Energy and Economic Growth

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GDP and production factors: Portugal 1960-2009
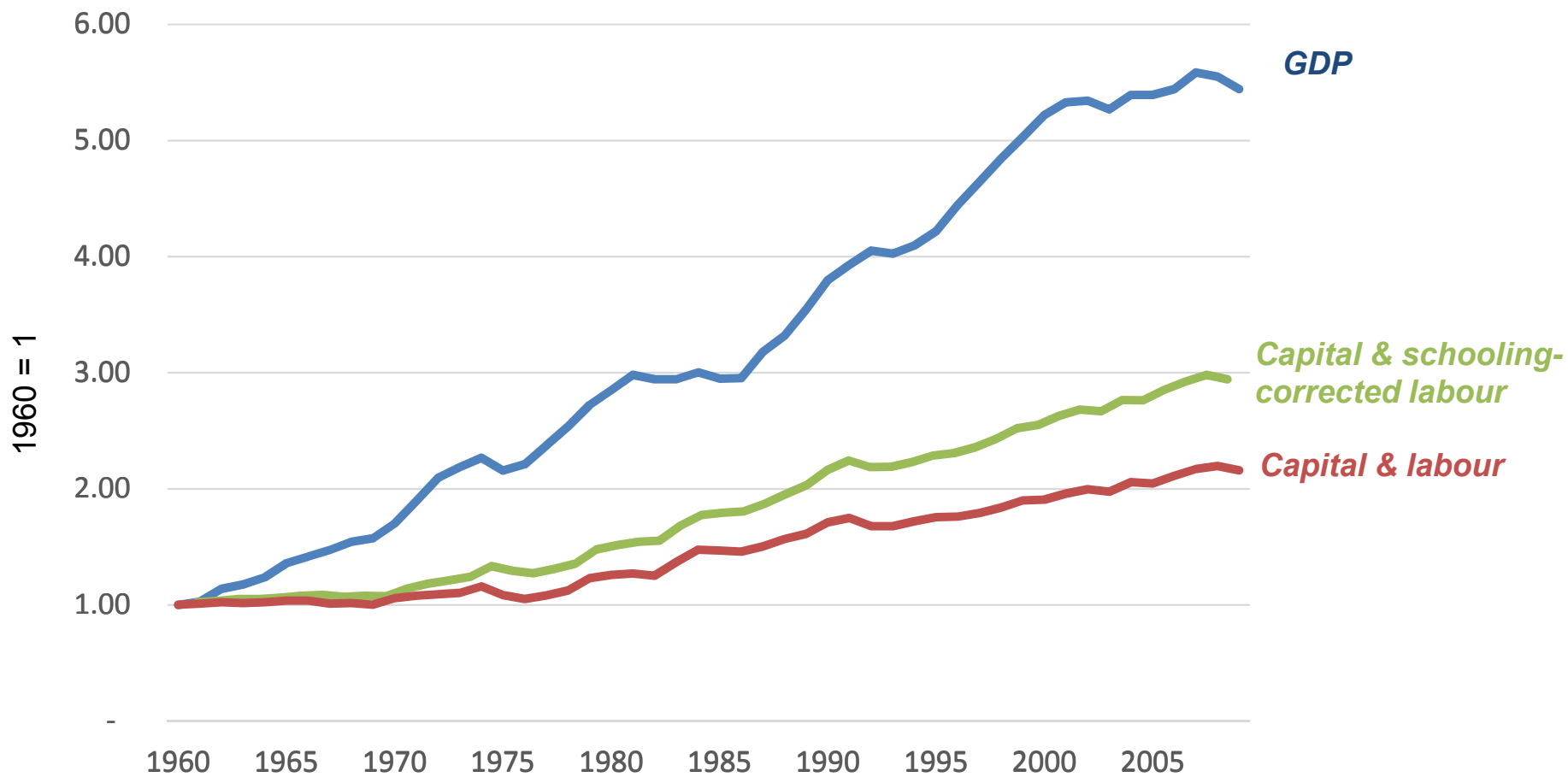
The main source of economic growth is essentially unknown

- Economic growth cannot be explained just by the increase in production factors: capital and labour

- Most of economic growth is explained by total factor productivity growth, the Solow residual

- As Abramovitz (1956) said, the Solow residual represents "a measure of our ignorance" of the growth process

- Could energy be an explanatory factor for the Solow residual?

- Let us measure energy considering *useful exergy*

The Laws of Thermodynamics

- First law: in any physical process, energy is conserved.

  - "In nature nothing is created, nothing is lost, everything changes" (Lavoisier).

- Second law: in any physical process, entropy increases.

  - Entropy is not conserved

  - In any physical process, energy is dissipated, i.e., loses its capacity to produce work.
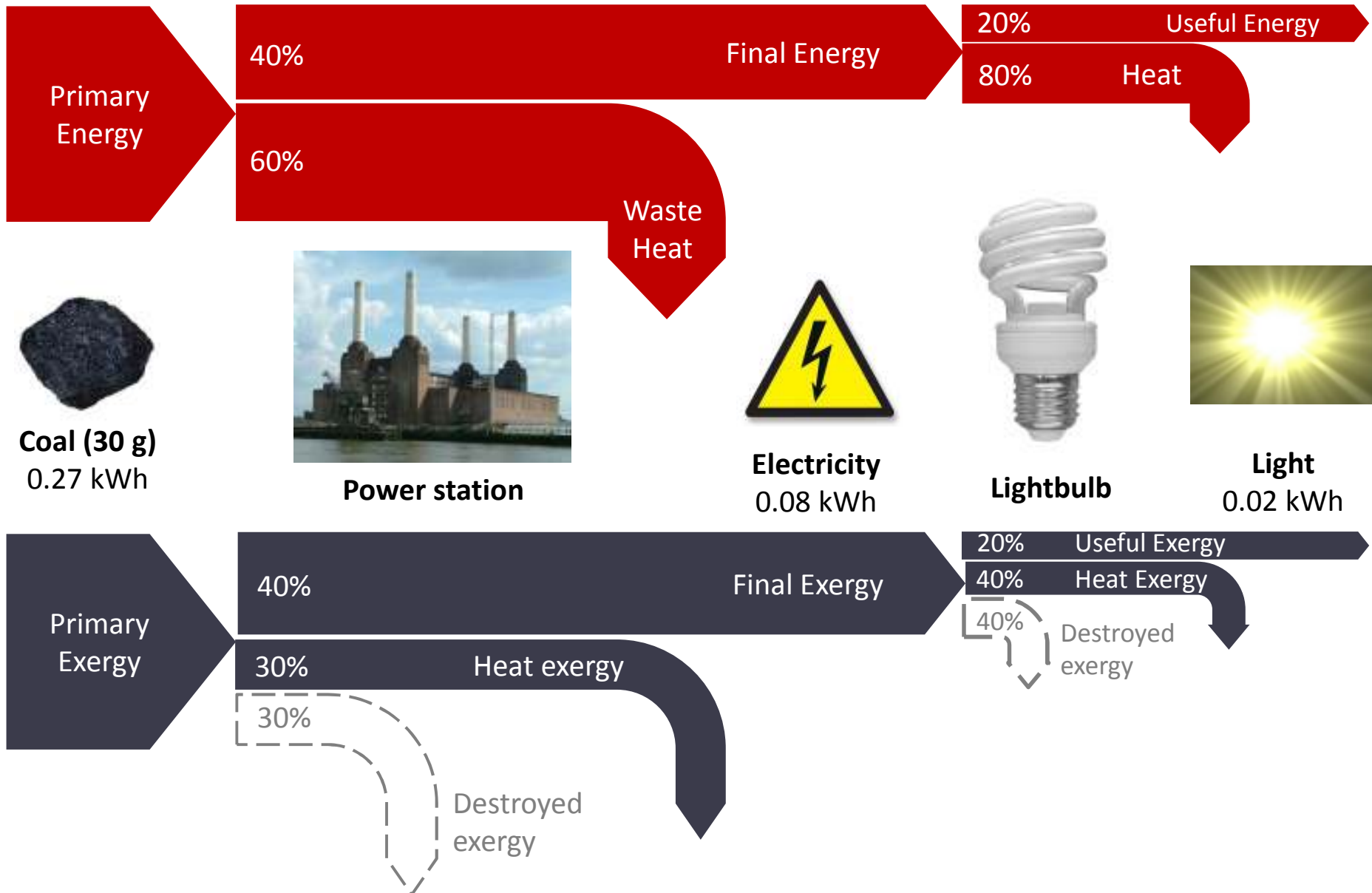
Why exergy?

- The statement "a lamp consumes energy" is WRONG

- Energy is conserved, so a lamp cannot *consume* energy

- A lamp *degrades* energy, reducing its quality

  - We can do much more with electricity than with heat and light

- So, electricity has a higher *exergy* than heat and light

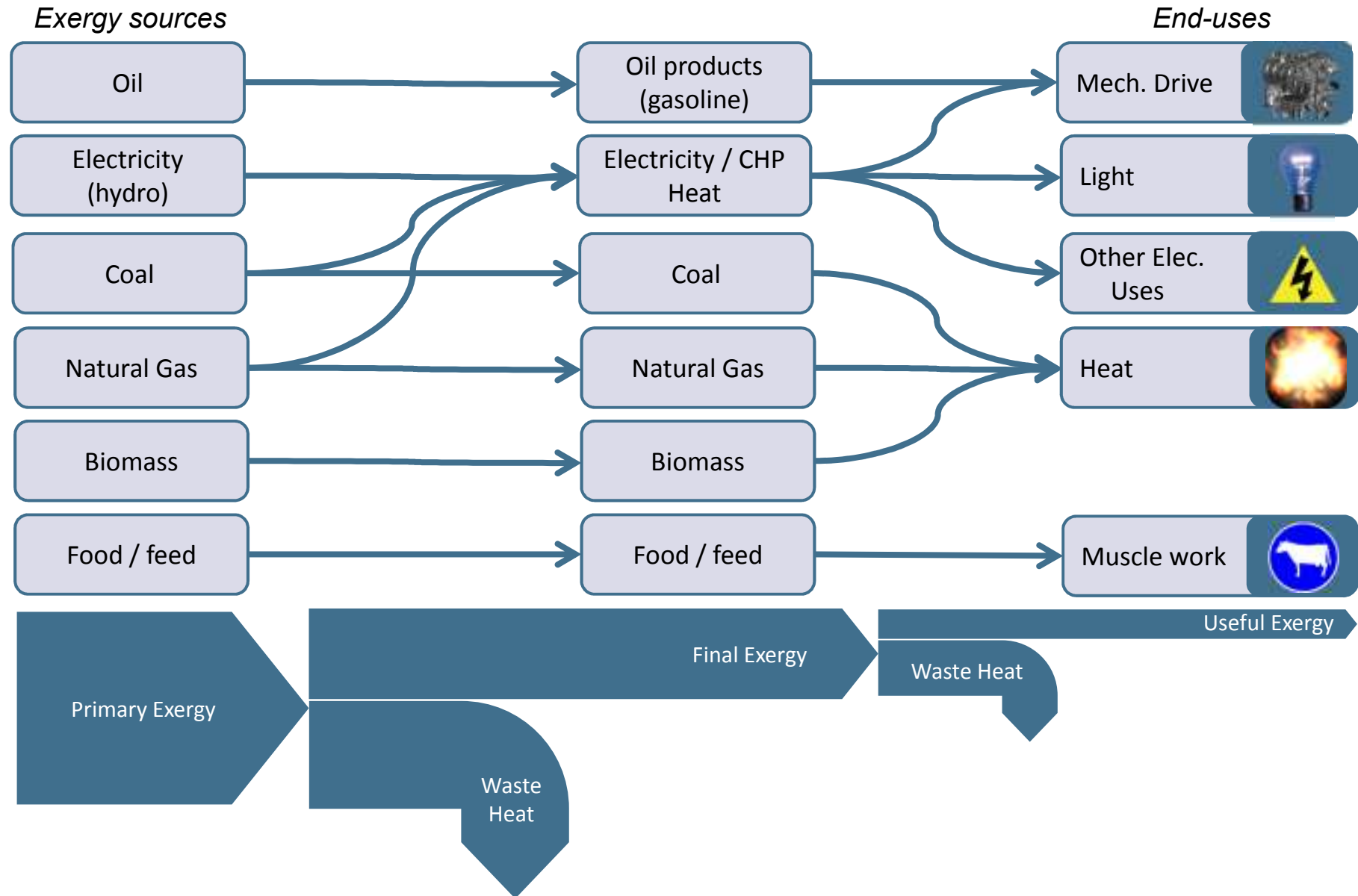- The statement a "lamp consumes *exergy"* is RIGHT

Why Useful Exergy

- Exergy correctly adds up heat and work
  - Work can be completely converted to heat, but heat cannot be completely converted to work
    - "All energies are equal, but some are more equal than others"
- Exergy destruction expresses the Second Law of Thermodynamics
  - The irreversibility and production of entropy in all physical processes (the Arrow of Time)
- The useful stage of energy transformation is the one closest to the creation of economic value
  - In fact, it is the last one, because after it energy is completely dissipated (exergy is completely destroyed)

Primary, Final and Useful Exergy

Primary Energy

40% Final Energy

60%

20% Useful Energy

80% Heat

Waste Heat

Coal (30 g)
0.27 kWh

Power station

Electricity
0.08 kWh

Lightbulb

Light
0.02 kWh

Primary Exergy

40% Final Exergy

30% Heat exergy

30% Destroyed exergy

20% Useful Exergy

40% Heat Exergy

40% Destroyed exergy

Exergy carriers & end-uses

Exergy sources

End-uses

Oil	→	Oil products (gasoline)		Mech. Drive
Electricity (hydro)		Electricity / CHP Heat		Light
Coal		Coal		Other Elec. Uses
Natural Gas		Natural Gas		Heat
Biomass		Biomass		
Food / feed		Food / feed		Muscle work

Primary Exergy

Final Exergy

Useful Exergy

Waste Heat

Waste Heat

Final and Useful exergy consumption – Portugal 1856-2009

⇨ International Energy Agency energy balances 1960-2010;
⇨ Henriques, Sofia (2011) *Energy Transitions, Economic Growth and Structural Changes*: Portuguese energy data 1856-2000.

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.
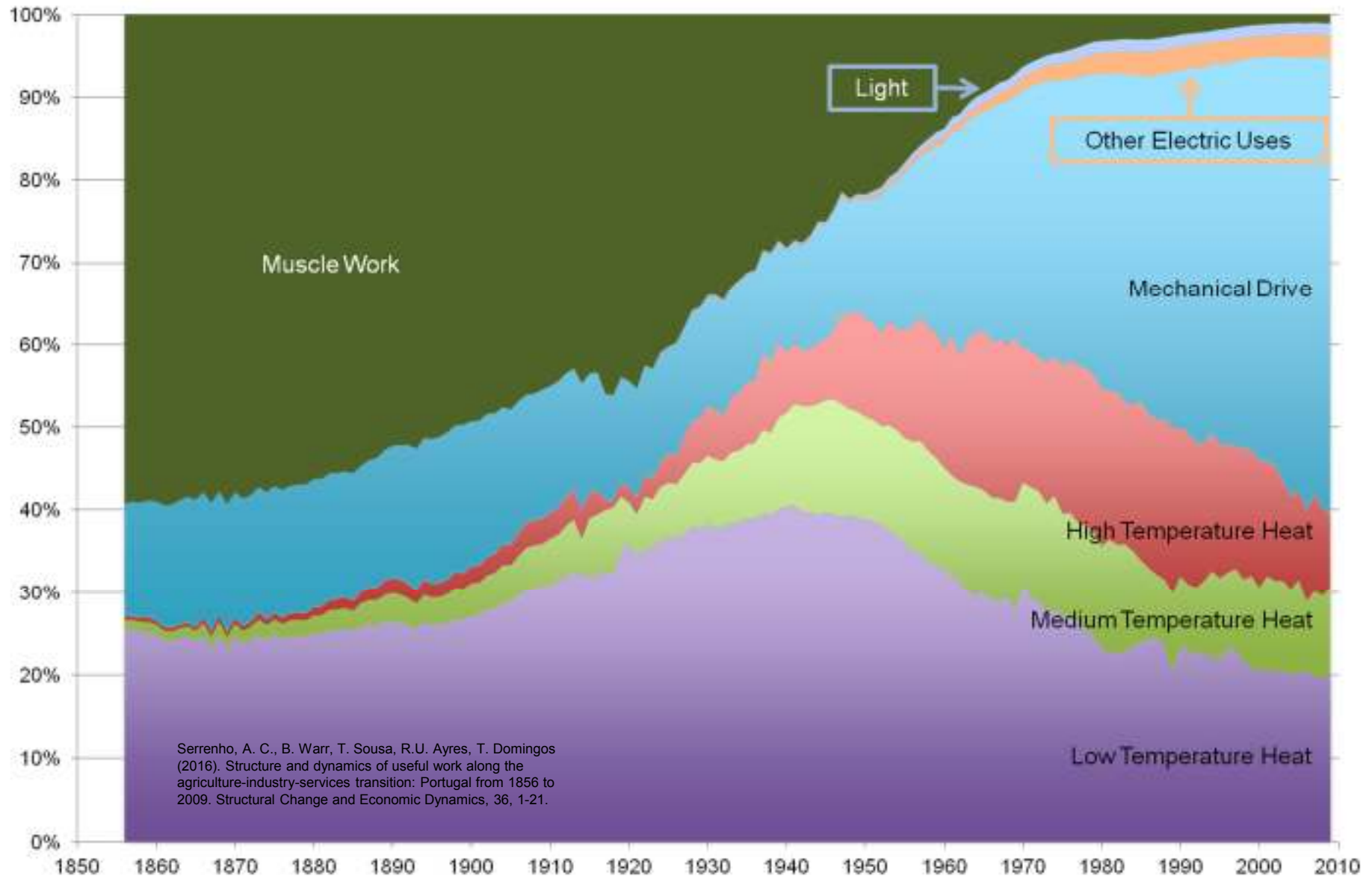
Final exergy

Useful exergy

Final exergy inputs by carrier – Portugal 1856-2009
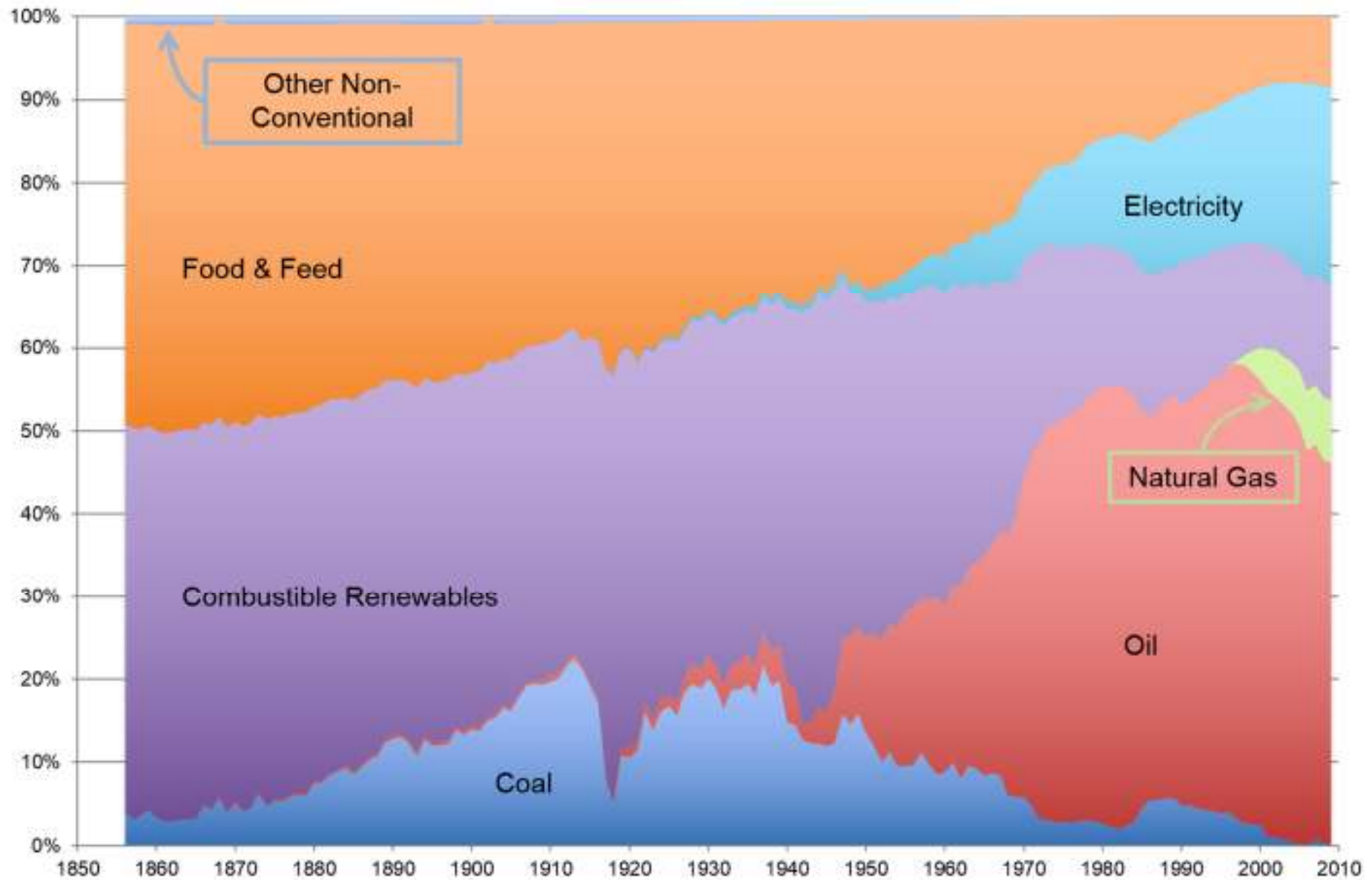
Aggregate Final-to-Useful efficiency – Portugal 1856-2009

Increase in heating efficiencies; Increasing use of heat.

Electrification: stationary power

Motorization: increase in mechanical drive uses from oil products

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Composition of Useful exergy – Portugal 1856-2009

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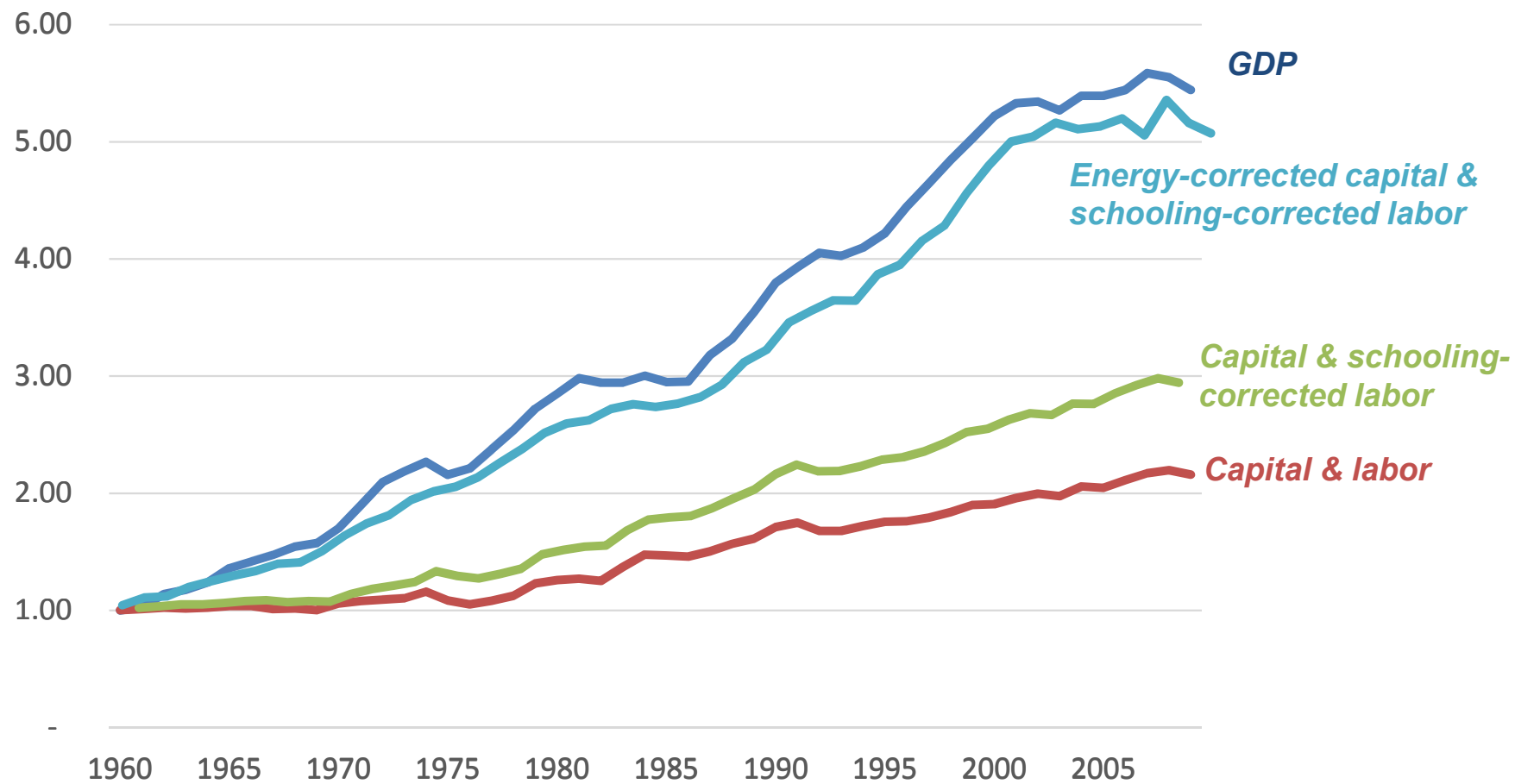
Final and useful exergy intensities, Portugal 1856-2009
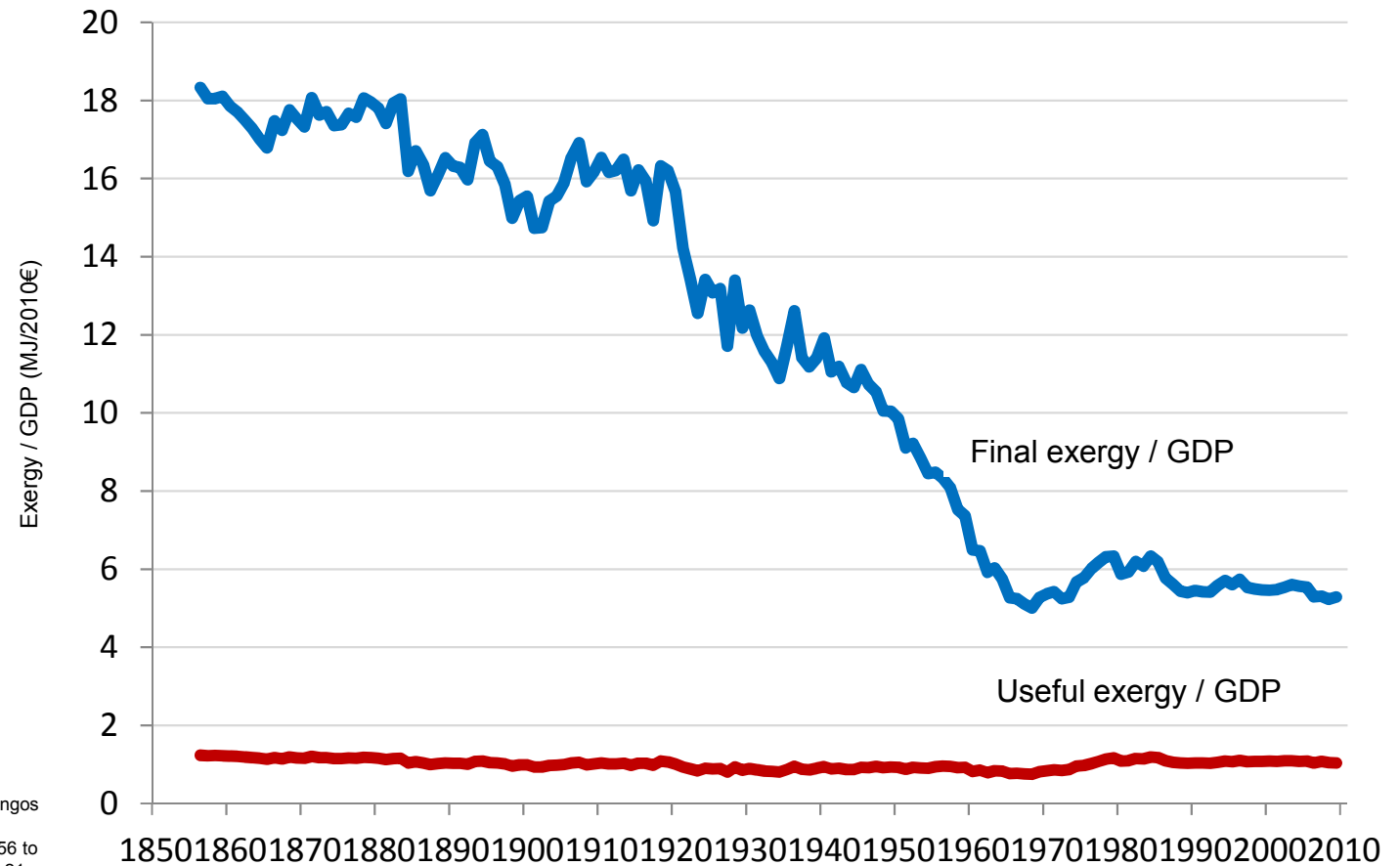
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Energy-corrected capital explains the Solow residual

- GDP
- Energy-corrected capital & schooling-corrected labor
- Capital & schooling-corrected labor
- Capital & labor