Some thoughts on EROI and macroeconomics

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WORK IN PROGRESS

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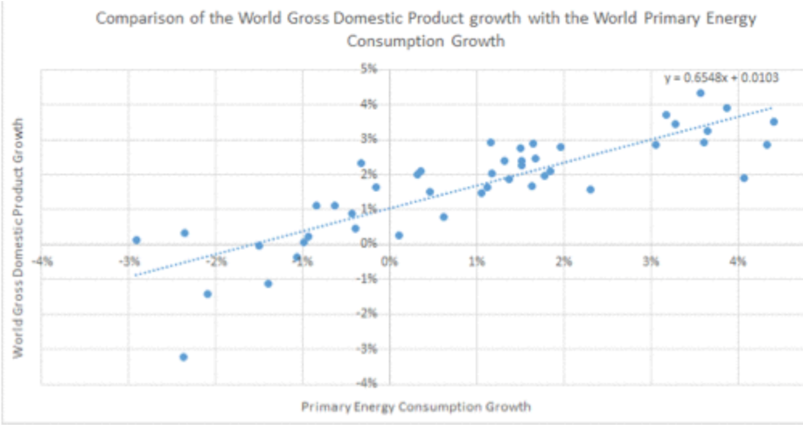
Intro

- Most macro-economic models violate the first 2 laws of thermodynamics.
- Complain of physicists from IPCC group 1.
- Tentatives to include energy in the "production function" (Stiglitz, 1974)
- Cost share theorem
- Georgescu Roegen (1971): when dissipating energy, human societies produce entropy which affects their environment.

Elasticity of GDP wrt energy “consumption” ?



Giraud and Kahraman (2016)

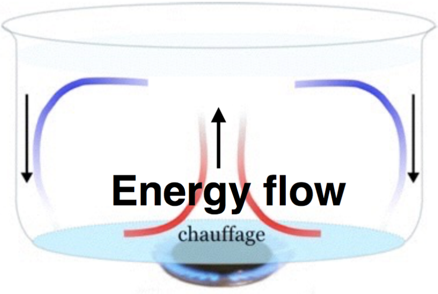
Intro

- Ludwig Boltzmann (1905): the struggle for life is a struggle for energy dissipation (entropy production)
- Alfred Lotka (1922): natural selection tends to favor those organisms that dissipate most energy (produce most entropy).
- Ilya Prigogine (1961): In the presence of a permanent flow of energy, dissipative structures self-organize to dissipate energy.
- A set of dissipative structures is also a dissipative structure:
  Examples: a cyclone, a living being, a human society.

- This paper: a thermodynamical setting with natural resources...
- where a macro-economic model can be embedded.

- Carnot's law (1824): Mechanical work can be sustainably produced only through cycles of transformations extracting heat from a hot source while releasing some to a cold source. Maximal efficiency obtains when all transformations are reversible.

- Applications to fluids:



- A convective cell behaves like a heat engine
- It follows cycles producing mechanical work: $W = Q_1 - Q_2$
- The hot source (T_1) gives energy Q_1.
  The cold source (T_2) receives energy Q_2.
- When $T_1 = T_2$, no mechanical work.
- In this paper, replace the convective cell by an economic metabolism...
  and mechanical work by useful work.

Thermo and Macro

- Marion K. Hubbert.
- Bardi and Lavacchi (2009)

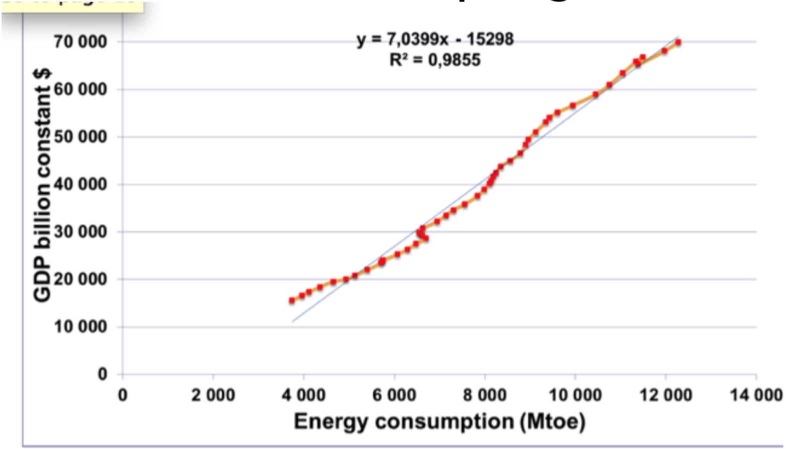
$$\dot{R} := k_1 K_R R \tag{1}$$

$$\dot{K}_R := k_2 K_R R - \delta K_R \tag{2}$$

R := non-renewable resource (fossil energy, minerals)
K_R := extractive capital.

- $E = -\dot{R}$
  Exergy (or Energy in another interpretation).
- $Y = \frac{E}{\tau} = u\frac{K}{\nu} = aL$ (First law)
  $u \in (0,1)$: endogenous usage rate of capital.
- $E \Rightarrow Y \Rightarrow u$ and L.
  1. $1/\tau \in (0,1)$: energy efficiency.
  2. Carnot limit for internal combustion engine: $\frac{1}{\tau} \simeq 0.37$ (Second law)
  3. Current car engines: $\frac{1}{\tau} \simeq 0.2$
  4. Coal conversion to electricity: $\frac{1}{\tau} \simeq 0.4$

Decoupling?


y = 7,0399x - 15298
R² = 0,9855
70 000
60 000
50 000
40 000
30 000
20 000
10 000
0
GDP billion constant $
0
2 000
4 000
6 000
8 000
10 000
12 000
14 000
Energy consumption (Mtoe)

Adding a toy macro-model

- $u = \frac{E\nu}{\tau K} = \frac{k_1 K_R R \nu}{\tau K}$
- Goodwin-Keen (1995) : $\dot{K} = I - \delta K = \kappa(\pi)Y - \delta K$.
  $\pi := \frac{\Pi}{Y}$ profit share.
  $\kappa(\cdot)$ investment function.
- $g = \frac{\dot{Y}}{Y}$
  At a steady state :

$$g^* = k_2 R^* + \frac{\kappa(\pi^*)u^*}{\nu} - 2\delta.$$

Of course, if resource non-renewable, $g^* = 0$!

Alternative extraction equation:

$$\dot{R} = -E + \sigma R + \rho(1 - \frac{1}{\tau})E$$

$\rho \in (0, 1) :=$ rate of recycling.
σ: rate of new discoveries or rate of regeneration.

Giraud, Rostom, Vidal (2016).

Back to thermo

- Economy = Aggregate metabolism that extracts ressource R, and rejects wastes, W.
- Ecosystem = Reservoir where R and W coexist.
  $\overline{\mu}_R :=$ potential (chemical, exergetic...) of R in the ecosystem.
  $\overline{\mu}_W :=$ potential of W in the ecosystem.
  $\overline{\mu}_R > \overline{\mu}_W$ (non-equilibrium, Mallick (2014)).
  Virgo (2011).
- $M = 1 - \frac{1}{\tau}E$ (or $(1-\rho)(1 - \frac{1}{\tau}E)$)= rate of conversion of R into W in the metabolism.
- $\dot{N}_R$ (resp. $\dot{N}_W$) = rate of flow of R (resp. W) across the "membrane" between the economic metabolism and the ecosystem.

- When econ and thermo meet:

$$\dot{N}_R = E - M = \frac{E}{\tau} = Y \quad (3)$$

$$= \frac{D_R(\overline{\mu}_R - \mu_R)}{T} - M \quad (4)$$

$\mu_R :=$ potential of the resource within the economic metabolism
$T :=$ temperature (e.g., $T = 287$ K, Svirezhev (2000))
D_R : diffusion parameter

- In an ideal solution, chemical potential:

$$\mu_X = \mu_{X_0} + RT \ln N_X$$

R $= 8.31\ JK^{-1}\text{mol}^{-1}$ gas constant. N_X: molar concentration.

- Any potential that is an increasing function of concentration.
  T constant in the ecosystem (not in the economic metabolism).
- $\dot{N_W} = \frac{D_W(\overline{\mu}_W - \mu_W)}{T} + M = M$
  $D_W < 0$ and $\mu_W = \overline{\mu}_W$: all wastes considered are of anthropic origin.

  Pollution = exergy left in our wastes (Ayres).
- $\mu_R = \overline{\mu}_R - \frac{TE}{D_R}$.

- Total entropy produced by the economic metabolism per unit of R converted into W:

$$d\Sigma = \frac{\mu_R - \mu_W}{T} \quad (5)$$

$$= \frac{\overline{\mu}_R - \overline{\mu}_W}{T} - \frac{E}{D_R} \quad (6)$$

$$= \frac{\overline{\mu}_R - \overline{\mu}_W}{T} - kM \quad (7)$$

$k := \frac{\tau}{(\tau-1)D_R}$.

- $M^{\max} = \frac{\overline{\mu_R} - \overline{\mu_W}}{kT}$
$d\Sigma = 0$. No useful work.
Converting R to W faster than $M^{\max}$ would require work to be done rather than being a source of work.
(generalization of EROI). Odum and Pinkerton (1955).

- Total entropy produced by the economic metabolism:

$$dS := Md\Sigma = \frac{\overline{\mu}_R - \overline{\mu}_W}{T} M - kM^2.$$

"Red Queen" effect. (Lewis Caroll, Leigh van Valen (1973)).