# Une histoire d'énergie : équations et transition

**Sustainable Energy, April 24th 2018**

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Joint work with Pr Damien Ernst - thanks to many other people

# In the news

## Quinze mille scientifiques alertent sur l'état de la planète

L'ampleur de l'initiative est sans précédent. Plus de 15 000 scientifiques de 184 pays signent un appel contre la dégradation catastrophique de l'environnement.

LE MONDE | 13.11.2017 à 16h05 • Mis à jour le 14.11.2017 à 14h18 |

Par Stéphane Foucart et Martine Valo

## La production de pétrole pourrait bientôt ne plus suffire

Par Armelle Bohineust | Mis à jour le 05/03/2018 à 15:54 / Publié le 05/03/2018 à 12:47

L'Agence internationale de l'énergie craint qu'après 2020 les capacités d'exploitation soient insuffisantes pour répondre à la hausse de la demande.

## Airbus décroche la plus importante commande de l'histoire de l'aéronautique

L'avionneur a vendu au loueur américain Indigo 430 moyen-courriers A320 Neo pour une valeur de 42 milliards d'euros.

Le Monde.fr avec AFP | 15.11.2017 à 07h50 • Mis à jour le 15.11.2017 à 12h17 |

Par Guy Dutheil

**What does this mean to you?**

# Outline

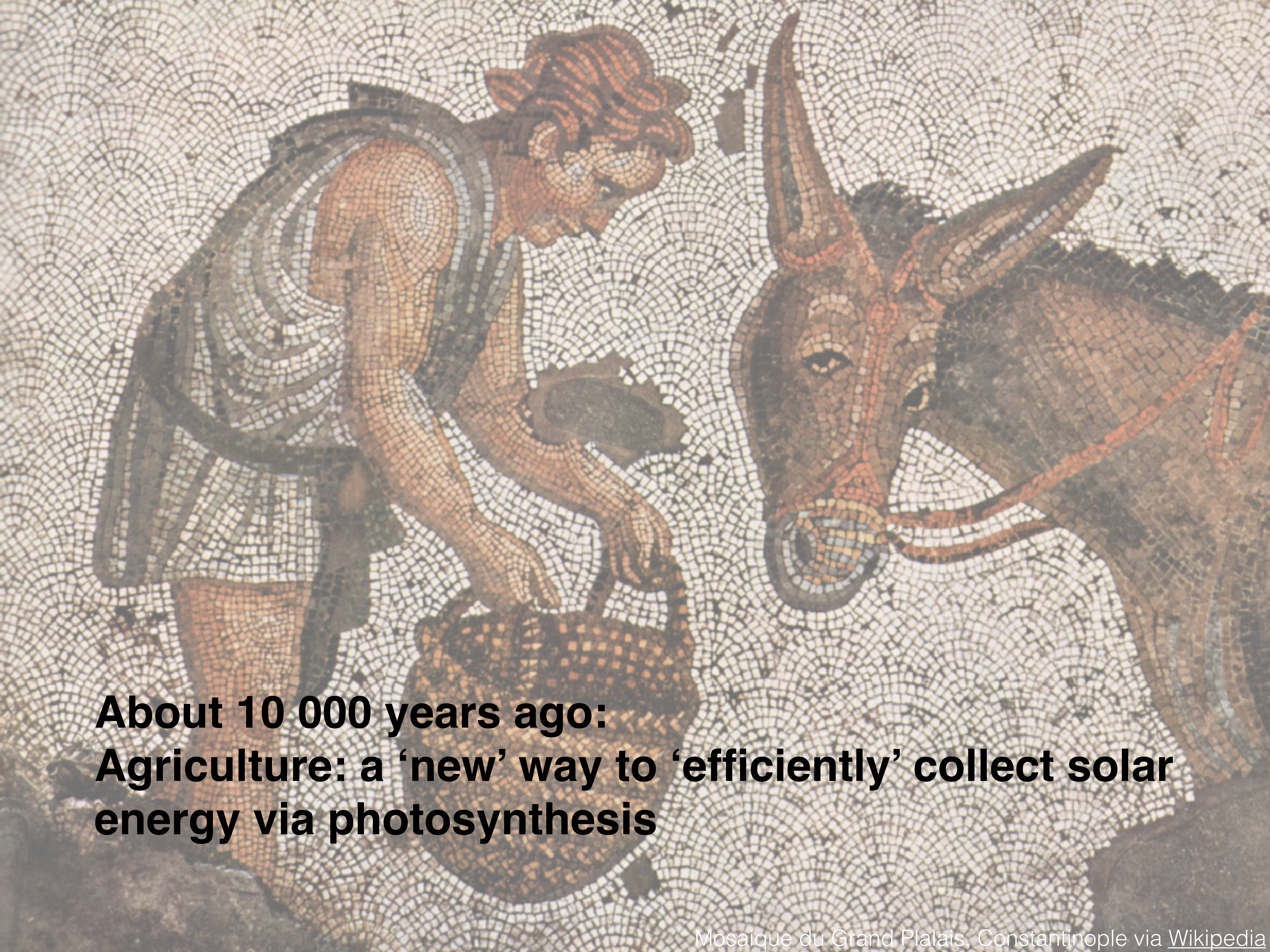
**Energy Stories**

**Modeling the Transition**

# Energy stories

**About 1 million years ago:**
**Fire domestication: lighting, heating, cooking**
**->improved health**

Chenspec via Wikipedia

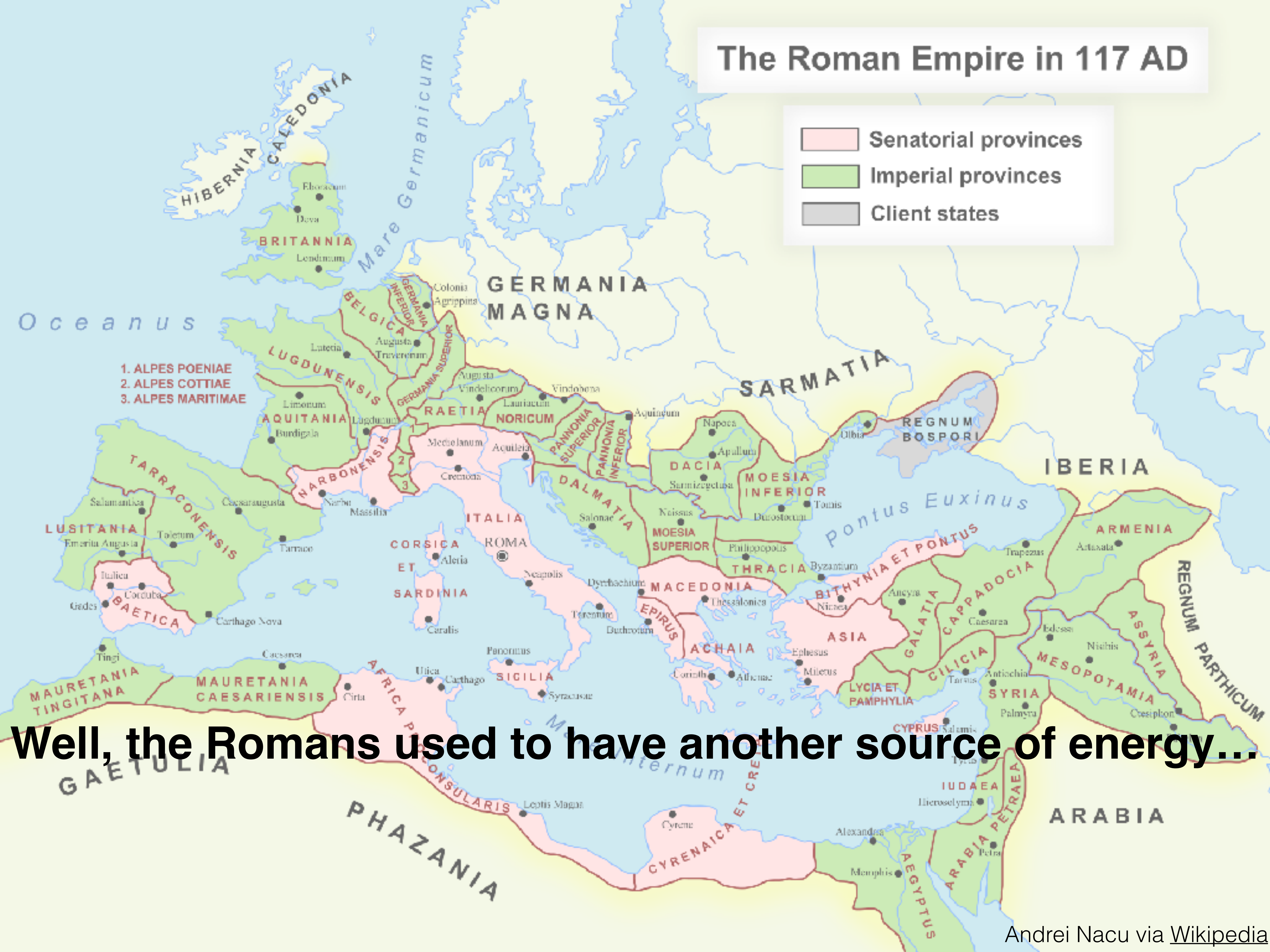


**About 10 000 years ago:**
**Agriculture: a ‘new’ way to ‘efficiently’ collect solar energy via photosynthesis**

Mosaique du Grand Plalais, Constantinople via Wikipedia

**During the Roman Empire, agriculture provided food to humans (some of them are slaves) and animals: this was (almost) the only source of energy**

Fiesco via Wikipedia




**Well, the Romans used to have another source of energy…**

Andrei Nacu via Wikipedia

Jacob van Ruisdael via Wikipedia

**During the Middle Ages, mills are deployed in Europe**

**1 mill corresponds to (about) 40 men in terms of power**

**- European GDP*2 between 1000 and 1500**

**- « Only » 30% in Asia during the same period**

## A famous example: the Dutch Golden Age (16th century)

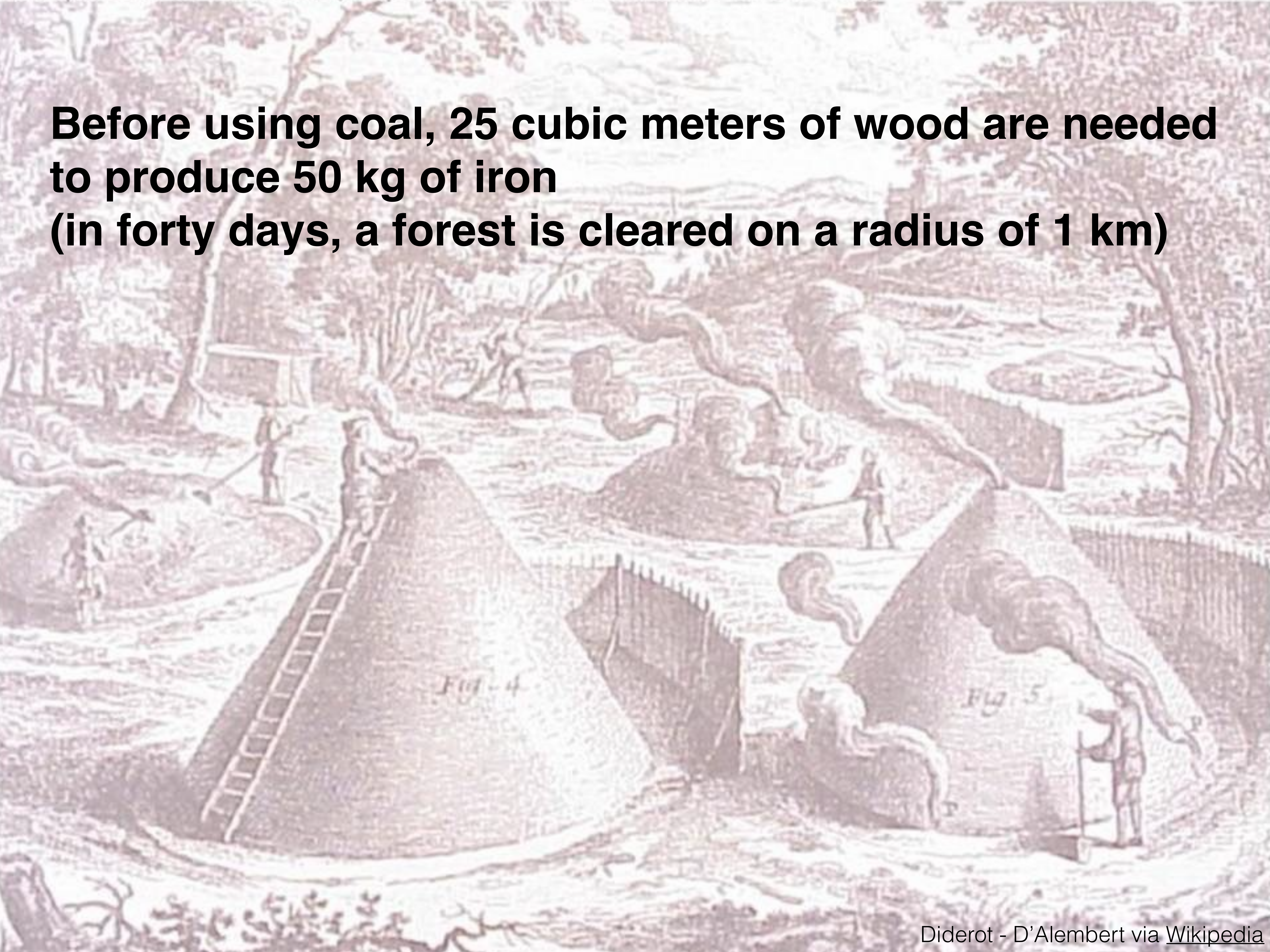
- Efficient agriculture
- Peat
- Waterways
- Trade, city development
- Sawmills for boat construction

Hendrick Cornelis Vroom via Wikipedia

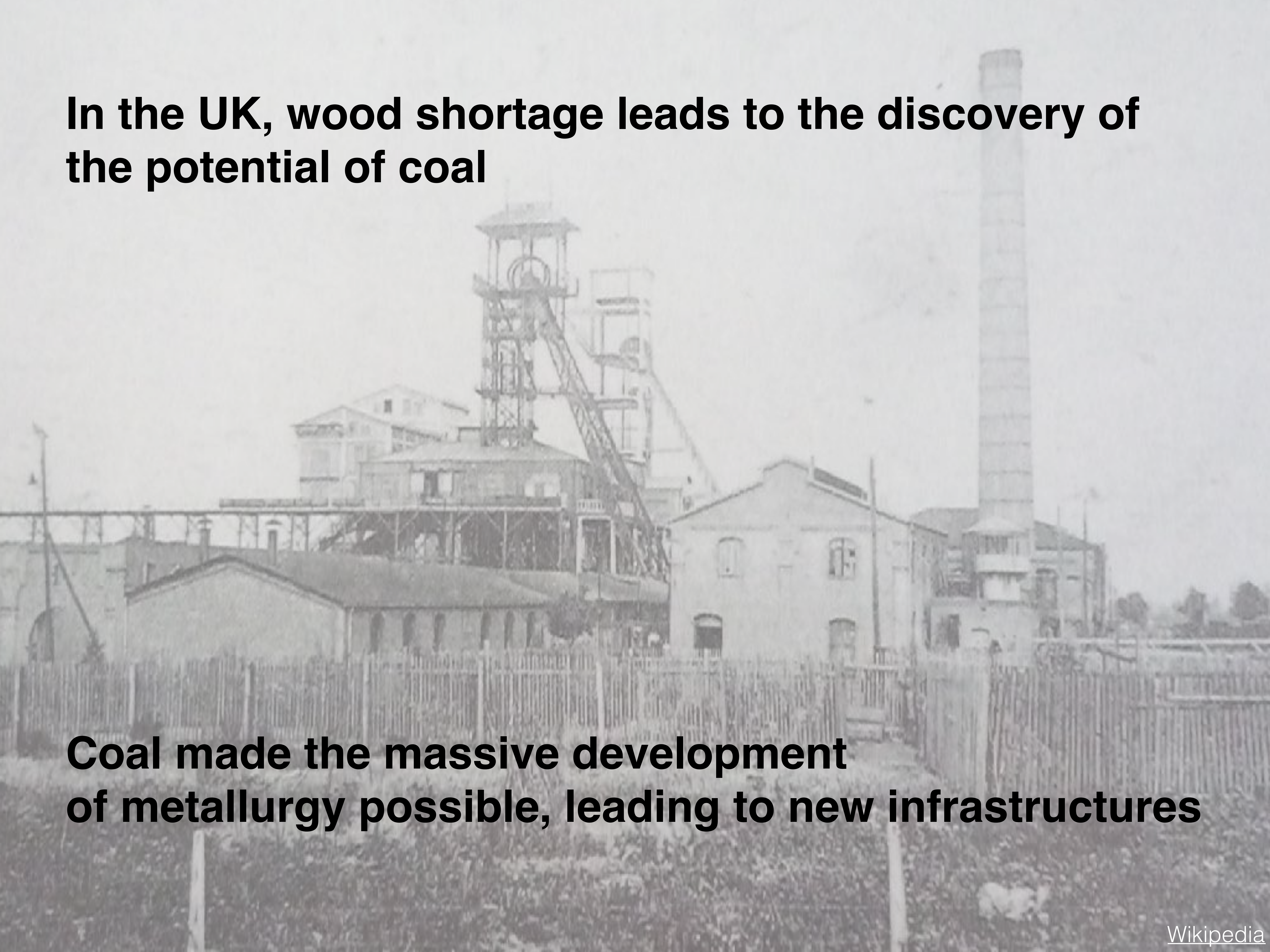

« ***Een Wonder en is gheen wonder*** »
Simon Stevin

Jacques de Gheyn via Wikipedia

**Before using coal, 25 cubic meters of wood are needed to produce 50 kg of iron**
**(in forty days, a forest is cleared on a radius of 1 km)**




Diderot - D'Alembert via Wikipedia

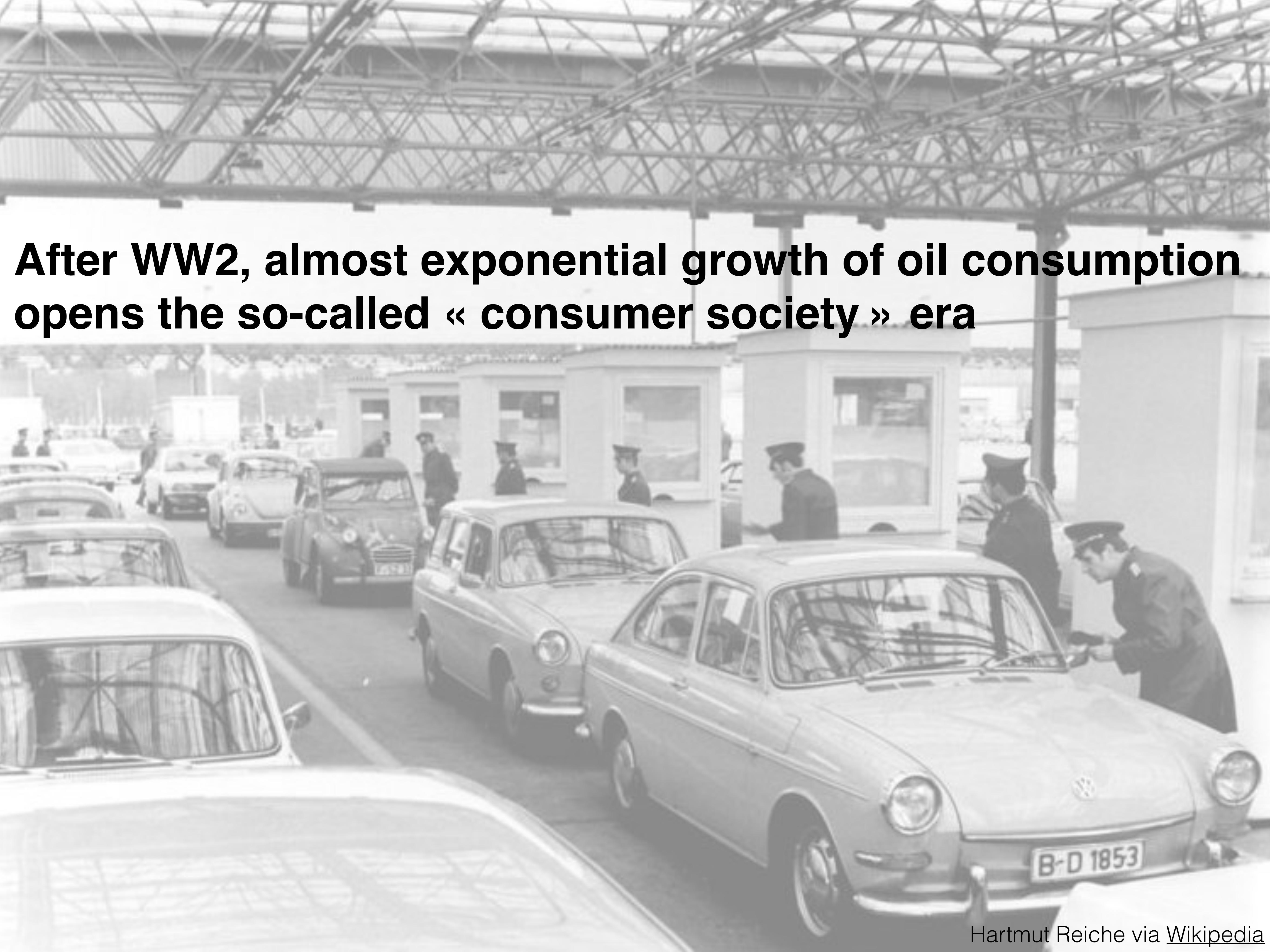


**In the UK, wood shortage leads to the discovery of the potential of coal**

**Coal made the massive development of metallurgy possible, leading to new infrastructures**

Wikipedia

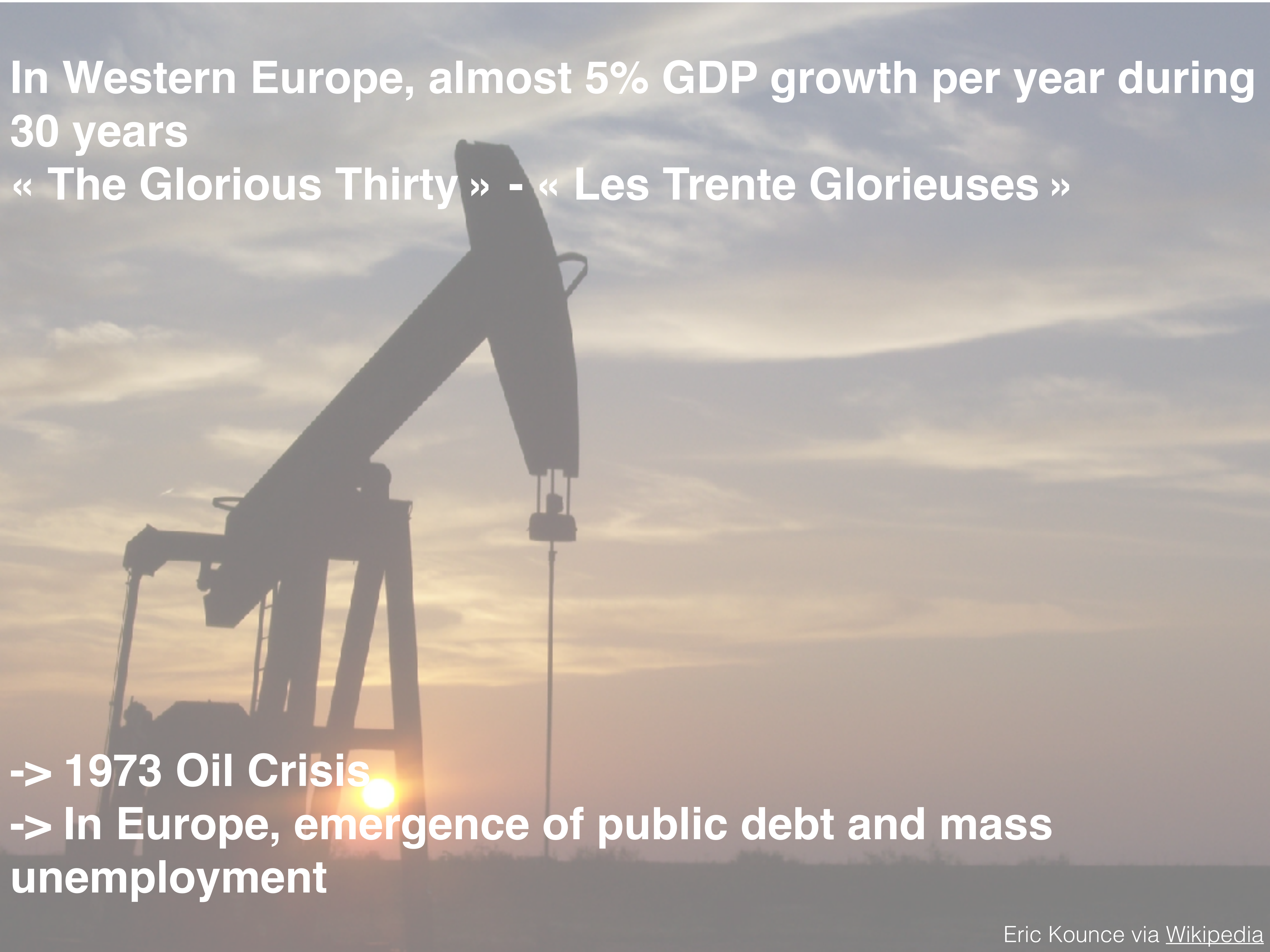
**After WW2, almost exponential growth of oil consumption opens the so-called « consumer society » era**




Hartmut Reiche via Wikipedia

In Western Europe, almost 5% GDP growth per year during 30 years

« The Glorious Thirty » - « Les Trente Glorieuses »

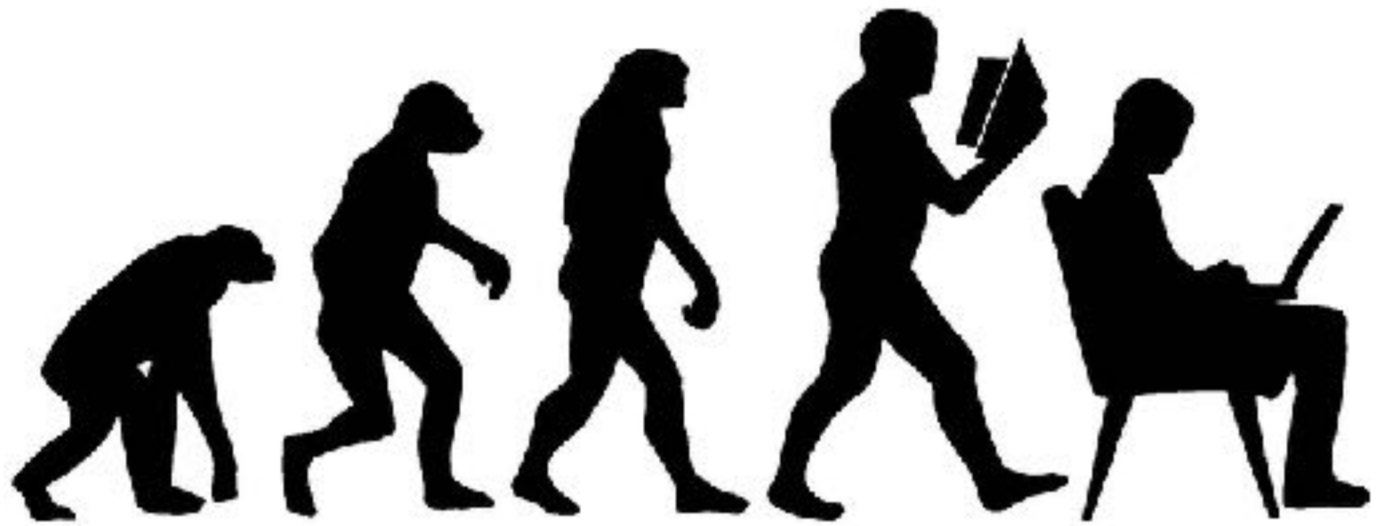


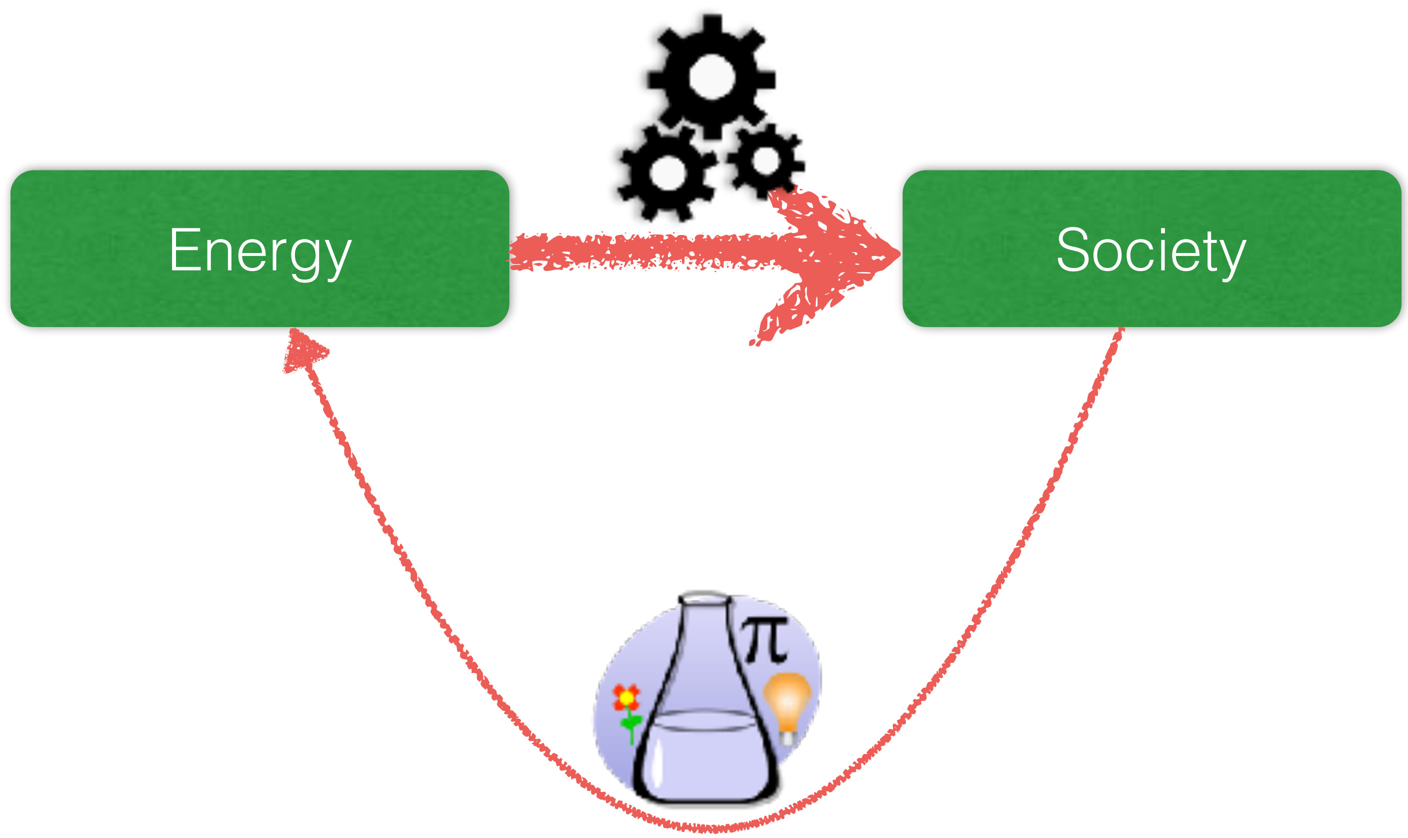
-> 1973 Oil Crisis

-> In Europe, emergence of public debt and mass unemployment

Eric Kounce via Wikipedia

# Trajectories of Societies





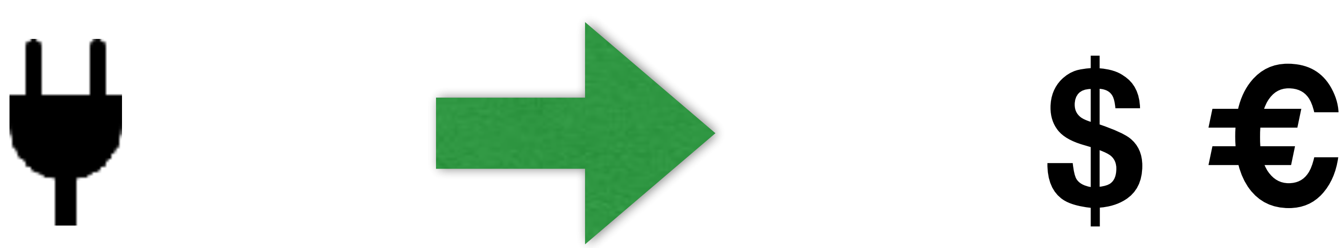

Johanna Pung via Wikipedia

# Energy & GDP

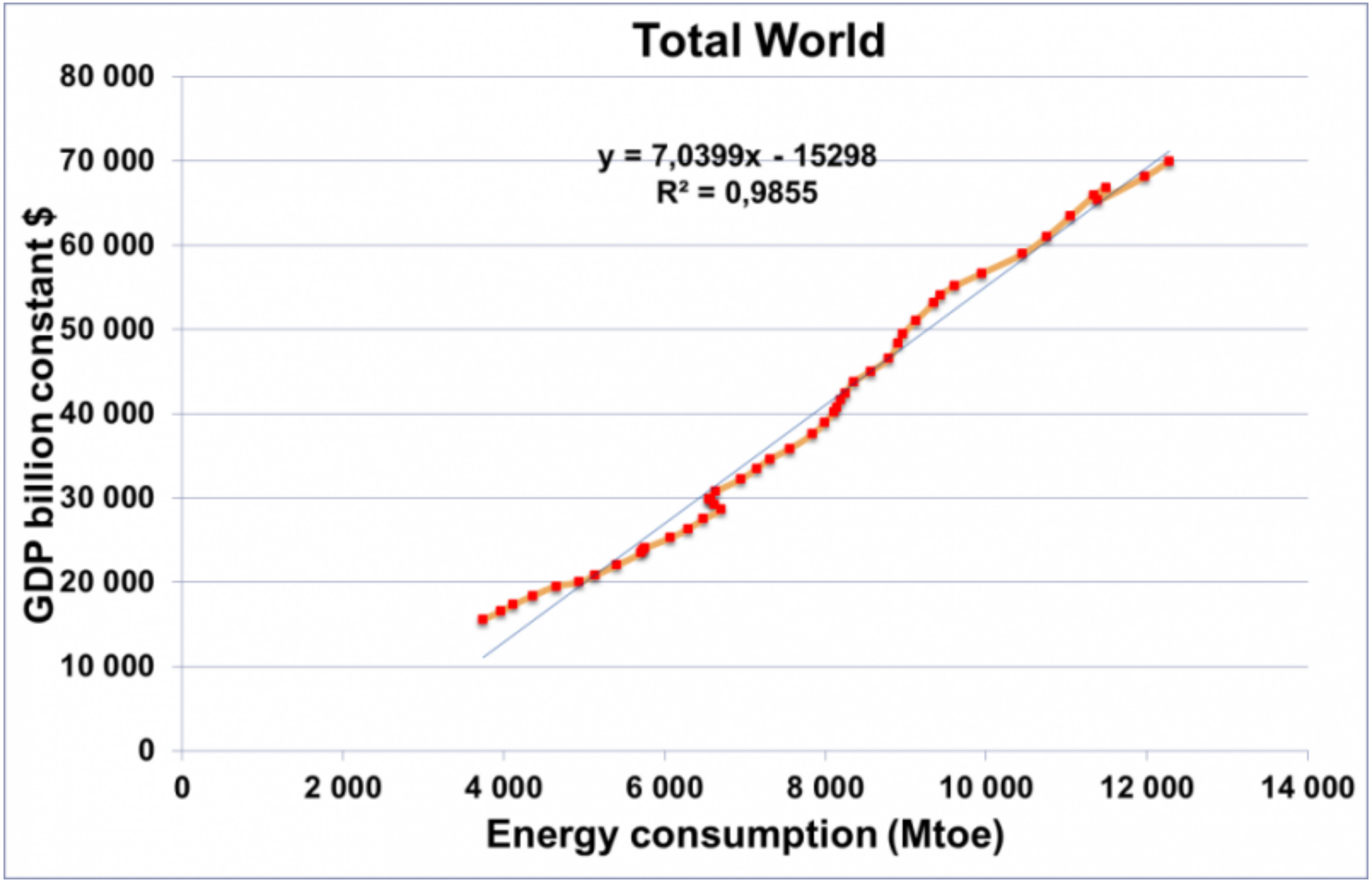
- Recent research in Economics has shown that:
  - The empirical elasticity (measured from time series among OECD countries over the last 50 years) of the consumption of primary energy into the GDP is about 60%, which is 10 times higher that what is predicted by the « *Cost Share Theorem* »

*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

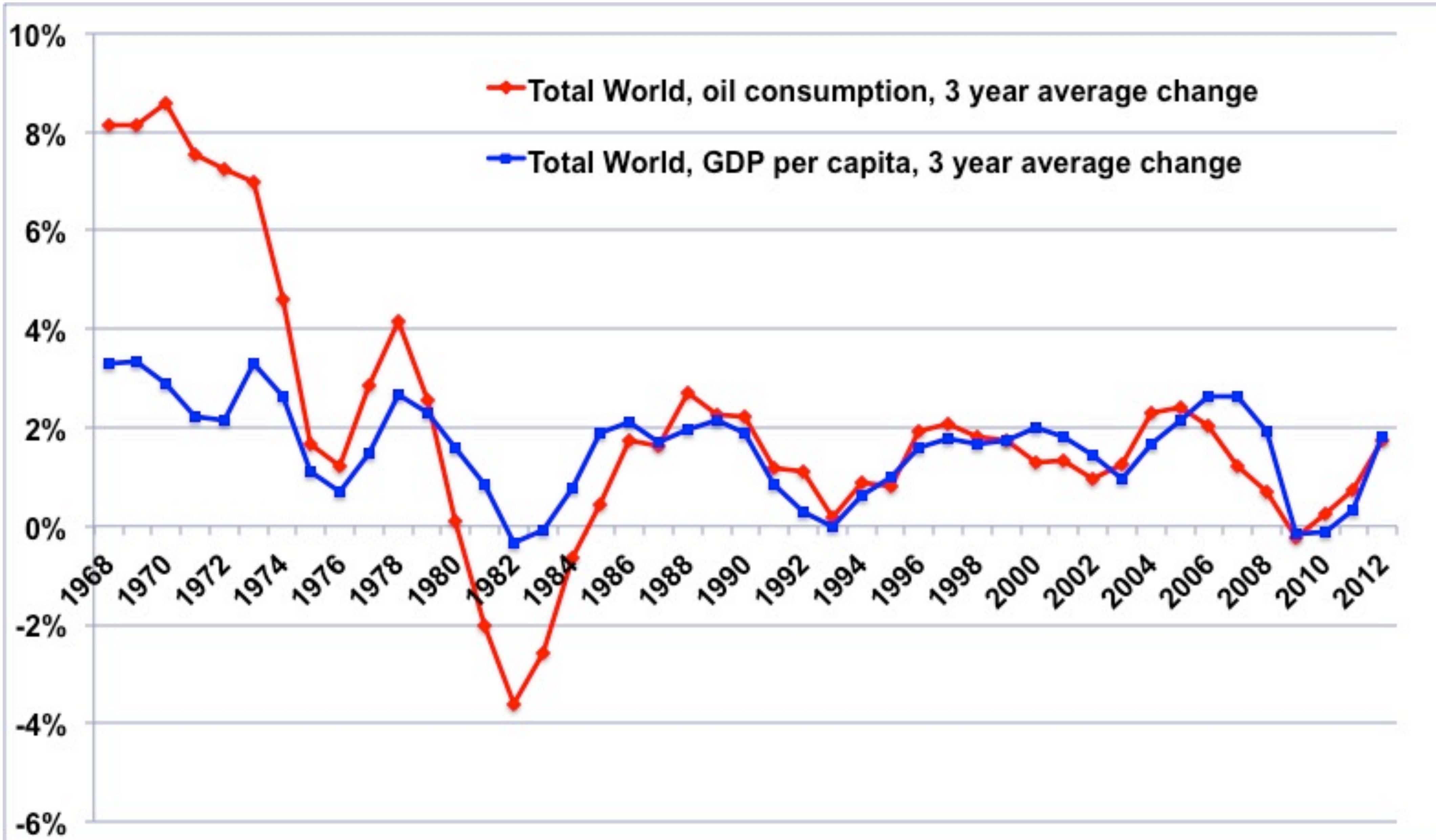


# Energy & GDP




Source: The Shift Project - JM Jancovici

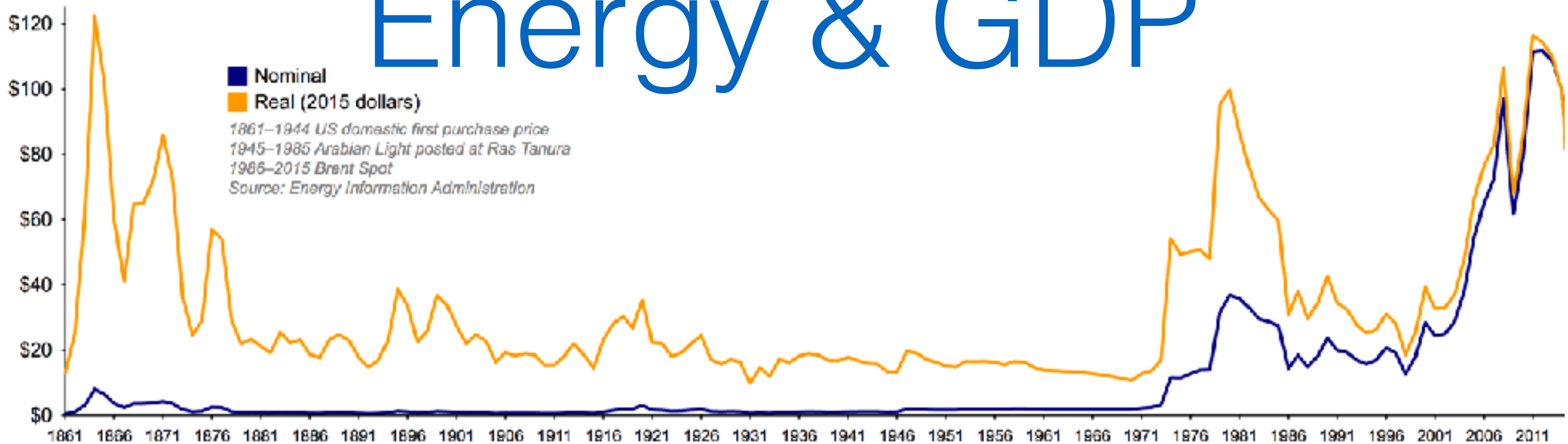
# Energy & GDP



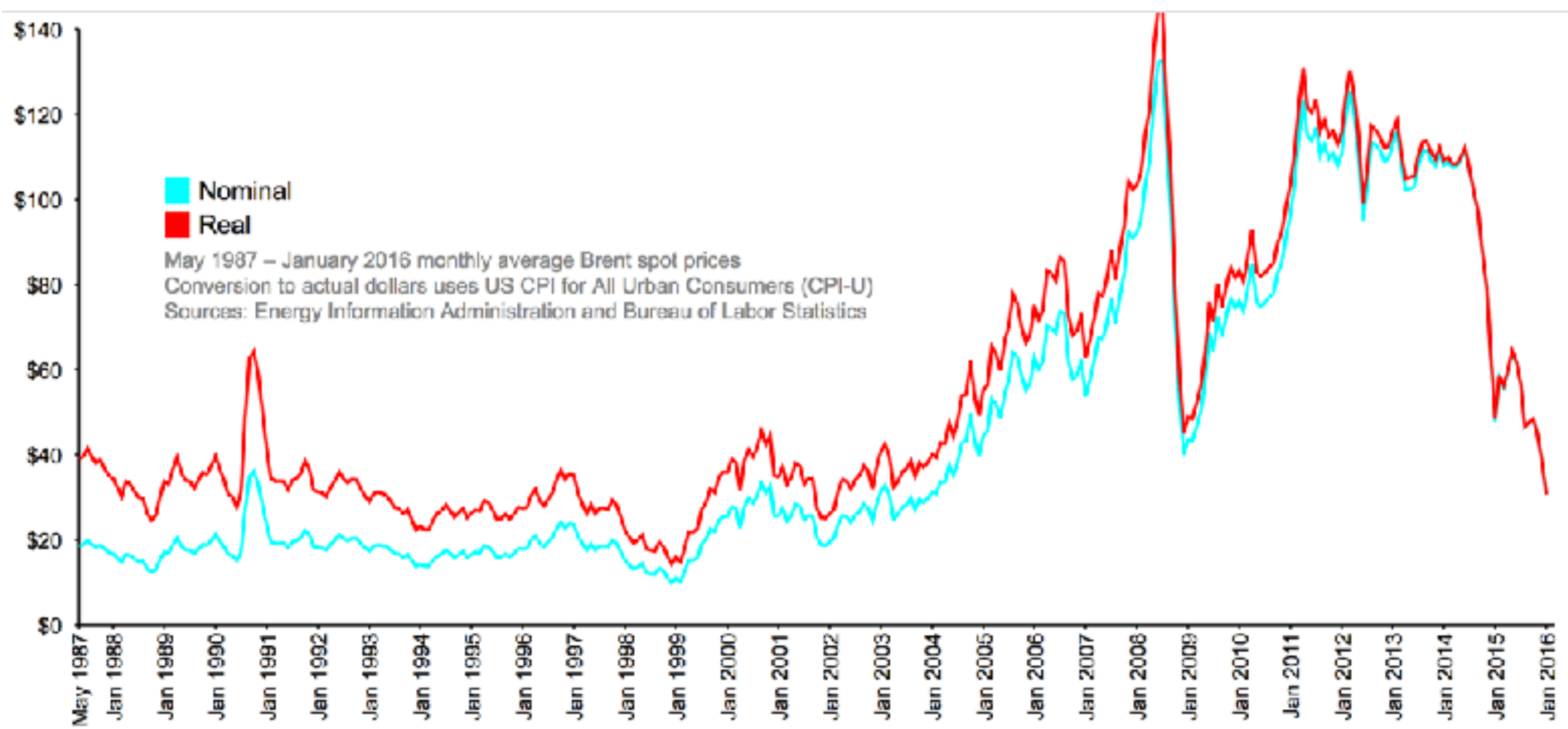

**Variation lissée de la consommation mondiale de pétrole (rouge) et du PIB par personne (bleu). Source World Bank 2013 pour le PIB, BP Stat 2013 pour le pétrole**

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

# Energy & GDP

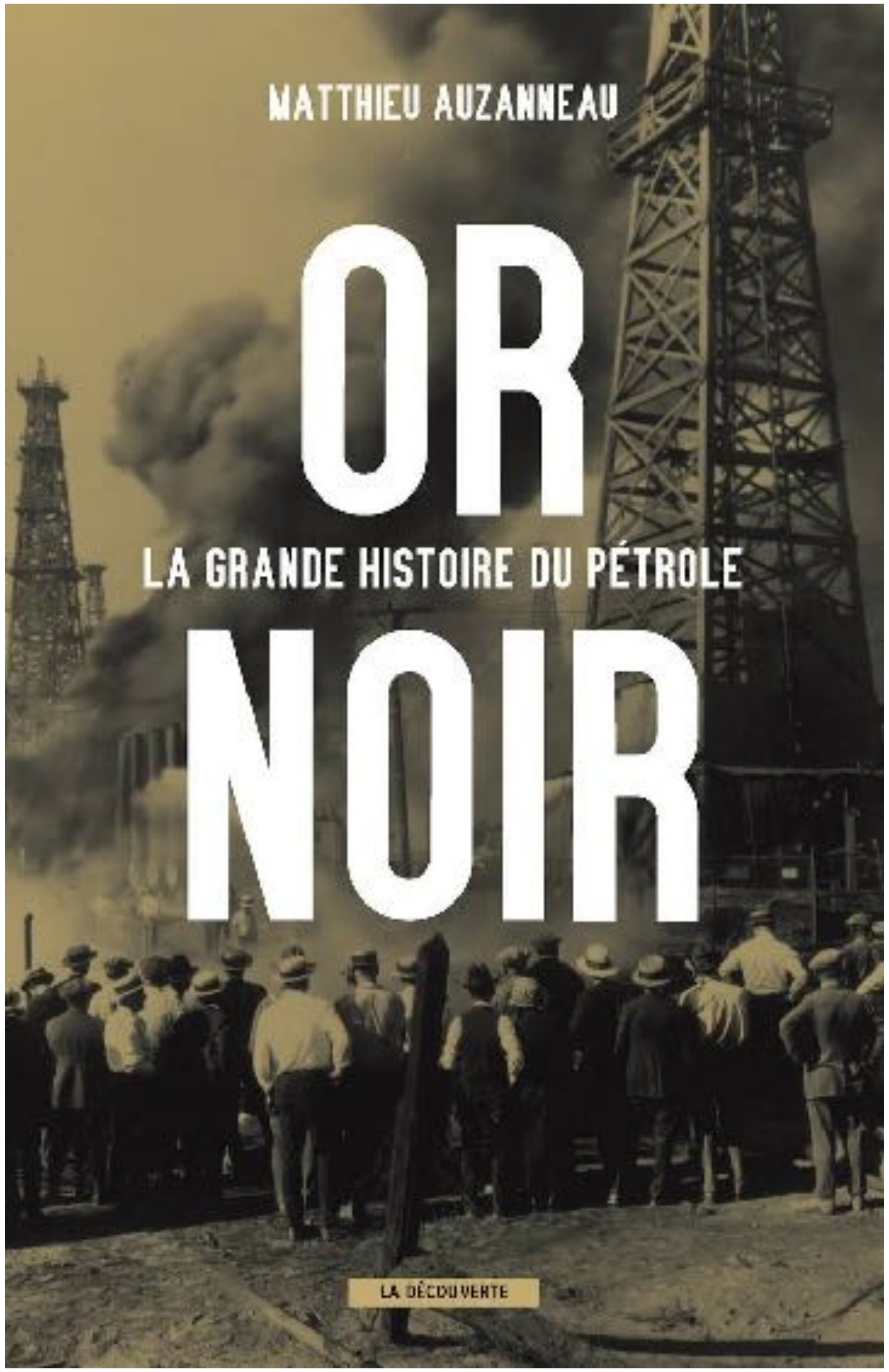


Nominal
Real (2015 dollars)
1861–1944 US domestic first purchase price
1945–1985 Arabian Light posted at Ras Tanura
1986–2015 Brent Spot
Source: Energy Information Administration
$120
$100
$80
$60
$40
$20
$0
1861 1866 1871 1876 1881 1886 1891 1896 1901 1906 1911 1916 1921 1926 1931 1936 1941 1946 1951 1956 1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011

Nominal
Real
May 1987 – January 2016 monthly average Brent spot prices
Conversion to actual dollars uses US CPI for All Urban Consumers (CPI-U)
Sources: Energy Information Administration and Bureau of Labor Statistics
$140
$120
$100
$80
$60
$40
$20
$0
May 1987 Jan 1988 Jan 1989 Jan 1990 Jan 1991 Jan 1992 Jan 1993 Jan 1994 Jan 1995 Jan 1996 Jan 1997 Jan 1998 Jan 1999 Jan 2000 Jan 2001 Jan 2002 Jan 2003 Jan 2004 Jan 2005 Jan 2006 Jan 2007 Jan 2008 Jan 2009 Jan 2010 Jan 2011 Jan 2012 Jan 2013 Jan 2014 Jan 2015 Jan 2016

# A must read


MATTHIEU AUZANNEAU
OR NOIR
LA GRANDE HISTOIRE DU PÉTROLE
LA DÉCOUVERTE

# The Challenge (1)

Non renewable

> 80% - < 20%

Renewable

# The Challenge (2)

Dematerialized economy does not exist on its own.

« You cannot compute food, and even if you could, you would need an industry to build computers ».

D.R.

# Modeling the transition

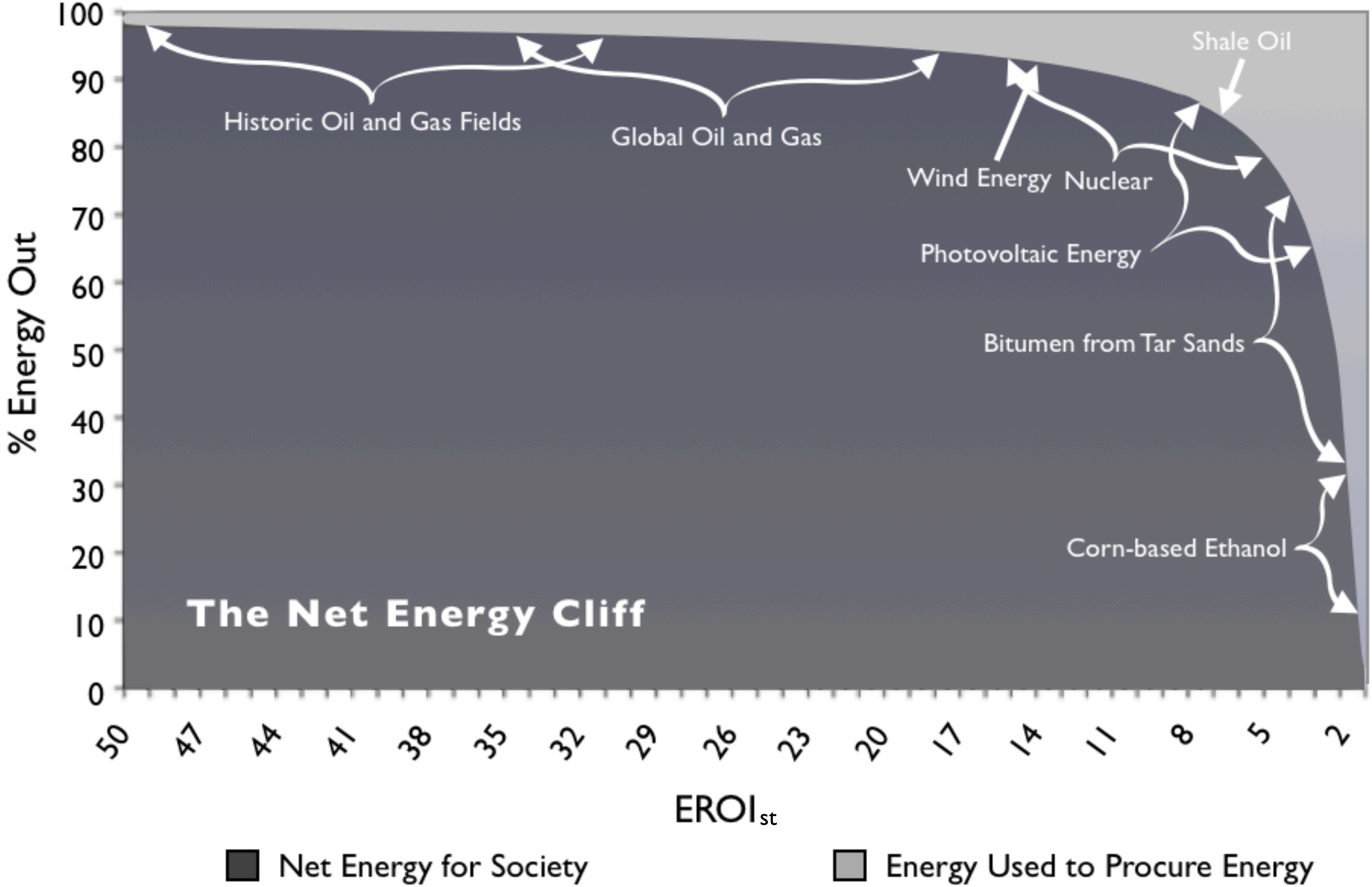
# ERoEI

- **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:

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

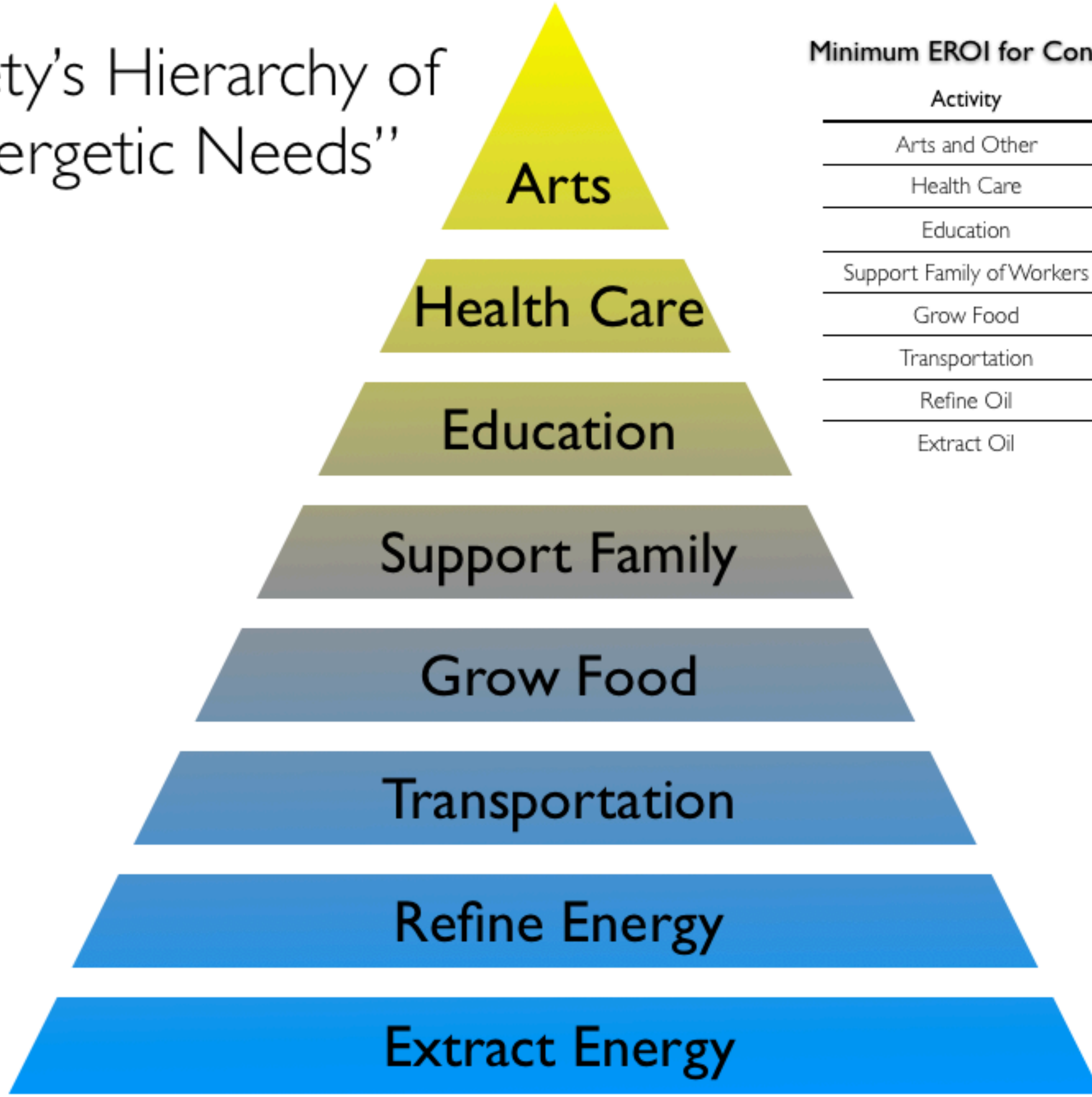
- The highest this ratio, the more energy a technology brings back to society

- 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*

# Society's Hierarchy of "Energetic Needs"




**Minimum EROI for Conventional Sweet Crude Oil**

| Activity | Minimum EROI Required |
|---|---|
| Arts and Other | 14 : 1 |
| Health Care | 12 : 1 |
| Education | 9 or 10 : 1 |
| Support Family of Workers | 7 or 8 : 1 |
| Grow Food | 5 : 1 |
| Transportation | 3 : 1 |
| Refine Oil | 1.2 : 1 |
| Extract Oil | 1.1 : 1 |

*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*

# Modeling the transition

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

- Budget of non-renewable energy

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

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

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

# Modeling the transition

- Set of renewable energy production technologies:

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

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

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

- Deployment strategy

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

# Modeling the transition

- Energy costs for growth and long-term replacement

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

$$C_{n,t}\left(R_{n,t}, \alpha_{n,t}\right) \geq 0 \qquad M_{n,t} \geq 0$$

- Total energy and net energy to society

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

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

# Modeling the transition

- Constraint on the quantity of energy invested for energy production

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

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

# Modeling the transition

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

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

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

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

$$E_0 = 1$$

$$B_0 = 0.85E_0$$

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

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

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

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

$$\sigma_t = 14$$

Constant growth if possible, else max admissible

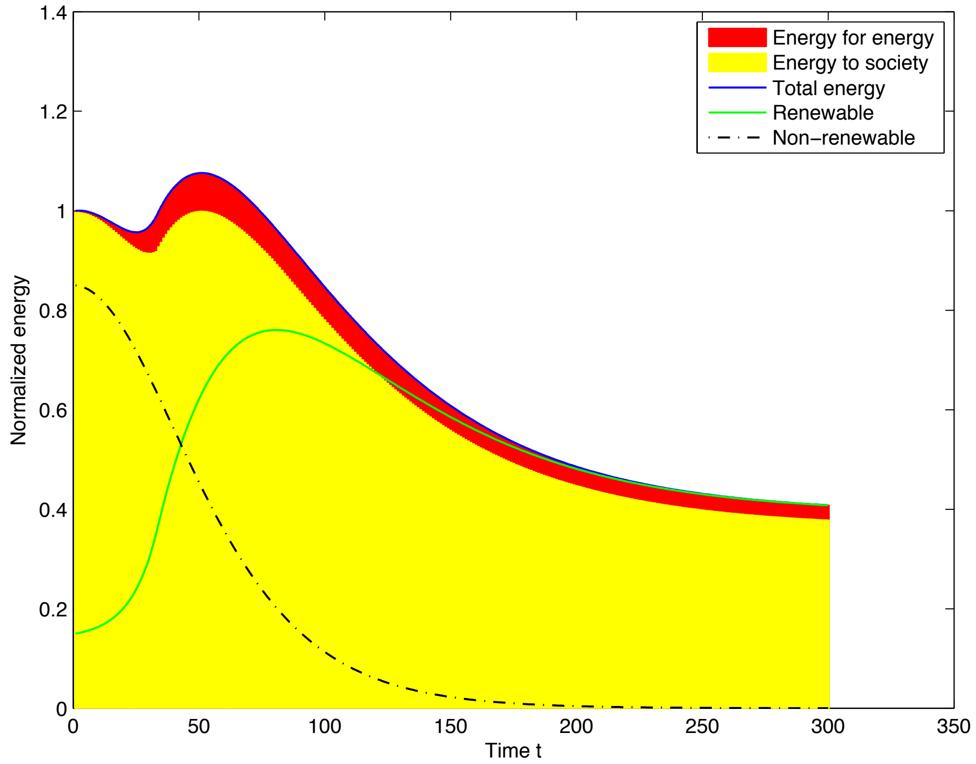



**Fig. 2.** Scenario "peak at time t=0"

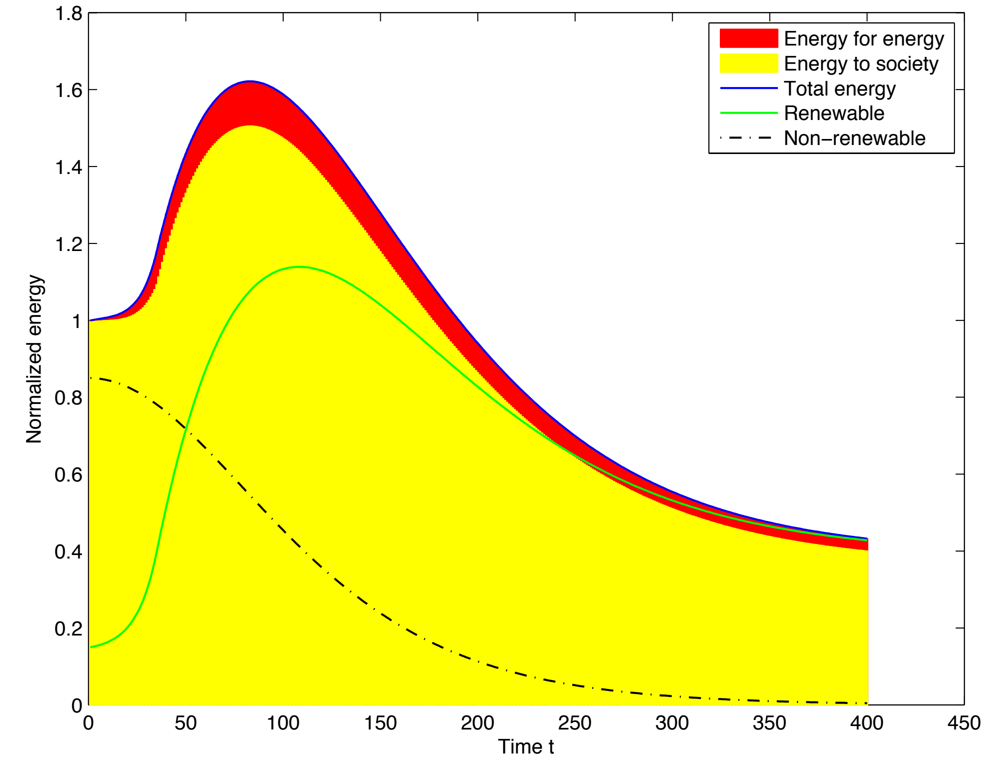



**Fig. 3.** Scenario "plateau at time t=0"

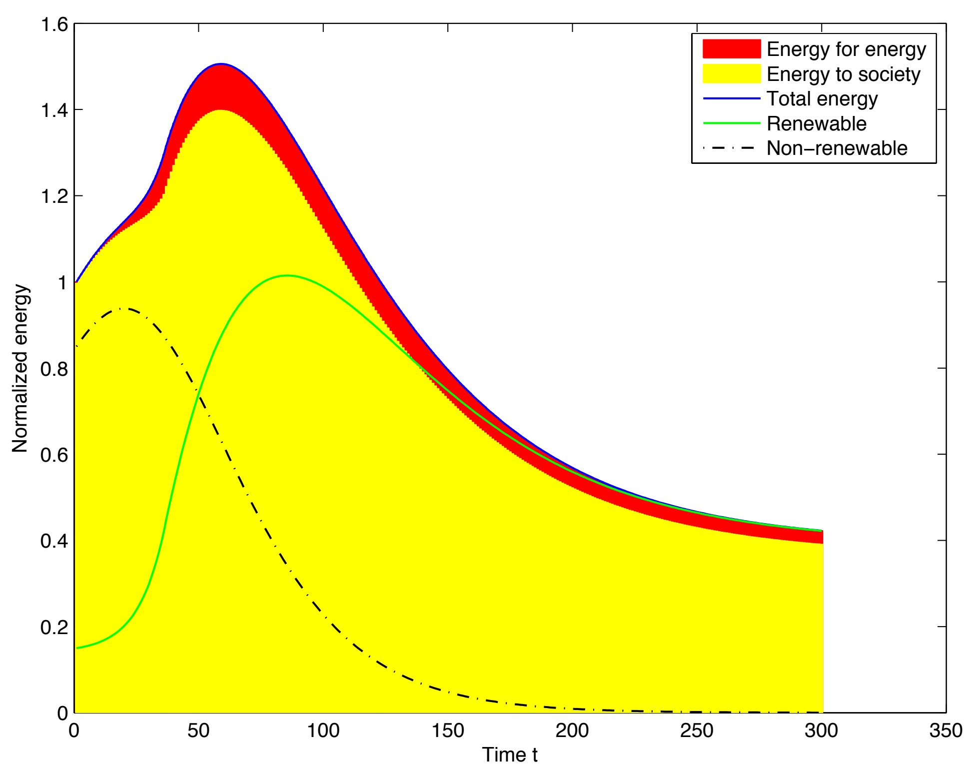



**Fig. 4.** Scenario "peak at time t=20"

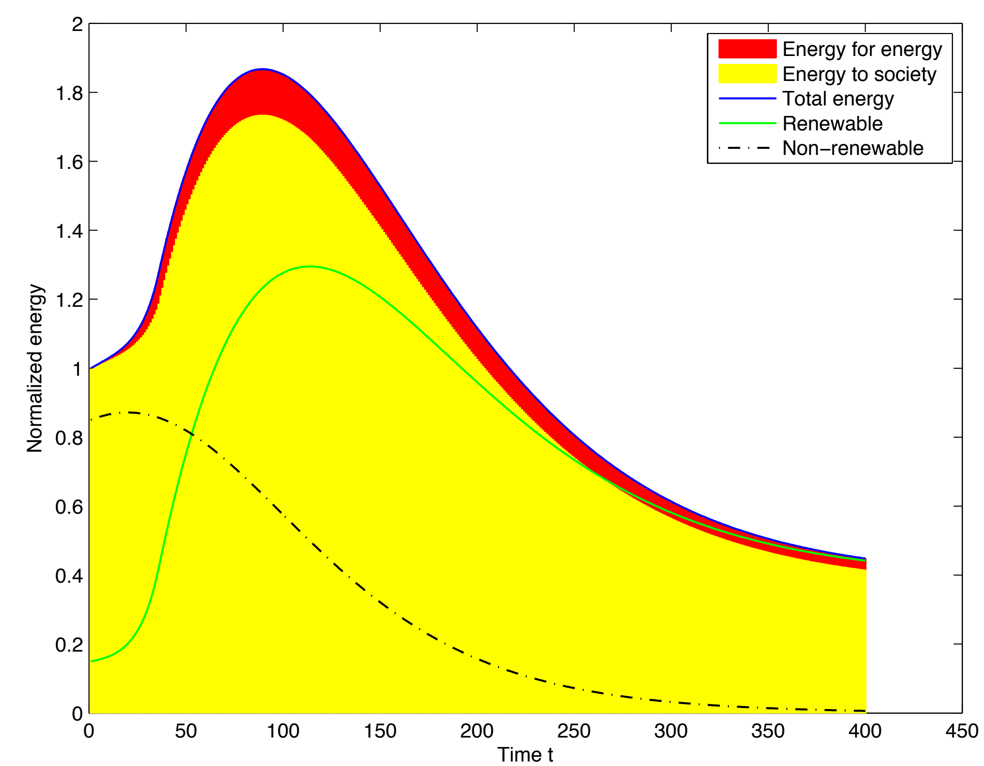
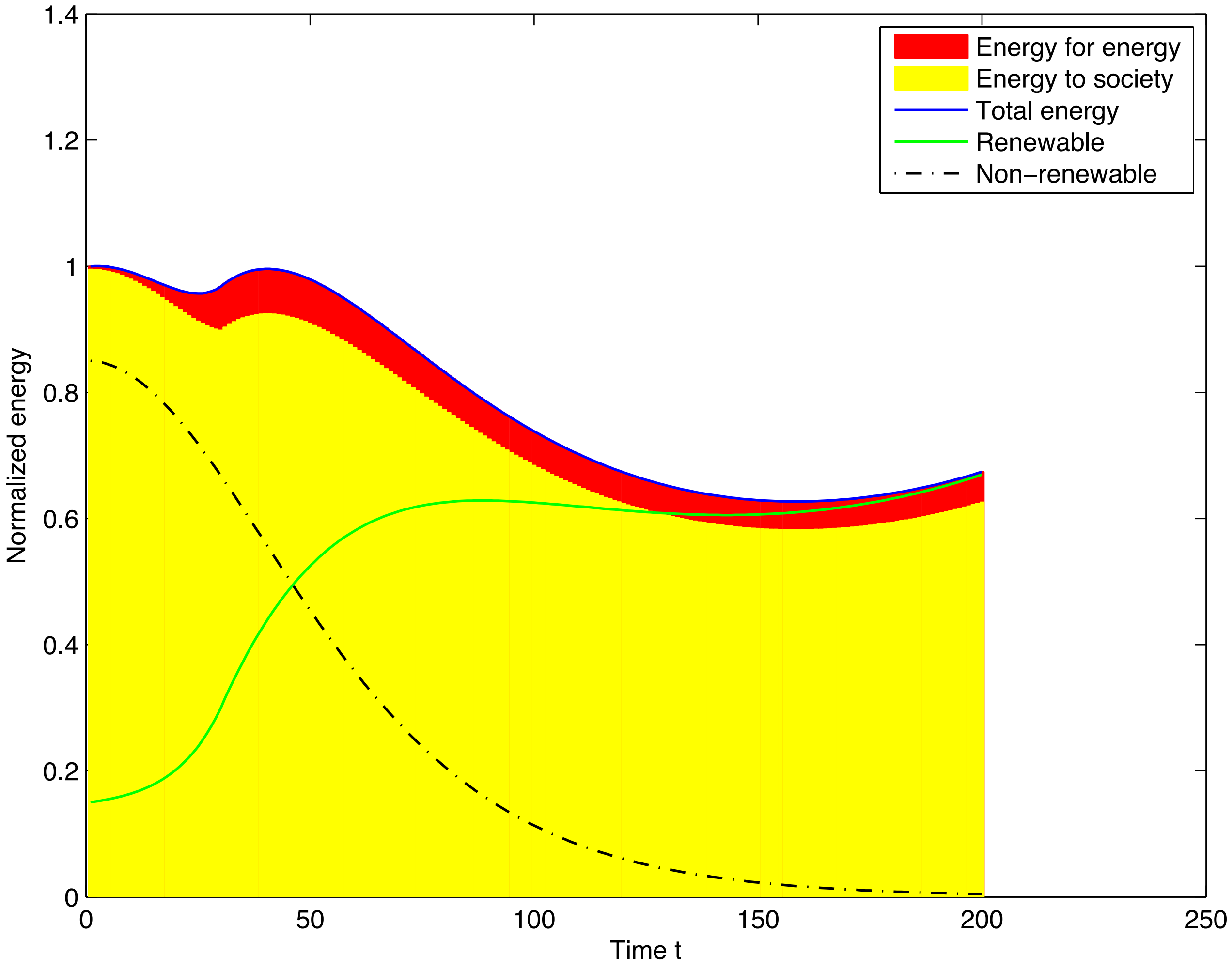



**Fig. 5.** Scenario "plateau at time t=20"

# Modeling the transition

- Increasing the ERoEI parameter




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

So?

# A few suggestions

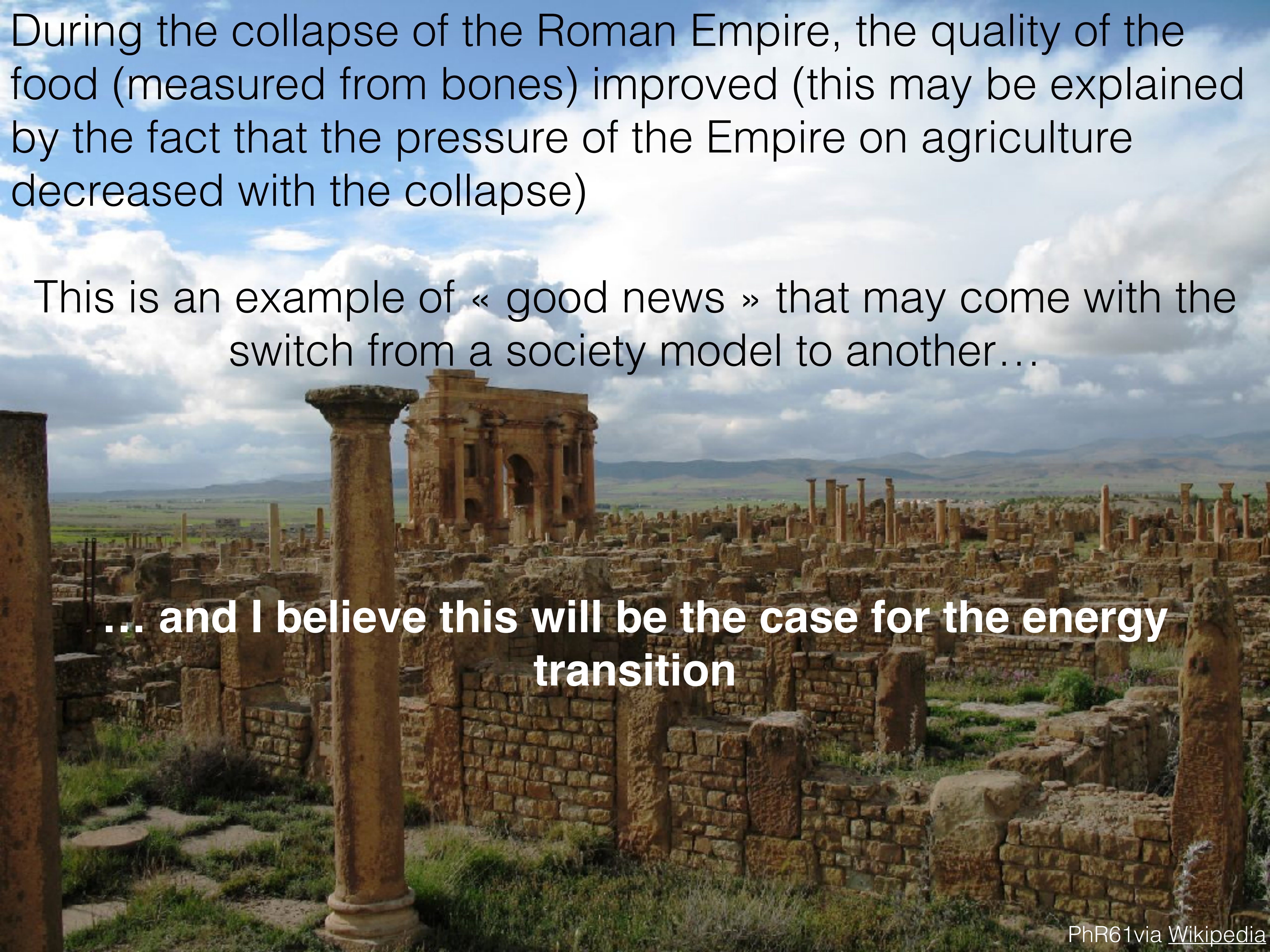
- What kind of decisions can be suggested by such a « rough model »?
    - Price may not always be a good indicator
    - Pay attention to the ERoEI
    - Energy efficiency: « do better with less »
- The energy transition is a global process: how to prioritize actions?
    - Back to Maslow

# Epilogue

During the collapse of the Roman Empire, the quality of the food (measured from bones) improved (this may be explained by the fact that the pressure of the Empire on agriculture decreased with the collapse)

This is an example of « good news » that may come with the switch from a society model to another…

**… and I believe this will be the case for the energy transition**



PhR61via Wikipedia

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