

Energy stories, equations and transition

Une histoire d'énergie:
équations et transition

Sustainable Energy
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Energy Stories





Fiesco via [Wikipedia](#)



Mosaïque du Grand Palais, Constantinople via [Wikipedia](#)

The Roman Empire in 117 AD





Jacob van Ruisdael via Wikipedia



Hendrick Cornelis Vroom via Wikipedia

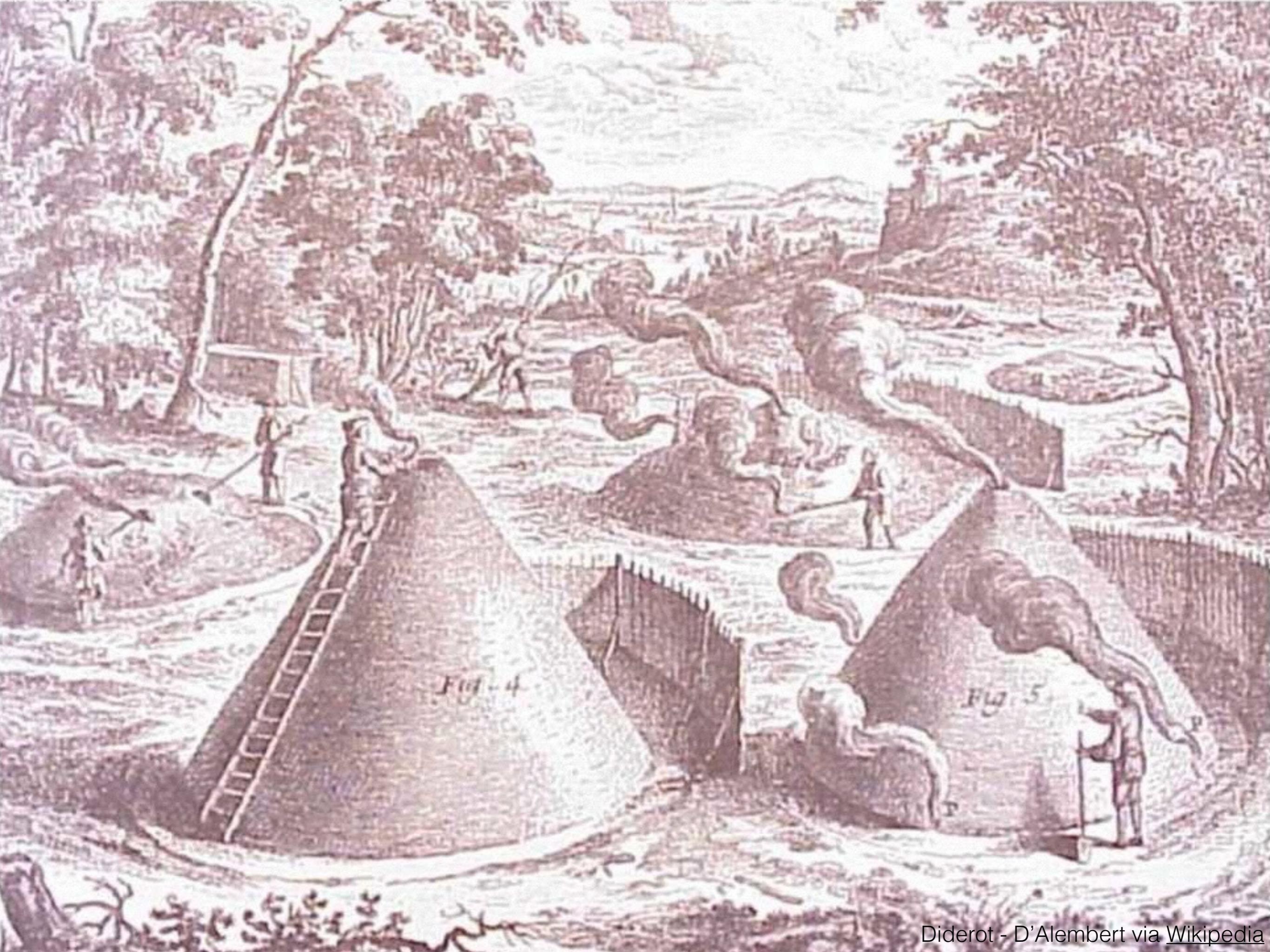
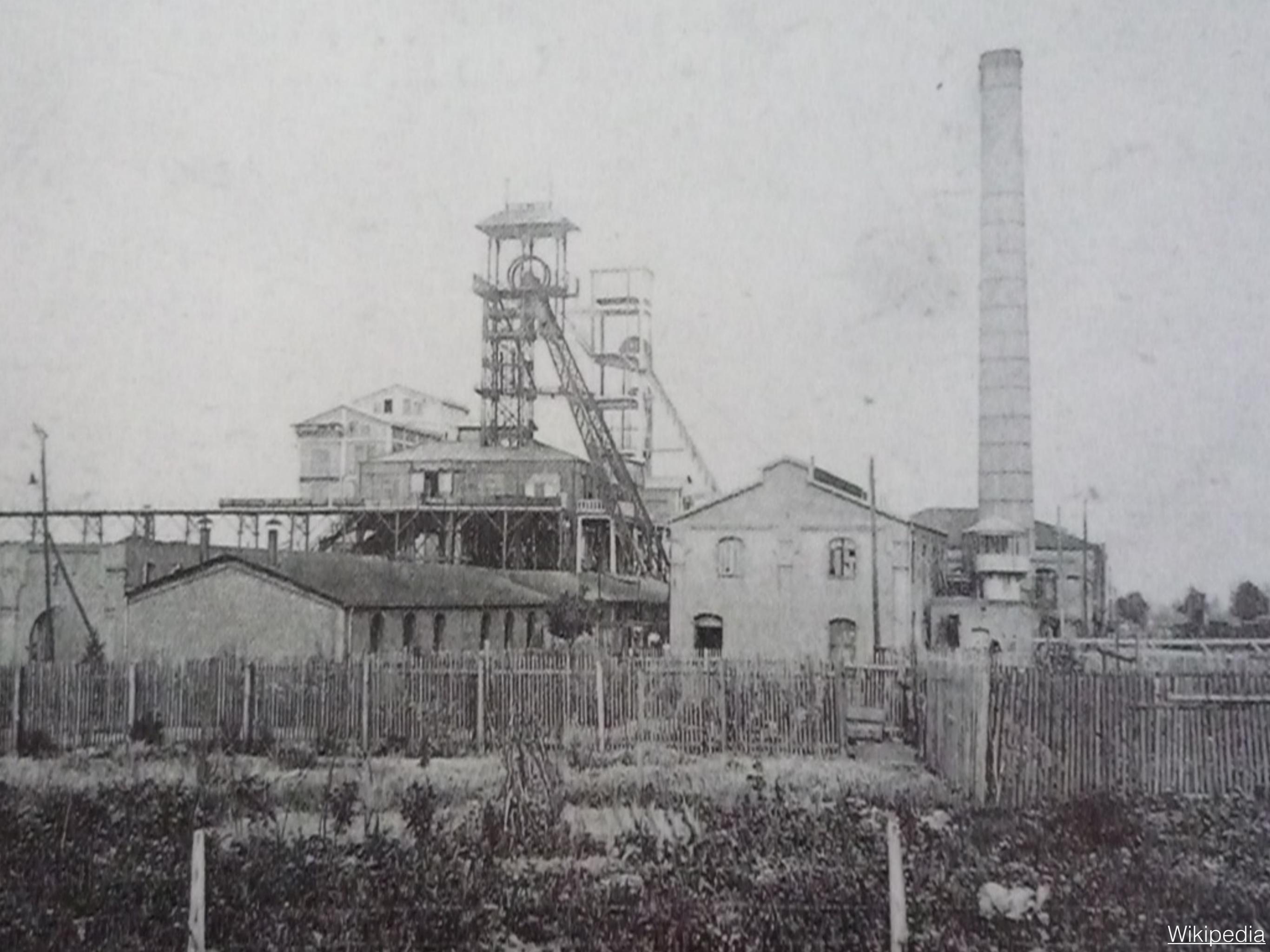


Fig. 4

Fig. 5



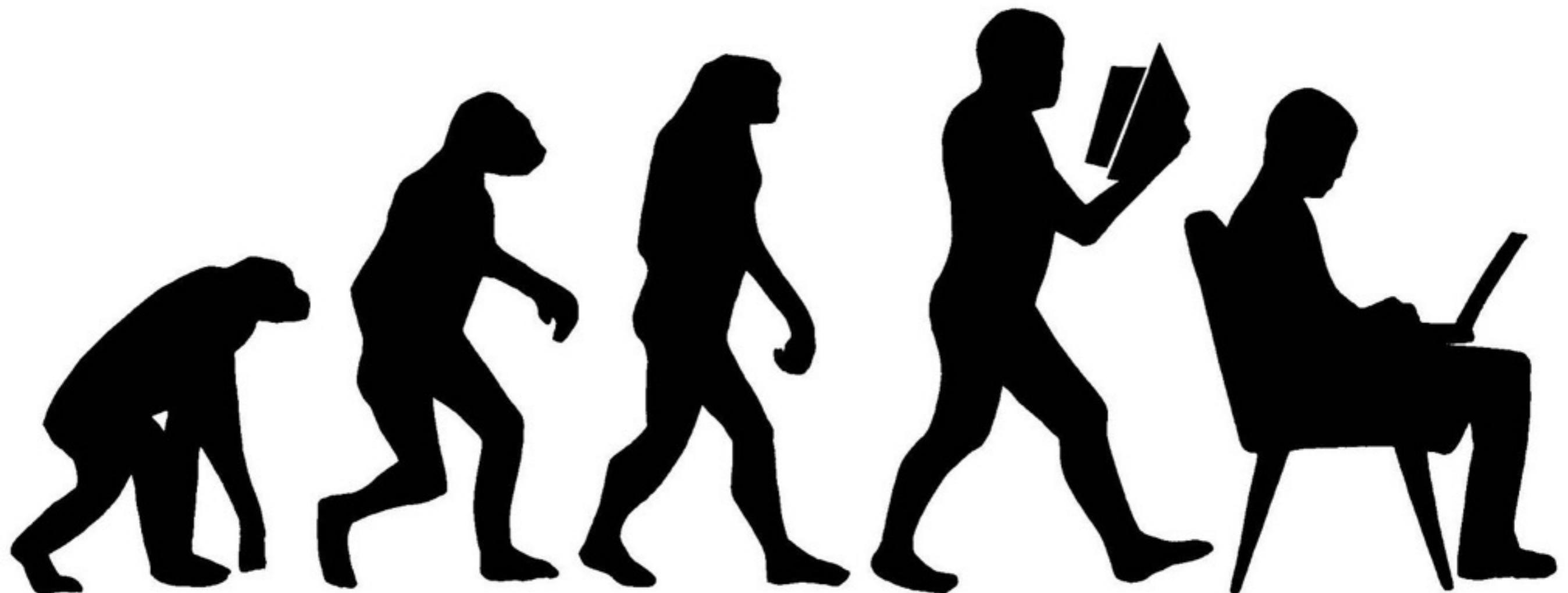


Hartmut Reiche via Wikipedia

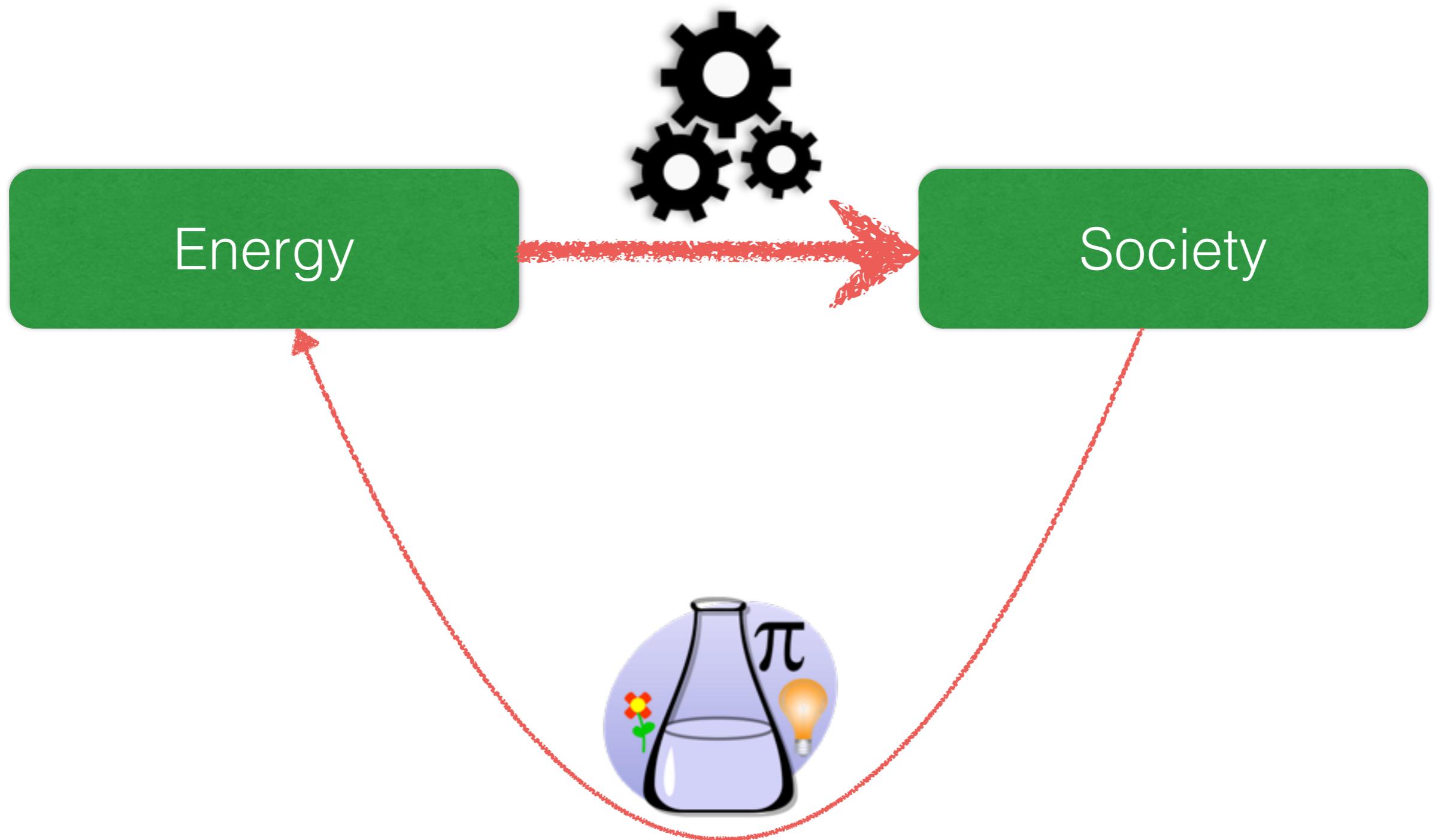


Eric Kounce via [Wikipedia](#)

Trajectories of Societies



Trajectories of Societies

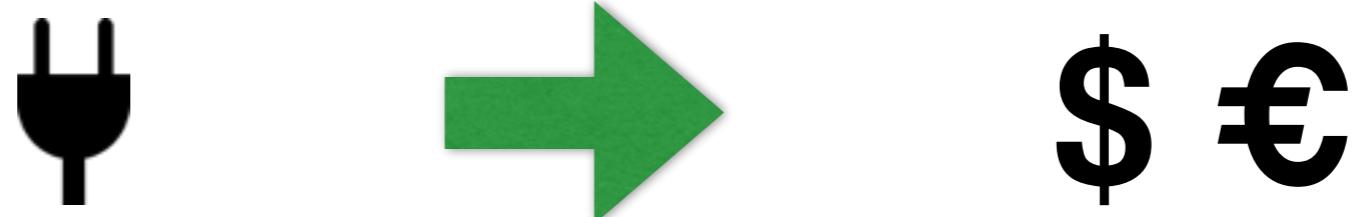


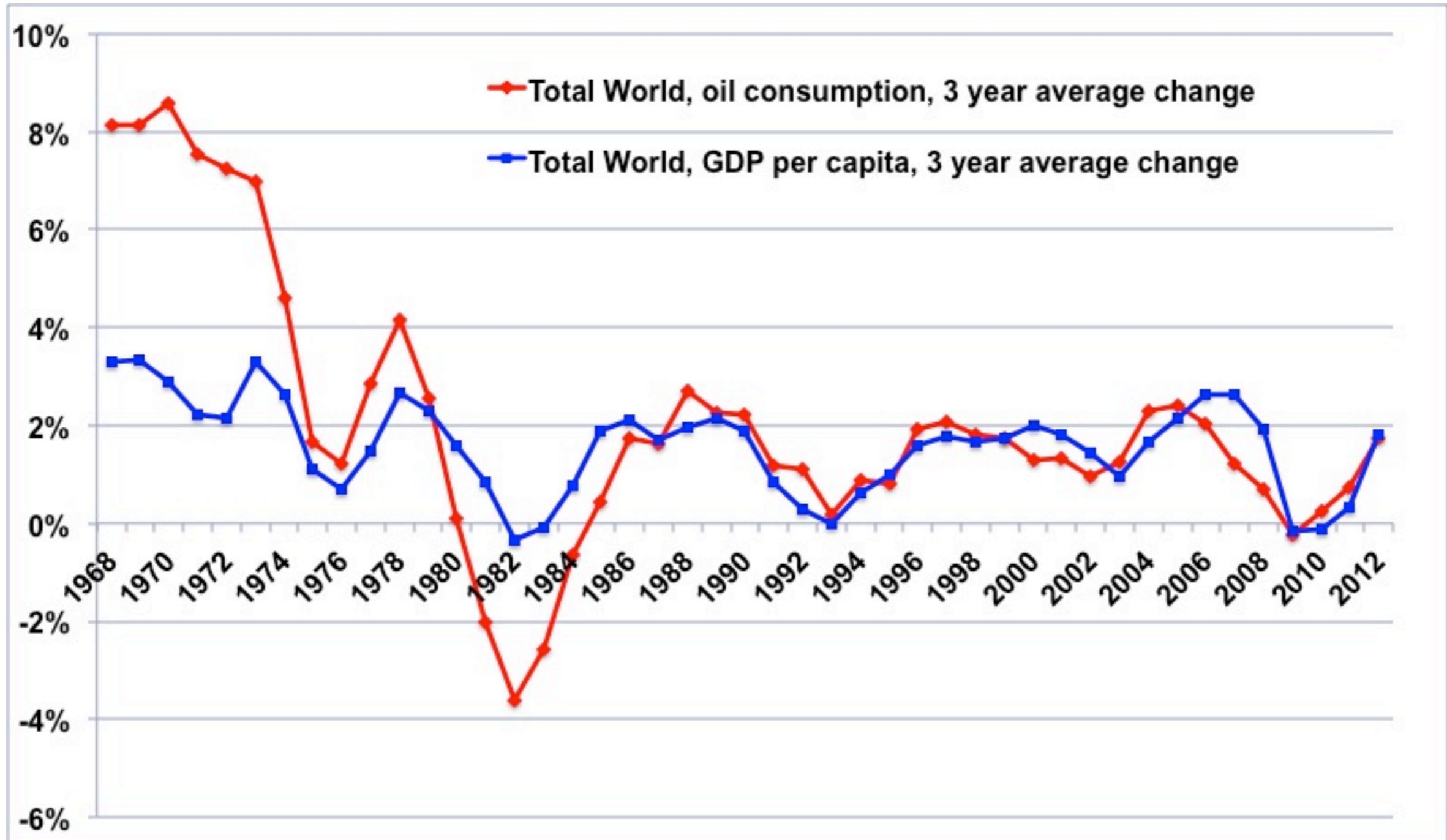
2. Energy <-> Economy

- Recent research in Economics has shown that:
 - The empirical elasticity (measured from time series among OECD countries over the last 50 years) of the consumption of primary energy into the GDP is about 60%, which is 10 times higher than what is predicted by the Cost Share Theorem

Elasticity can be quantified as the ratio of the percentage change in one variable to the percentage change in another variable

- There is a causality link between the consumption of primary energy and the GDP in the direction Energy -> GDP





Variation of the world oil consumption (red) and GDP per inhabitant (blue) - Data from the the
World Bank for GDP and BP stat for energy

Source (in French): Jean-Marc Jancovici, « L'économie aurait-elle un vague rapport avec l'énergie? », LH Forum,
27 septembre 2013

The challenge

Non renewable

> 80% - < 20%

Renewable

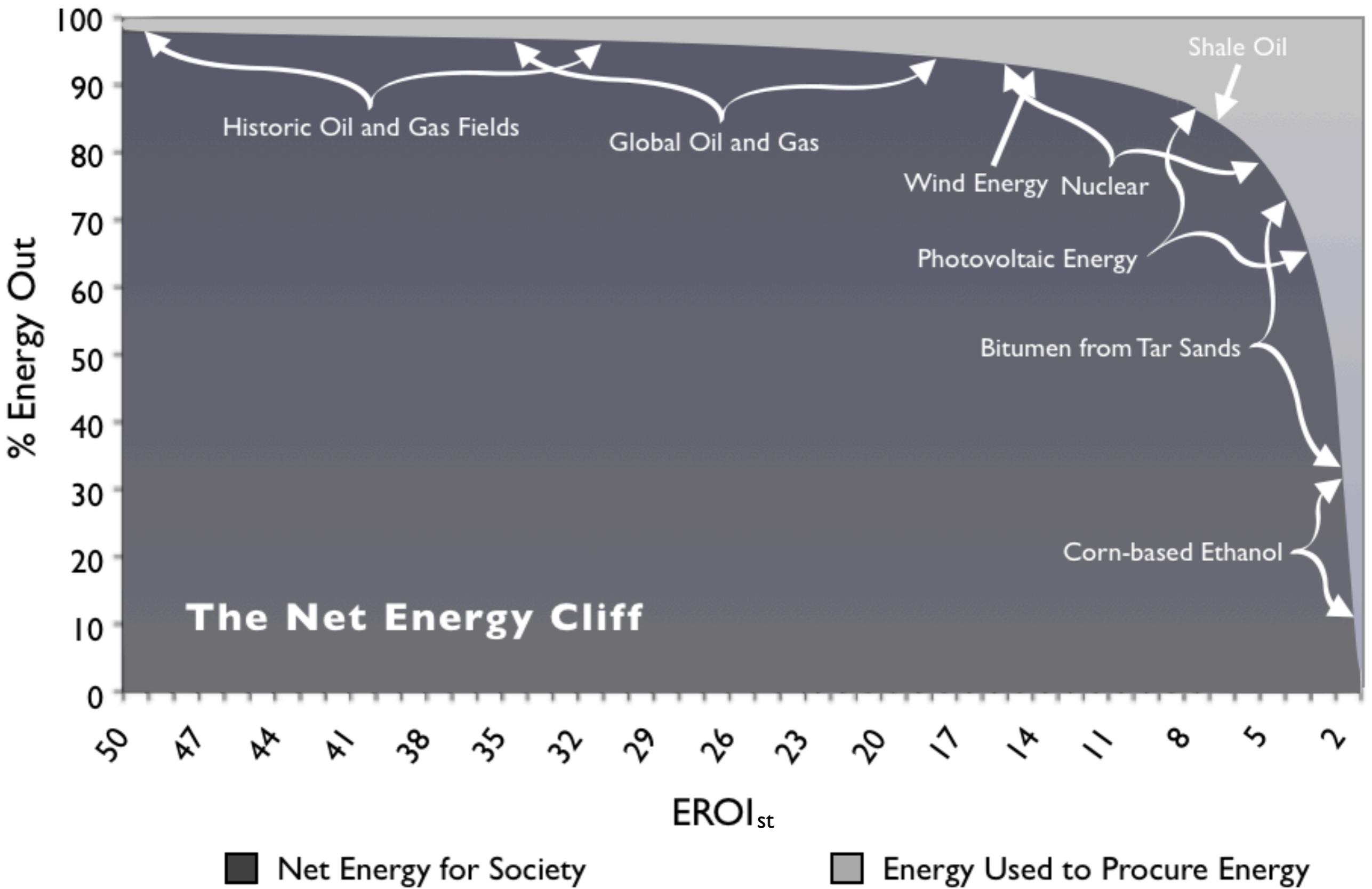
Equations and Transition

ERoEI

- **ERoEI for « Energy Return over Energy Investment »** (also called EROI) is the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource:

$$EROI = \frac{\textit{Usable Acquired Energy}}{\textit{Energy Expended}}$$

- The highest this ratio, the more energy a technology brings back to society
- Notation : 1:X



Source: *EROI of Global Energy Resources - Preliminary Status and Trends* - Jessica Lambert, Charles Hall, Steve Balogh, Alex Poisson, and Ajay Gupta State University of New York, College of Environmental Science and Forestry Report 1 - Revised Submitted - 2 November 2012 DFID - 59717

Modelling the transition?

- A discrete-time model of the deployment of « renewable energy » production capacities
- Budget of non-renewable energy

$$\forall t \in \{0, \dots, T-1\}, B_t \geq 0$$

$$\exists r > 0, \exists \tau > 0, \exists t_0 \in \mathbb{R} : \forall t \in \{0, \dots, T-1\},$$

$$B_t = \frac{1}{r} \frac{e^{\frac{-(t-t_0)}{\tau}}}{\left(1 + e^{\frac{-(t-t_0)}{\tau}}\right)^2}$$

Modelling the transition?

- Set of renewable energy production technologies:

$$\forall n \in \{1, \dots, N\}, \forall t \in \{0, \dots, T - 1\}, R_{n,t} \geq 0$$

- Characteristics $\Delta_{n,t} \geq 0$

$$ERoEI_{n,t} \geq 0$$

- Deployment strategy

$$R_{n,t+1} = (1 + \alpha_{n,t})R_{n,t} \quad \alpha_{n,t} \in [-1, \infty[$$

Modelling the transition?

- Energy costs for growth and long-term replacement

$$\forall n \in \{1, \dots, N\}, \forall t \in \{0, \dots, T-1\},$$

$$C_{n,t}(R_{n,t}, \alpha_{n,t}) \geq 0 \quad M_{n,t} \geq 0$$

- Total energy and net energy to society

$$\forall t \in \{0, \dots, T-1\}, E_t = B_t + \sum_{n=1}^N R_{n,t}$$

$$S_t = E_t - \left(\sum_{n=1}^N C_{n,t}(R_{n,t}, \alpha_{n,t}) + M_{n,t} \right)$$

Modelling the transition?

- Constraint on the quantity of energy invested for energy production

$$\forall t \in \{0, \dots, T-1\},$$

$$\exists \sigma_t : C_{n,t}(R_{n,t}, \alpha_{n,t}) + M_{n,t} \leq \frac{1}{\sigma_t} E_t$$

Modelling the transition?

- Further assumptions
 - Energy cost for growth is proportional to growth, and done initially:

$$C_{n,t} (R_{n,t}, \alpha_{n,t}) = \frac{\Delta_{n,t}}{ERoEI_{n,t}} \alpha_{n,t} R_{n,t} \text{ if } \alpha_{n,t} \geq 0$$

- Long-term replacement cost is (i) proportional and (ii) annualized

$$M_{n,t} (R_{n,t}) = \frac{1}{ERoEI_{n,t}} R_{n,t}$$

$$E_0 = 1$$

$$B_0 = 0.85E_0$$

$$R_{1,0} = 0.01E_0$$

$$\sum_{n=2}^N R_{n,0} = 0.14E_0$$

$$ERoEI_{1,t} = 9$$

$$\Delta_{1,t} = 20$$

$$\sigma_t = 14$$

Constant growth
if possible, else
max admissible

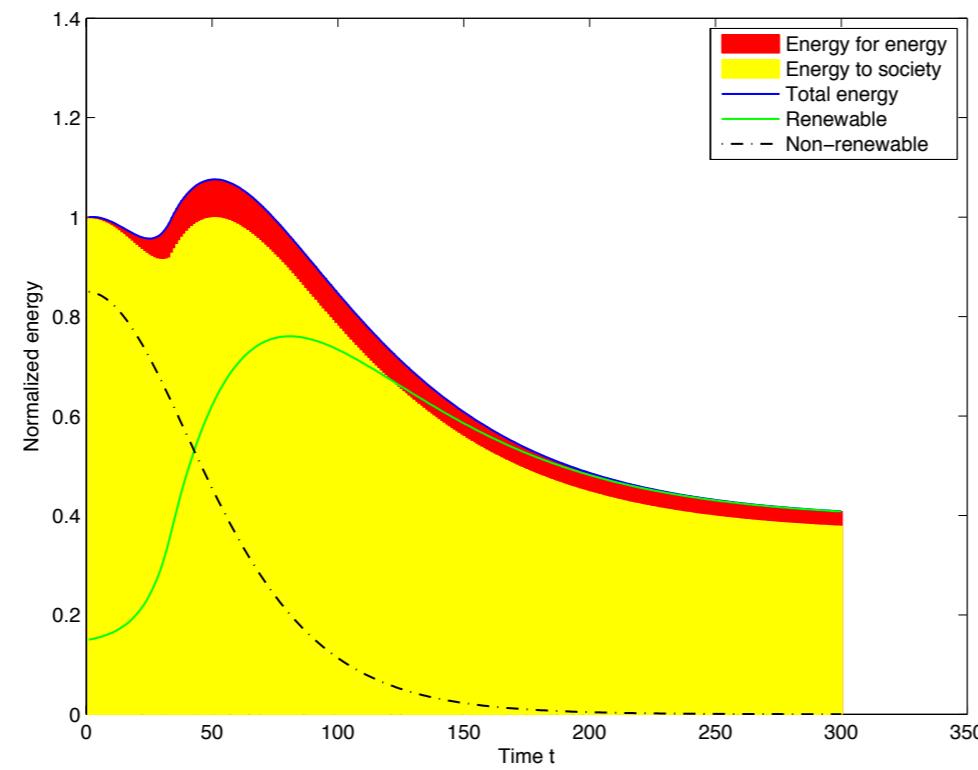


Fig. 2. Scenario “peak at time $t=0$ ”

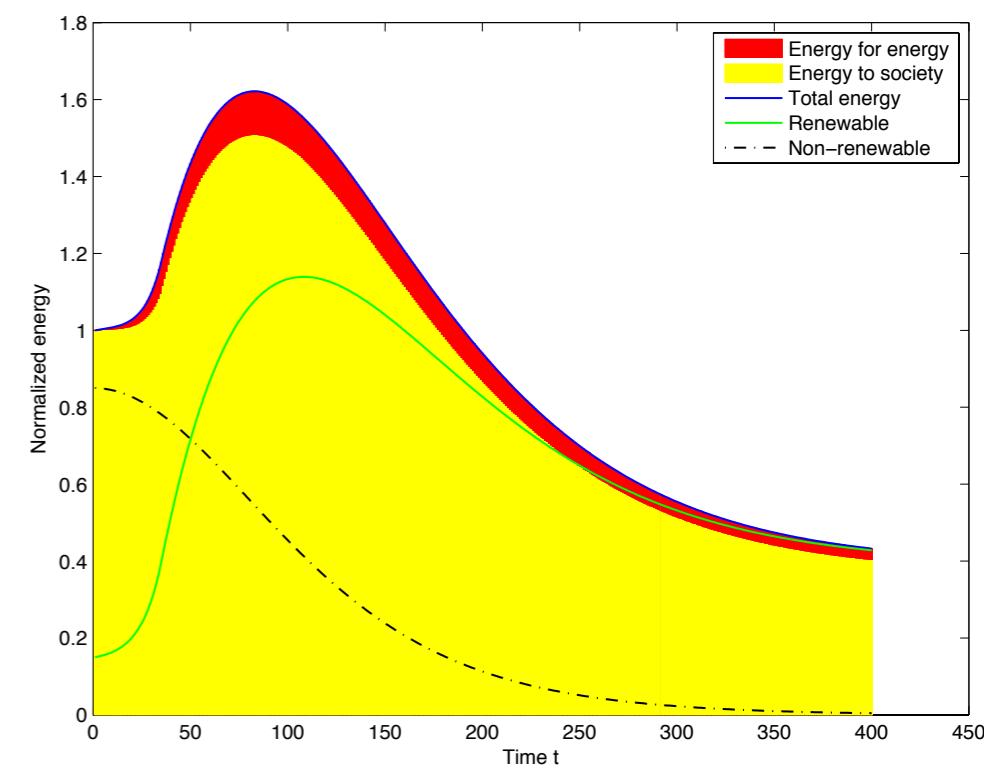


Fig. 3. Scenario “plateau at time $t=0$ ”

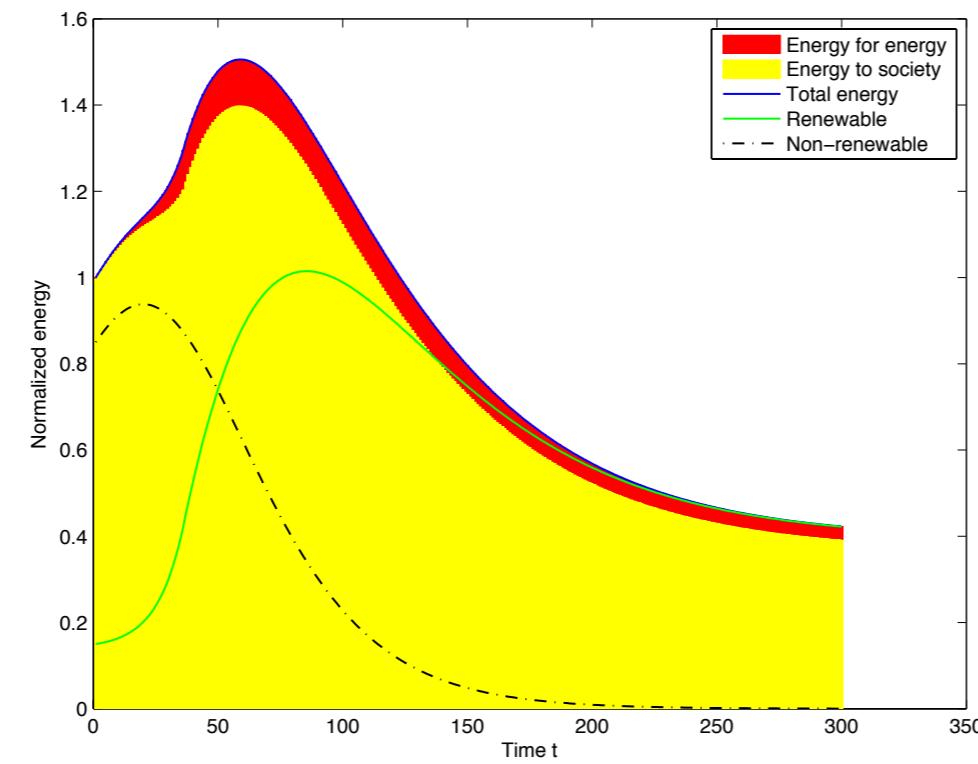


Fig. 4. Scenario “peak at time $t=20$ ”

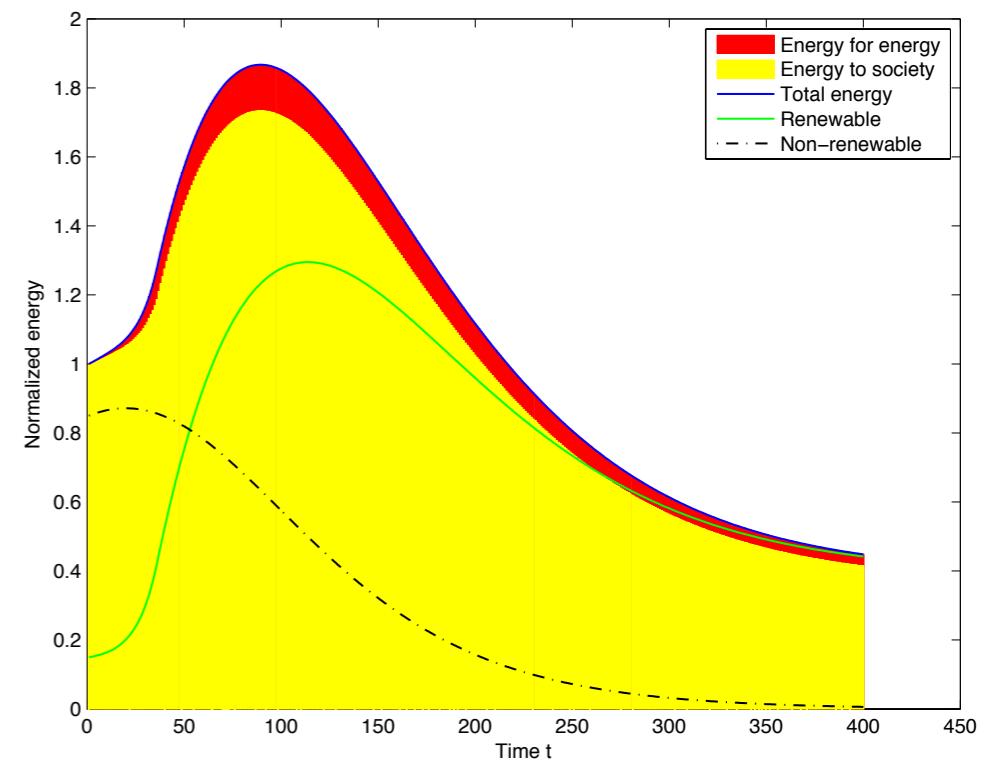
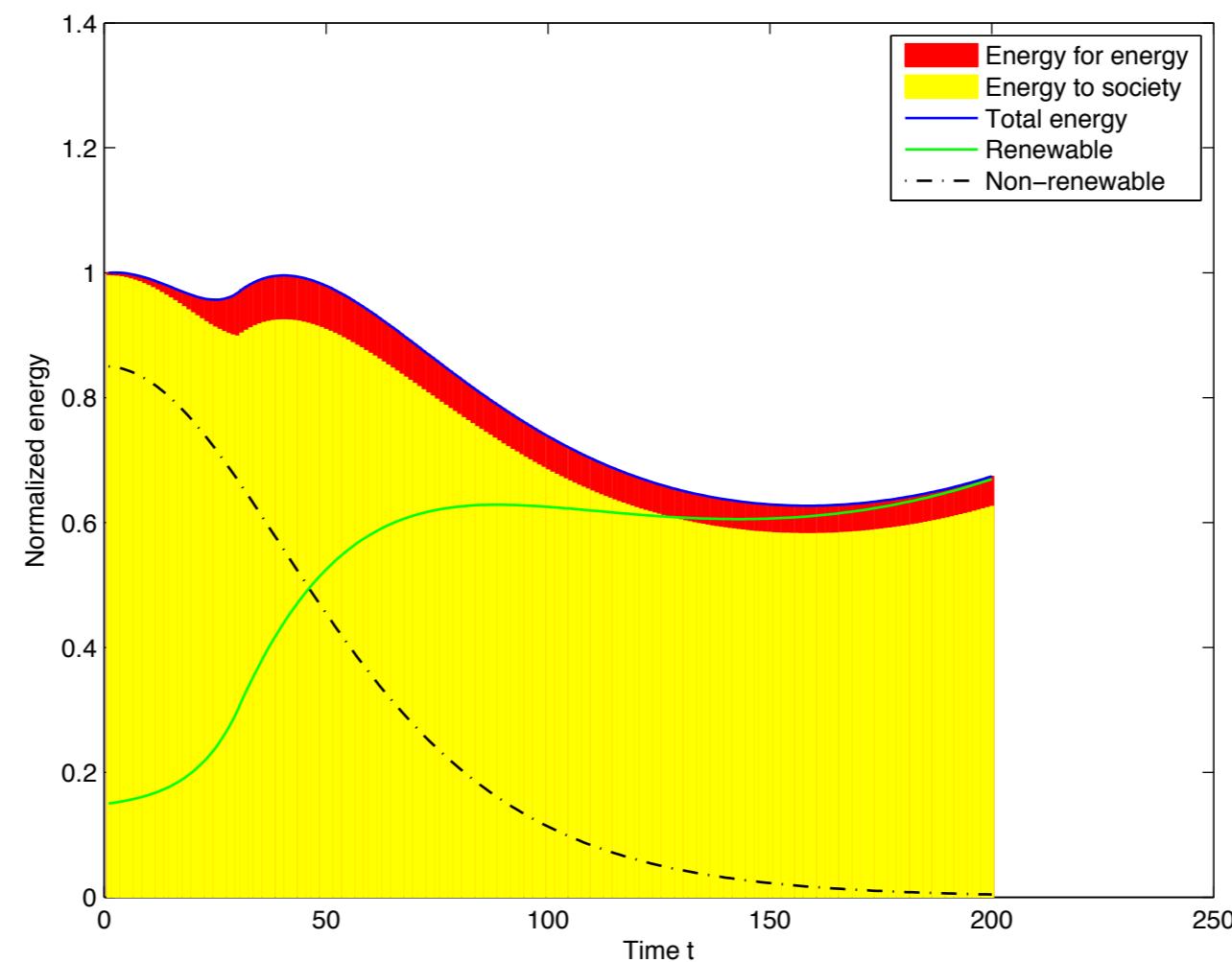


Fig. 5. Scenario “plateau at time $t=20$ ”

Modelling the transition

- Increasing the ERoEI parameter



$$\forall t \in \{0, \dots, T-1\}, ERoEI_{1,t} = 9 + \frac{t}{T}(12 - 9)$$

Epilogue



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