Crossing the Energy Divide:
The Economic Imperative of Energy Efficiency

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Economic Production Functions

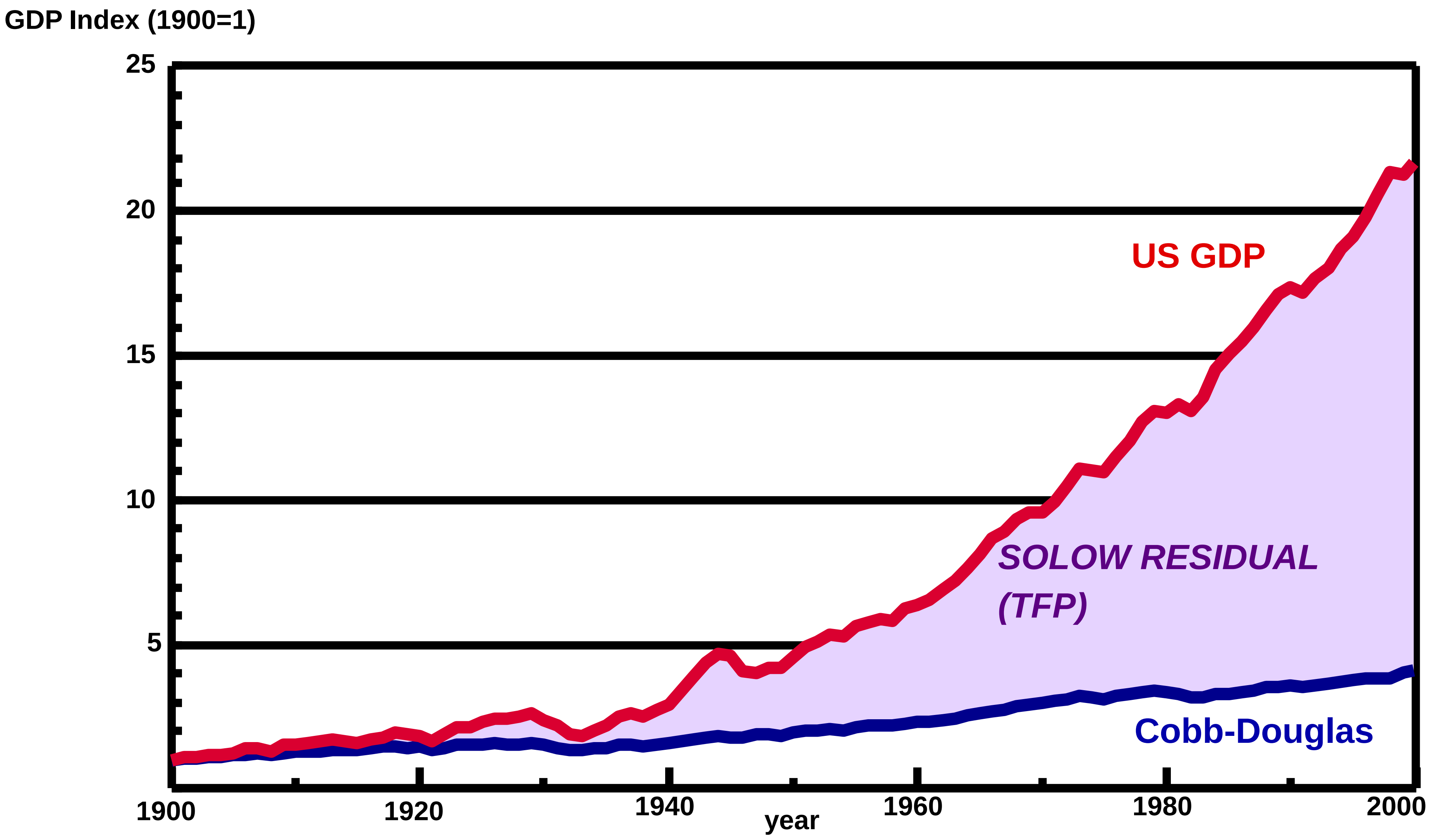
Common practice: Cobb-Douglas

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

Y_t is output at time t, a function of,

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

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



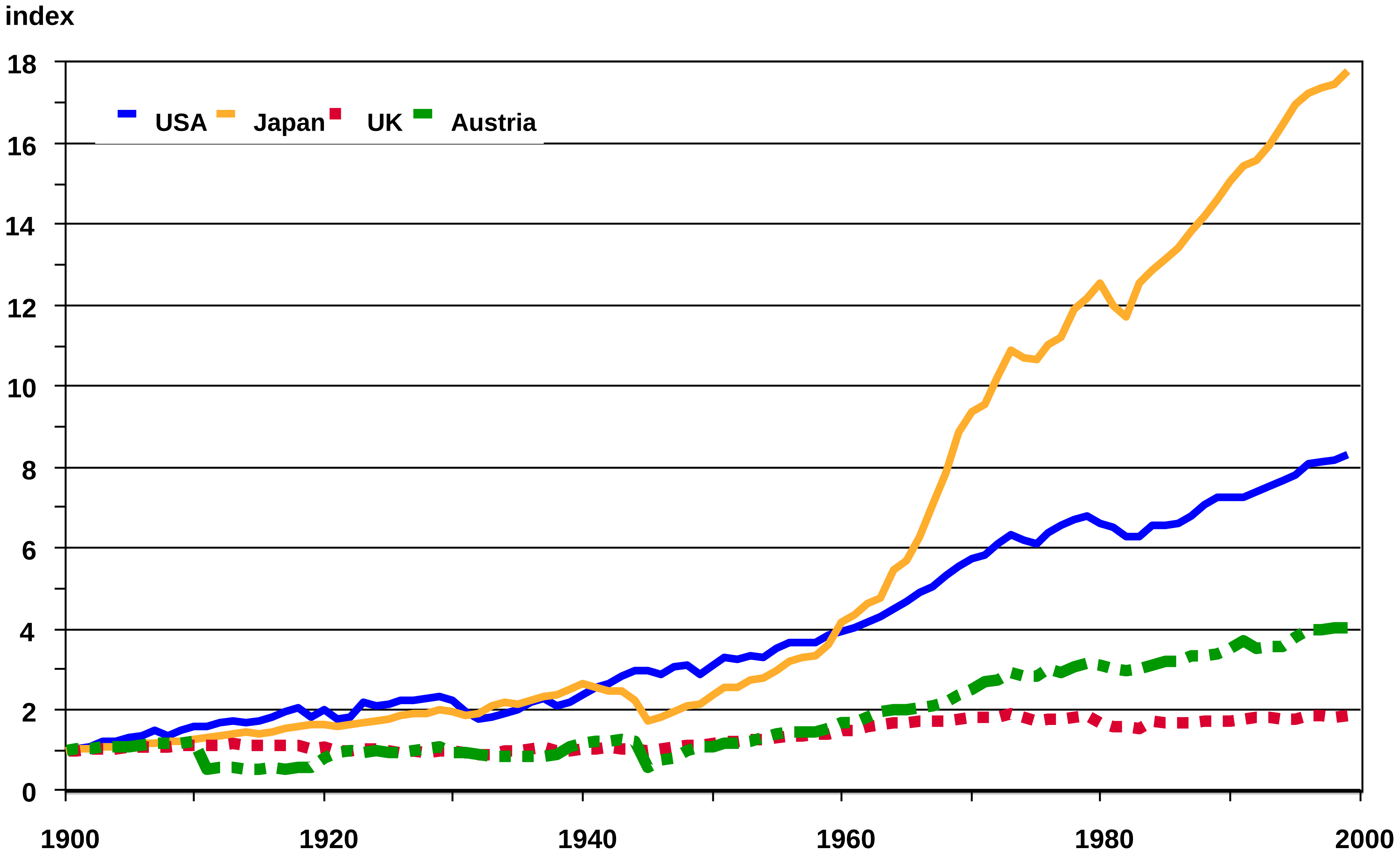
A Critical Perspective: Energy, Exergy and Useful Work

- **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**.

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

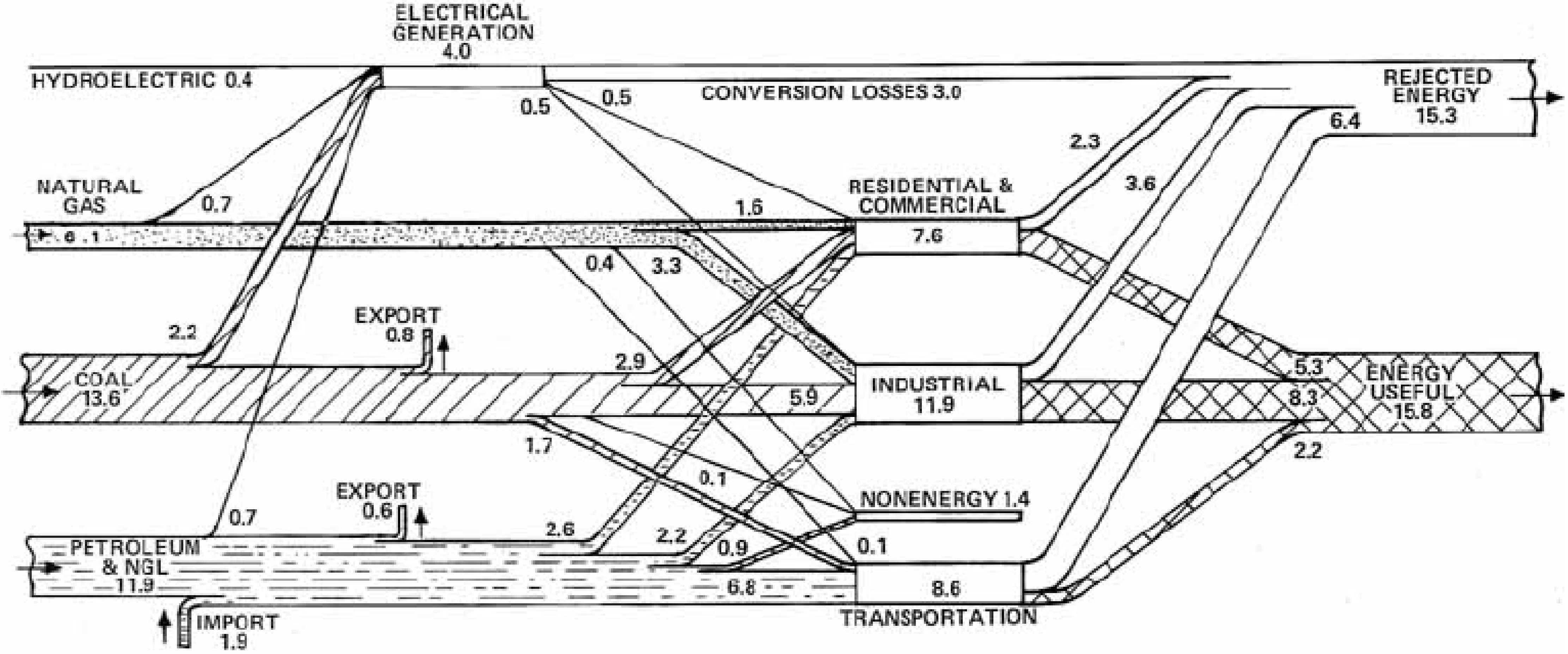


EXERGY - DEFINITION

MAXIMUM WORK OBTAINABLE FROM A SUBSYSTEM APPROACHING THERMODYNAMIC EQUILIBRIUM

EFFICIENCY - DEFINITION

RATIO OF ACTUAL WORK PERFORMED TO MAXIMUM WORK (EXERGY)



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.

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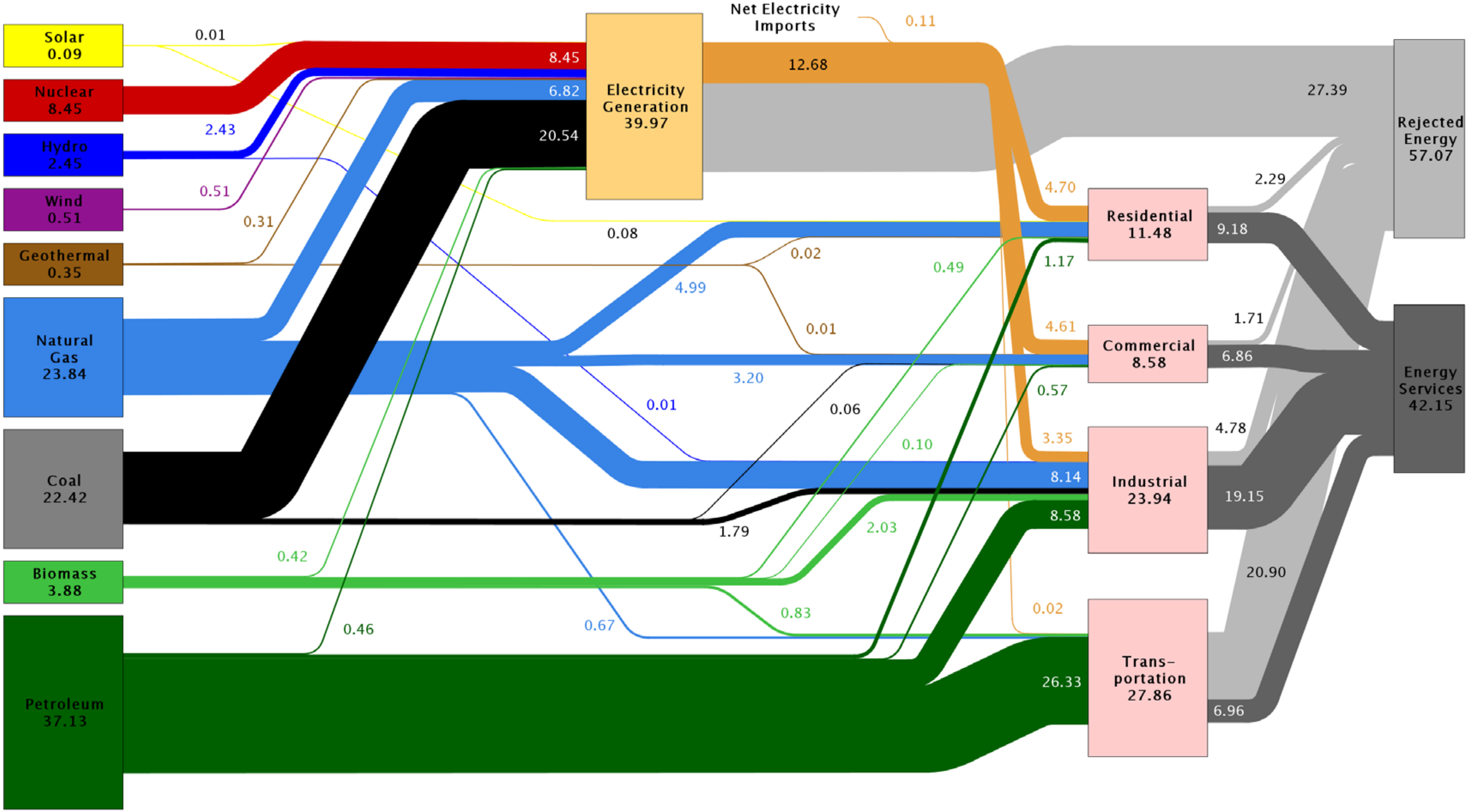
Estimated U.S. Energy Use in 2008: ~99.2 Quads

Lawrence Livermore National Laboratory

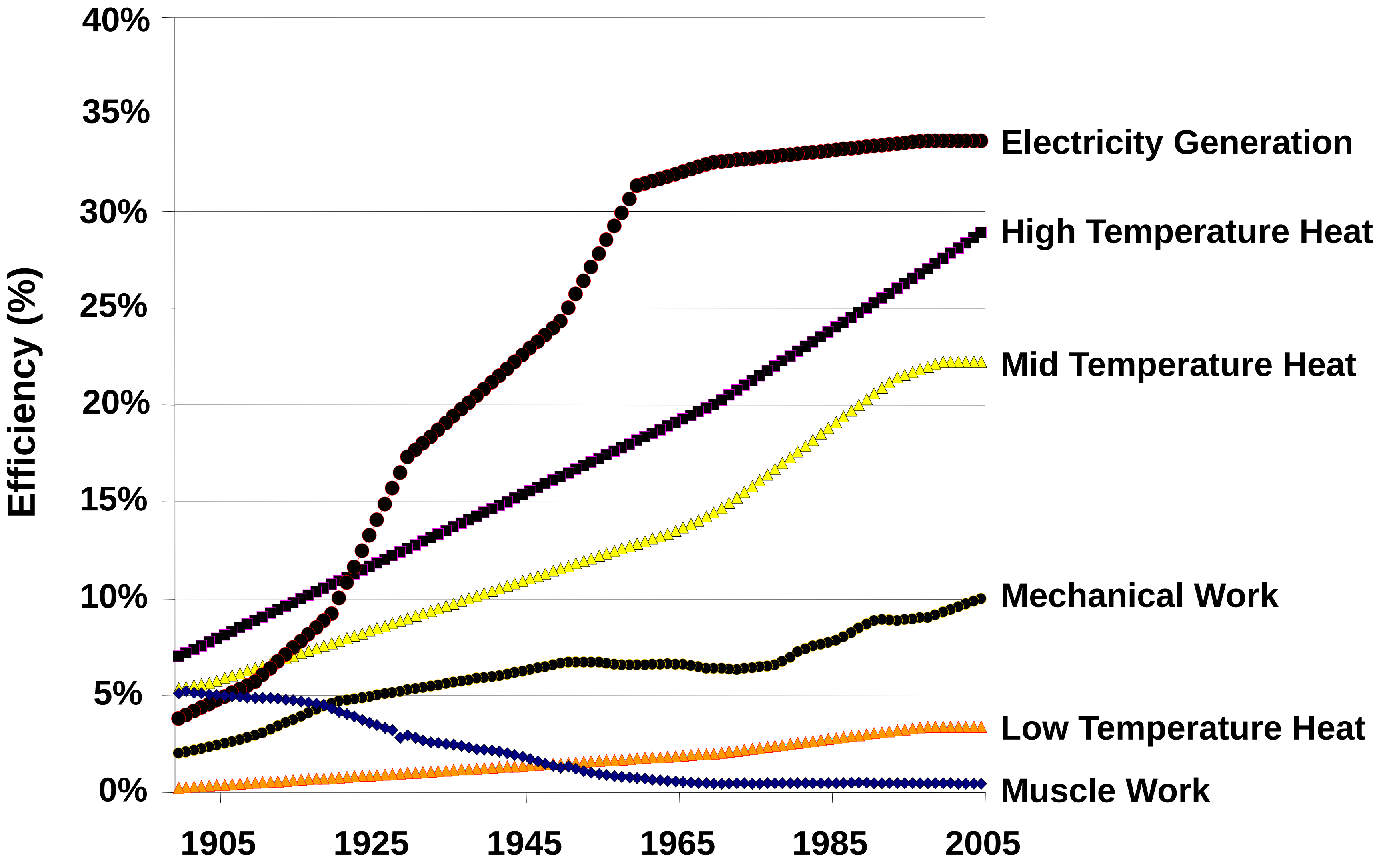


Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only 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

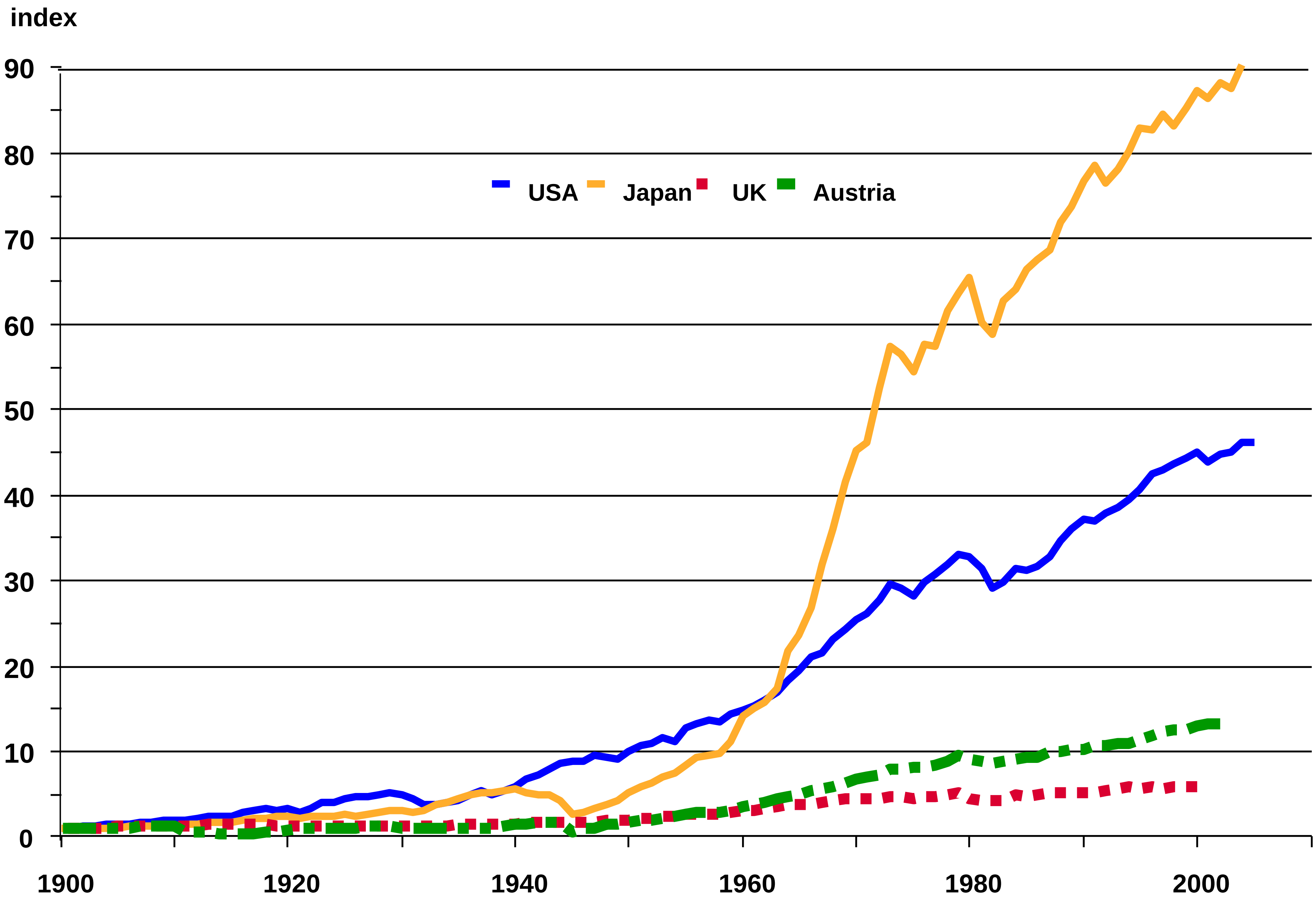
US Estimated Energy “Efficiencies” (LLNL, Based on DOE)

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

Conversion Efficiencies



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



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: II

The linear-exponential (LINEX) production function

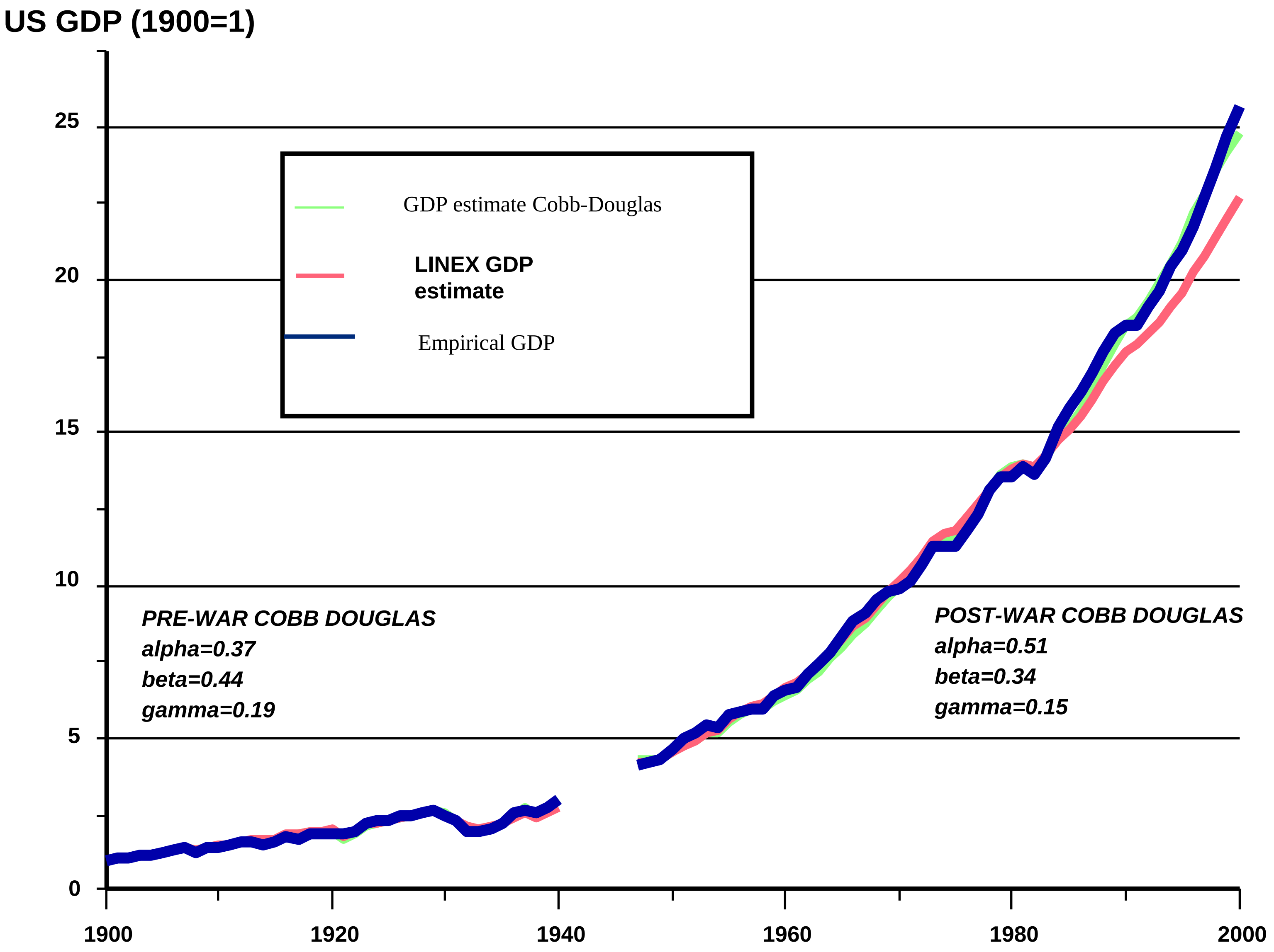
$$Y_t = U \exp\left\{ a\left(2 - \left(\frac{L+U}{K}\right)\right) + ab\left(\frac{L}{U} - 1\right)\right\}$$

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

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

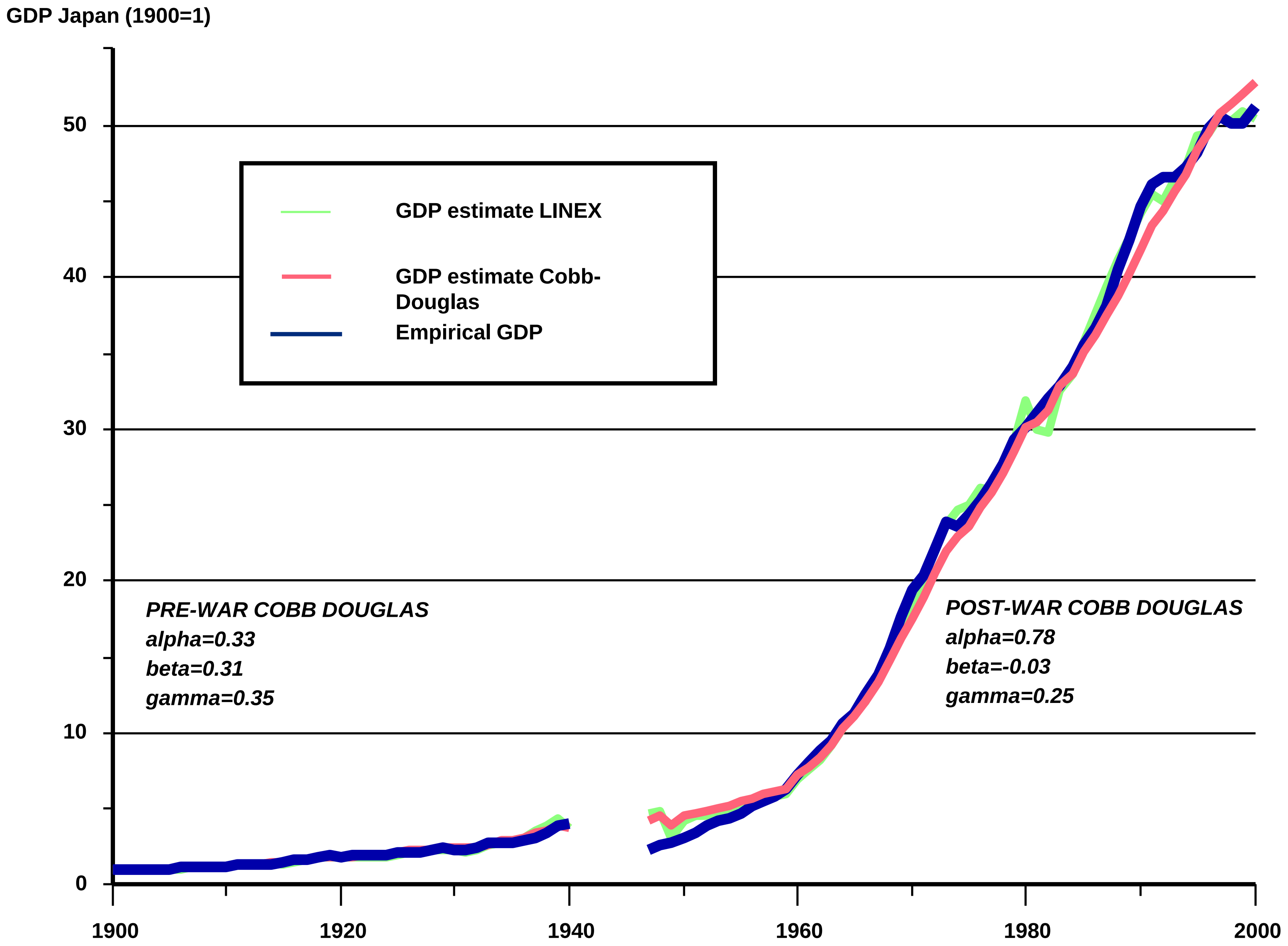
- ***A_t , 'total factor productivity', is REMOVED***
- ***Resources (Energy & Materials) replaced by WORK***
- ***F_t = energy-to-work conversion efficiency***
- ***Factors ARE MUTUALLY DEPENDENT***
- ***Empirical elasticities DO NOT EQUAL COST SHARE***

Empirical and Estimated US GDP: 1900-2000



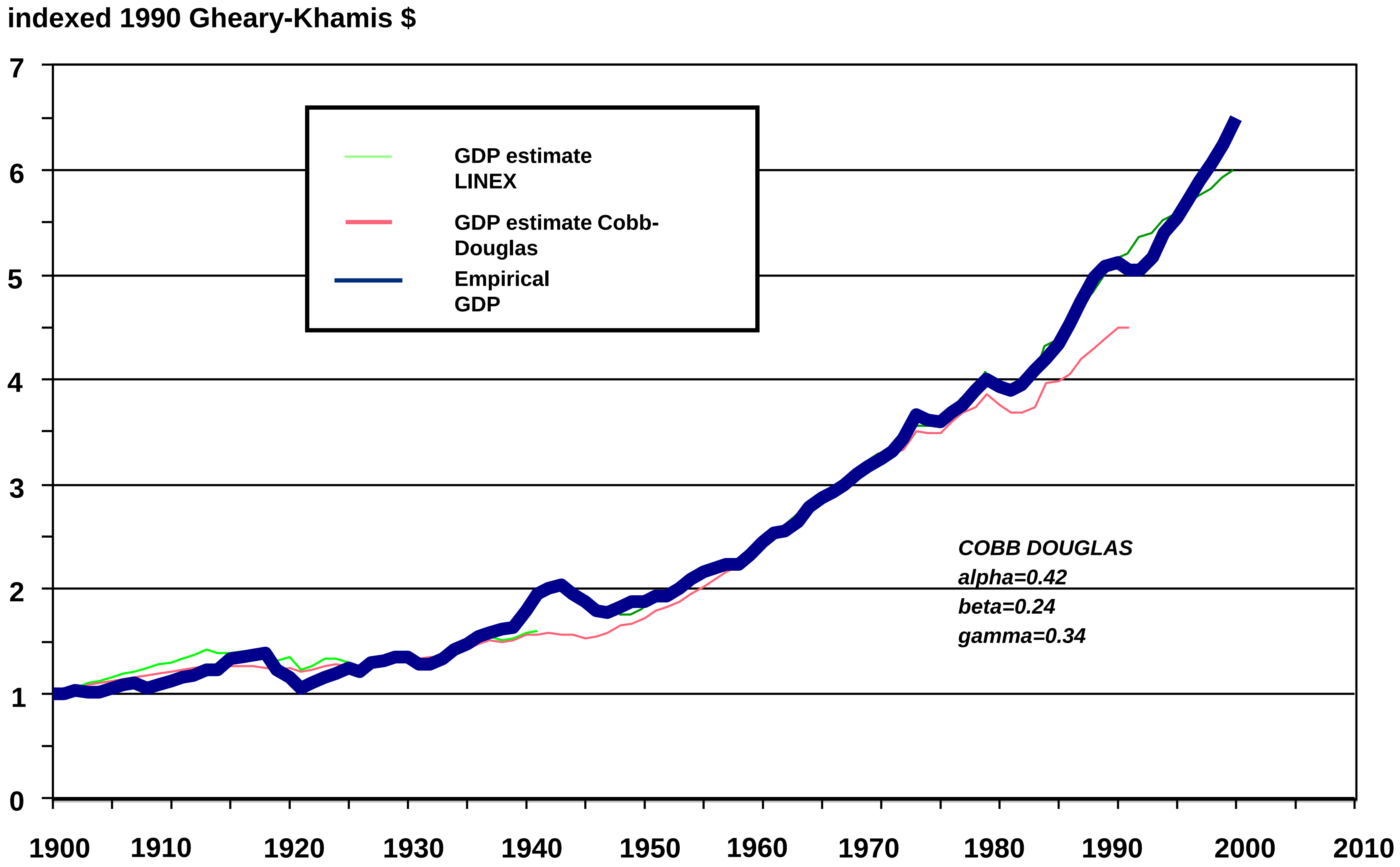
Empirical GDP from Groningen GGDC Total Economy Growth Accounting Database: Marcel P. Timmer, Gerard Ypma and Bart van Ark (2003), *IT in the European Union: Driving Productivity Divergence?*, GGDC Research Memorandum GD-67 (October 2003), University of Groningen, Appendix Tables, updated June 2005

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)



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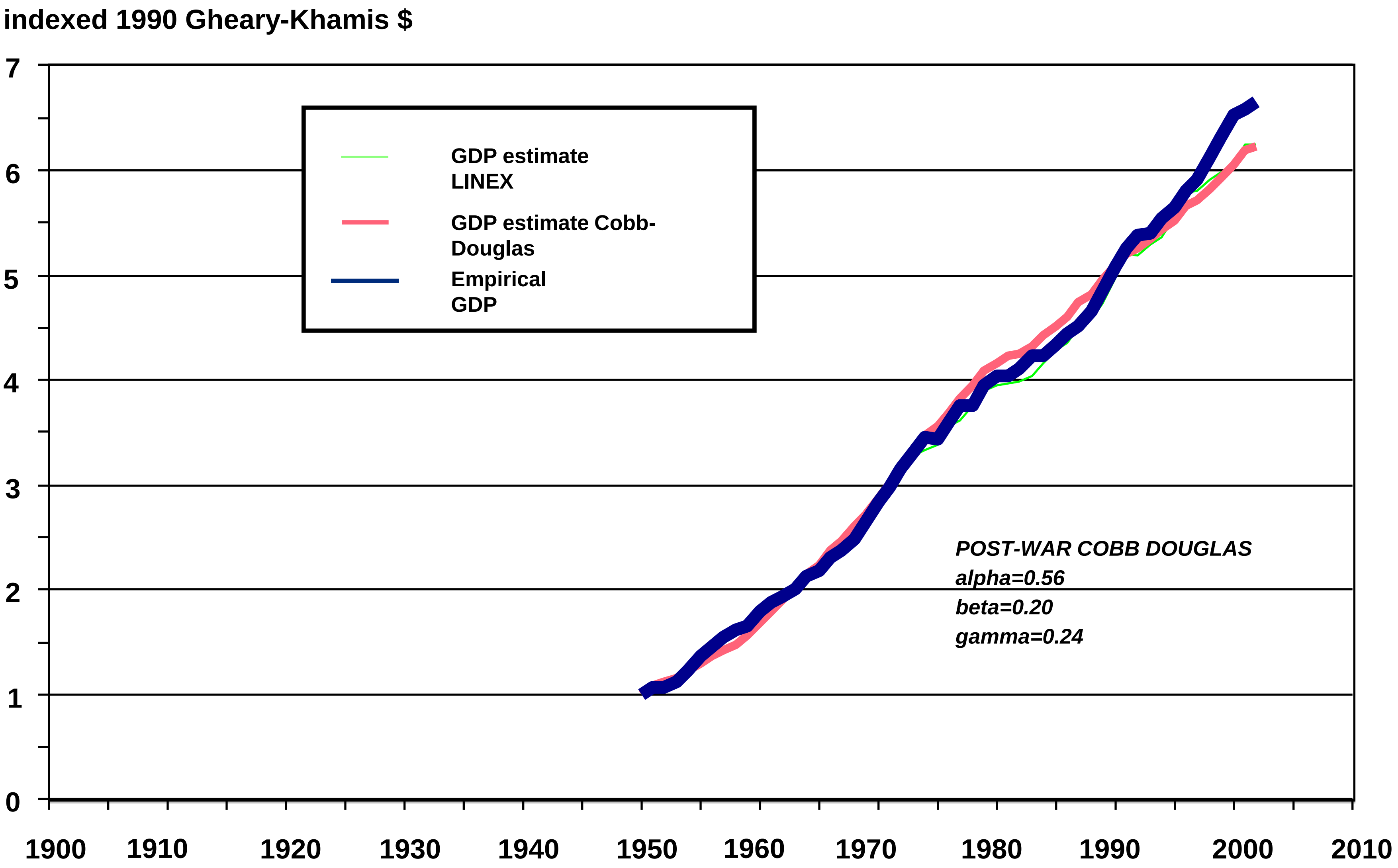
Empirical & Estimated GDP, Austria 1950-2005 (1950=1)



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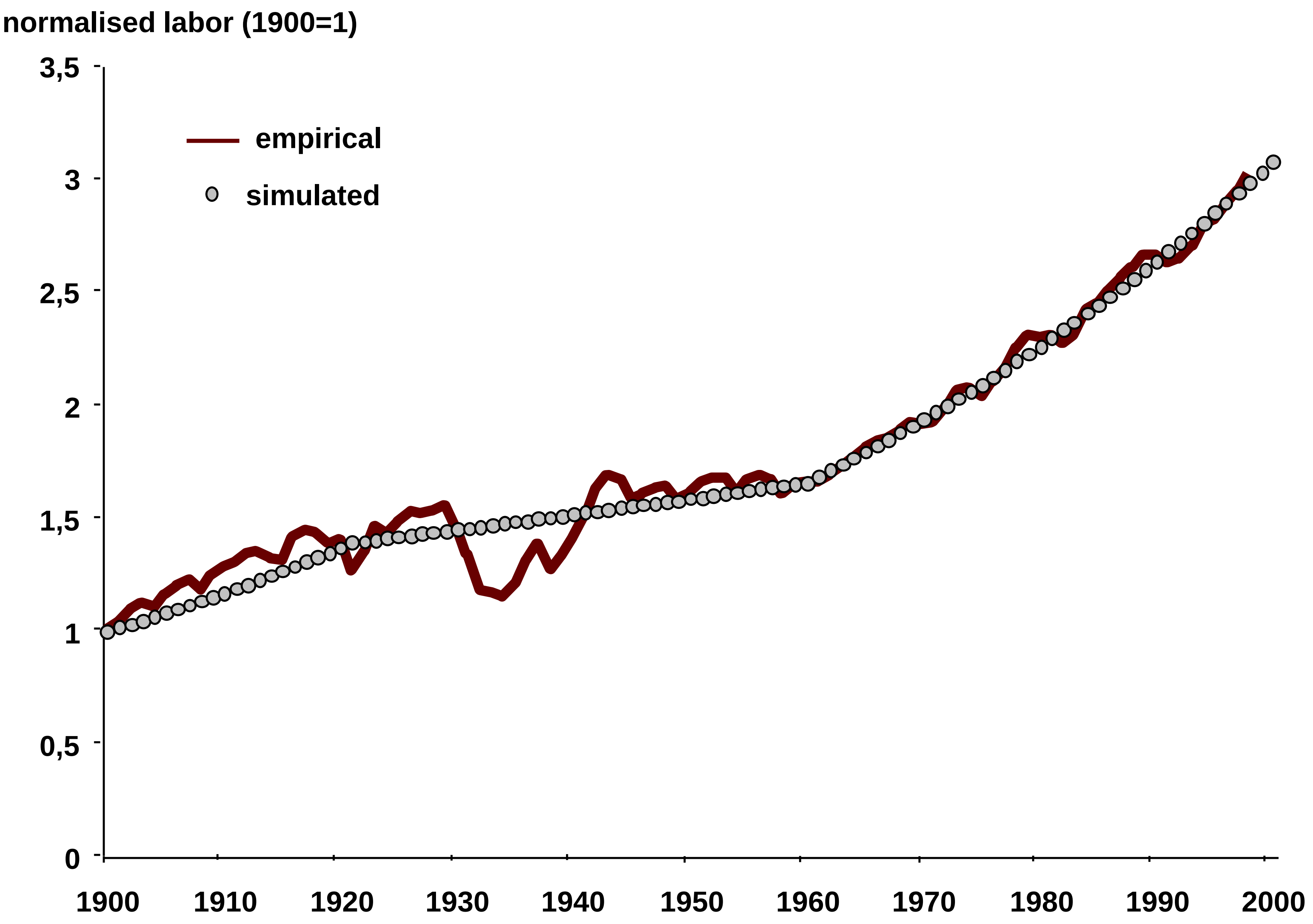
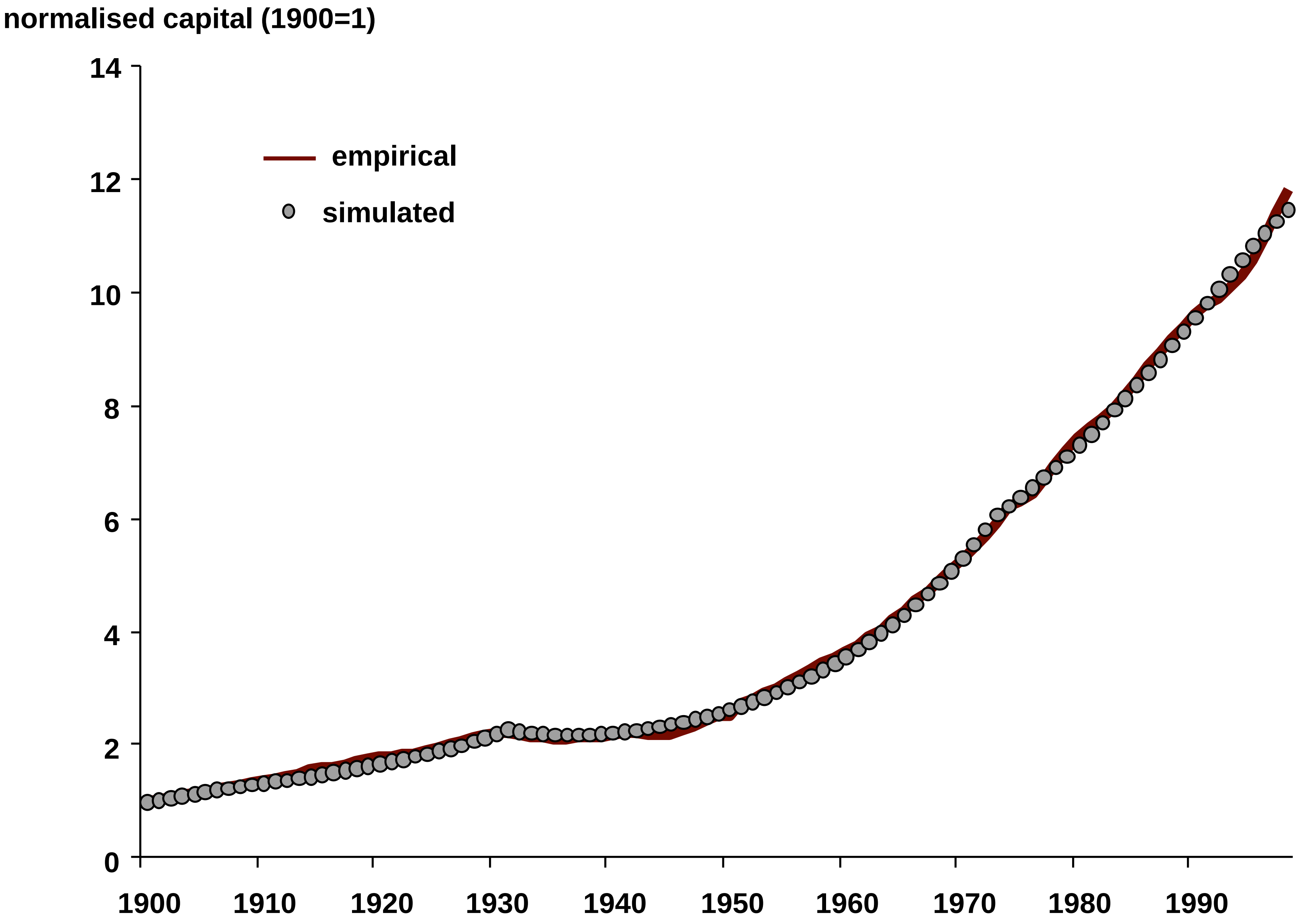
Interim Conclusions

- 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.

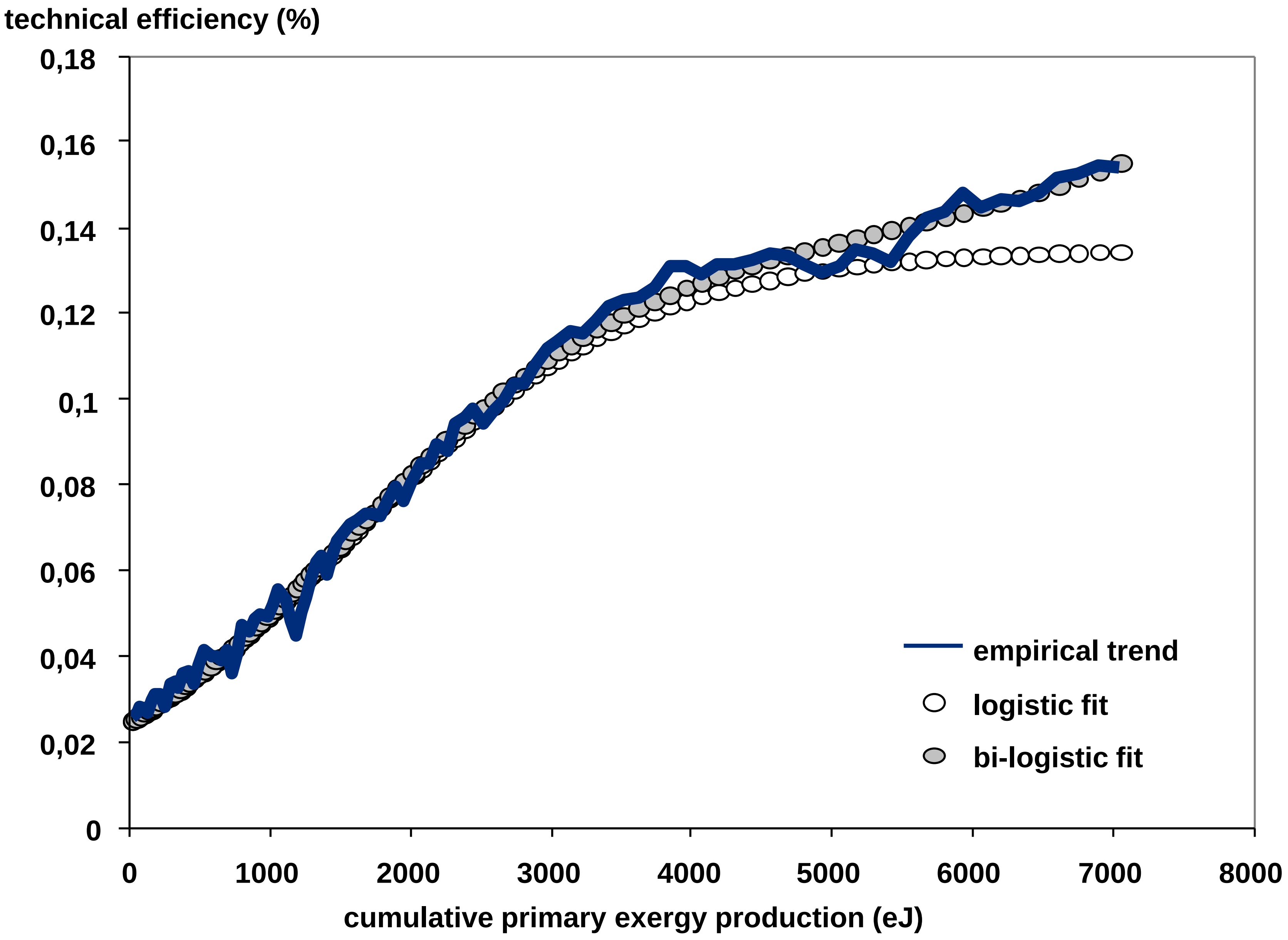
Model - Simulated and Empirical Labor, USA 1900-2000



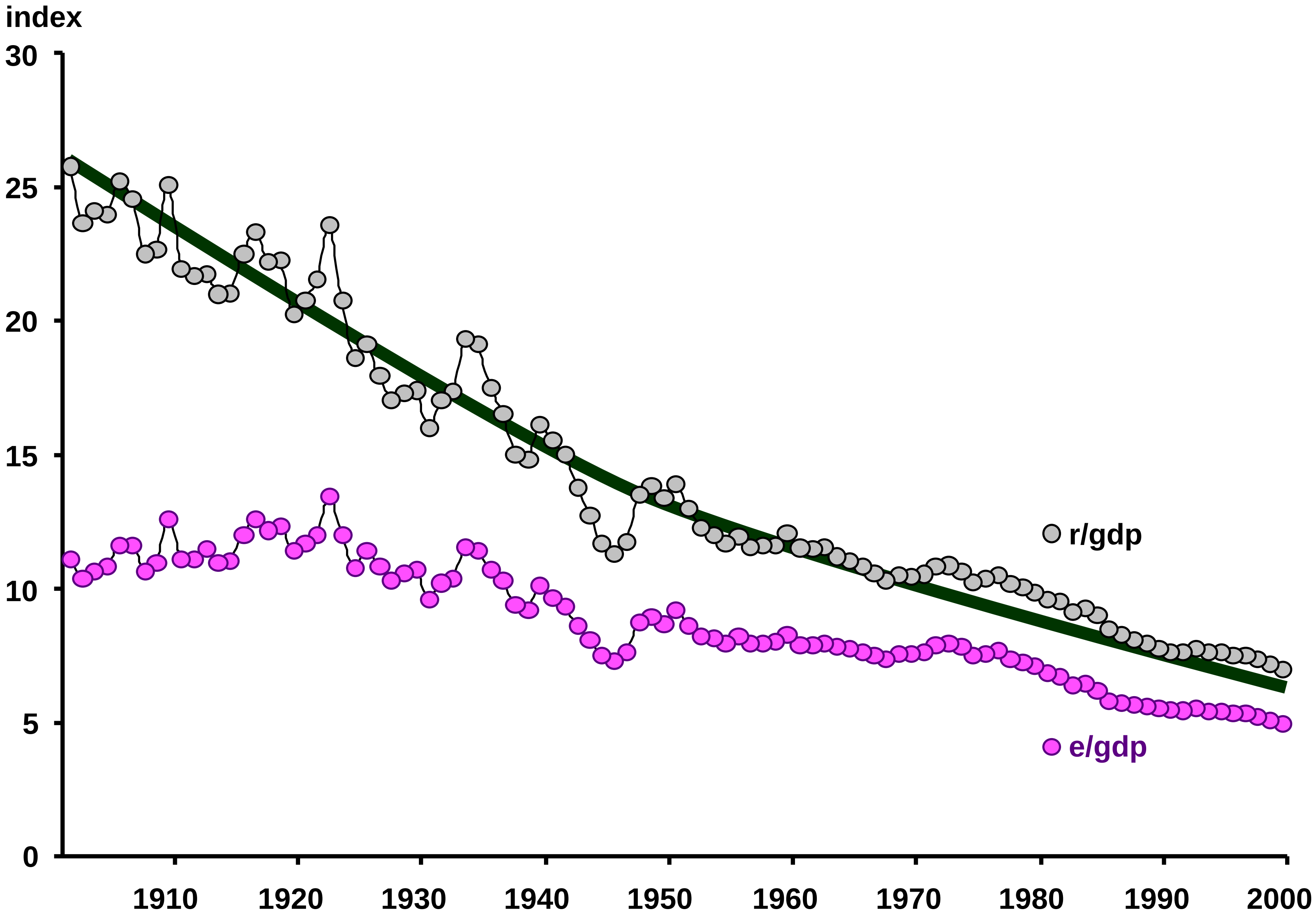
Model - Simulated and Empirical Capital, USA 1900-2000



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



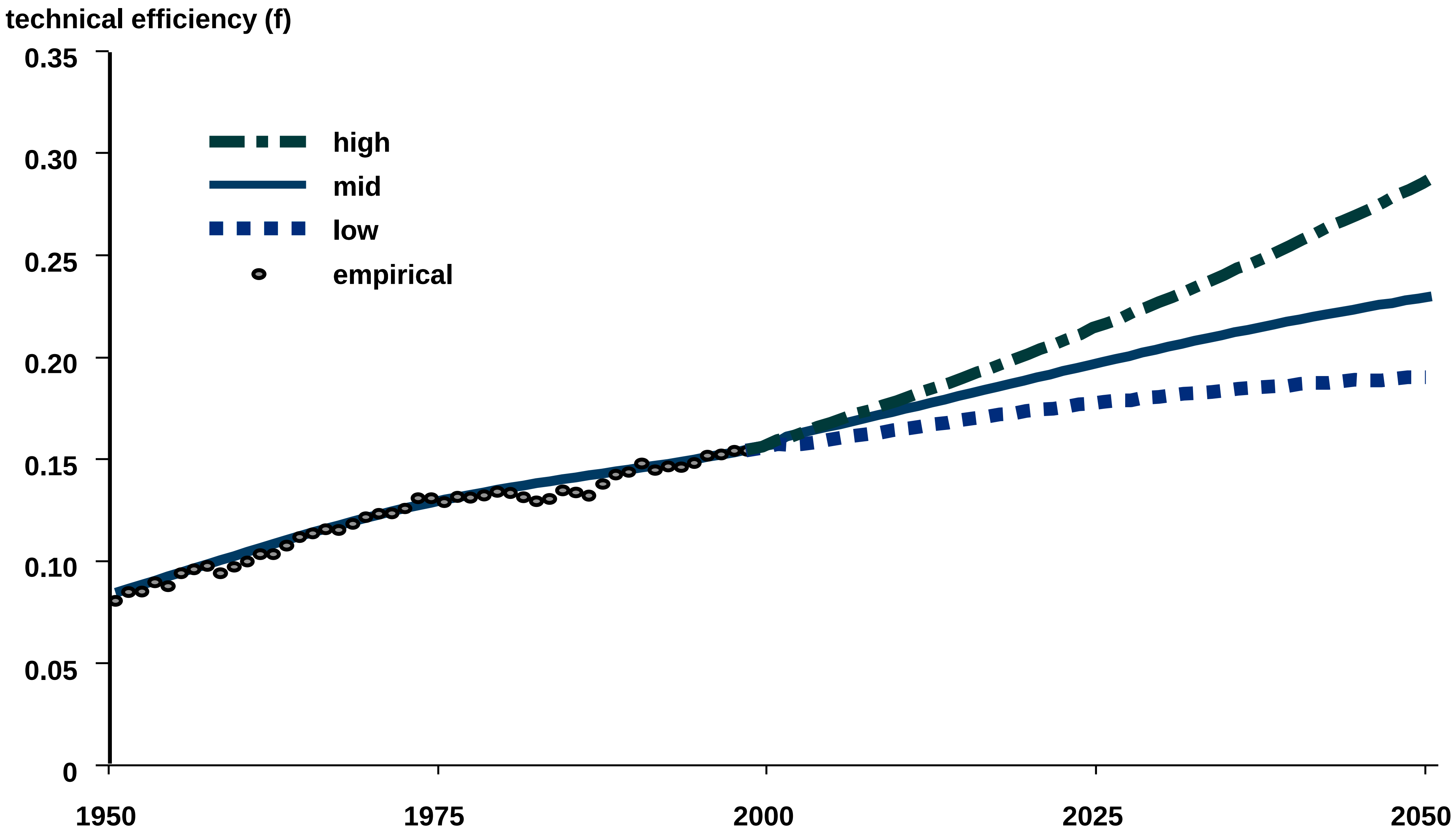
Model - Energy Intensity of GDP, USA 1900-2000



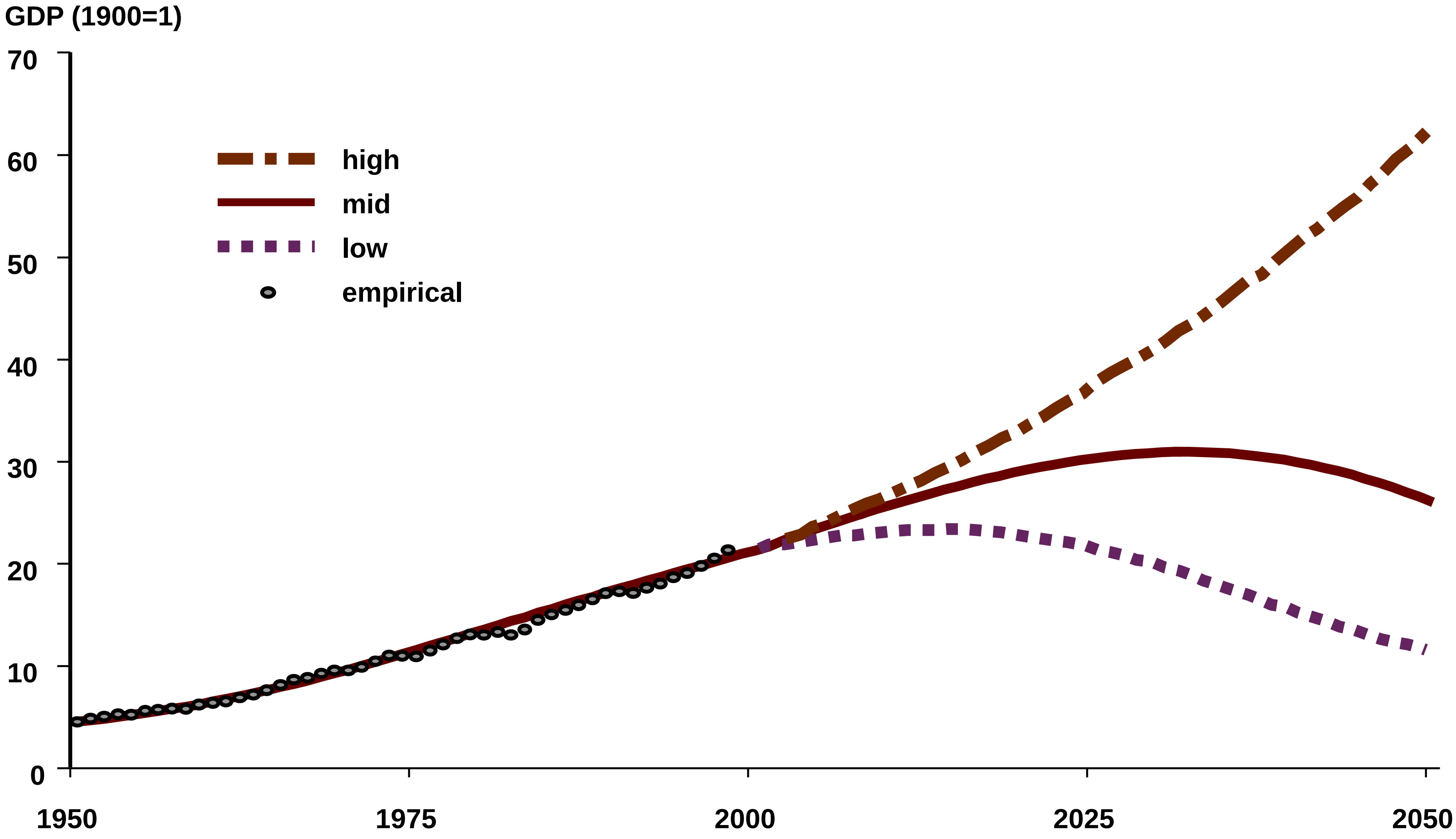
US Model - Historical (1950-2000) and Forecast (2000-2050)

Technical Efficiency of Energy Conversion

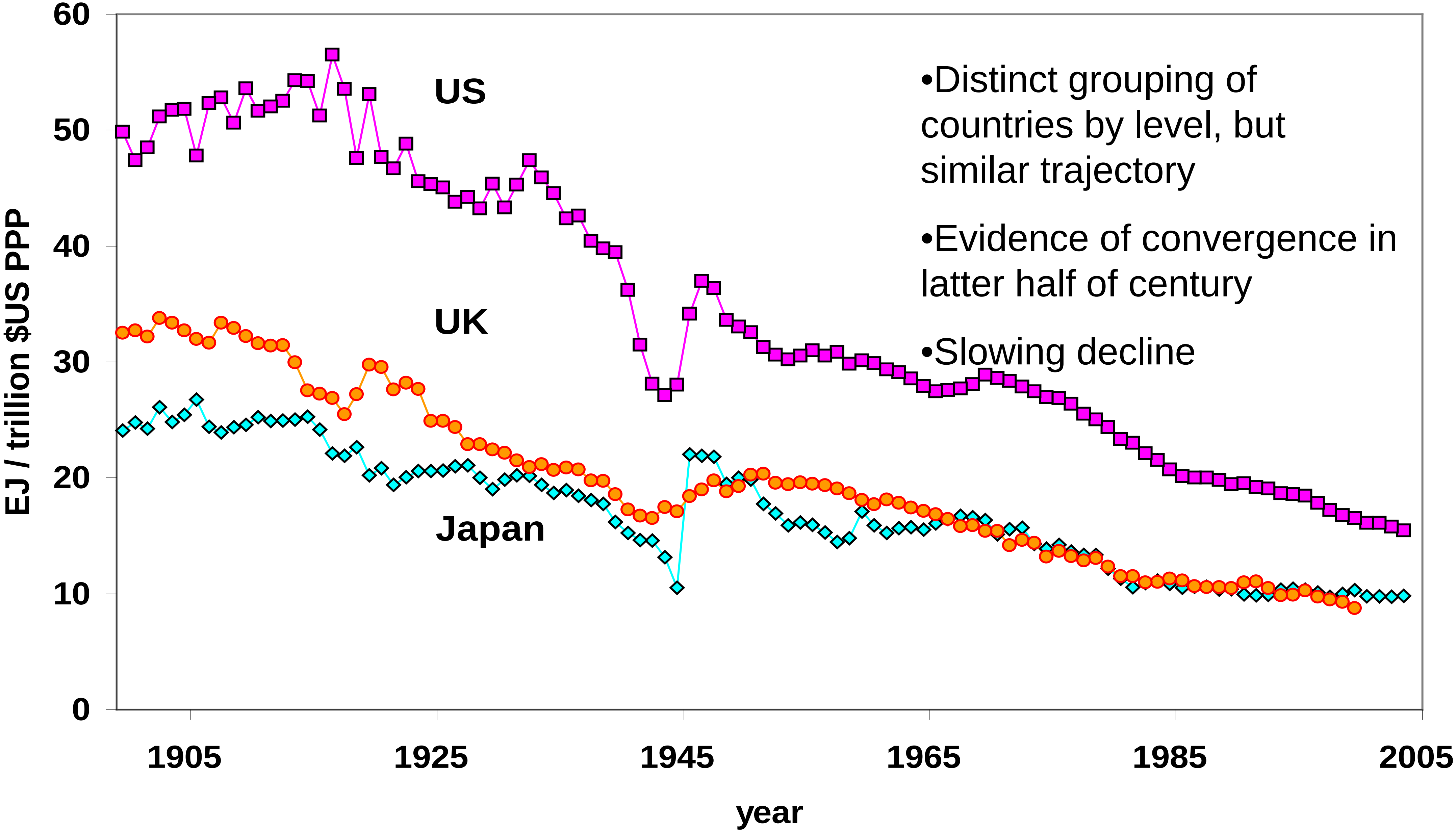
for Alternate Rates of Technical Efficiency Growth



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

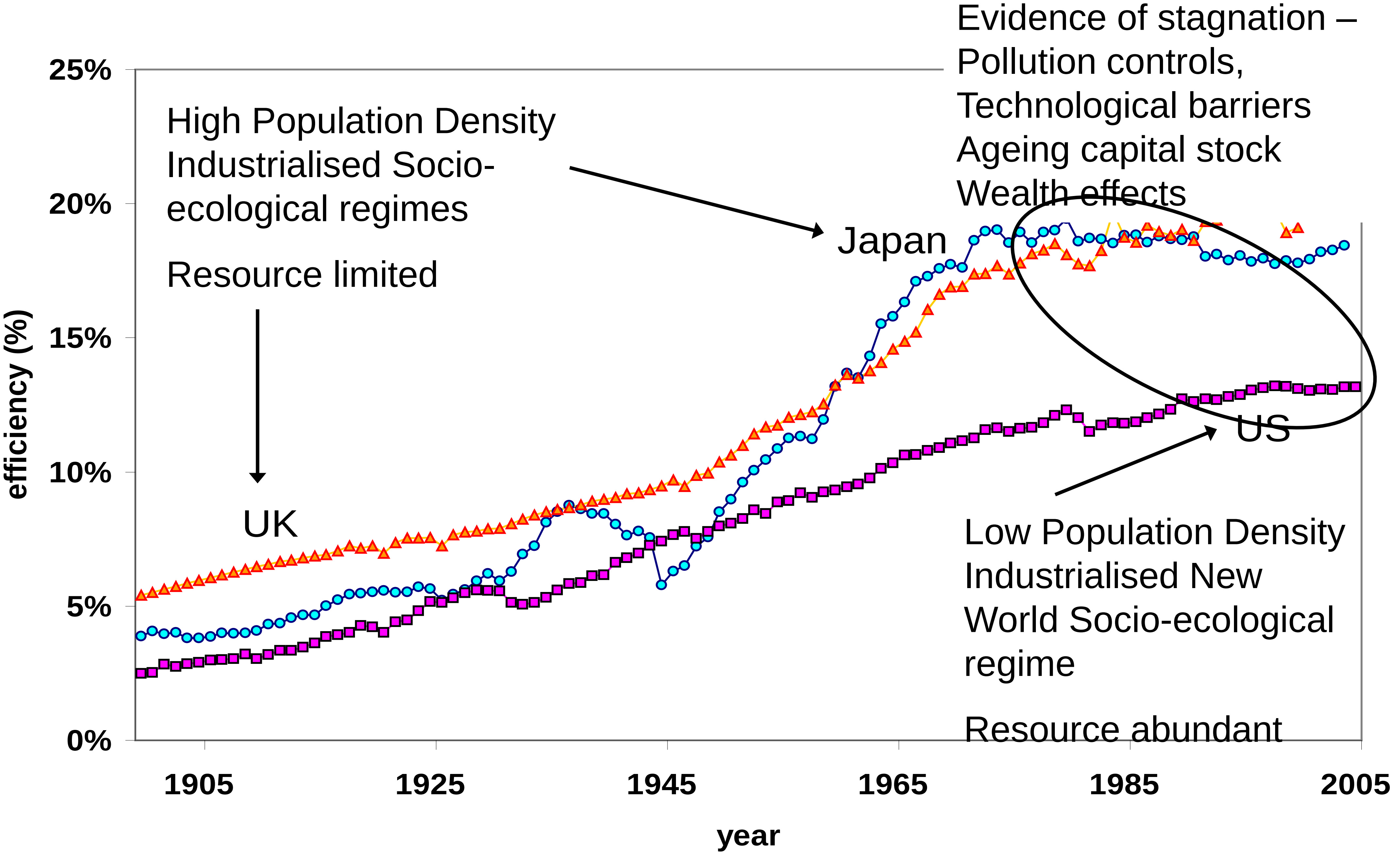


Exergy Intensity of GDP Indicator



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

Exergy to Useful Work Conversion Efficiency



High Population Density
Industrialised Socio-ecological regimes

Resource limited

Evidence of stagnation –
Pollution controls,
Technological barriers
Ageing capital stock
Wealth effects

Low Population Density
Industrialised New World Socio-ecological regime

Resource abundant

Why Are The Others More Efficient?

- Part of the difference is higher population density. Energy consumption in compact cities is more efficient than urban sprawl.
- Part due to is more public transport, more small cars, more diesel. More bicycles.
- Part is buildings (multi-family, masonry vs. single family wood-frame).
- Part is more use of combined heat and power (CHP)
- Part is due to much higher energy prices.

On the Existence of “Free Lunches” in the Real Economy

- An economist was walking with his grandson. The boy sees a $100 bill lying on their path. The economist says “that must be a forgery. If it were real, somebody would have picked it up already.”
- Most PhD economists insist that (1) the economy is in (or very near) equilibrium, and (2) when in equilibrium, that free lunches can’t exist for long because some entrepreneur would soon take advantage of the opportunity.
- Problem: all sorts of barriers.

But Empirical Evidence of Neglected-Opportunities is Very Strong

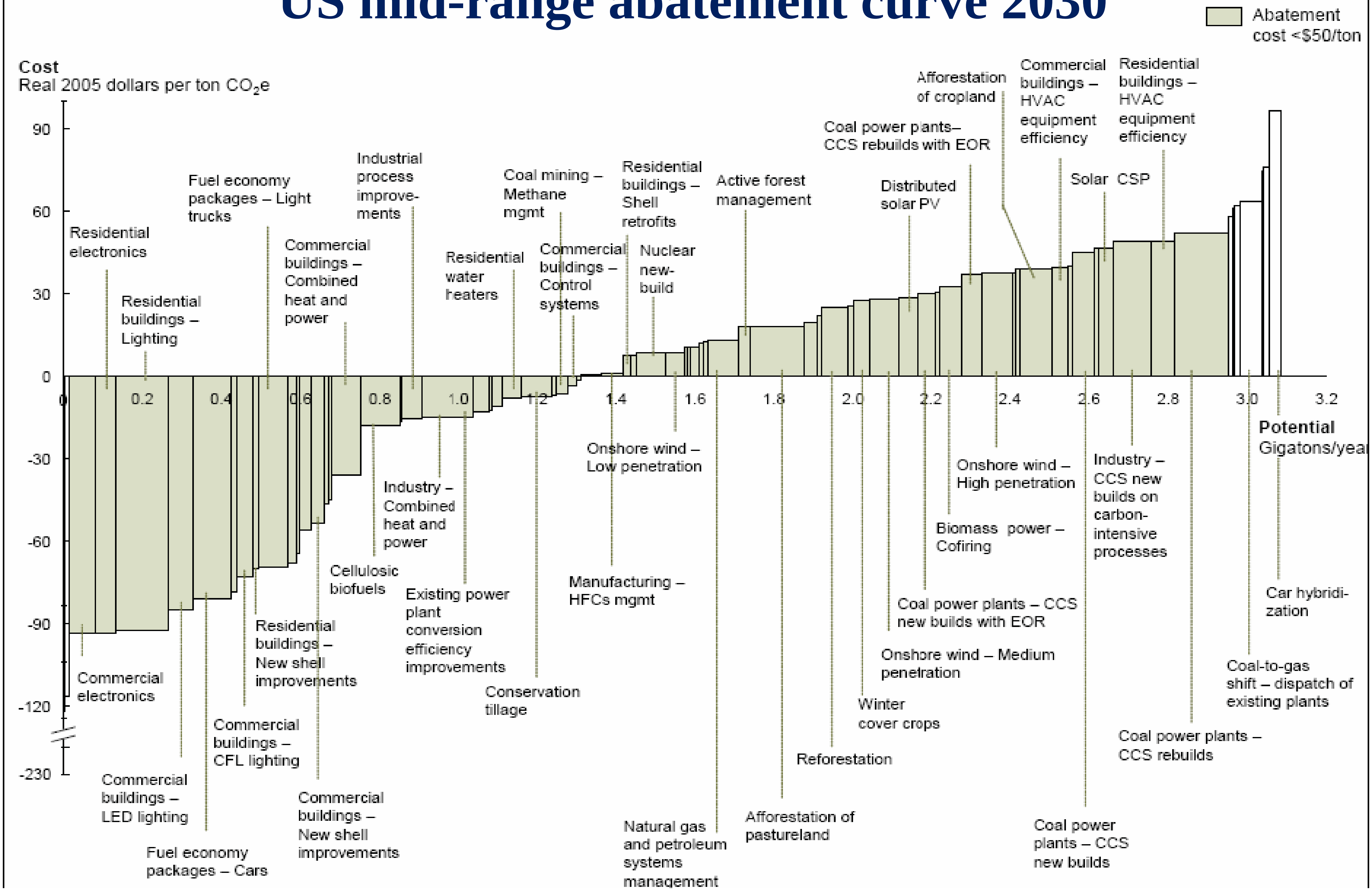
- Many examples have been discussed (but economists always say they are exceptional).
- However, here is one that is hard to shrug off. In 1981 Ken Nelson, an engineer at Dow, Louisiana Division, proposed an “energy contest”. The GM agreed, on condition that only projects with a 1-year or less payback would be supported. ROI in Year 1 was 169%. The contest continued for 12 years. In the last three years ROIs averaged 300%.

Summary of Dow Energy Contest Results – All Projects

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Winning Projects	27	32	38	59	60	90	94	64	115	108	109	140
Capital, $MM	1.7	2.2	4.0	7.1	7.1	10.6	9.3	7.5	13.1	8.6	6.4	9.1
Average ROI (%)	173	340	208	124	106	97	182	470	122	309	305	298
ROI Cut-Off (%)	100	100	100	50	40	30	30	30	30	30	50	50
Savings, $M/yr												
Fuel Gas(a)	2970	7650	6903	7533	7136	5530	4171	3050	5113	2109	5167	4586
Capacity	83	-63	1506	2498	798	3747	13368	32735	8656	17909	11645	20311
Maintenance	10	45	-59	187	357	2206	583	1121	1675	2358	2947	2756
Miscellaneous	___	___	___	___	___	19	-98	154	2130	5270	518	788
Total Savings	3063	7632	8350	10218	8291	11502	18024	37060	17575	27647	20277	28440

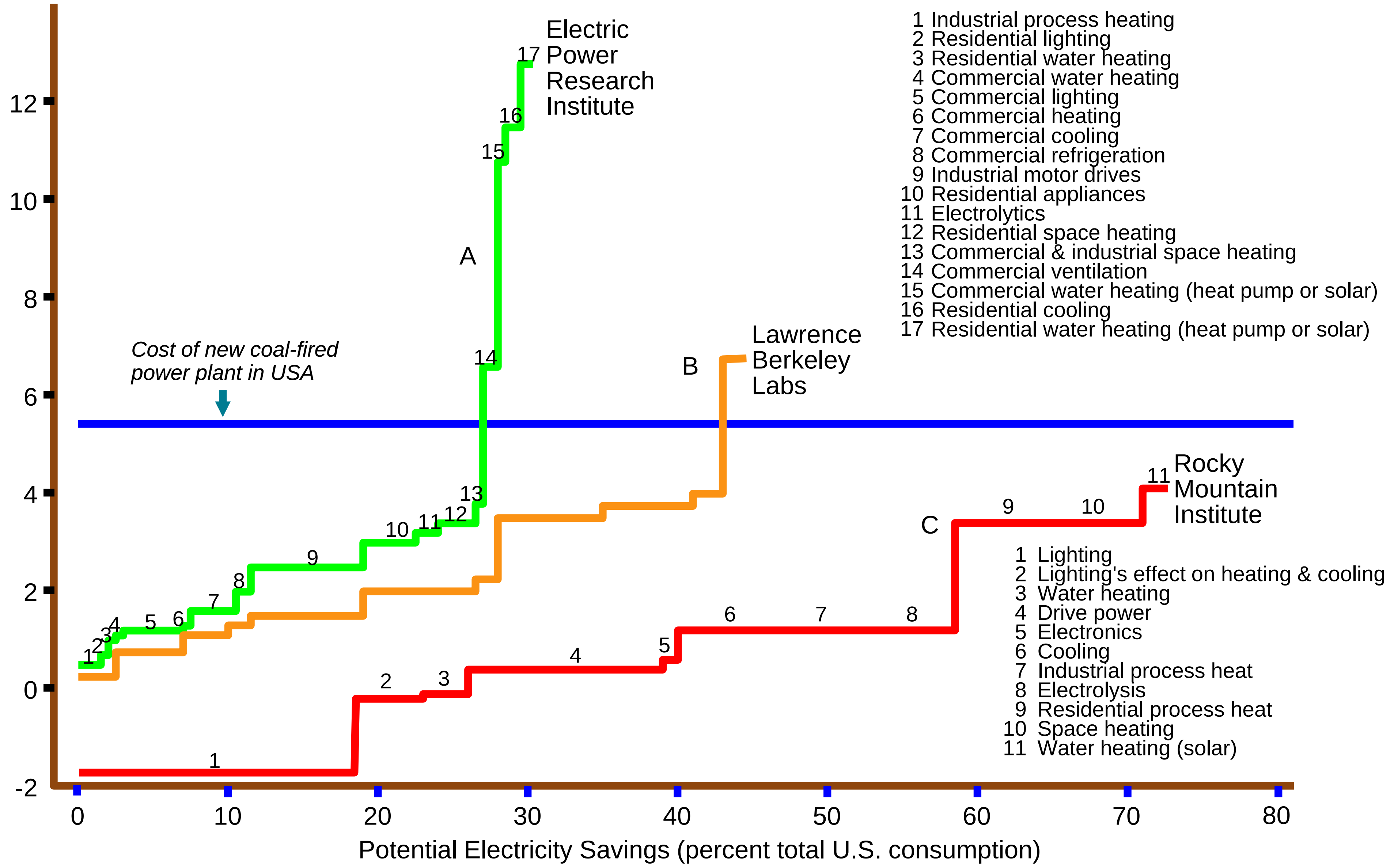
Source: (Nelson and Rosenberg 1993): Tables 4 and 6

US mid-range abatement curve 2030



Source: McKinsey & Co.

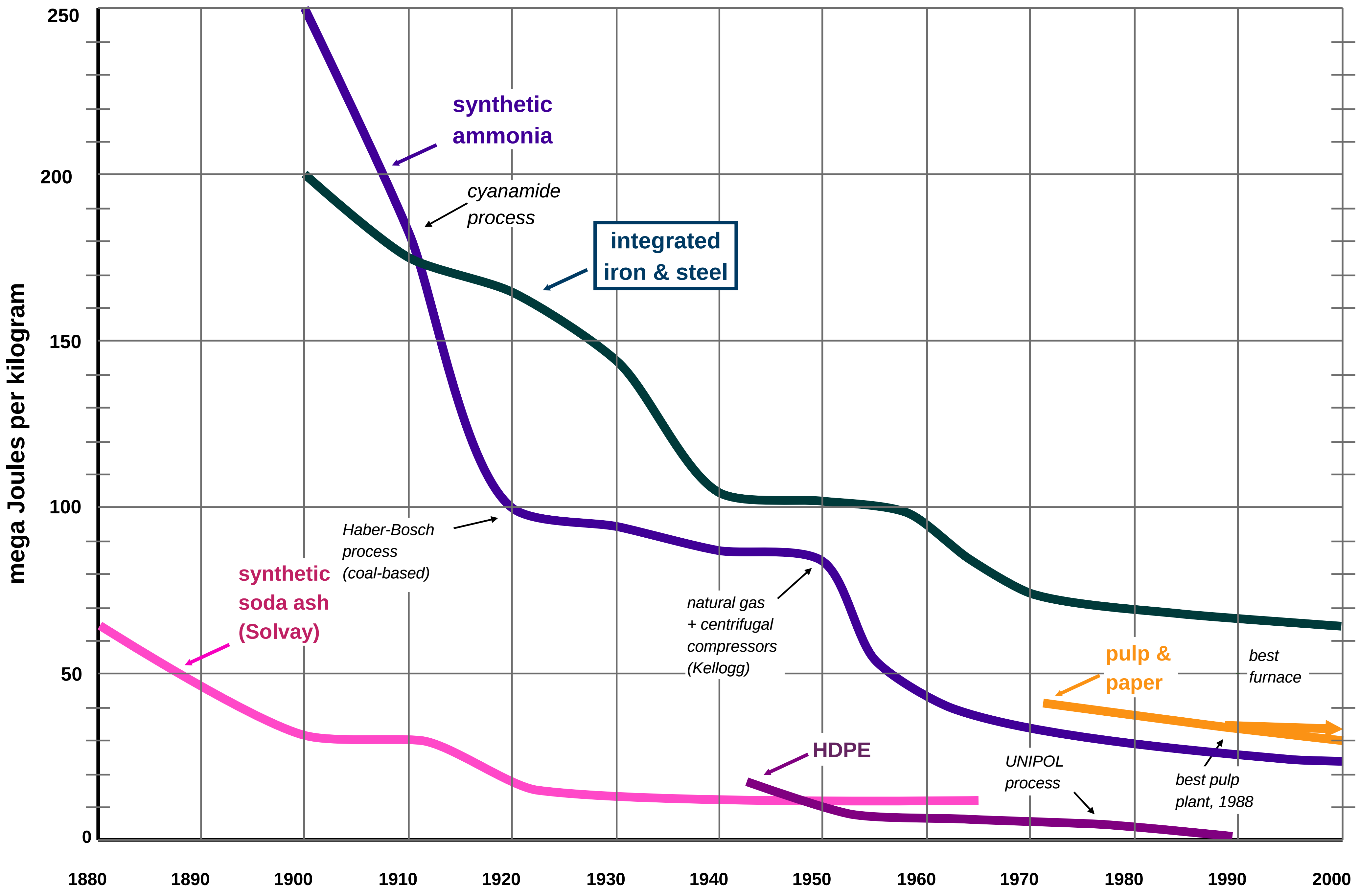
Three Estimates of Marginal Cost of Electricity Efficiency (in cents per kWh)



What is the Best Way to Cut Exergy Costs in Metal Production?

- In the cases of steel and aluminum there may not be much potential efficiency gain in the near term, although studies suggest gains of up to 20% as older facilities are replaced.
- To cut exergy consumption in metals the best solution is to **use less metal** in the product (e.g. replace copper wire by glass fiber) or
- **Recycle much more**. This is mainly a systems (reverse logistics) problem.

Figure 16: Exergy consumption by industrial processes: USA 1880-2000



Energy Efficiency in Manufacturing?

- In the case of primary metals and some chemicals one can make fairly accurate calculations. Up to 50% is now possible in some cases (with BAT).
- The efficiency of a complex multi-stage process with losses at every stage is much lower: a 6-stage process with 90 % efficiency at each stage is only 24 % efficient overall.
- To save energy the best strategy is re-use, renovation, re-manufacturing and recycling.

Example: How We Could Cut Energy Consumption in Transportation

- Discourage private automobiles by parking fees, congestion fees, bus-taxi lanes,etc.
- Use cars more efficiently (e.g. commuter vans, special lanes for high occupancy vehicles, etc.)
- Improve public transportation, e.g. with Bus Rapid Transit (BRT), integration of urban networks, etc.
- Encourage more use of bicycles, including e-bikes.
- And encourage EVs, with free recharge stations

So, Why Isn’t It Happening? Why Doesn’t the ‘Invisible Hand’ Work?

- Economists deny that win-win opportunities exist, but there are plenty of examples (e.g. Dow)
- From an ‘inside’ business perspective, the question is ‘why do firms not invest in profitable energy-saving opportunities that do exist? Survey questions highlight managerial problems, lack of expertise, lack of capital, and even lack of time (managers are busy “putting out fires”)

Why Don’t Firms Invest in Profitable Energy-Saving Opportunities?

- From an ‘outside’ business perspective, the answer is really simple: the prevailing managerial culture puts much more emphasis on growth than on cost-saving or profit-maximizing.
- Why is this the case? The answer is probably that growth, in a competitive environment, is seen as the key to survival. Firms that don’t grow will die or be swallowed up by bigger rivals.

Why Don’t Firms Invest in Profitable Energy-Saving Opportunities (con’t)?

- From a societal perspective, the answer is even simpler: the biggest and most powerful firms that exist today got big by capturing and selling natural resources. (The biggest firms in the world are oil companies. They make money by selling oil.)
- On the other hand, hardly any firms make profits by saving energy or helping others save it. One problem with that line of business is that success puts you out of business.

Many Opportunities Exist Now, But They Are Prevented by Barriers

- Energy has been too cheap and is still subsidized; too many people think cheap energy is a “right” like health care.
- Managers do not realize where easy savings are possible
- Managers (and investors) are focused on growth, not saving
- Developers minimize construction cost, not operating cost.
- Energy expertise is scarce; trust in consultants is scarcer
- Inefficient technologies (like utility monopolies) are “locked in” by economies of adoption and scale.
- Government regulations prohibit some sensible options

Crossing the Energy Divide by Increasing Efficiency (Barrier Busting)

- There are huge opportunities for energy recycling but they are resisted by monopoly electric power companies. We need true utility de-regulation, plus “feed-in tariffs” (like Germany and 40 other countries) to kick-start decentralized power.
- Stop subsidizing cars: Start with parking fees, congestion charges, bus-lanes, bicycle lanes, etc.
- Get rid of regulations that inhibit innovation, such as the New Source Standards regulations.

Barrier Busting, Continued

- The greatest barrier of all is the growth imperative: the deep-seated conviction that growth assures survival in the competitive global race.
- But the race is to where? Growth that consumes limited resources is itself unsustainable. A new paradigm is urgently needed.
- The new paradigm must focus on re-use, renovation, remanufacturing and recycling. The energy firms need to sell efficiency, and energy security, not fuel.

Energy Service Companies: A New Business Opportunity

- Fact: improving energy efficiency in homes and industrial establishments requires special skills
- Fact: firms try to focus on their “core business. They are reluctant to invest in projects that do not pay for themselves in a few months or a year.
- Opportunity: firms with special skills can pay for the investments, share the savings, and make profits. However, ESCs need legal support, finance, insurance, economies of scale and “success stories”.

Conclusion

- Current approaches are counter-productive: CCS cuts efficiency, ethanol competes with food.
- Even with government help, the transition to wind, solar and geothermal, from a very small starting share of the total, will take several decades
- There are ways to bridge the gap by using fossil energy much more efficiently (as Europe and Japan already do), without radical new technology
- The key is to recognize and bust the barriers.

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