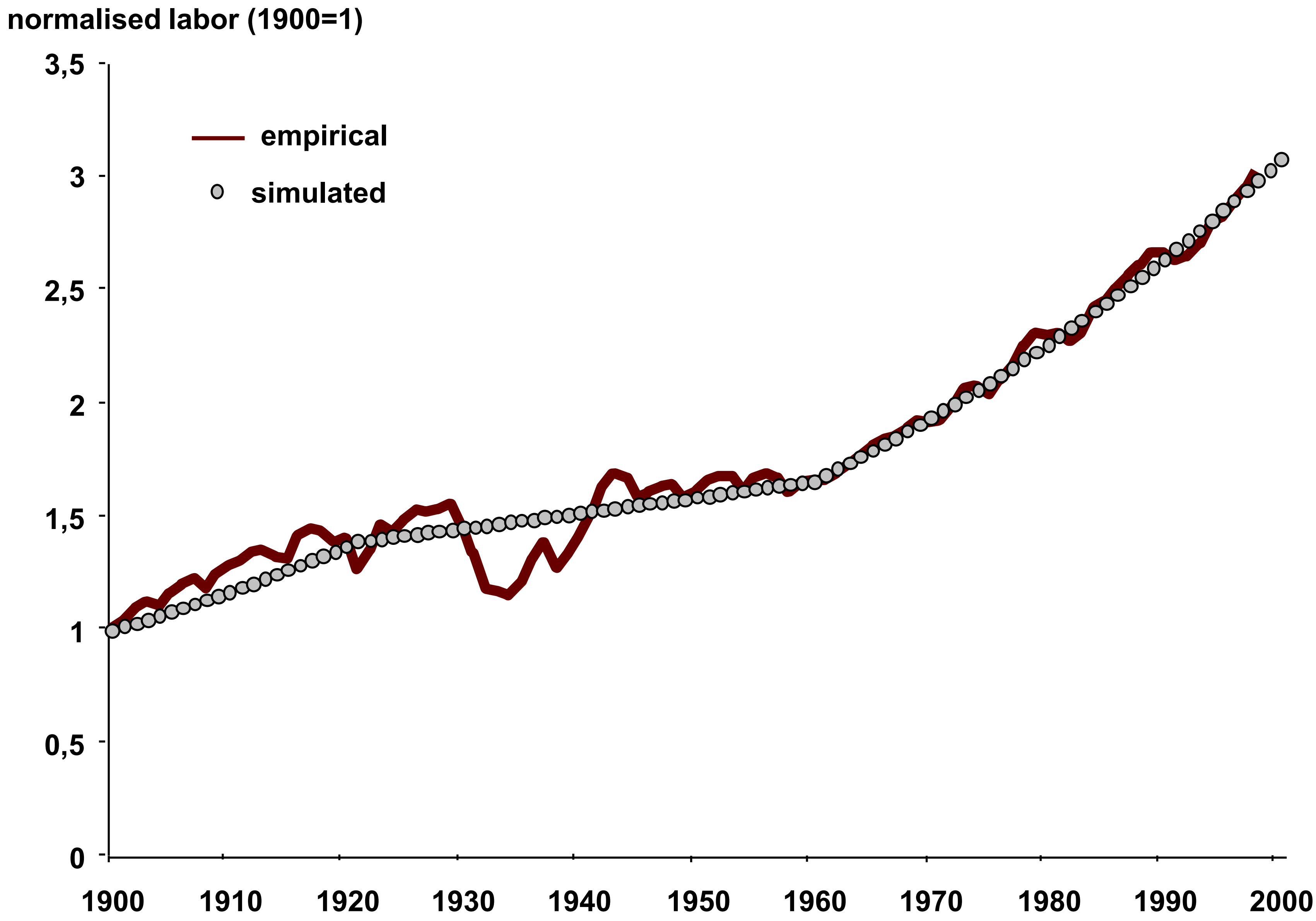



US LINEX elasticities
1.20
1.00
0.80
0.60
0.40
0.20
0.00
elasticity
1946
1950
1954
1958
1962
1966
1970
1974
1978
1982
1986
1990
1994
1998
year
capital
labour
useful work

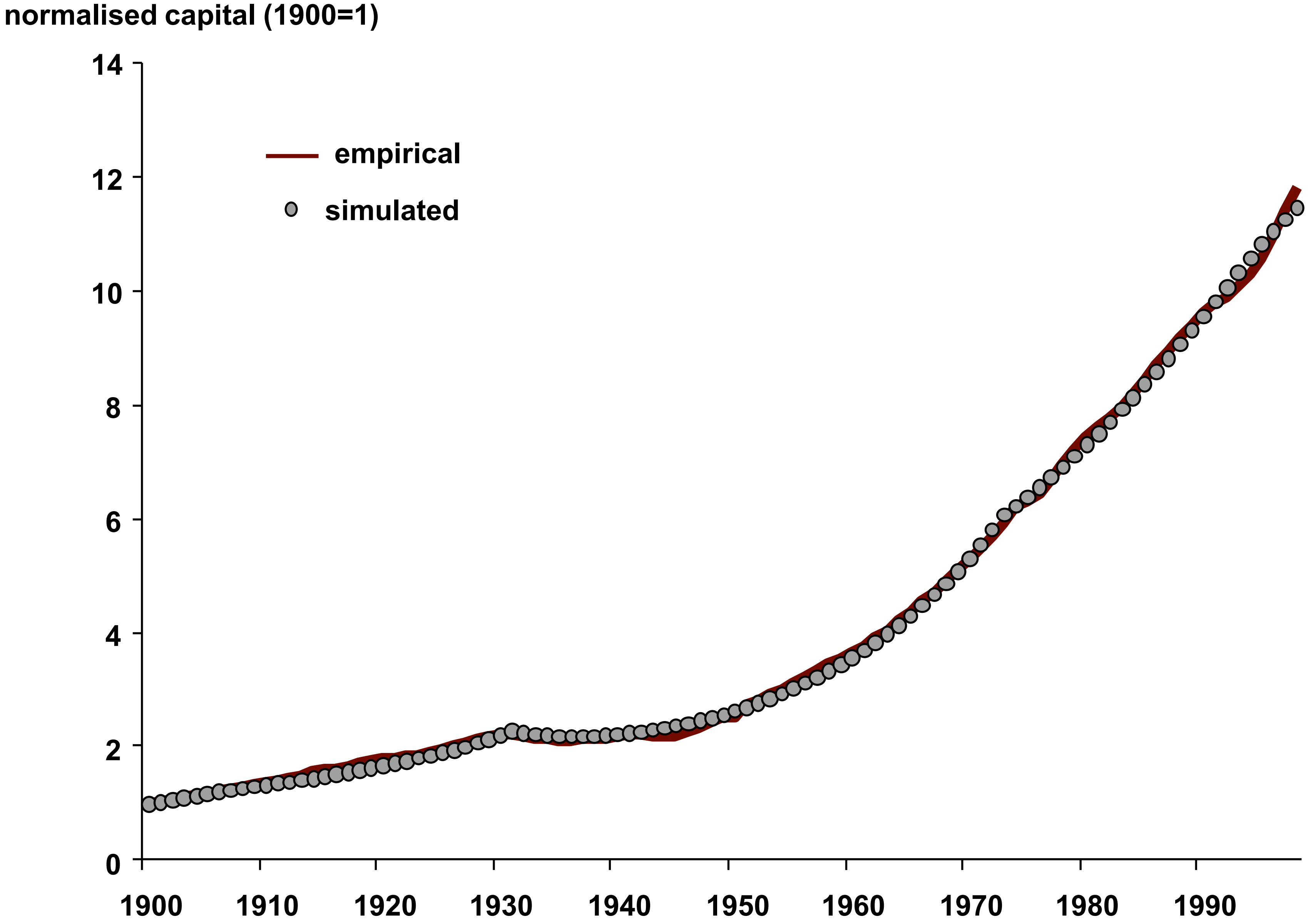
Interim Conclusions

- The LINEX production function with useful work as a third factor explains past economic growth rather well, with only two parameters. Statistical causality analysis confirms that GDP growth does not drive energy or useful work consumption, but useful work does drive GDP growth.
- N.B. Adding information capital to conventional capital achieves an even better fit in recent years.

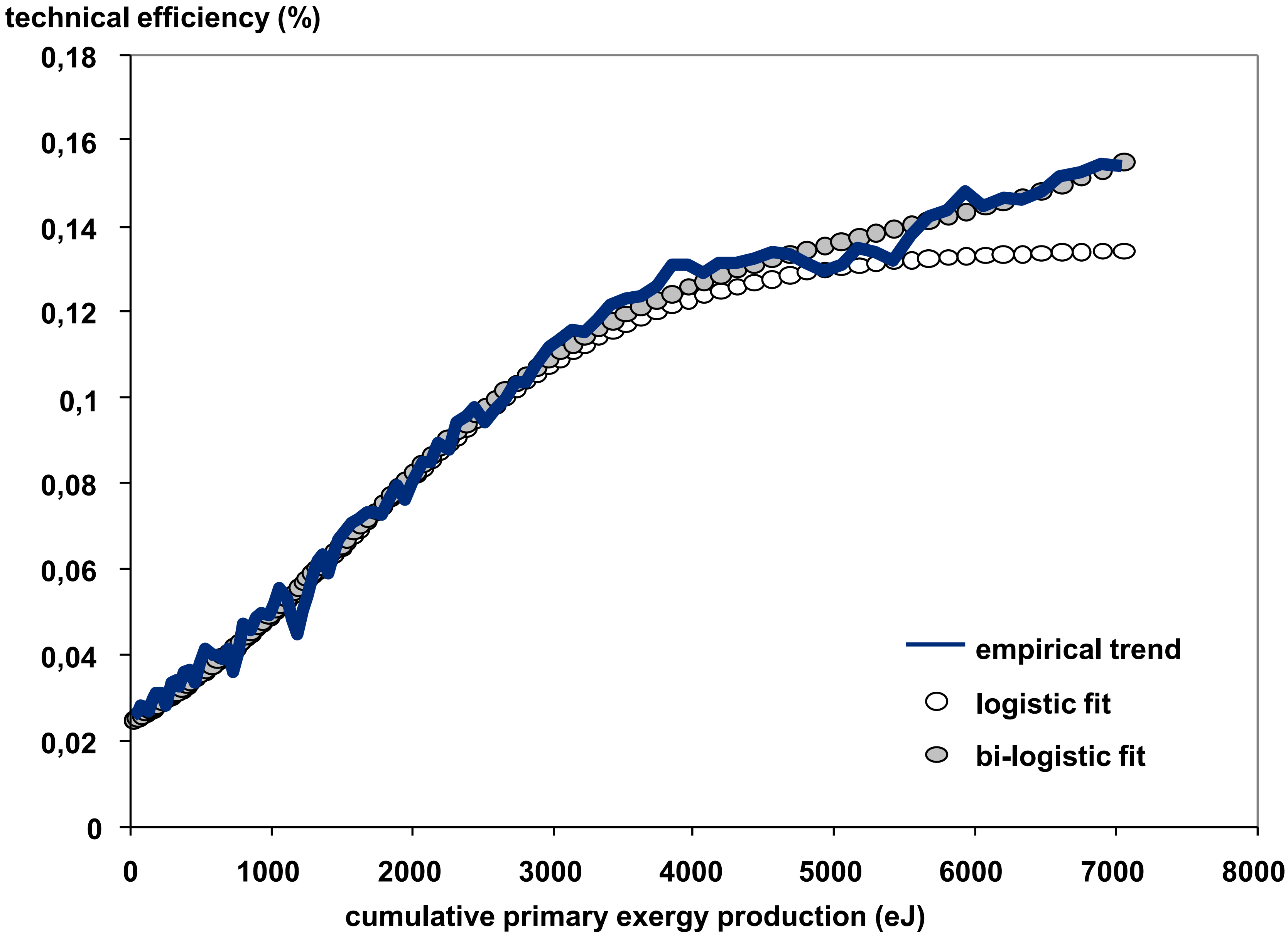
Model - Simulated and Empirical Labor, USA 1900-2000



Model - Simulated and Empirical Capital, USA 1900-2000

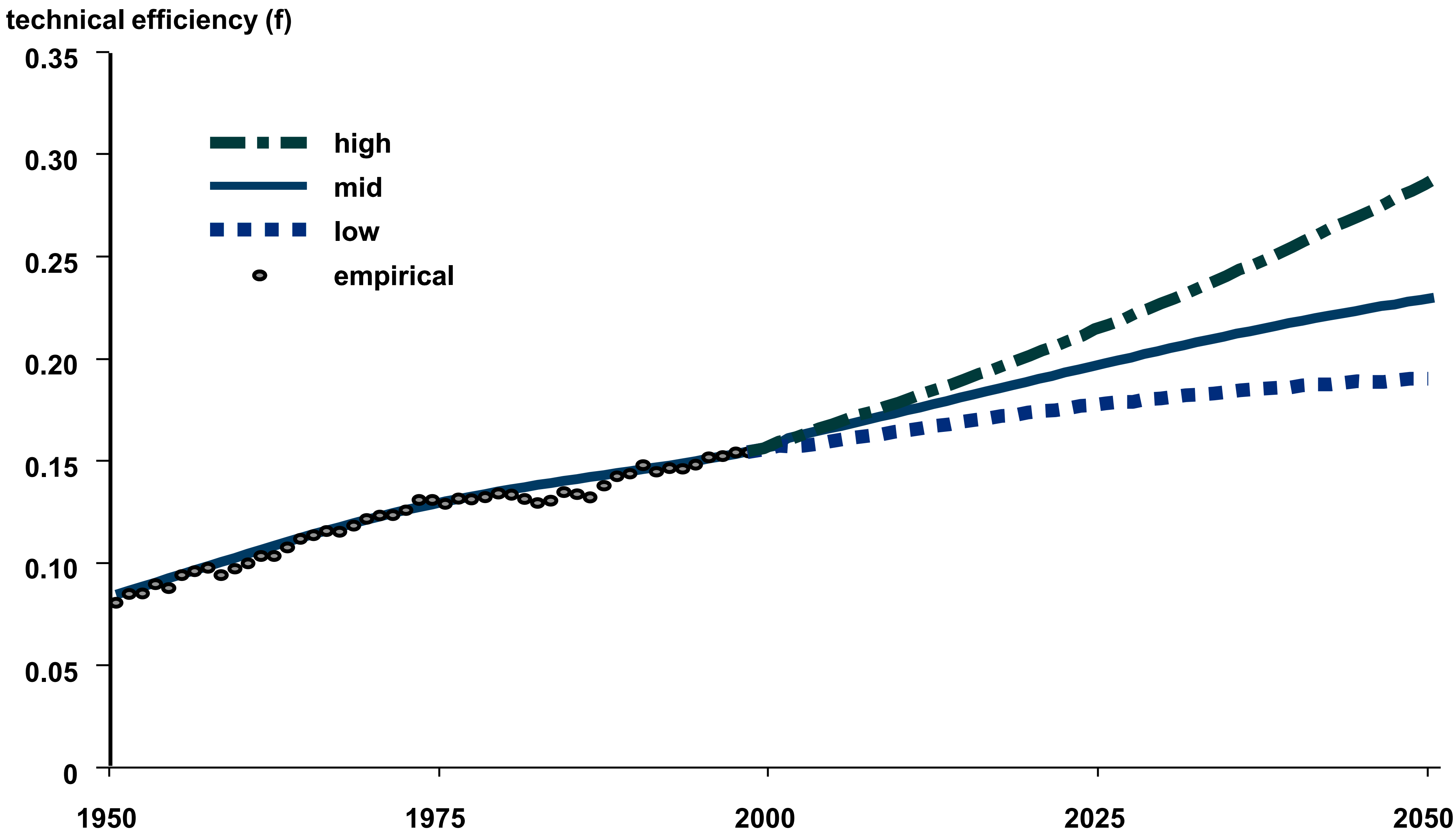


Model - Logistic and Bi-Logistic S-curve Fits to the Trend of Aggregate Technical Efficiency in the US 1900-2000

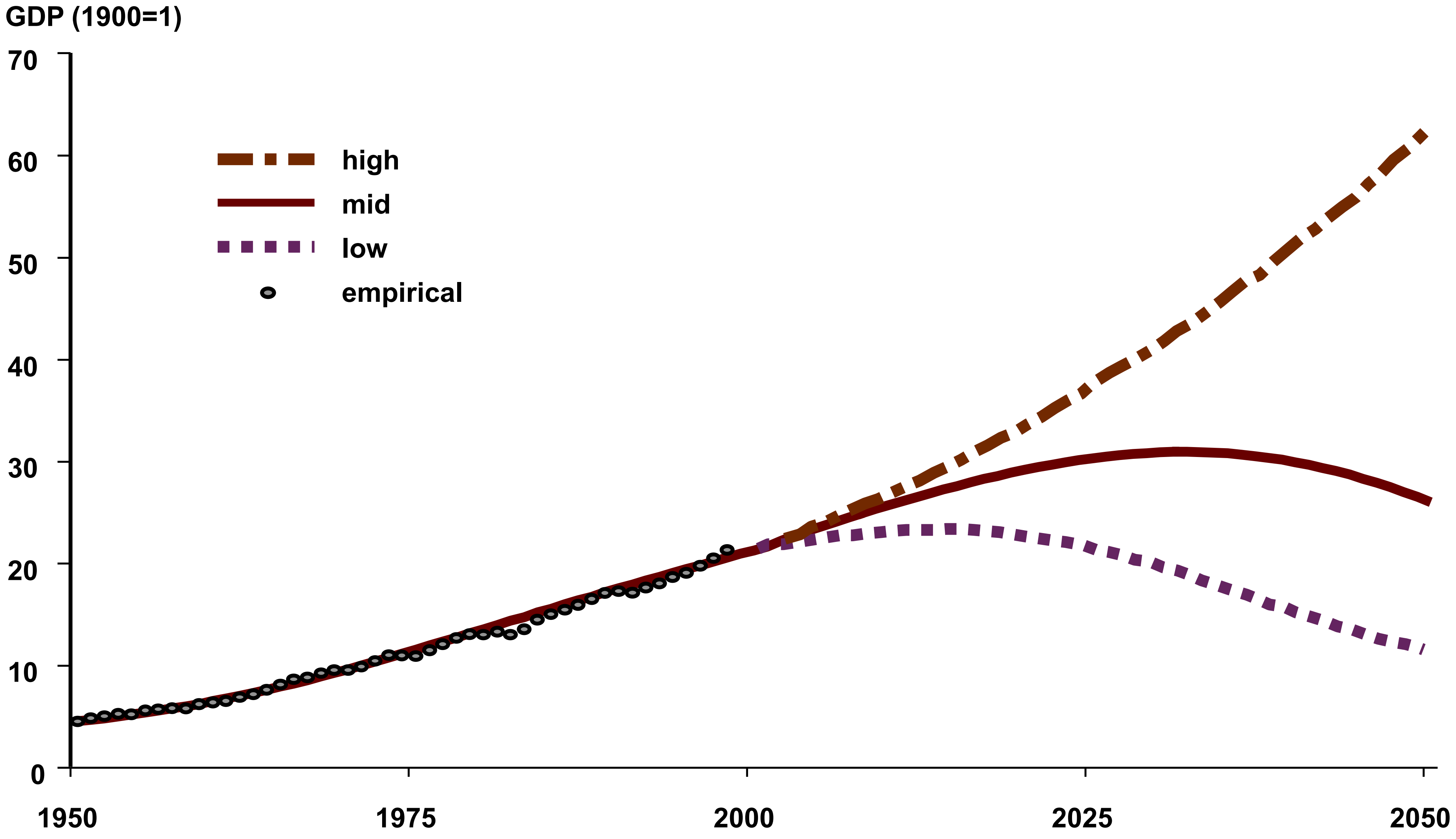


US Model - Historical (1950-2000) and Forecast (2000-2050)

Technical Efficiency of Energy Conversion
for Alternate Rates of Technical Efficiency Growth



US Model - Historical (1950-2000) and Forecast (2000-2050) GDP for Alternate Rates of Technical Efficiency Growth



Conclusions & next steps

- LINEX with useful work as a third factor explains long term growth well, but cannot reproduce all the short term fluctuations because our efficiency data is time-averaged. (Hence D-W statistics not good)
- LINEX with ICT adjustment may be a useful tool for medium term growth forecasting (more work)
- C-D or CES forecasts in which energy is treated as an intermediate may lead to risky assumptions.

For example

- The White House staff thought "recovery" was beginning in early 2010. It wasn't, and they lost the election. Why? Their forecasting tools did not reflect the rebound in energy prices.
- Some famous economists have said "Our grand-children will be a lot richer than we are" neglecting peak oil and rising energy prices. Implication: the next generation can pay to fix the environmental damages we made. Dangerously wrong.

Thanks for your patience