



TÉCNICO
LISBOA

IV Workshop SHAI0

*Albacete, Spain
25 September 2014*

Is There a Minimum Energy Requirement for Economic Growth?

*Tiago Domingos**

with

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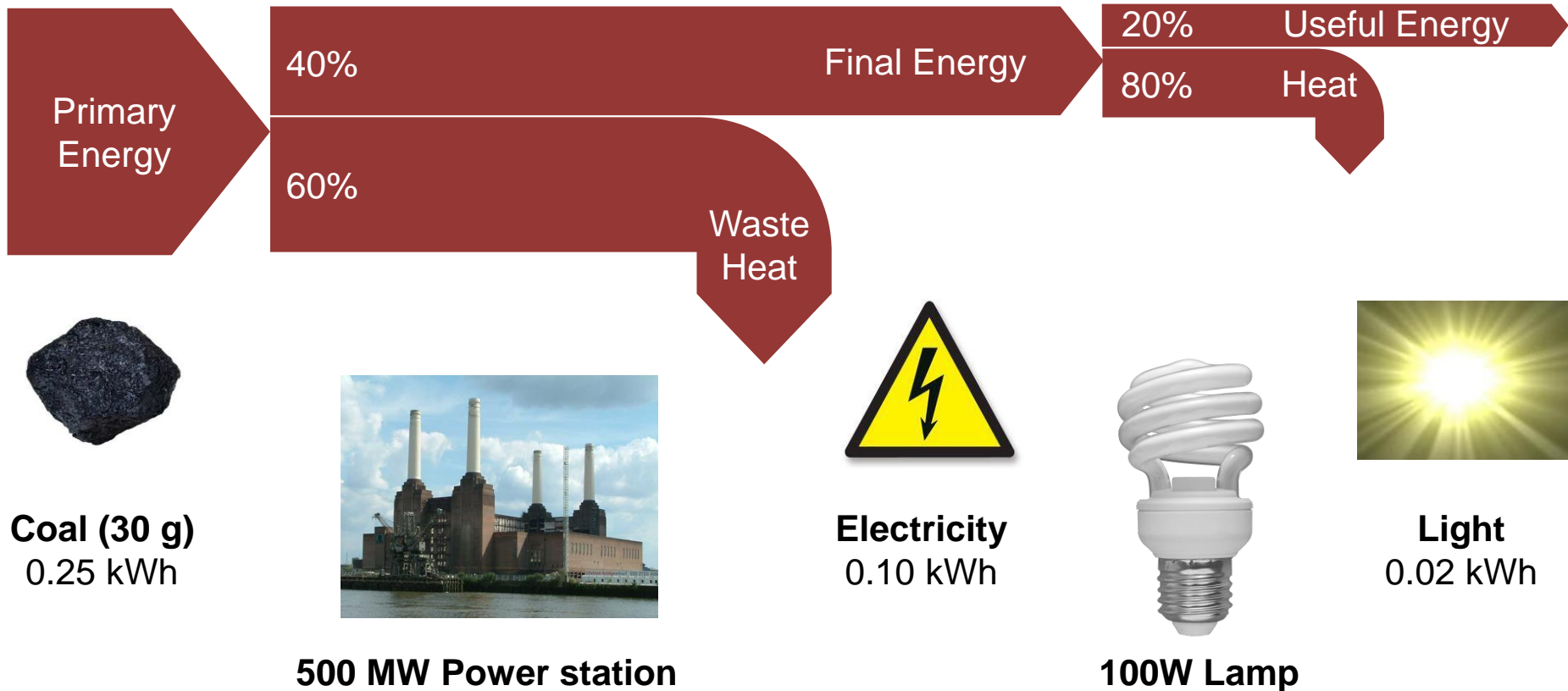
Robert U. Ayres

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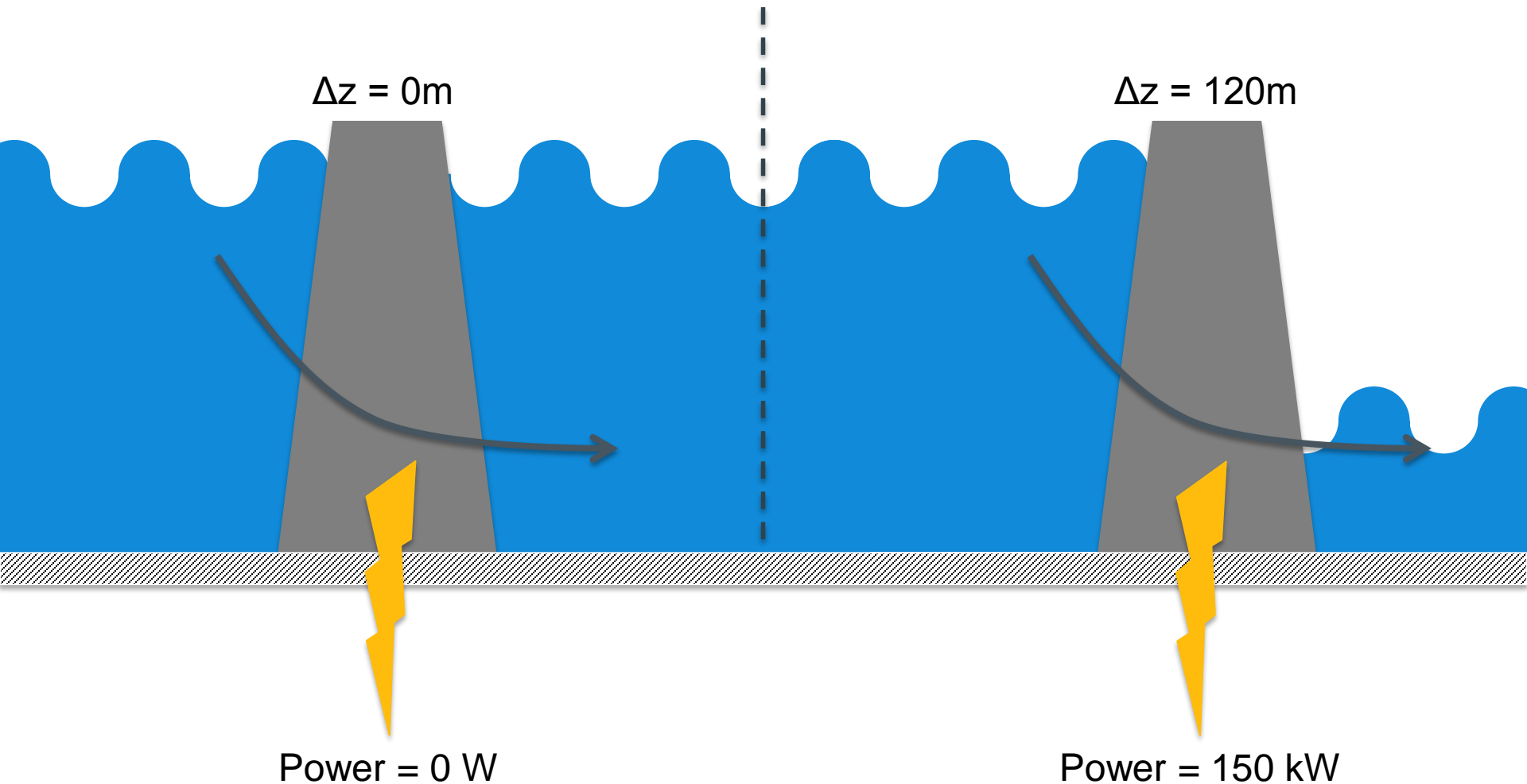
Reducing carbon emissions requires acting on the three components in this equation

$$\text{CO}_2 = \frac{\text{CO}_2}{\text{Energy}} \cdot \frac{\text{Energy}}{\text{GDP}} \cdot \text{GDP}$$

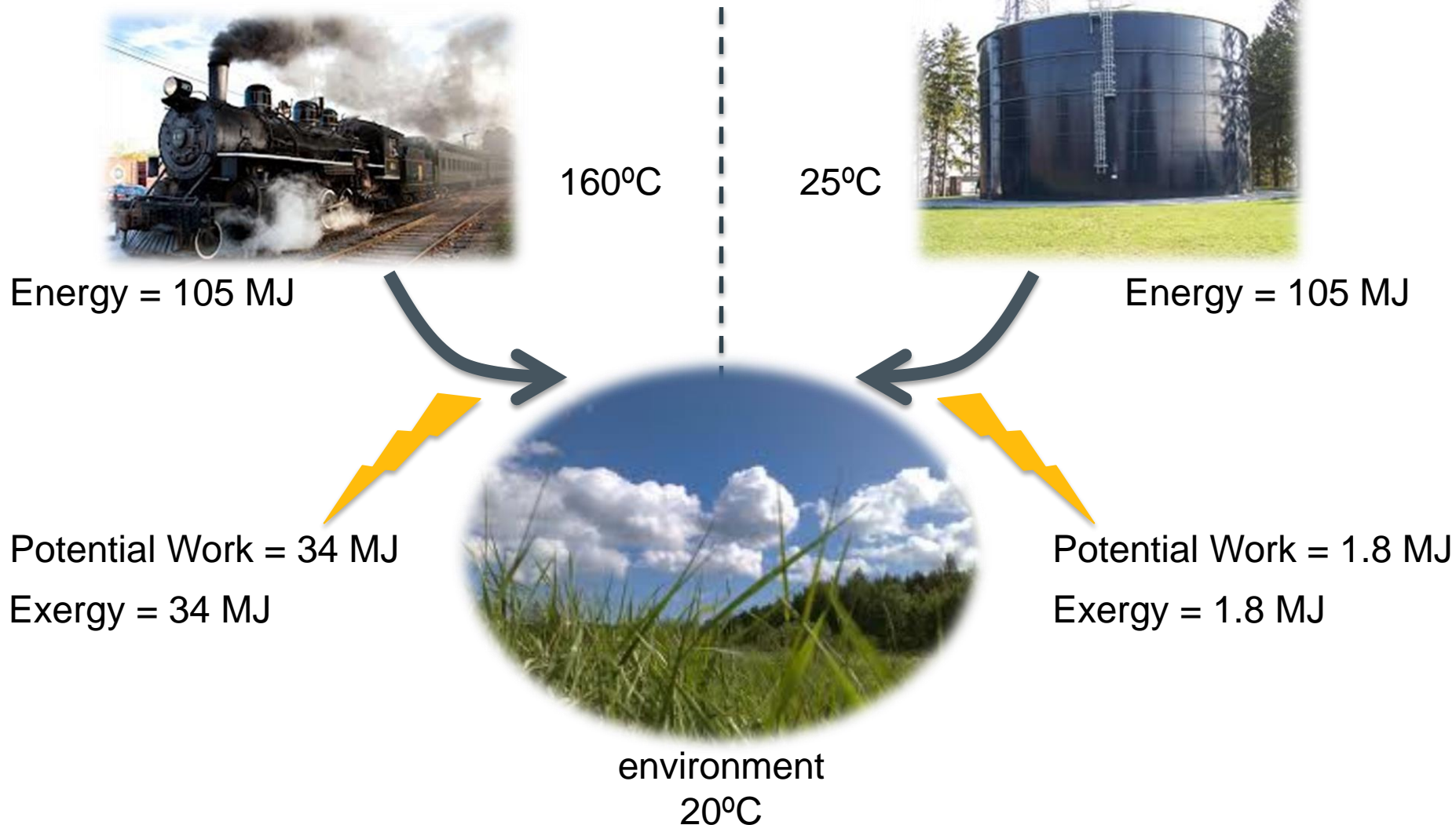
Here we will focus on the Energy/GDP ratio



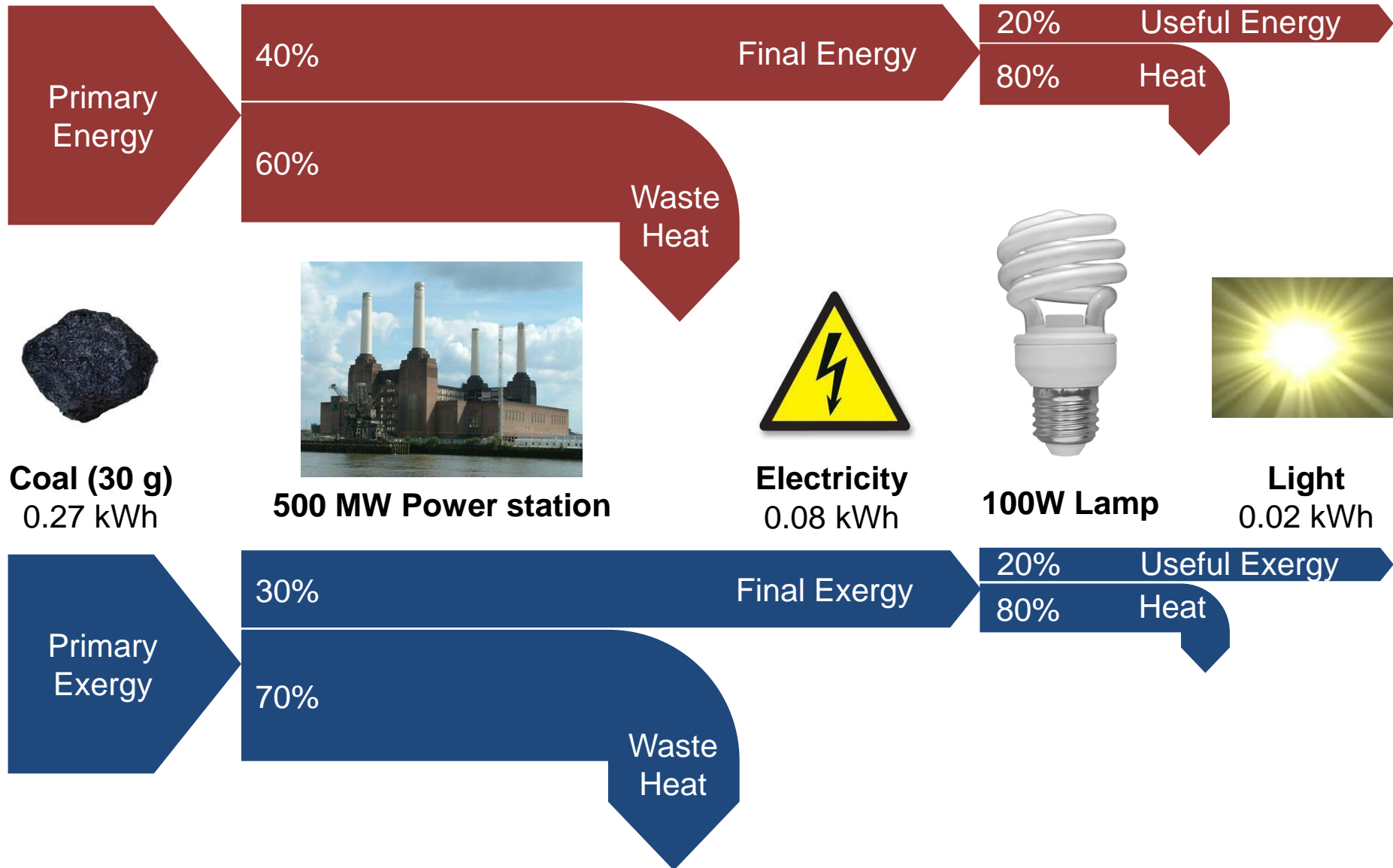
- What is exergy?



- Energy vs. Exergy

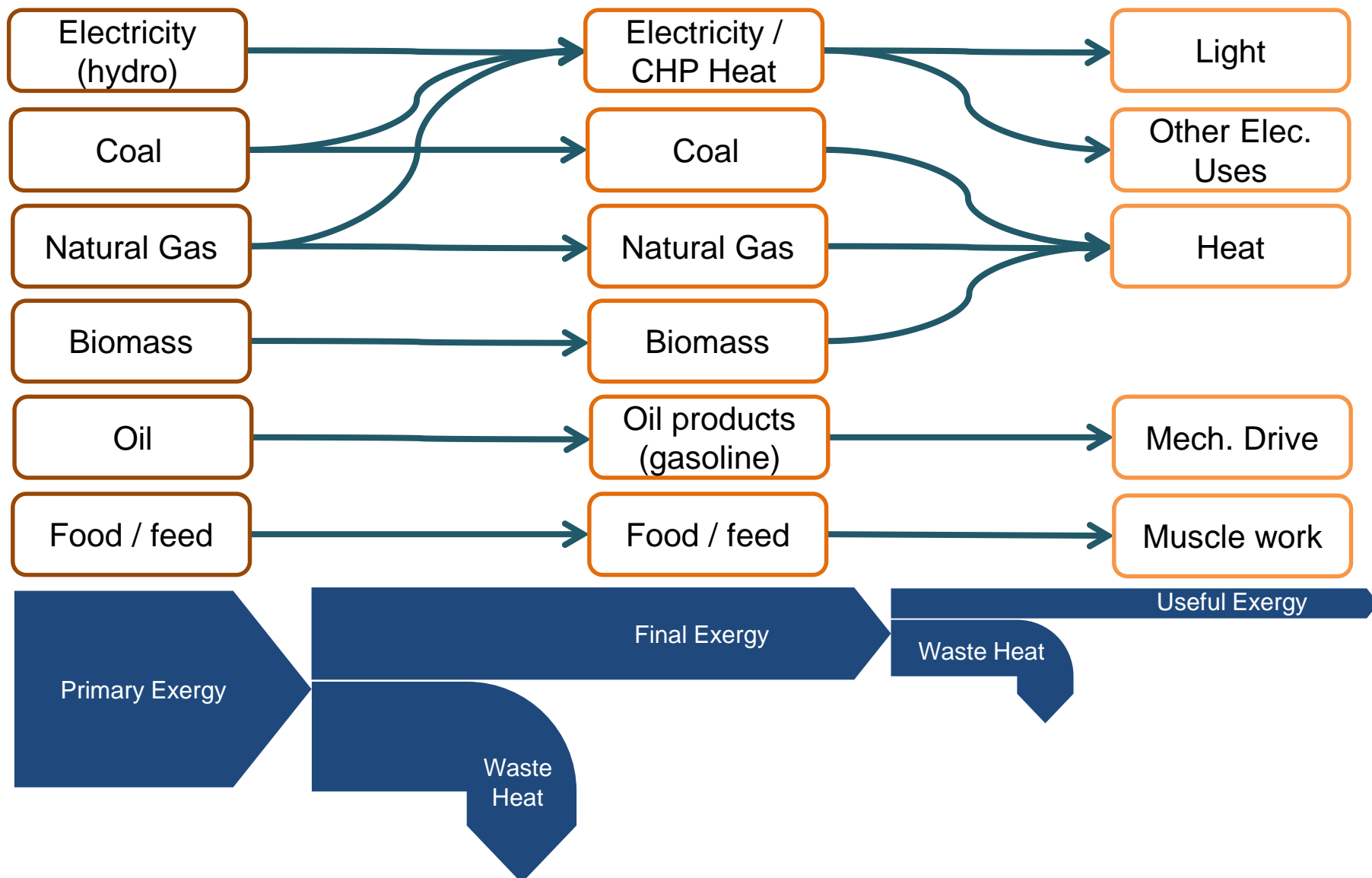


Primary, Final and Useful Exergy

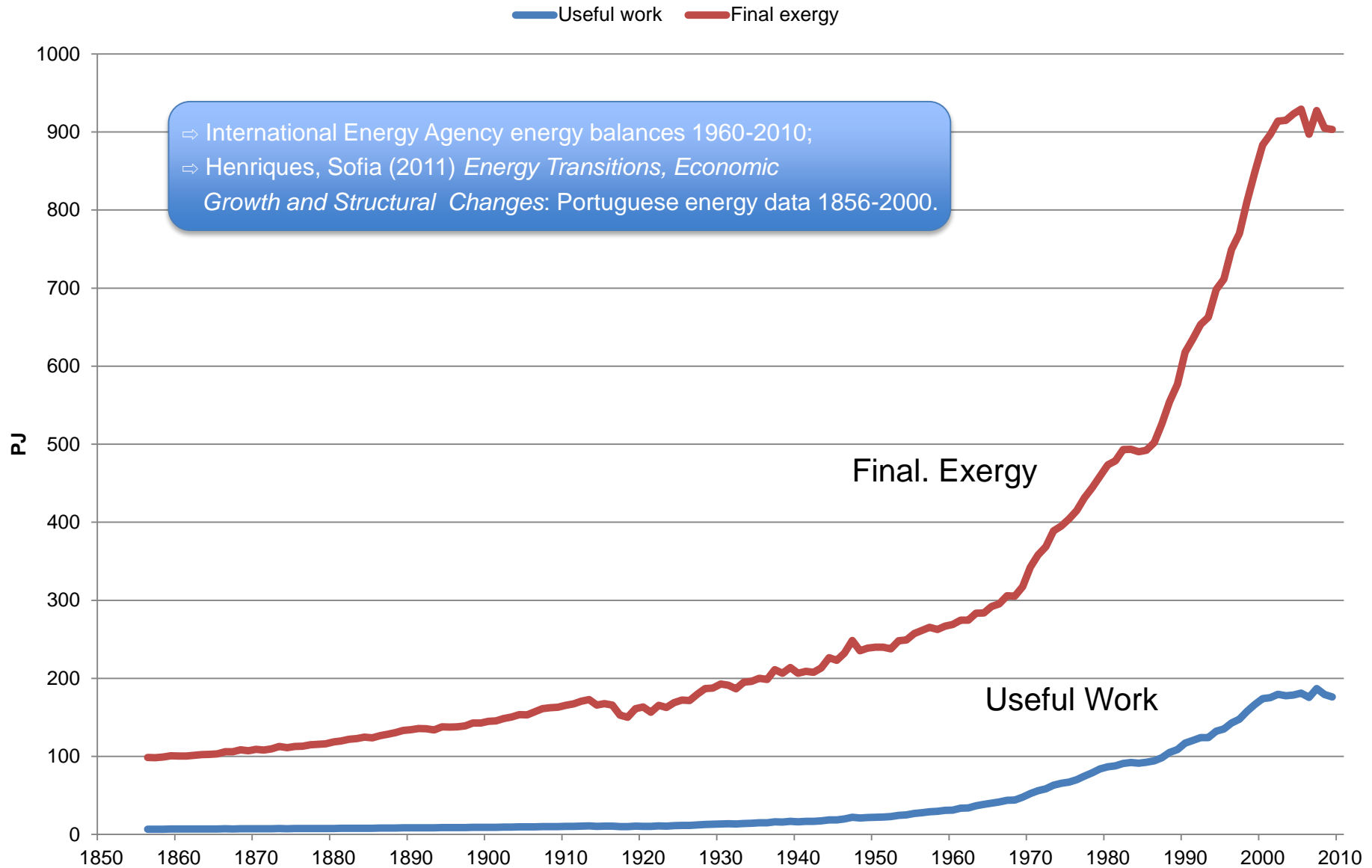


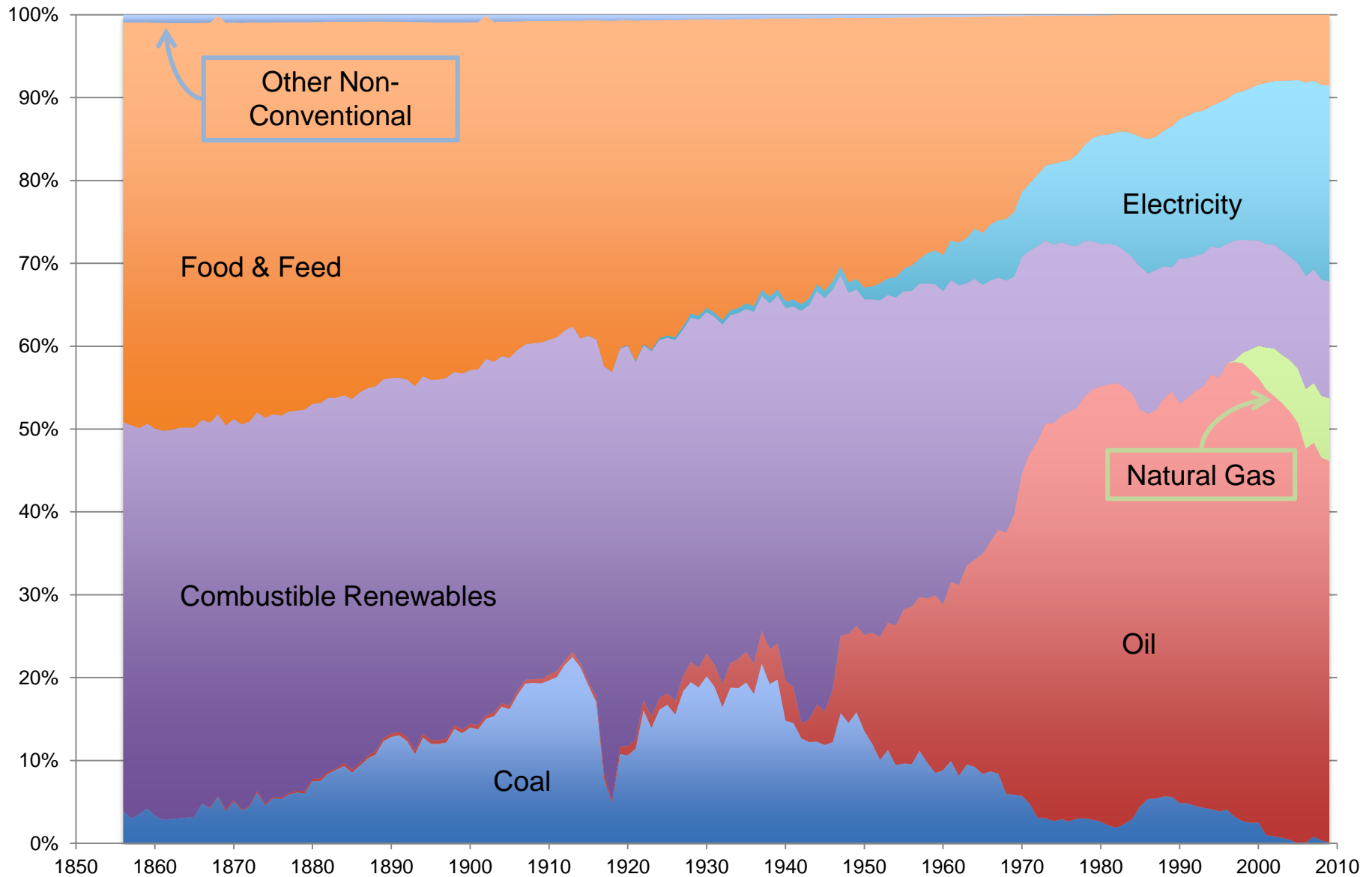
Exergy sources

End-uses

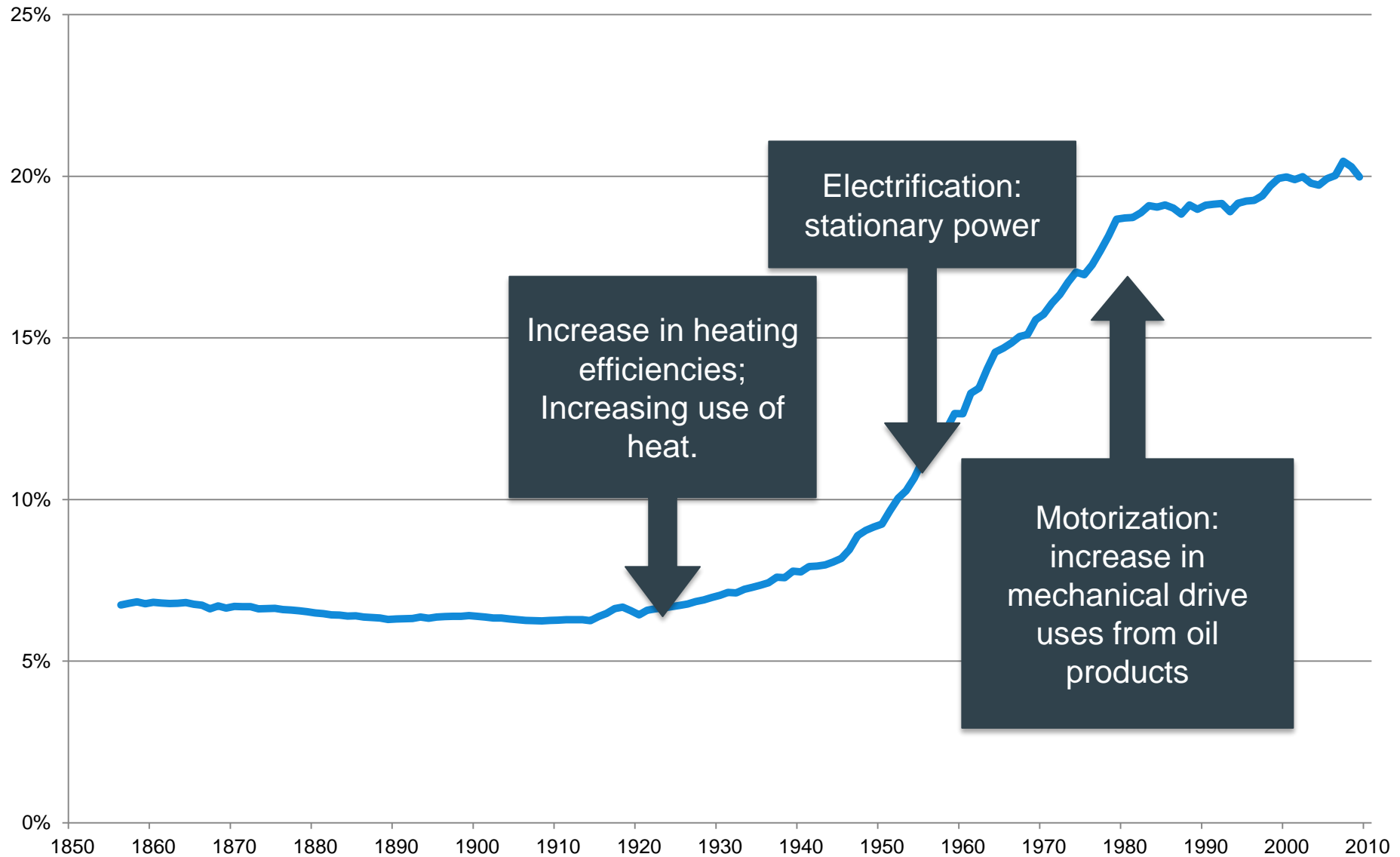


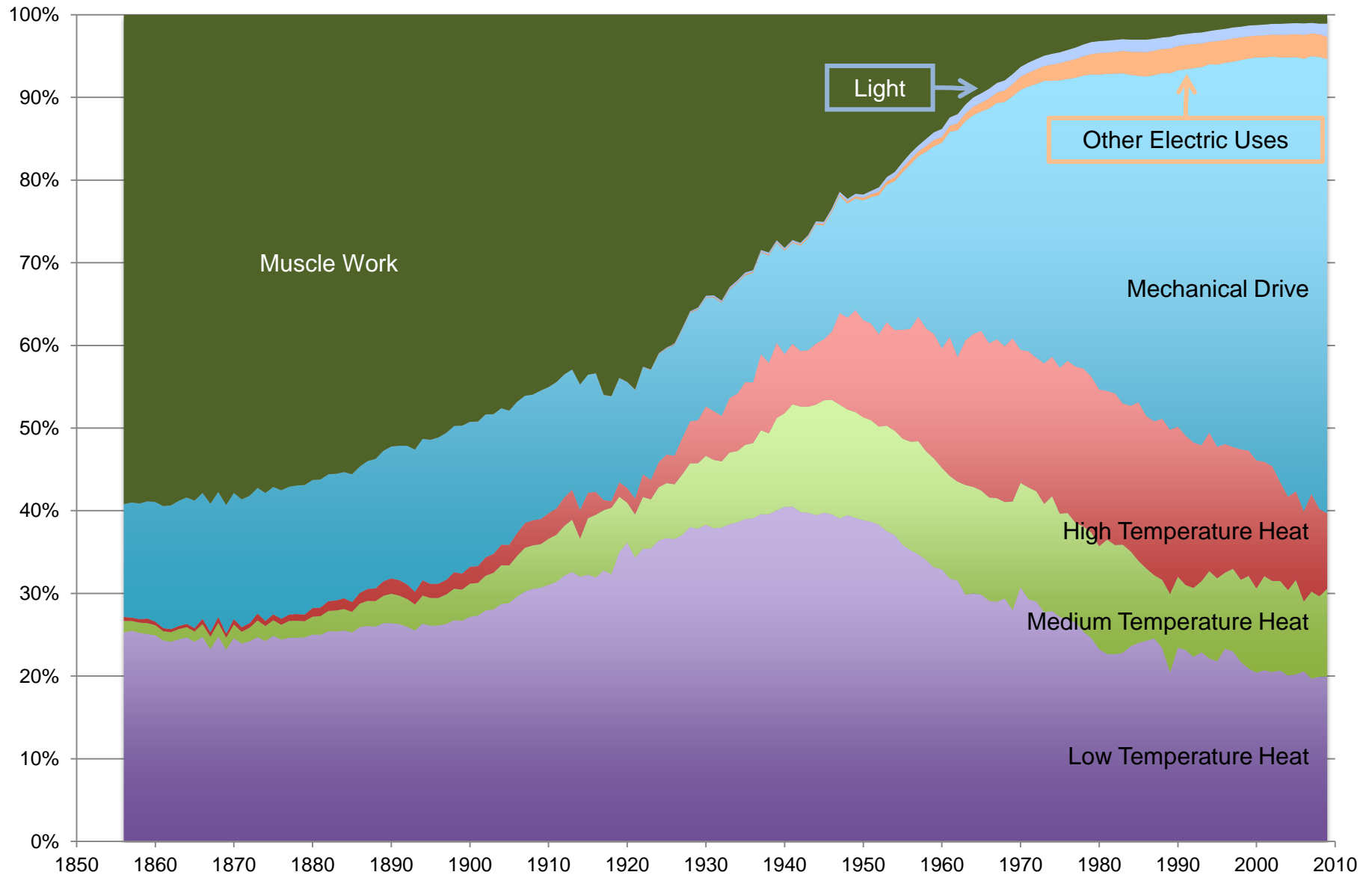
Final Exergy and Useful Work



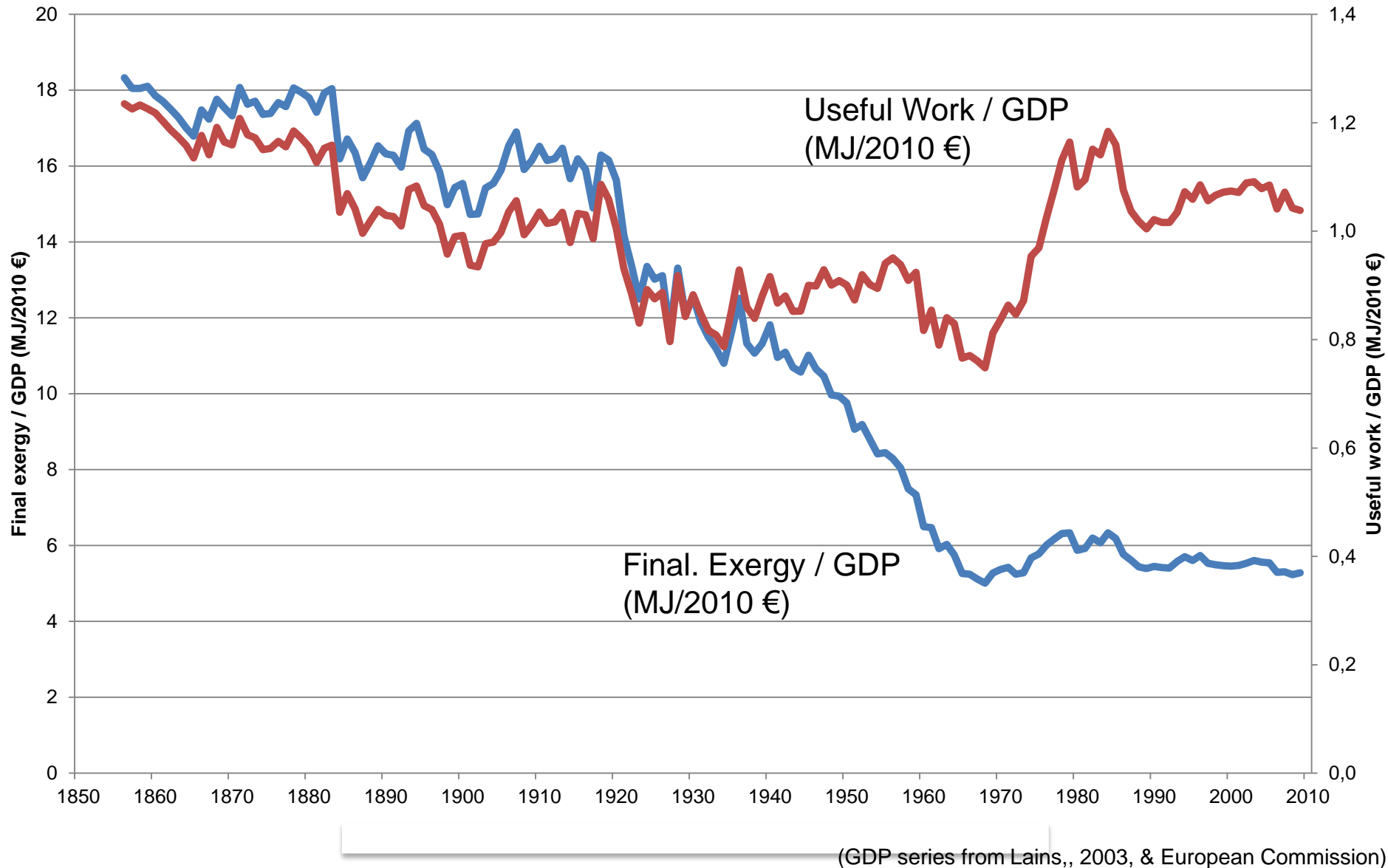


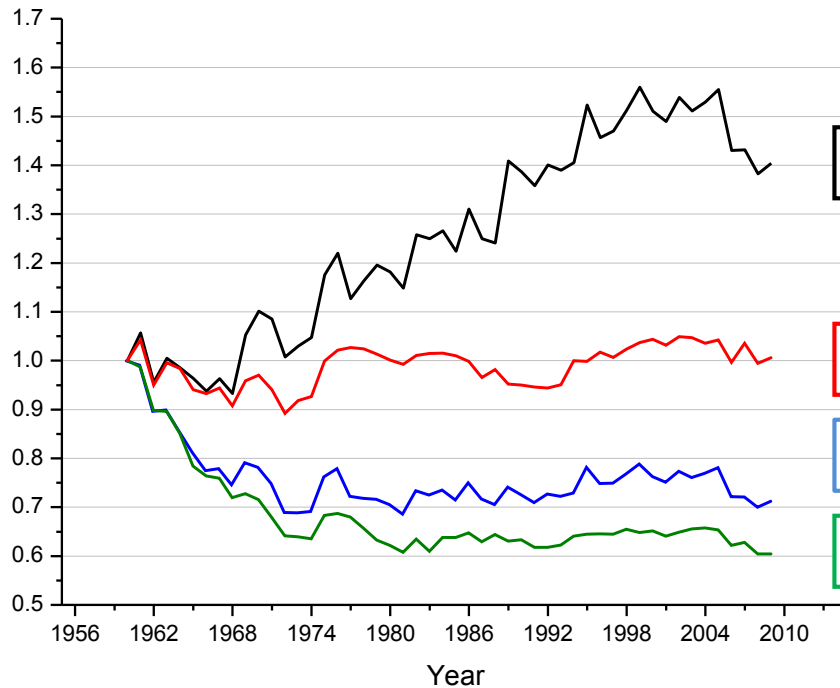
Aggregate Final-to-Useful Efficiency





Final Exergy and Useful Work Intensities





Primary energy consumption (IEA) / GDP

Useful work (IEA + food/feed & other) / GDP

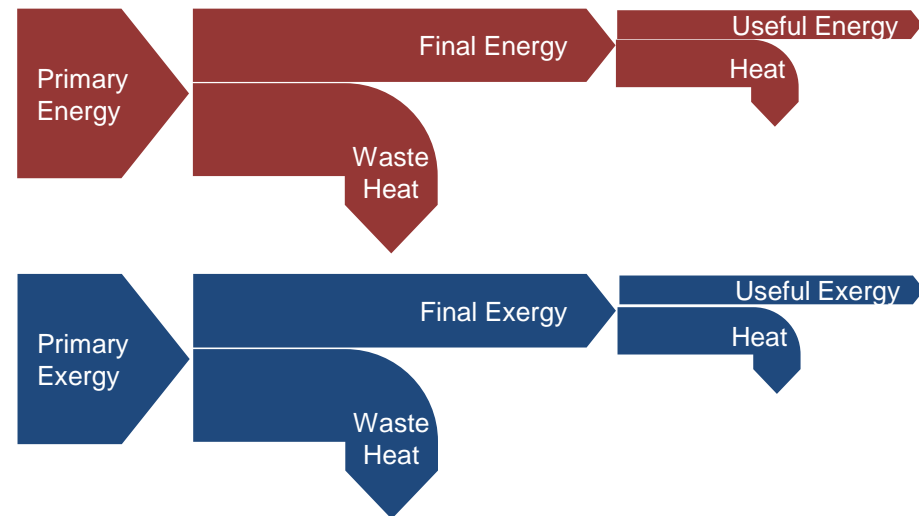
Primary exergy (IEA + food/feed & other) / GDP

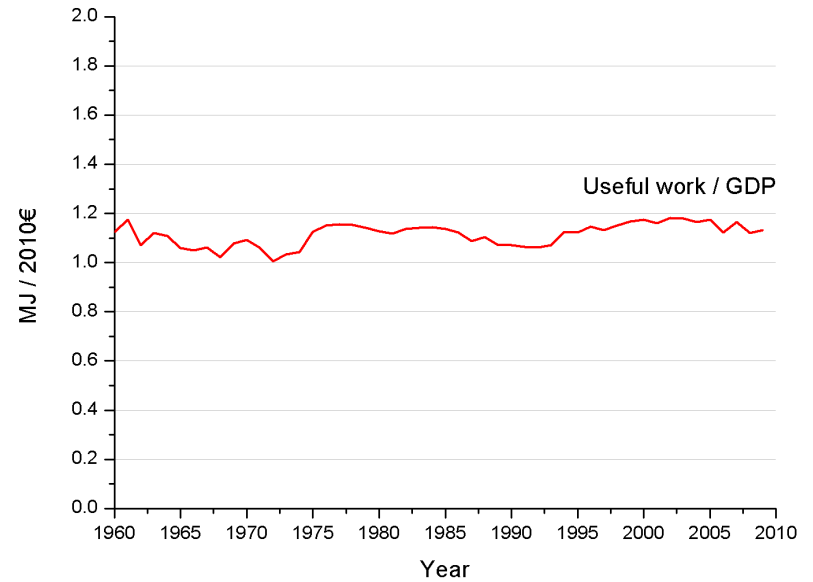
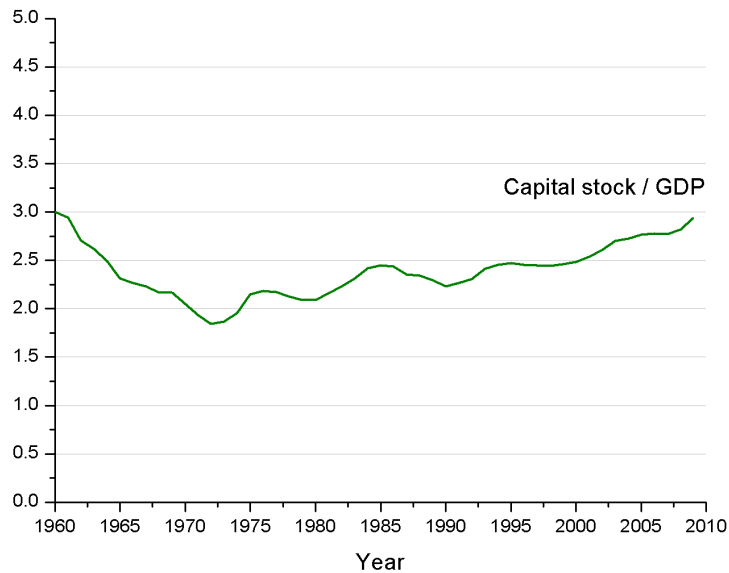
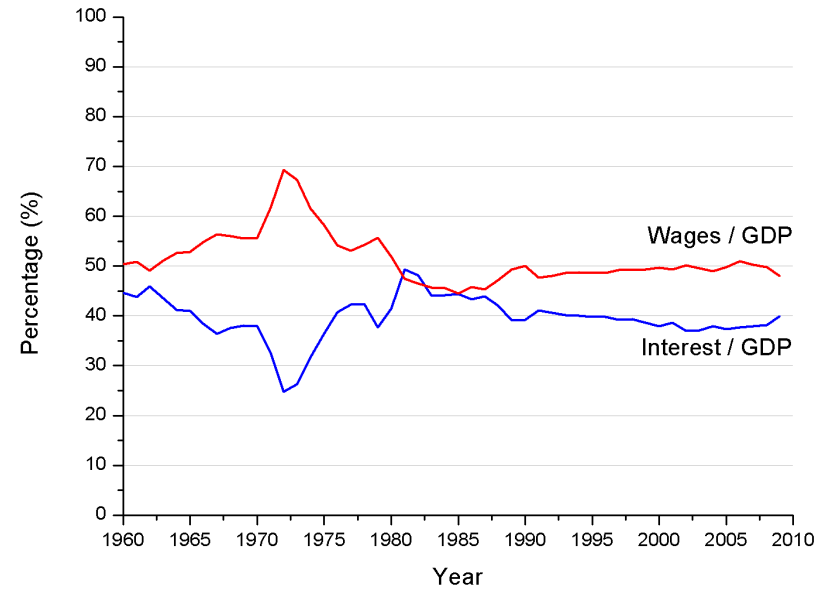
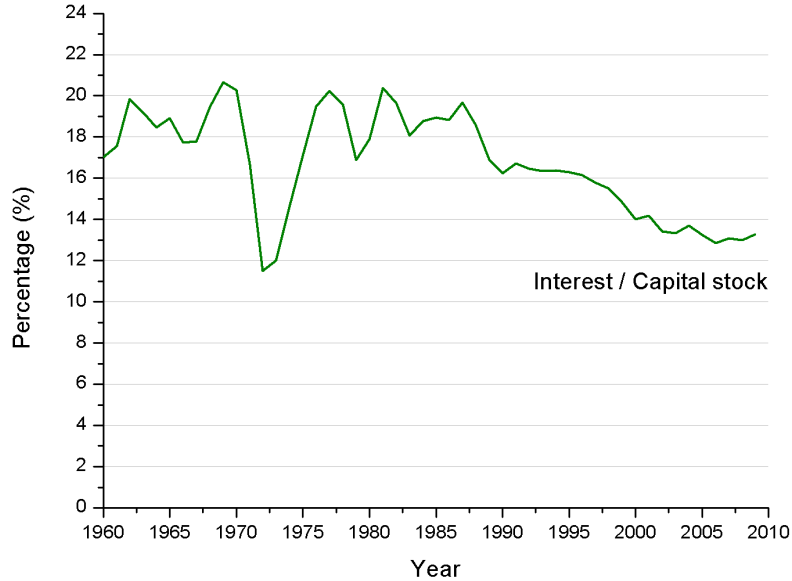
Final exergy (IEA + food/feed & other) / GDP

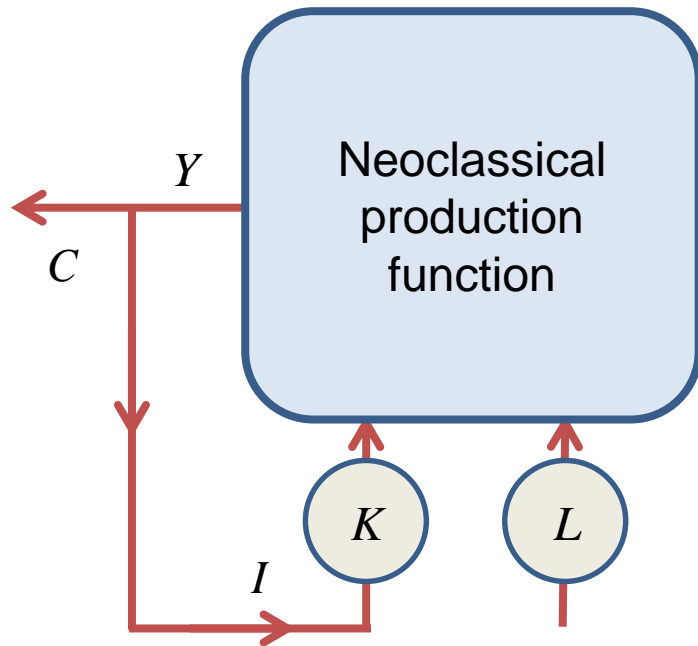
IEA: Coal
Oil
Natural gas
Biomass
Electricity
CHP Heat

Food/feed: Food & feed for humans and animals

Other: Non-conventional sources (wind, tidal)







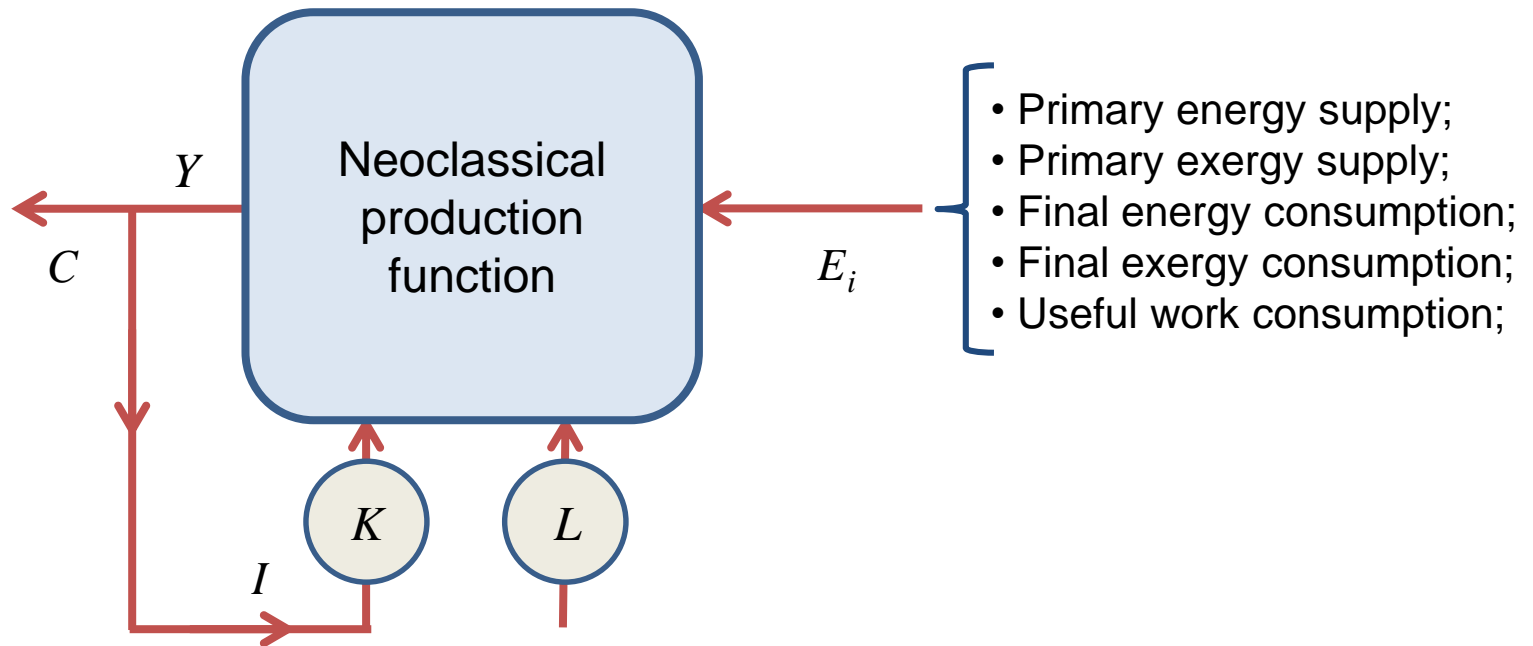
Average growth rates 1960-2009.

- ⇒ European Commission's annual macroeconomic database (AMECO).
- ⇒ Groningen Growth and Development Database (GGDC).
- ⇒ Luciano Amaral (2009). New Series for GDP per capita, per worker, and per worker hour in Portugal, 1950-2007.

$$\frac{\Delta GDP}{GDP} = \frac{\text{interest}}{GDP} \frac{\Delta K}{K} + \frac{\text{wages}}{GDP} \frac{\Delta L}{L} + \underbrace{\text{Residual}}$$

$$3.6\% = 0.27 \times 3.5\% + 0.64 \times 0.5\% + 2.3\%$$

(65 % of economic growth)



How much of the Solow residual can be explained by introducing an additional energy consumption variable in the Solow model?

$$\frac{\Delta GDP}{GDP} = \frac{\text{interest}}{GDP} \frac{\Delta K}{K} + \frac{\text{wages}}{GDP} \frac{\Delta L}{L} + \underbrace{\text{Residual}}_{\alpha_i \frac{\Delta E_i}{E_i} + \text{Reduced residual}}$$

E_i

$$\text{Residual} = \alpha_i \frac{\Delta E_i}{E_i} + \text{Reduced residual}$$

Primary Energy

$$2.3\% = 0.15 \times 2.9\% + 1.9\%$$

Primary Exergy

(53 % of economic growth)

Final Energy

$$2.3\% = 0.43 \times 2.5\% + 1.2\%$$

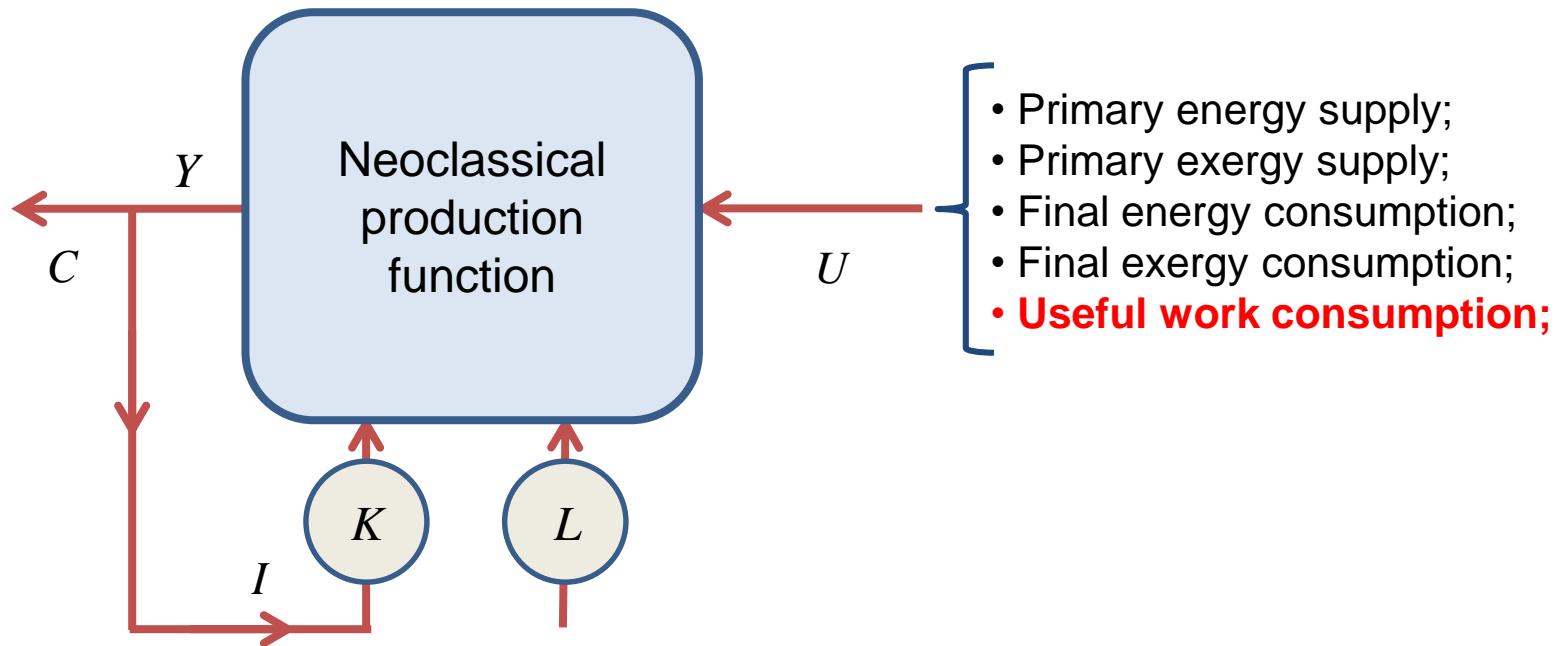
Final Exergy

(34 % of economic growth)

Useful Work

$$2.3\% = 0.49 \times 3.6\% + 0.6\%$$

(16 % of economic growth)



$$\frac{\Delta GDP}{GDP} = \frac{\text{interest}}{GDP} \frac{\Delta K}{K} + \frac{\text{wages}}{GDP} \frac{\Delta L}{L} + \alpha_U \frac{\Delta U}{U} + \underbrace{\text{Residual;}}$$

$$3.6\% = 0.27 \times 3.5\% + 0.64 \times 0.5\% + 0.49 \times 3.6\% + \mathbf{0.6\%}$$

(16 % of growth)

- Useful work intensity in Portugal has varied only about
 - 20% since 1856
 - 7% since 1960; a lower variation than for any of the Kaldor “facts”
- Evidence that useful work and capital are complements
- Evidence that useful work is underpaid and capital and labour are overpaid

- Decoupling requires the increase in multiple efficiencies:

$$\text{CO}_2 = \frac{\text{CO}_2}{\text{Primary Exergy}} \cdot \frac{\text{Primary Exergy}}{\text{Final Exergy}} \cdot \frac{\text{Final Exergy}}{\text{Useful Exergy}} \cdot \frac{\text{Useful Exergy}}{\text{GDP}} \cdot \text{GDP}$$

but ...

- there are strict thermodynamic limits to primary-to-final and final-to-useful efficiencies ,
- so the continued constancy of useful work / GDP will imply clear limits to decoupling.



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