Energiewirtschaftliches Institut an der Universität zu Köln

The Underestimated Role of Energy in Economic Growth

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Workshop “Capping Macroeconomic Rebounds“ (ReCap)

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Agenda

- Motivation
- Some Introductory Theses
- Energy and Growth: The Capital-Labor-Energy-Creativity (KLEC) Model
- Summary&Conclusions

- Appendix: Path of German Industry in Factor Cost Mountain

Motivation

„Central determinants of the size of the rebound are (1) the role of energy for economic growth (the output-elasticity of energy and the additional energy demand due to increases in output), **(2) the elasticity of supply of energy and (3) the embodied energy in new technology…*"***

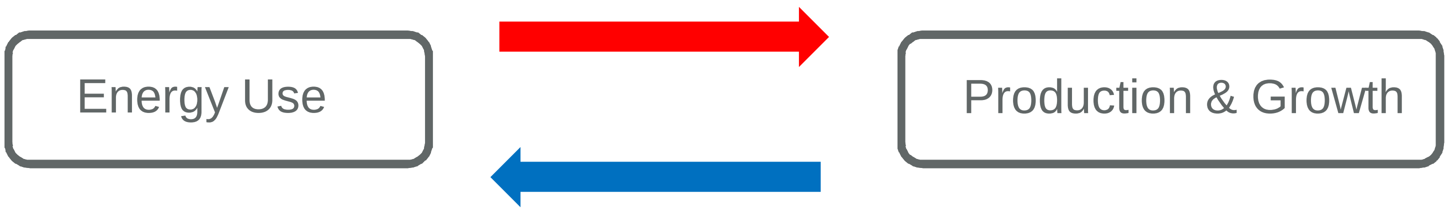
ReCap Discussion Paper 1, p.31 (Conclusion)

Thesis 1: Causality
between Energy Use and Economic Growth

There is bi-directional causality between Energy Use and Economic Growth:

Technical Causality

(through work performance and information processing in production – both coupled to energy flows)



Behavioral Causality

(entrepreneurial decision on factor demand following output demand)

Thesis 2: Natural Science Foundation

What is „energy"?

Energy is the potential to cause changes in the world.

Thermodynamics: „Nothing happens without energy conversion and entropy production"
(Summary of 1st and 2nd Laws of Thermodynamics)

Quantum Mechanics: Time Evolution Operator ***<u>is</u>*** the Energy Operator.
(Time-dep. Schrödinger Eq: $ih \frac{\partial}{\partial t} \psi = H \psi$)

Thesis 3: On the Industrial Revolution

What changed through the Industrial Revolution?

In pre-industrial production, mostly agriculture and handcrafting, physical work was performed by muscles and brains (plus natural energy flows driving e.g. wind & water mills)

The industrial revolution enabled outscourcing work performance and information processing from muscles and brains into the industrial capital stock (machines).

Key technological innovations, successively introduced into the capital stock:
- steam engines (converting heat to mech. work, tapping the vast fossil energy sources)
- generators (converting mechanical work to electricity)
- microprocessors (enabling electric information processing based on semi-conductor physics)

The industrial capital stock is activated by energy, and handled and supervised by labor.

Energy and Growth: The KLEC Model

The Capital-Labor-Energy-Creativity (KLEC) Model of Economic Growth

1. KLEC-Model: Conception
2. KLEC-Model: Production Functions
3. Results
4. Interpretation and Conclusions

KLEC-Model: Conception

- Physically, the elementary processes of production are work performance and information processing.

- Work performance and information processing are carried out in the cooperation of (instrumental) capital, labor, and energy.

- Energy activates capital. Labor manipulates capital.

- Materials, be it raw materials or preprocessed intermediates, do not actively contribute to the generation of value through work perfomance and information processing. They are the passive partners of the production process, on which value is imprinted upon.

- Based on this physical interpretation, the consistent output quantity is net output i.e. value added or GDP (not gross output including intermediates).

KLEC-Model and Production Functions I

Ansatz : $Q = Q(K, L, E; t)$

Q: **Value Added** [real €]

K: **Capital** Stock [real €]

-> measure of productive capacity

L: **Labor** [hours worked]

-> manipulates capital

E: **Energy** [Peta Joule]

-> activates capital

t: **Time**

Dimensionsless, relative quantities (‘0‘=base year):

$$k = \frac{K}{K_0}, \qquad l = \frac{L}{L_0}, \qquad e = \frac{E}{E_0}, \qquad q = \frac{Q}{Q_0}.$$

Production Functions II

The **Total Differential** of *q=q(k(t),l(t),e(t),t):*

$$\frac{dq}{dt} = \frac{\delta q}{\delta k}\frac{dk}{dt} + \frac{\delta q}{\delta l}\frac{dl}{dt} + \frac{\delta q}{\delta e}\frac{de}{dt} + \frac{\delta q}{\delta t}$$

can be transformed into the Growth Equation

$$\frac{dq}{q} = \alpha\frac{dk}{k} + \beta\frac{dl}{l} + \gamma\frac{de}{e} + \frac{\delta \ln q}{\delta t}dt,$$

with **Output Elasticities** of Capital, Labor, and Energy:

$$\alpha \equiv \frac{k}{q}\frac{\delta q}{\delta k}, \qquad \beta \equiv \frac{l}{q}\frac{\delta q}{\delta l}, \qquad \gamma \equiv \frac{e}{q}\frac{\delta q}{\delta e}$$

Production Functions III

In the Growth Equation

$$\frac{dq}{q} = \alpha \frac{dk}{k} + \beta \frac{dl}{l} + \gamma \frac{de}{e} + \frac{\delta \ln q}{\delta t} dt$$

the output elasticities of capital (α), labor (β), energy (γ) are unknown.

The output elasticities measure the economic weight with which the relative growth of the inputs contributes to the relative growth of output. I.e. they measure the productive power of the inputs.

Options:

1) Neoclassical approach (based on cost share theorem):

   - α, β, γ are set equal the resp. factor cost shares (K: ≈0,25; L: ≈0,70; E: ≈0,05)
   - Most of empirical growth remains unexplained („Solow-Residual“)

2) Determine α, β, γ from technological considerations and empirical analysis

Production Functions IV

Result of cost share-weighting of production factors (Solow Residual)

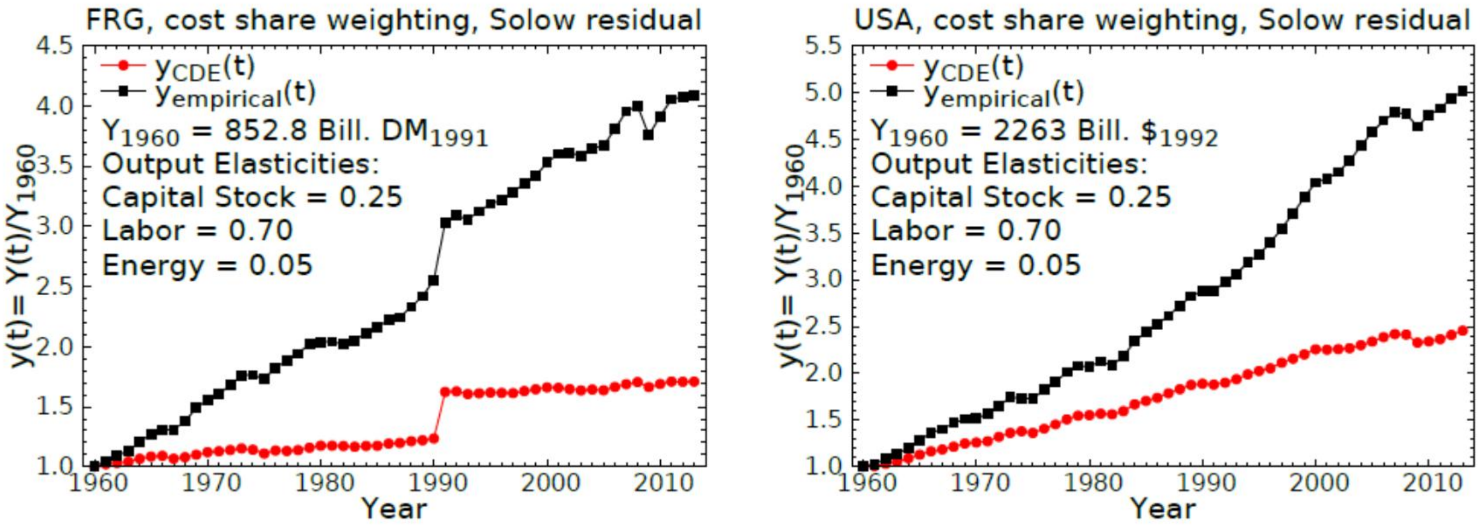


Figure 1: Empirical outputs (squares) and theoretical outputs (circles) for the total economies of Germany (FRG) and the USA. The theoretical growth is computed with the energy-dependent Cobb-Douglas function (8) and cost-share weighting of the production factors. The differences between the empirical and the theoretical growth curves are called "Solow residuals". The empirical growth of the inputs is shown in Figs. 2(c) and 4(c).

(Mathematical Supplement I)

Conditions of Integrability of the Production Function

(Identity of mixed 2nd order derivatives w.r.t. factor inputs):

$$\frac{\delta^2 q}{\delta l\,\delta k} = \frac{\delta^2 q}{\delta k\,\delta l}, \qquad \frac{\delta^2 q}{\delta l\,\delta e} = \frac{\delta^2 q}{\delta e\,\delta l}, \qquad \frac{\delta^2 q}{\delta k\,\delta e} = \frac{\delta^2 q}{\delta e\,\delta k},$$

Combined with the Output-Elasticities

$$\alpha \equiv \frac{k}{q}\frac{\delta q}{\delta k}, \qquad \beta \equiv \frac{l}{q}\frac{\delta q}{\delta l}, \qquad \gamma \equiv \frac{e}{q}\frac{\delta q}{\delta e},$$

Yields three (symmetrical) coupled differential equations for the output elasticities:

$$l\frac{\delta \alpha}{\delta l} = k\frac{\delta \beta}{\delta k}, \qquad e\frac{\delta \alpha}{\delta e} = k\frac{\delta \gamma}{\delta k}, \qquad e\frac{\delta \beta}{\delta e} = l\frac{\delta \gamma}{\delta l}.$$

(Mathematical Supplement II)

Given constant returns to scale $(\alpha + \beta + \gamma = 1)$, e.g. γ can be eliminated,

$\gamma(k,l,e) = 1 - \alpha(k,l,e) - \beta(k,l,e).$

This leads to:

$$k\frac{\delta\alpha}{\delta k} + l\frac{\delta\alpha}{\delta l} + e\frac{\delta\alpha}{\delta e} = 0, \qquad k\frac{\delta\beta}{\delta k} + l\frac{\delta\beta}{\delta l} + e\frac{\delta\beta}{\delta e} = 0,$$

$$l\frac{\delta\alpha}{\delta l} = k\frac{\delta\beta}{\delta k}, \qquad (*)$$

With the general solution:

$$\alpha = \alpha(l/k, e/k), \qquad \beta = \beta(l/k, e/k),$$

where α and β have to fulfil the coupling equation (*).

Production Functions V

- Vanishing output elasticity of capital lying idle:

  $\lim \alpha \to 0,$ if: $l/k \to 0$ and $e/k \to 0$

  („capital growth contributes to output growth to the extent it is utilized by energy and labor; capital lying idle does not contribute output growth")

- Vanishing output elasticity of labor in the state of total automation:

  $\lim \beta \to 0,$ if: $e \to e_t$ and $k \to k_t$

  (e_t , k_t: energy requirement of the fully utilized capital stock; $e_t = c_t k_t$)

- Simplest *integrable* solution – under constant returns to scale:

$$\alpha = a_0 \frac{l+e}{k}, \qquad \beta = a_0 \left(c_t \frac{l}{e} - \frac{l}{k} \right), \qquad \gamma = 1 - \alpha - \beta,$$

Inserted into the Growth Equation yields, by integration…

Production Functions VI

… the (first) LINEX-Production Function (q_{L1})

$$q_{L1} = q_0\, e\, \exp\left[a_0 \left(2 - \frac{l+e}{k} \right) + a_0\, c_t \left(\frac{l}{e} - 1 \right) \right]$$

with technology parameters a_0: capital effectiveness

c_t : energy requirement of fully utilized capital stock

Technology parameters have to be determined by fitting the LINEX function to time-series data: *k(t), l(t), e(t), q(t)* observing the (non-linear) constraints of non-negative output elasticities

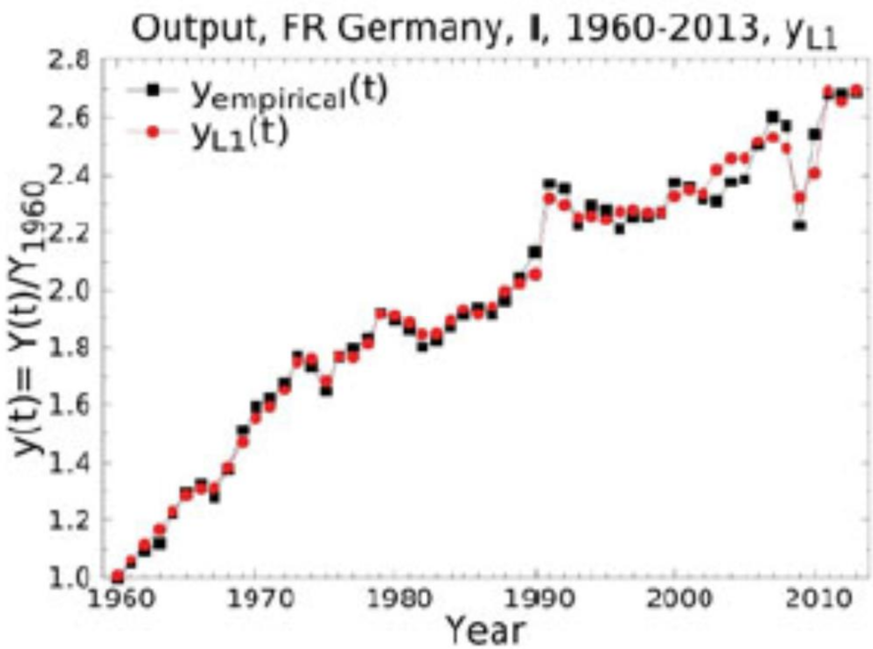
$$\alpha \geq 0, \qquad \beta \geq 0, \qquad 0 \leq \alpha + \beta < 1$$

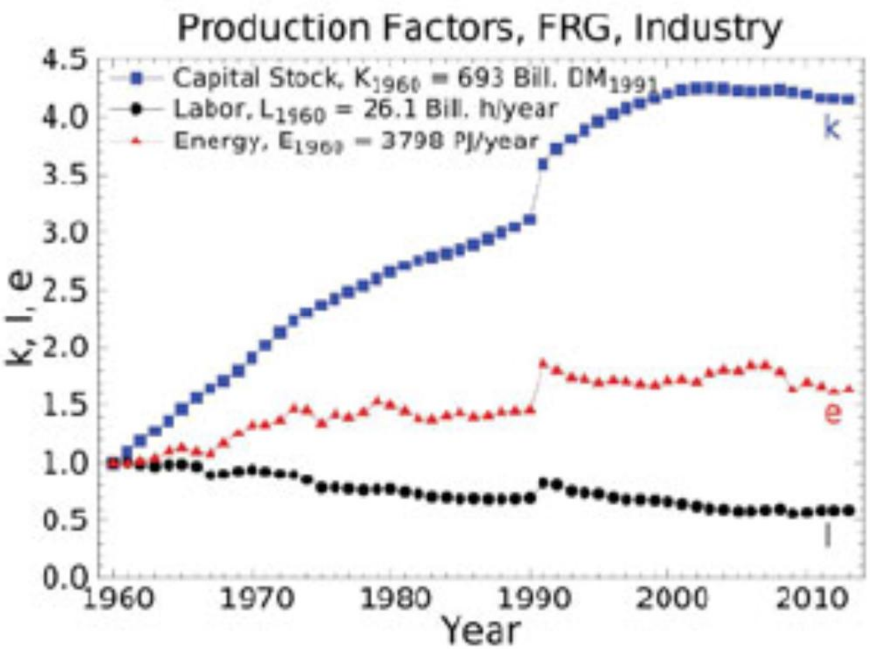
and taking into account limits to factor substitution, e.g.:

$\beta \geq 0 \quad \Leftrightarrow \quad e_t \leq c_t\, k_t$ (one cannot feed-in more energy into the machines of the capital stock than required at full utilisation according to their technical design)

Results I

Fit of Linex production function $Y_{L1}(k,l,e;t)$





Details including time-dependencies of technolgy parameters and output elasticities as well as results for the total economies of Germany and the U.S.A. are discussed in: Economic Growth in Germany and the USA 1960-2013: The Underestimated Role of Energy, Lindenberger et al., Biophys Econ Resour Qual (2017) 2:10

Results II: Time-averaged output elasticities of capital, labor, energy, creativity (α,β,γ,δ)

Y_{L1}, System:	FRG TE	FRG I	USA TE
$\bar{\alpha}$	0.367 ± 0.006	0.248 ± 0.008	0.518 ± 0.023
$\bar{\beta}$	0.188 ± 0.004	0.076 ± 0.008	0.188 ± 0.041
$\bar{\gamma}$	0.445 ± 0.007	0.640 ± 0.011	0.294 ± 0.047
$\bar{\delta}$	0.217 ± 0.006	0.132 ± 0.007	0.200 ± 0.023
R^2	0.999	0.989	0.998
d_W	1.650	1.747	0.715
Y_{L11}, System:	FRG TE	FRG I	USA TE
$\bar{\alpha}$	0.399 ± 0.008	0.221 ± 0.020	0.533 ± 0.016
$\bar{\beta}$	0.236 ± 0.012	0.015 ± 0.009	0.242 ± 0.035
$\bar{\gamma}$	0.365 ± 0.014	0.765 ± 0.022	0.226 ± 0.039
$\bar{\delta}$	0.236 ± 0.032	0.27 ± 0.16	0.168 ± 0.019
R^2	0.999	0.988	0.999
d_W	1.508	1.581	0.762

Table 1 Time-averaged output elasticities of capital, $\bar{\alpha}$, labor, $\bar{\beta}$, energy, $\bar{\gamma}$, creativity, $\bar{\delta}$, adjusted coefficient of determination $\bar{R}^2$, and Durbin–Watson coefficient d_W obtained with the LinEx production functions Y_{L1} and Y_{L11} for the systems FR Germany Total Economy (FRG TE), FR Germany Industry (FRG I), and USA Total Economy (USA TE). Observation time is 1960–2013. Appendix 3 comments on the d_W of the USA

Source: Lindenberger, Weiser, Winkler, Kümmel, Biophys Econ Resour Qual (2017) 2:10

Results III

Fit of energy-dependent Cobb-Douglas production function yCDE

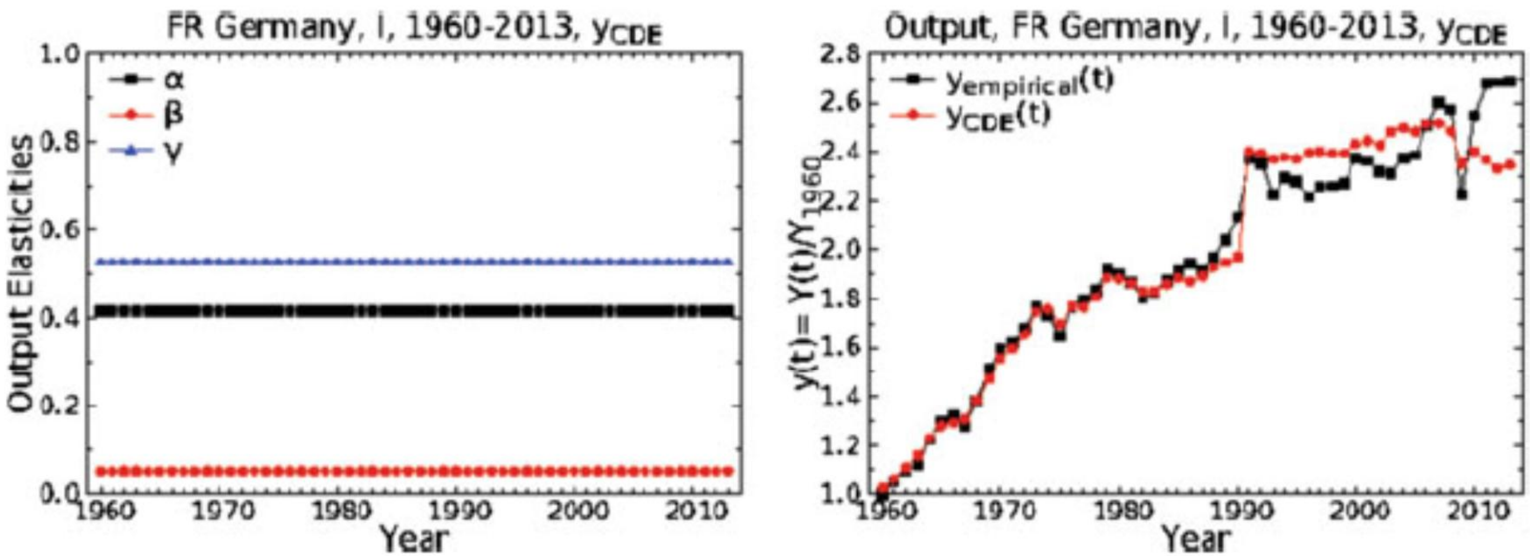


Abb. 3.6 BRD Industrie 1960–2013. Produktionselastizitäten (links) und Wachstum der Wertschöpfung (rechts) gemäß der energieabhängigen Cobb-Douglas Produktionsfunktion der Gl. (3.31) [119] Source: Lindenberger, Weiser, Winkler, Kümmel, Biophys Econ Resour Qual (2017) 2:10

Interpretation and Conclusions I

1. Energy is an essential factor of production (Laws of Thermodynamics).
2. Energy dependent production functions reproduce the growth of output in industrialized countries with small residuals (resolving the “Solow-Residual“).
3. Improvements of the capital stock‘s energy conversion efficiencies after the oil price shocks in the 1970s are identified.
4. Model results indicate that in industrial economies the productive power (output elasticity) of the production factor energy significantly exceeds its low factor cost share, whereas for routine labor the opposite is the case.
5. This result is consistent with the observed direction of technological progress, where expensive routine labor is substituted by combinations of cheap energy and increasingly automated capital.

Interpretation and Conclusion II

5. In standard neoclassical economics, if technological constraints are not taken into account, output elasticities equal factor cost shares (*1*) („cost share theorem“) and marginal factor productivities equal factor prices (*2*).

6. However, in industrial economies technological constraints do exist, especially:
   i) degree of capital utilization ≤ 1 („hard constraint“)
   ii) degree of automation ≤ maximum degree of automation(t) ≤ 1 („hard constraint“)
   (where the degrees of cap. utilization and automation are functions of factor ratios)
   iii) „soft constraints“, e.g. social laws, may prevent the immediate realization of technologically feasible cost-minimal factor mix (social constraints on rationalization).

7. If one or more of those constraints are (virtually) binding, this results in positive factor shadow prices of those constraints that modify the above relations (*1*) and (*2*).

Appendix: Path of German Industry

in Factor Cost Mountain 1960-1989

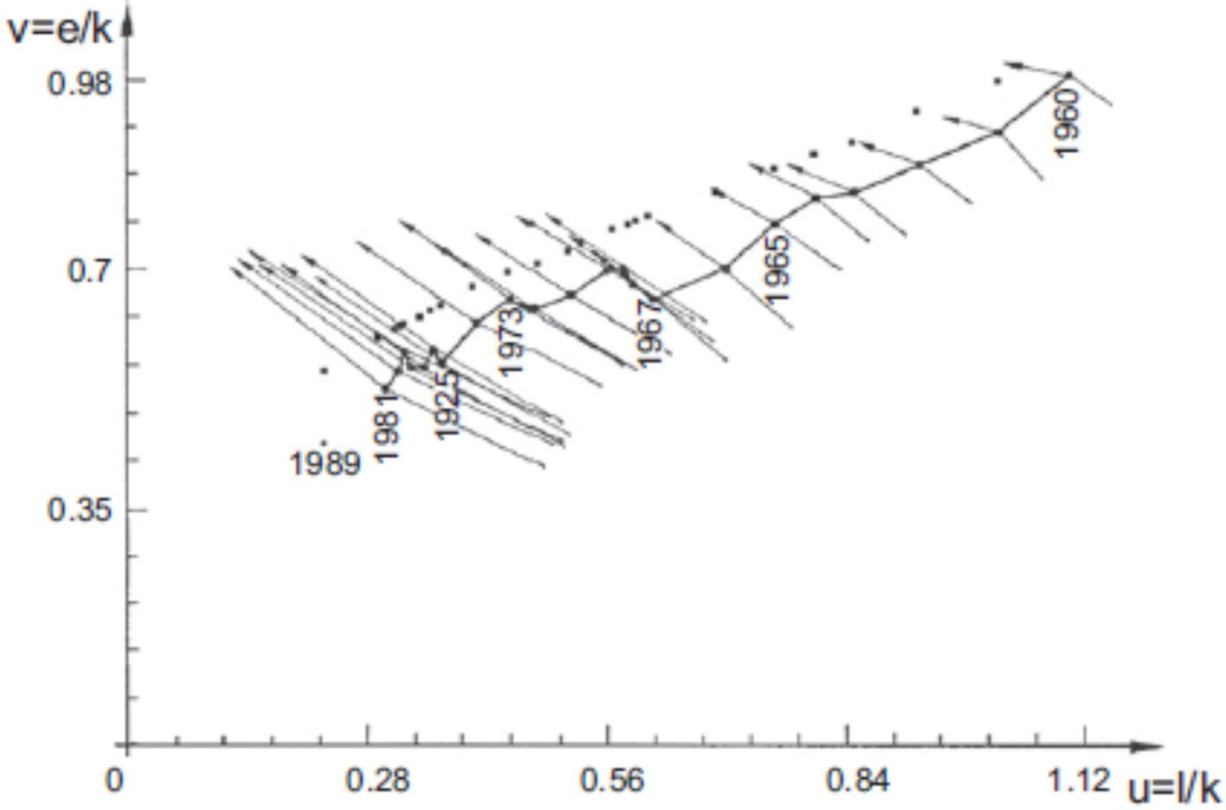


Figure 6. The solid line indicates the path of the German industrial sector 'Warenproduzierendes Gewerbe' (GWG) in the cost mountain between the years 1960 and 1981, projected onto the $u - v$ plane; $u \equiv l/k$ and $v \equiv e/k$, where k, l, and e are multiples of capital, labor, and energy in the base year $t_0 = 1960$. The full squares mark the barrier from the limit to capacity utilization. The way of computing them from equation (40) is described below that equation. They complement (the modified) figure 4 of [17].

Source: Kümmel, Lindenberger, New J Phys 16 (2014)