Useful exergy is key in obtaining plausible APFs and in recognizing the role of energy in economic growth: Portugal 1960-2009

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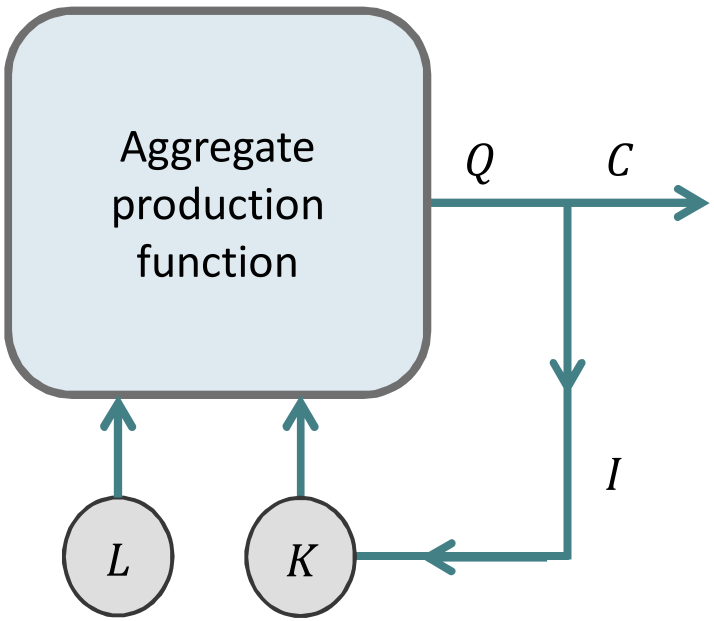
João Santos
(joao.dos.santos@tecnico.ulisboa.pt)
Tiago Domingos
Tânia Sousa
Miguel St. Aubyn

Summary

- **Motivation:**
  - The role of energy in contrasting approaches to economic growth;
  - Accounting for energy flows: exergy and useful exergy;
- **Methods:**
  - Cointegration analysis;
  - Criteria for statistically significant and economically plausible APFs;
- **Results:**
  - Macroeconomic and energy data;
  - Results and interpretation.
- **Conclusions**

Neoclassical theory of economic growth



Single-sector growth model

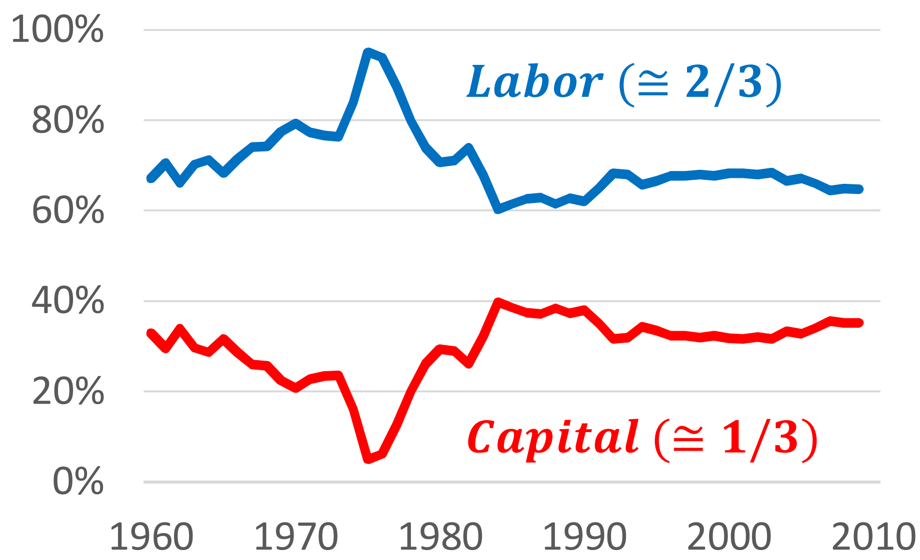
Solow, R. M. (1957). Technical change and the aggregate production function. The review of Economics and Statistics, 312-320.

Swan, T. W. (1956). Economic growth and capital accumulation. Economic record, 32(2), 334-361.

Economic growth explained through accumulation of capital (K), labor force growth (L), and mostly exogenous total factor productivity (TFP).

Energy resources are either downplayed or ignored altogether, and do not significantly contribute to economic growth.

- "*Cost-share theorem*": factors of production are paid according to their productive power.

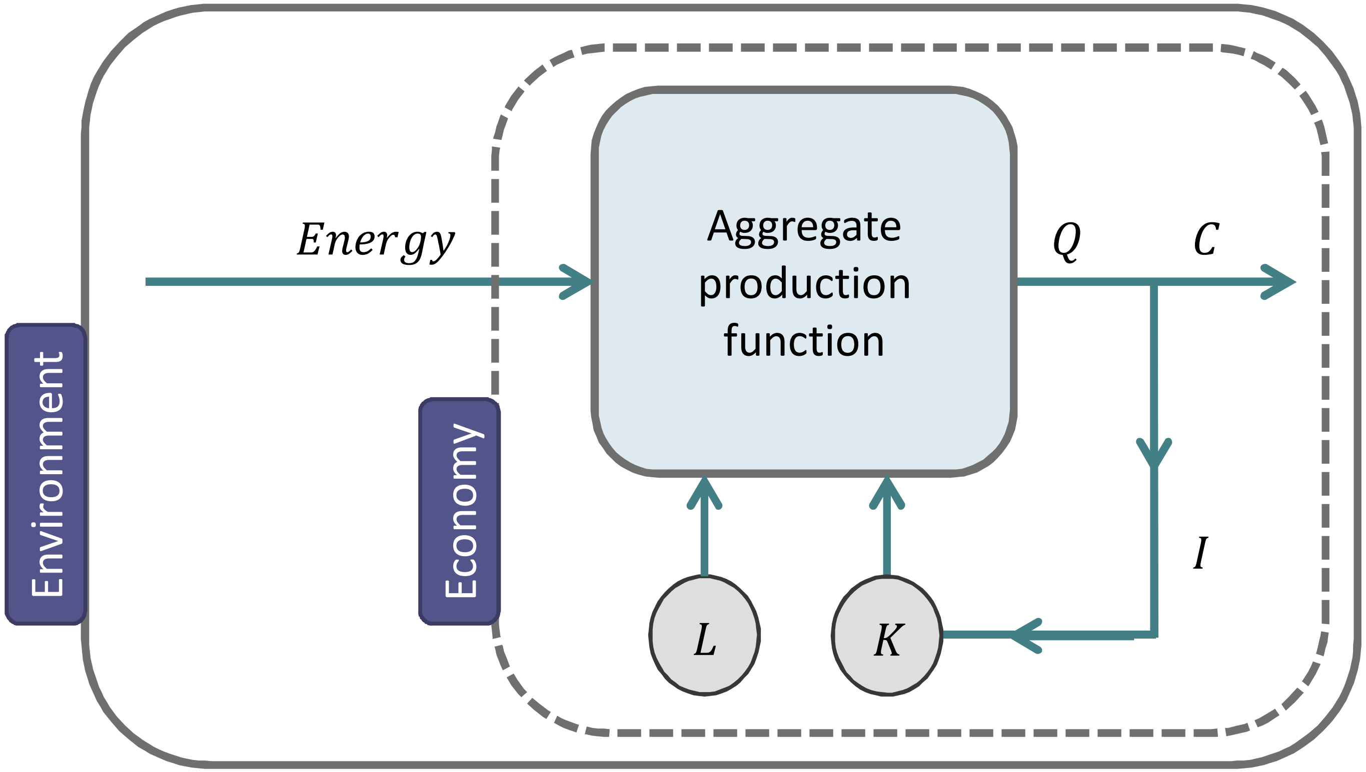


The role of energy in production: Ecological Economics

Real-world economic processes cannot be fully understood without accounting for energy use, i.e. energy is essential to production

The economic system is embedded within a larger, environmental system, with interactions grounded on the laws of thermodynamics.

The importance of energy to growth is higher than suggested by its cost share ($< 10\%$).



Aggregate Production Function critique

"…the estimation of aggregate production functions is problematic, to say the least."

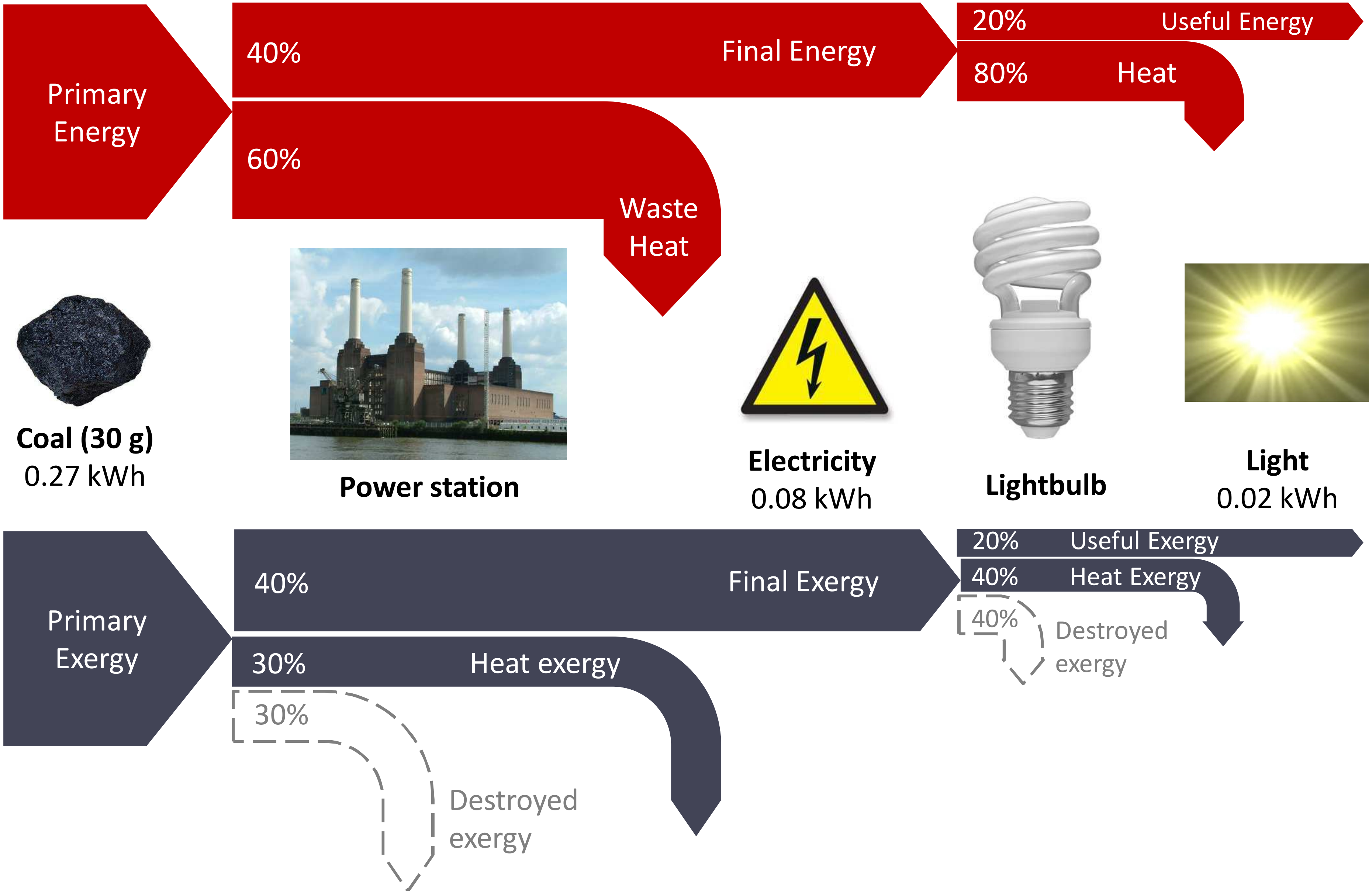
"…all those areas of neoclassical macroeconomics that use the aggregate production function (…) have no theoretical or empirical basis."

- Existence of an homogeneous degree one APF linking output and inputs to production is often merely assumed;
- Conditions under which APF can be written are stringent enough to doubt its existence;
- Aggregate measurement of capital inputs implies adding up incomparable heterogeneous assets:
  - *Cambridge capital controversy*;

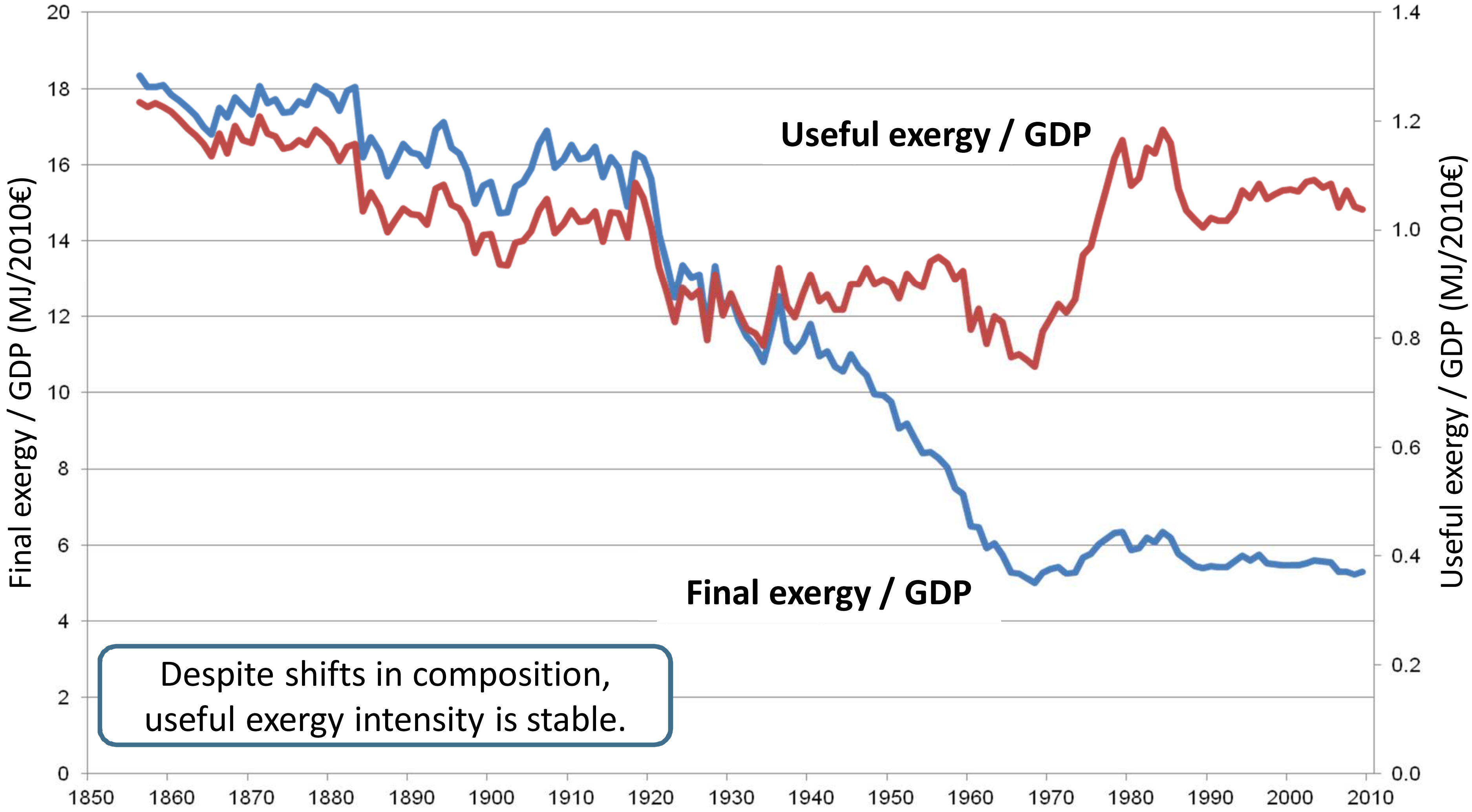
Felipe, J., & McCombie, J. S. (2005). How sound are the foundations of the aggregate production function?. Eastern Economic Journal, 31(3), 467-488.

Felipe, J., & McCombie, J. S. (2013). The Aggregate Production Function and the Measurement of Technical Change: Not Even Wrong . Edward Elgar Publishing.

Energy, exergy, and useful exergy



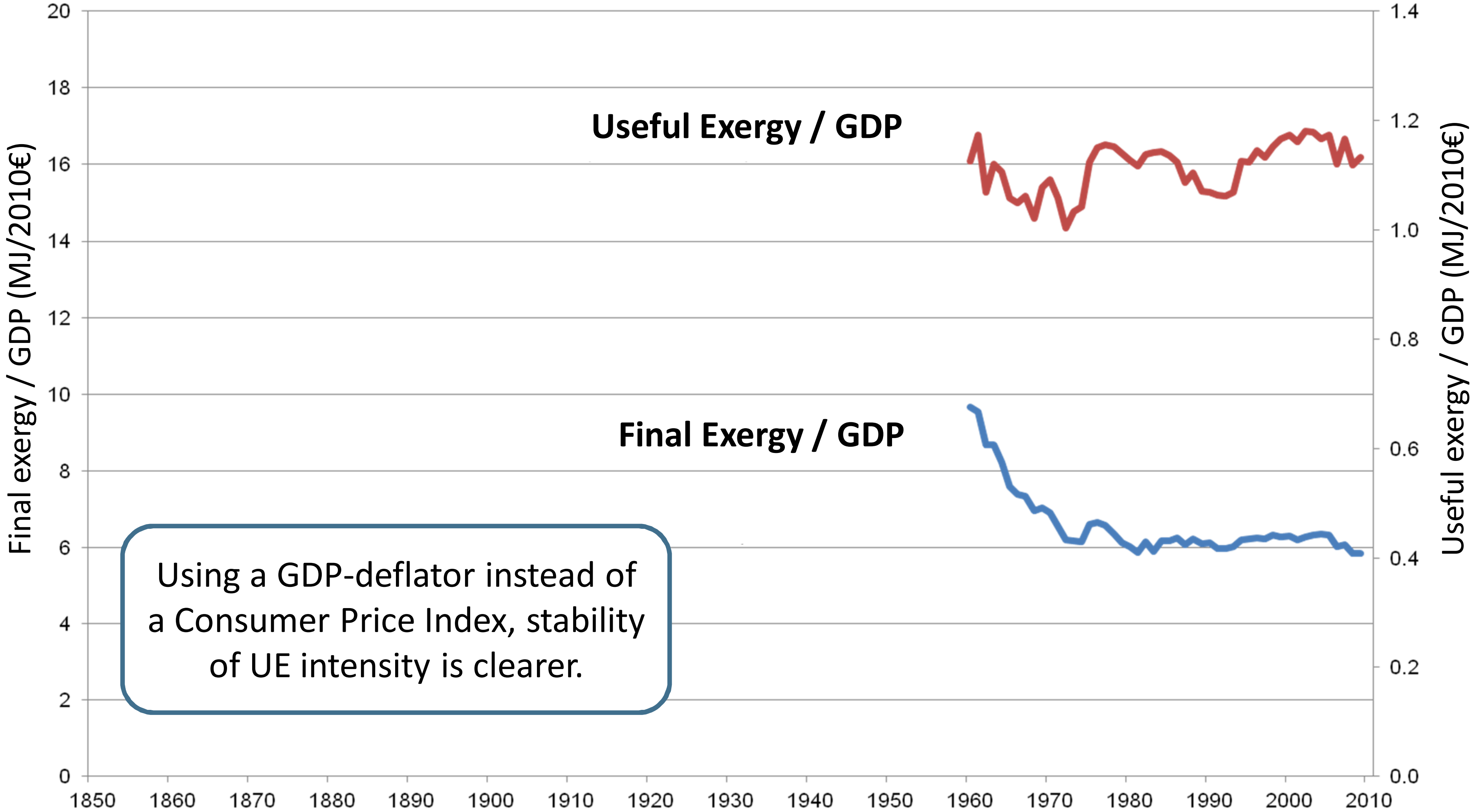
Exergy and useful exergy: Portugal 1856-2009



(GDP series from Lains,, 2003, & European Commission)

Serrenho, A. C., B. Warr, T. Sousa, R.U. Ayres, T. Domingos (2016). Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. Structural Change and Economic Dynamics, 36, 1-21.

Exergy and useful exergy: Portugal 1960-2009



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Cointegration: a drunk and her dog

A Drunk and Her Dog: An Illustration of Cointegration and Error Correction

Michael P. MURRAY

Murray, M. P. (1994). A drunk and her dog: an illustration of cointegration and error correction. The American Statistician, 48(1), 37-39.

Drunk: $x_t - x_{t-1} = u_t$

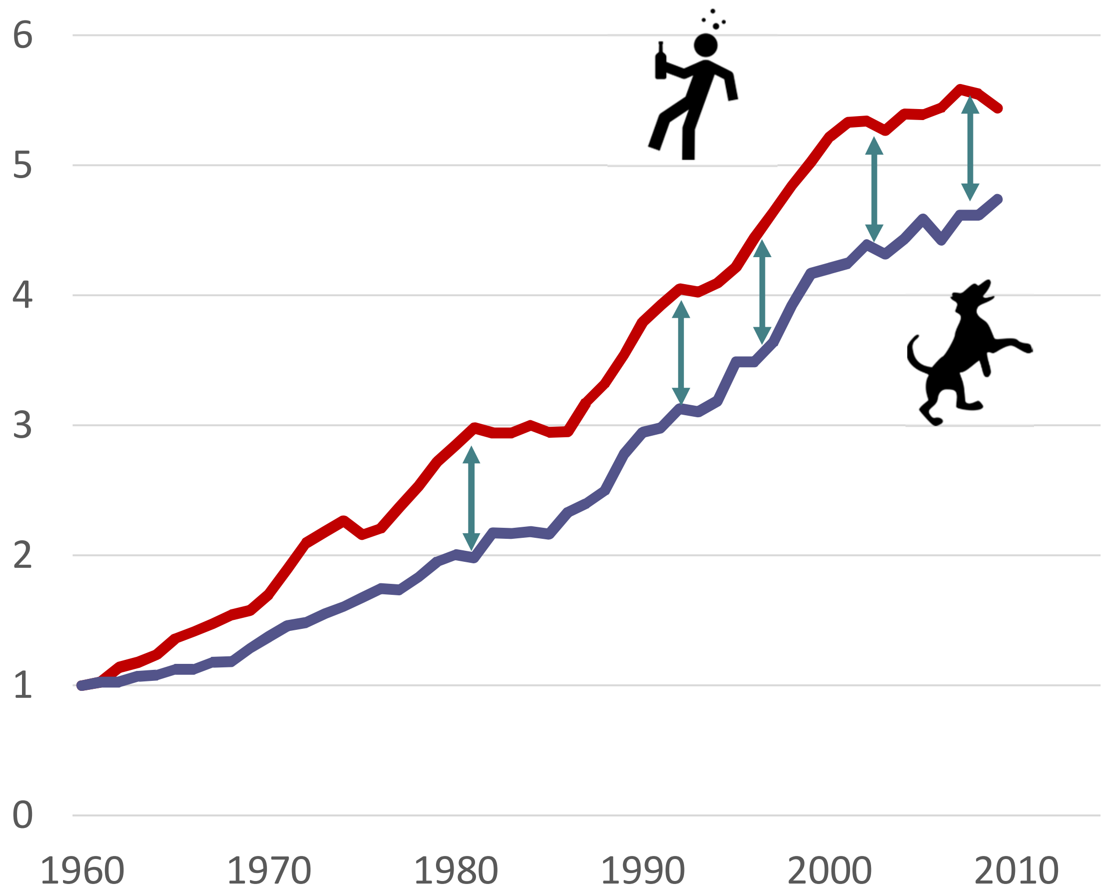
Dog: $y_t - y_{t-1} = w_t$

Each corrects his path so as not to stray too far from the other.

Cointegration:

$$x_t - x_{t-1} = u_t + c(y_{t-1} - x_{t-1})$$

$$y_t - y_{t-1} = w_t + d(x_{t-1} - y_{t-1})$$



Cointegration tests: Johansen* procedure and working variables

**Johansen, S. (1988). Statistical analysis of cointegration vectors. Journal of economic dynamics and control, 12(2-3), 231-254.*

The Johansen procedure to test for cointegration requires all time series to be $I(1)$.

Economic output – $\boldsymbol{Q}$

Capital inputs – $\boldsymbol{K}$

Labor inputs – $\boldsymbol{L}$

Energy inputs – $\boldsymbol{E}$

Likely to be $I(2)$

The order of integration can be tested resorting to <u>unit root tests</u>:

- **Augmented Dickey-Fuller;**
- **Philips-Perron.**

For time series with different order of integration, a set of $I(1)$ working variables can be defined to test for cointegration using the Johansen procedure:

$$q = \ln\left(\frac{Q}{L}\right) \qquad k = \ln\left(\frac{K}{L}\right) \qquad e = \ln\left(\frac{E}{L}\right)$$

Adoption of this set of working variables will impose constant returns to scale on APF formulations considered in our analysis.

From cointegration to aggregate production functions

The simplest model:

$$(\boldsymbol{q}, \boldsymbol{k})$$

- *Output and capital (no energy);*
- *No linear time trend;*
- *At most one cointegration vector.*

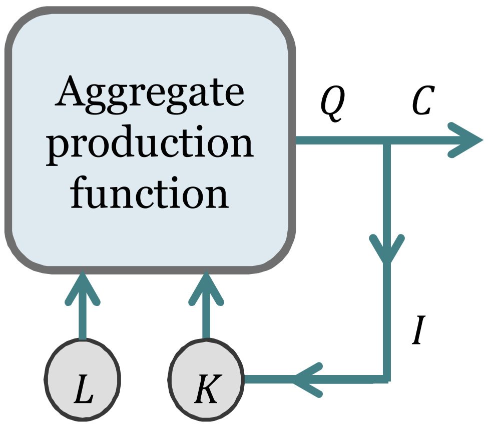
Cointegrating relationship (vector):

$$\beta_1 q - \beta_2 k - \mu = 0$$

$$q = \alpha_K \cdot k + \mu'$$

$$\frac{Q}{L} = \underbrace{\exp(\mu')}_{\theta} \cdot \left(\frac{K}{L}\right)^{\alpha_K}$$

$$Q = \theta \cdot K^{\alpha_K} \cdot L^{1-\alpha_K}$$



Aggregate production function criteria

1) Cointegration between factor inputs and output;
2) Output elasticities must be positive and significant;
3) Granger causality between inputs and output;
4) Output elasticities ≈ cost shares.

From cointegration to aggregate production functions

The simplest model:

$$(\boldsymbol{q}, \boldsymbol{k}, \boldsymbol{e})$$

- ***Output, capital, and energy;***
- *No linear time trend;*
- *At most one cointegration vector.*

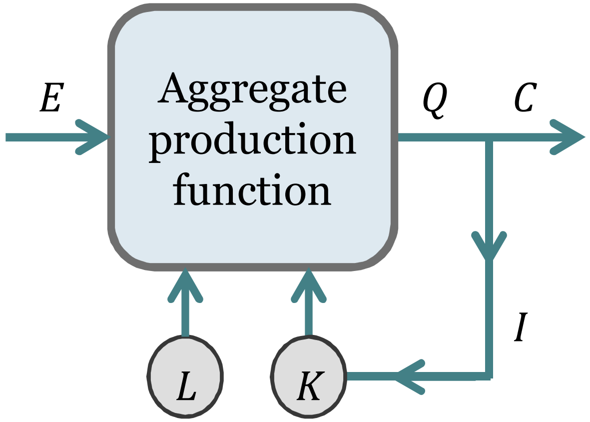
Cointegrating relationship (vector):

$$\beta_1 q - \beta_2 k - \beta_3 e - \mu = 0$$

$$q = \alpha_K \cdot k + \alpha_E \cdot e + \mu'$$

$$\frac{Q}{L} = \underbrace{\exp(\mu')}_{\theta} \cdot \left(\frac{K}{L}\right)^{\alpha_K} \cdot \left(\frac{E}{L}\right)^{\alpha_E}$$

$$Q = \theta \cdot K^{\alpha_K} \cdot E^{\alpha_E} \cdot L^{1-\alpha_K-\alpha_E}$$



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Cointegrating relationship (vector):

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$$q = \alpha_E \cdot e + \mu'$$

$$\frac{Q}{L} = \underbrace{\exp(\mu')}_{\theta} \cdot \left(\frac{E}{L}\right)^{\alpha_E}$$

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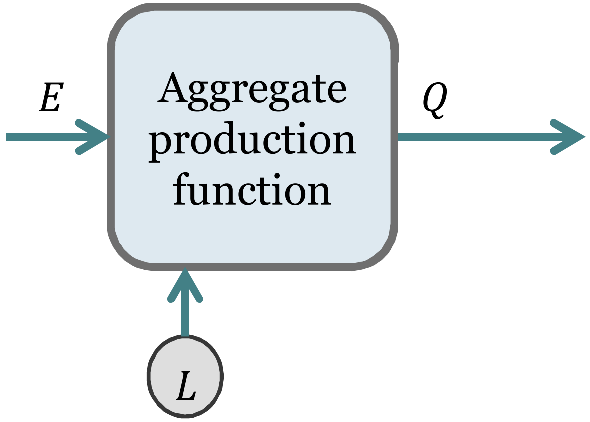

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From cointegration to aggregate production functions

The simplest model:

$$(\boldsymbol{q}, \boldsymbol{k})$$

- *Output and capital (no energy);*
- ***Linear time trend;***
- *At most one cointegration vector.*

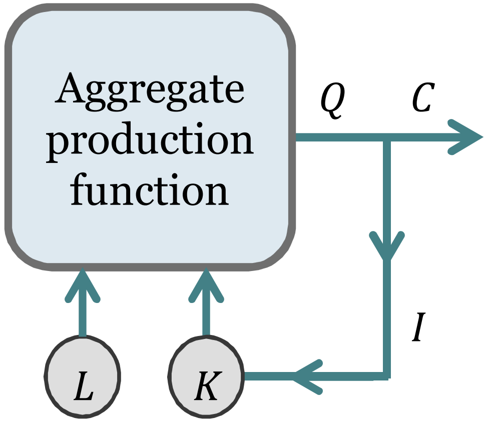
Cointegrating relationship (vector):

$$\beta_1 q - \beta_2 k - \lambda t - \mu = 0$$

$$q = \alpha_K \cdot k + \lambda' t + \mu'$$

$$\frac{Q}{L} = \underbrace{\exp(\mu')}_{\theta} \cdot \exp(\lambda' t) \cdot \left(\frac{K}{L}\right)^{\alpha_K}$$

$$Q = \theta \cdot \exp(\lambda' t) \cdot K^{\alpha_K} \cdot L^{1-\alpha_K}$$



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1) Cointegration between factor inputs and output;
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4) Output elasticities ≈ cost shares.

From cointegration to aggregate production functions

The simplest model:

$$(\boldsymbol{q}, \boldsymbol{k}, \boldsymbol{e})$$

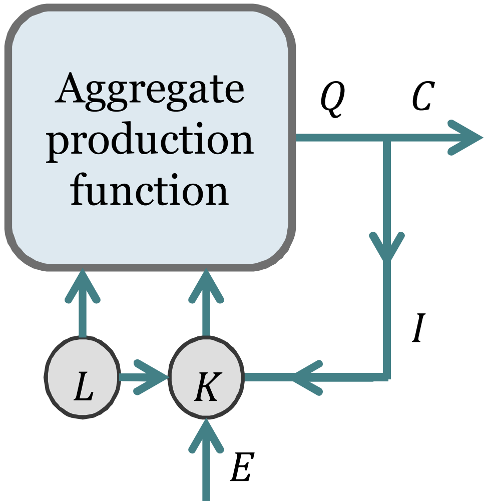
- ***Output, capital, and energy;***
- *No linear time trend;*
- ***At most two cointegration vectors*.**

Cointegrating relationship (vector):

$$\begin{cases} \beta_1 q - \beta_2 k - \mu_1 = 0 \\ \beta_3 k - \beta_4 e - \mu_2 = 0 \end{cases}$$

$$\begin{cases} \dfrac{Q}{L} = \exp(\mu_1') \cdot \left(\dfrac{K}{L}\right)^{\alpha_K} \\ \dfrac{K}{L} = \exp(\mu_2') \cdot \left(\dfrac{E}{L}\right)^{\tau} \end{cases}$$

$$\begin{cases} Q = \theta_1 \cdot K^{\alpha_K} \cdot L^{1-\alpha_K} \\ K = \theta_2 \cdot E^{\tau} \cdot L^{1-\tau} \end{cases}$$



Aggregate production function criteria

1) Cointegration between factor inputs and output;
2) Output elasticities must be positive and significant;
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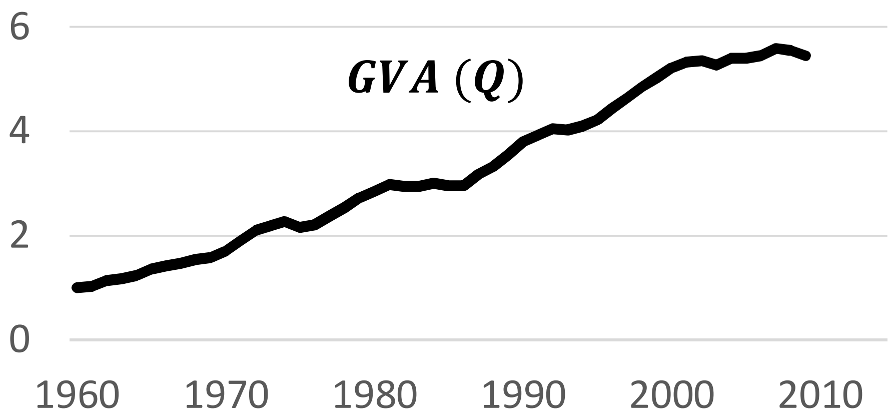
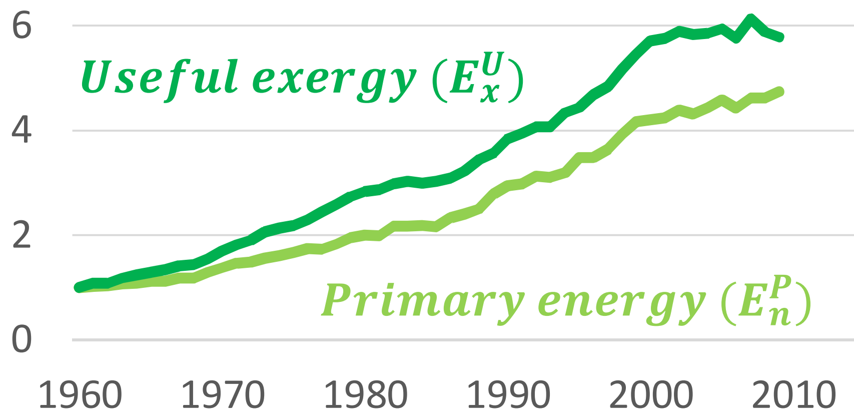
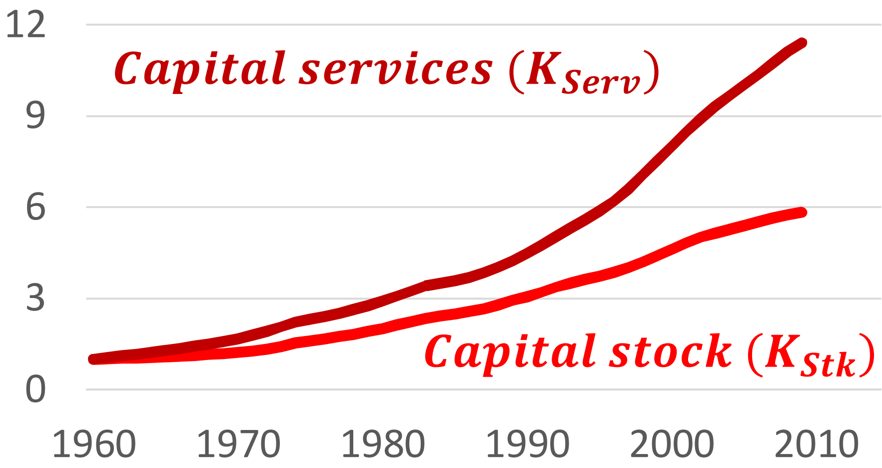
Cointegration: data for Portugal 1960-2009



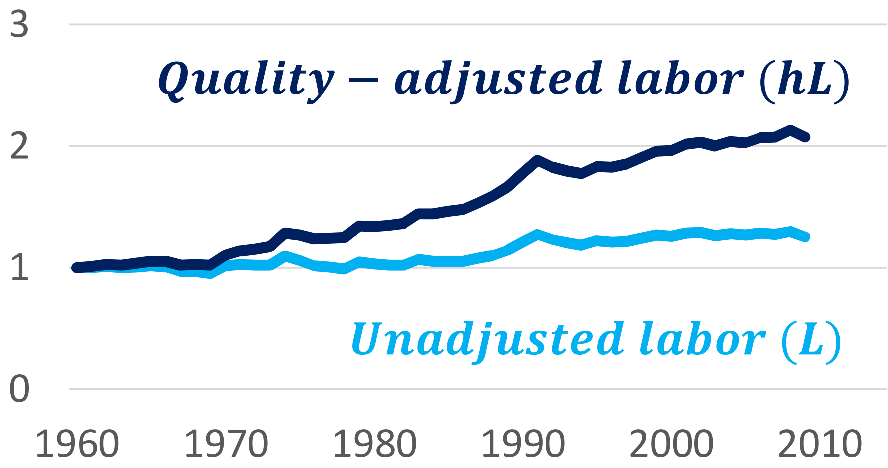
Sources: ***Pinheiro, M. (1997).*** *Séries Longas para a Economia Portuguesa, Pós-II Guerra Mundial, Vol. 1 – Séries Estatísticas, Lisbon, Banco de Portugal.*



Sources: ***Serrenho, A. C., Warr, B., Sousa, T., Ayres, R. U., & Domingos, T. (2016).*** *Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. Structural Change and Economic Dynamics, 36, 1-21.*



Sources: *AMECO /* ***da Silva, E. G. & Lains, P. (2014).*** *Capital formation and long-run growth: Evidence from Portuguese data, 1910-2011 (http://estructuraehistoria.unizar.es/personal/vpinilla/prog.htm)*



Sources: *Penn World Tables 8.1 /* ***Amaral, L. (2009).*** *New Series for GDP per capita, per worker, and per worker-hour in Portugal, 1950-2007 (No. wp540). Universidade Nova de Lisboa, Faculdade de Economia.*

Cointegration: results and interpretation

Model	Cointegrating relationships found	
$(Q, K^{AMECO}_{Stock}, L)$	$Q \propto e^{0.02t} \cdot K^{-0.06} \cdot L^{1.06}$	Implausible K elasticity
$(Q, K^{S\&L}_{Services}, L)$	———	No cointegration.
$(Q, K^{AMECO}_{Stock}, hL)$	$Q \propto e^{0.02t} \cdot K^{-0.58} \cdot L^{1.58}$	Implausible K elasticity
$(Q, K^{S\&L}_{Services}, hL)$	———	No cointegration.
(Q, E^{P}_{n}, L)	———	No cointegration.
(Q, E^{U}_{x}, L)	———	No cointegration.
(Q, E^{P}_{n}, hL)	———	No cointegration.
(Q, E^{U}_{x}, hL)	———	No cointegration.

Cointegration: results and interpretation

Model	Cointegrating relationships found	
$\left(Q, K_{Stock}^{AMECO}, E_n^P, L\right)$	$Q \propto e^{0.001t} \cdot K^{0.14} \cdot E^{0.64} \cdot L^{0.22}$	Elasticities not significant
$\left(Q, K_{Services}^{S\&L}, E_n^P, L\right)$	$Q \propto e^{-0.02t} \cdot K^{0.40} \cdot E^{0.75} \cdot L^{-0.15}$	Implausible L elasticity
$\left(Q, K_{Stock}^{AMECO}, E_x^U, L\right)$	———	No cointegration.
$\left(Q, K_{Services}^{S\&L}, E_x^U, L\right)$	———	No cointegration.
$\left(Q, K_{Stock}^{AMECO}, E_n^P, hL\right)$	$Q \propto e^{-0.001t} \cdot K^{-0.12} \cdot E^{0.88} \cdot L^{0.25}$	Implausible K elasticity
$\left(Q, K_{Services}^{S\&L}, E_n^P, hL\right)$	$Q \propto e^{-0.01t} \cdot K^{0.98} \cdot E^{-0.71} \cdot L^{0.72}$	Implausible E elasticity
$\left(Q, K_{Stock}^{AMECO}, E_x^U, hL\right)$	$Q \propto e^{0.002t} \cdot K^{-0.58} \cdot E^{1.52} \cdot L^{0.06}$	Implausible K, E elasticities
$\left(Q, K_{Services}^{S\&L}, E_x^U, hL\right)$	———	No cointegration.

Cointegration: results and interpretation

Model	Cointegrating relationships found	
$(Q, K_{Stock}^{AMECO}, L)$	$Q \propto K^{0.60} \cdot L^{0.40}$	Implausible cost shares
$(Q, K_{Services}^{S\&L}, L)$	———	No cointegration.
$(Q, K_{Stock}^{AMECO}, hL)$	$Q \propto K^{0.45} \cdot L^{0.55}$	Implausible cost shares
$(Q, K_{Services}^{S\&L}, hL)$	$Q \propto K^{-0.34} \cdot L^{1.34}$	Implausible K elasticity
(Q, E_n^P, L)	$Q \propto E^{0.82} \cdot L^{0.18}$	
(Q, E_x^U, L)	$Q \propto E^{0.84} \cdot L^{0.16}$	
(Q, E_n^P, hL)	$Q \propto E^{0.78} \cdot L^{0.22}$	
(Q, E_x^U, hL)	$Q \propto E^{0.78} \cdot L^{0.22}$	

Cointegration: results and interpretation

Model	Cointegrating relationships found	
$(Q, K_{Stock}^{AMECO}, E_n^P, L)$	$Q \propto K^{0.57} \cdot E^{0.16} \cdot L^{0.27}$	Implausible cost shares
$(Q, K_{Services}^{S\&L}, E_n^P, L)$	$Q \propto K^{0.85} \cdot E^{-0.67} \cdot L^{0.82}$	Implausible E elasticity
$(Q, K_{Stock}^{AMECO}, E_x^U, L)$	$\begin{cases} Q \propto K^{0.64} \cdot L^{0.36} \\ K \propto E^{1.31} \cdot L^{-0.31} \end{cases}$	Implausible K, L elasticities
$(Q, K_{Services}^{S\&L}, E_x^U, L)$	$\begin{cases} Q \propto K^{0.37} \cdot L^{0.63} \\ K \propto E^{2.34} \cdot L^{-1.34} \end{cases}$	
$(Q, K_{Stock}^{AMECO}, E_n^P, hL)$	$Q \propto K^{-0.15} \cdot E^{0.86} \cdot L^{0.29}$	Implausible K elasticity
$(Q, K_{Services}^{S\&L}, E_n^P, hL)$	$Q \propto K^{1.18} \cdot E^{-2.07} \cdot L^{1.89}$	Implausible K, L, E elasticities
$(Q, K_{Stock}^{AMECO}, E_x^U, hL)$	$Q \propto K^{-0.52} \cdot E^{1.57} \cdot L^{-0.04}$	Implausible K, L elasticities
$(Q, K_{Services}^{S\&L}, E_x^U, hL)$	$\begin{cases} Q \propto K^{0.31} \cdot L^{0.69} \\ K \propto E^{3.11} \cdot L^{-2.11} \end{cases}$	

Cointegration: results and interpretation

For the "best" model:

Capital-labor plausible APF:

$$Q = e^{-9.651} \cdot K^{0.31} \cdot L^{0.69}$$

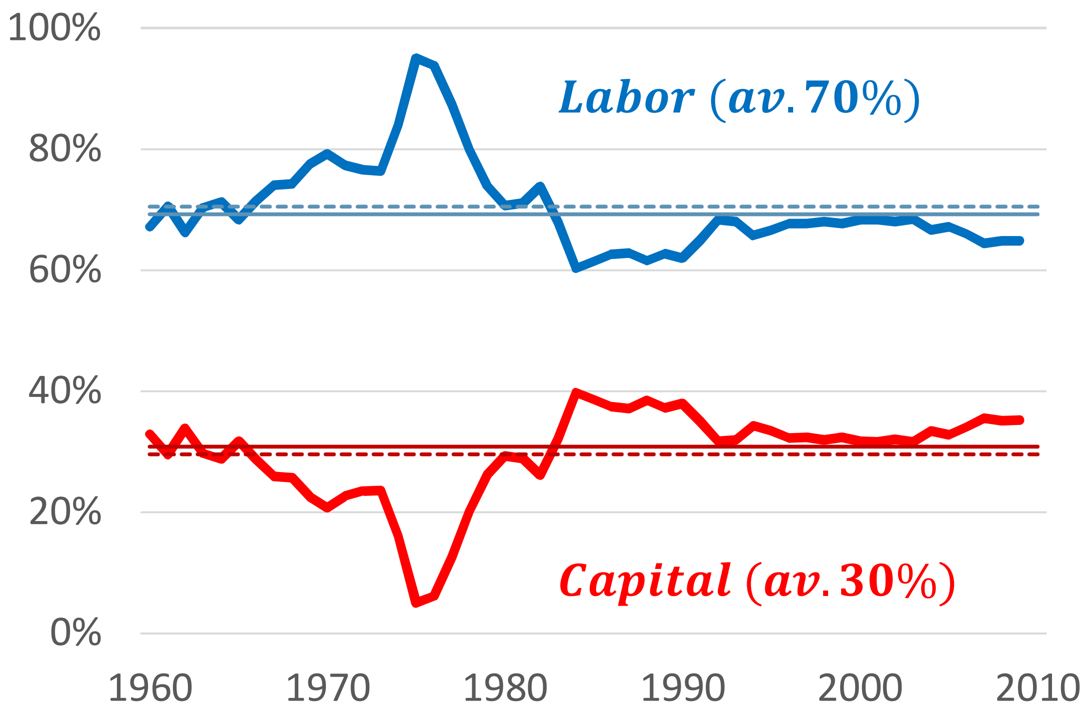
Estimated output elasticities compared with average historical cost shares for capital and labor.

For capital:

$$\hat{\alpha}_K \cong 31\%$$

For labor:

$$\hat{\alpha}_L \cong 69\%$$



Estimated output elasticities for capital and labor are remarkably similar to average historical cost shares for these factors of production.

The neoclassical cost share theorem is compatible with this model.

Cointegration: conclusions

- No economically plausible APFs are identified for models including a linear time trend;
- Unidirectional Granger causality running from energy inputs to economic output supports the *growth hypothesis*;
- The only model satisfying all APF criteria is one with:
  - a) no linear time trend;
  - b) capital, labor, and energy inputs;
  - c) quality-adjusted factors of production (capital services; human capital ajusted labor; useful exergy);
  - d) at most two cointegrating relationships among output and input variables.
- For this model:
  - The first cointegrating relationship is normalized to output – capital-labor APF:
  - The second cointegrating relationship – normalized to capital – expresses the real utilization of capital in production, as a function of labor and especially useful exergy:

$$K(E,L) = e^{7.69} \cdot E^{3.11} \cdot L^{-2.11}$$

Cointegration: conclusions (cont'd)

- Adoption of a useful exergy metric to account for energy use provides important insights to the relationships between energy use, macroeconomic factors of production, and economic output;
- A central role for useful exergy on economic production and growth is not incompatible with the neoclassical assumptions of the cost-share theorem;

***Santos, J.**, Domingos, T., Sousa, T., St Aubyn, M. (accepted). Useful exergy is key in obtaining plausible aggregate production functions and recognizing the role of energy in economic growth: Portugal 1960-2009. Ecological Economics.*

Cointegration: future work

- Expand the analysis to other countries, and/or groups of countries;
- Open up to alternative (more complex) APF formulations within the VAR cointegration framework;
- Consider additional variables to include in the cointegration space;
- Test for normalizing and over-identifying restrictions to the cointegration space.

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João Santos
joao.dos.santos@tecnico.ulisboa.pt
Ph.D. student in Sustainable Energy Systems
MIT Portugal doctoral program