

# On the Dynamics of the Deployment of Renewable Energy Production Capacities

**2015 Colloquium 'Contribution of the Belgian universities to the energy transition'**

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

# Outline

**Energy  
Stories**

**Modeling the  
Transition?**

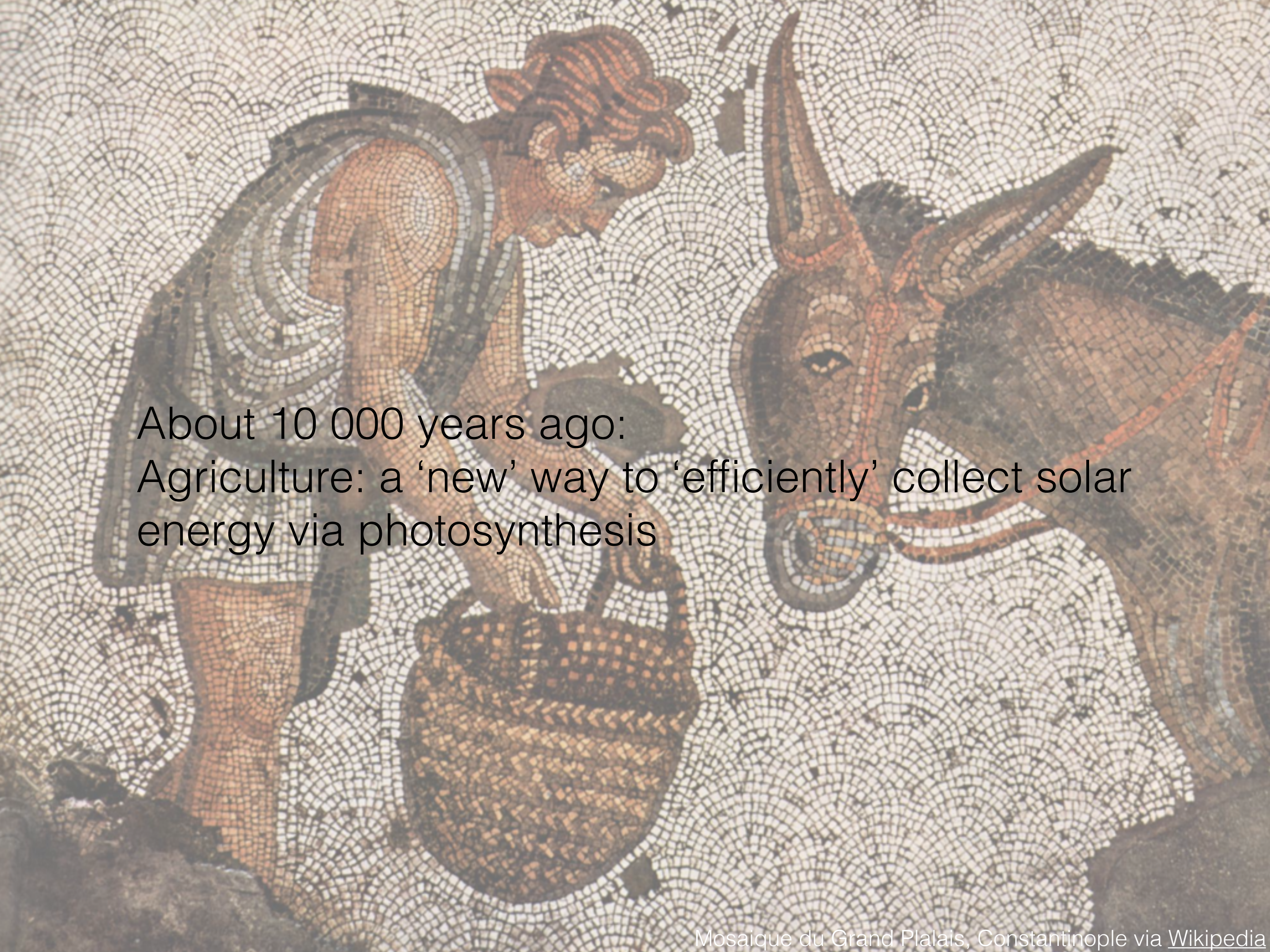
**The  
Challenge**

Energy stories




About 1 million years ago:

Fire domestication : heating, cooking, better health


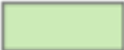
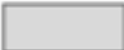


About 10 000 years ago:  
Agriculture: a 'new' way to 'efficiently' collect solar energy via photosynthesis

The image shows the Colosseum in Rome, Italy, under a hazy, overcast sky. The structure is a large, elliptical amphitheatre, partially ruined, with its iconic tiered arches visible. In the foreground, several tall, dark, conical cypress trees stand to the right of the Colosseum. The overall scene is somewhat muted and atmospheric.

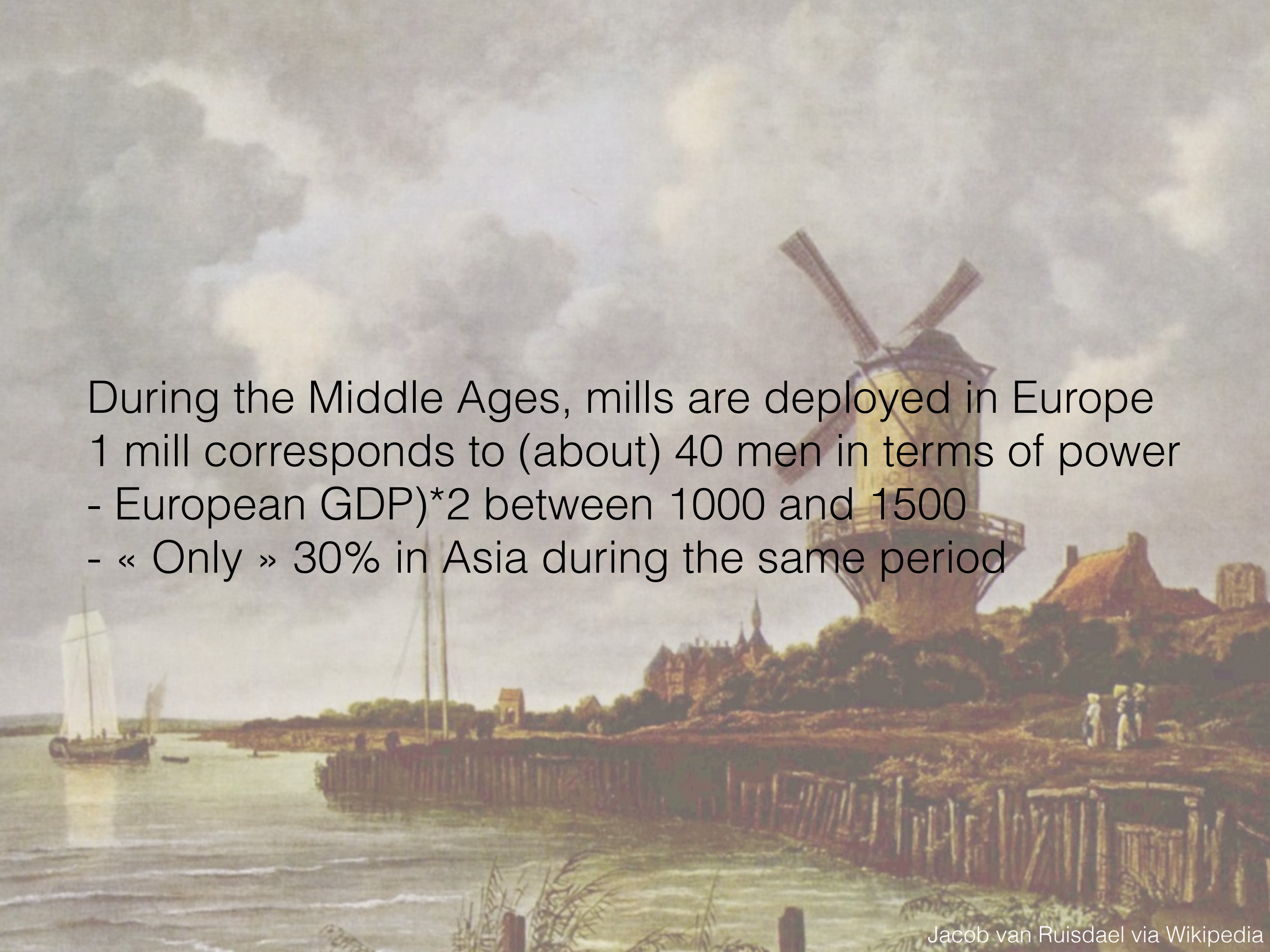
During the Roman Empire, agriculture provided food to humans (some of them are slaves) and animals: this was (almost) the only source of energy

# The Roman Empire in 117 AD

-  Senatorial provinces
-  Imperial provinces
-  Client states


Well, the Romans used to have another source of energy...



A painting by Jacob van Ruisdael depicting a Dutch landscape. In the foreground, a wooden dike runs along a river. A large windmill stands on a hill in the middle ground. In the background, a church with a spire is visible. A boat with a white sail is on the river. The sky is filled with dramatic, cloudy light.

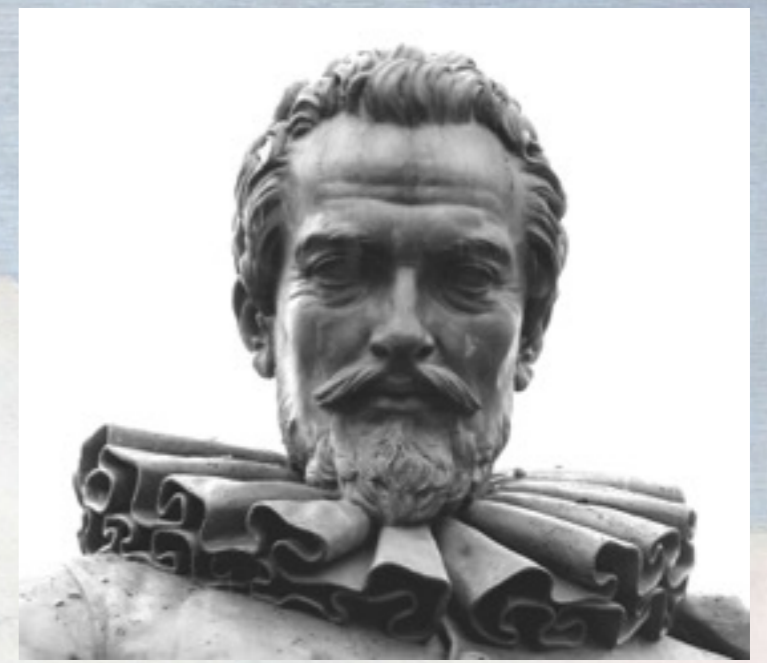
During the Middle Ages, mills are deployed in Europe  
1 mill corresponds to (about) 40 men in terms of power  
- European GDP)\*2 between 1000 and 1500  
- « Only » 30% in Asia during the same period



A painting of a large Dutch sailing ship at sea. The ship is a three-masted vessel with white sails and a yellow flag with a red lion on the mainmast. The ship is surrounded by smaller boats and a crowd of people on the deck. The scene is set against a blue sky with clouds and a blue sea.

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

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

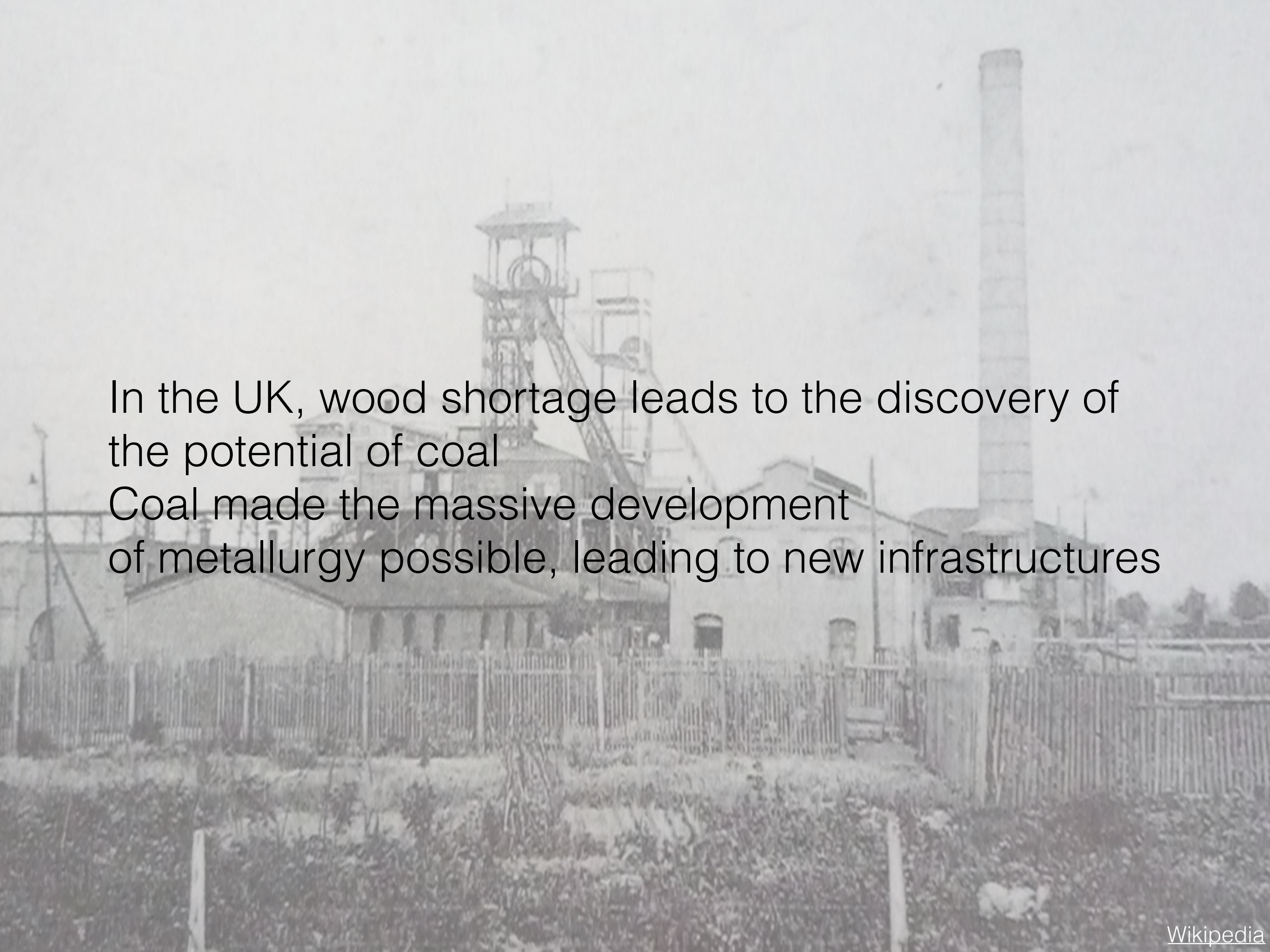


« *Een Wonder en is gheen wonder* »  
Simon Stevin





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

A black and white photograph of a coal mine. In the center, a tall, complex headframe structure is visible, used for winding ropes to move coal from underground. To the right, a very tall, slender brick chimney stack rises into the sky. In the foreground, a wooden picket fence runs across the frame, separating the viewer from the mine buildings. The background shows more industrial buildings and a hazy sky.

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

A black and white photograph of a busy gas station. In the foreground, a Volkswagen Beetle is being refueled by an attendant in a dark uniform and cap. The car's license plate reads "B-D 1853". Behind it, a line of other vintage cars is waiting. The station has several service bays with attendant booths. The roof is a complex metal truss structure. The overall scene depicts the post-war boom in automobile ownership and the rise of the consumer society.

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

The background of the slide is a photograph of an oil pumpjack (jack-o'-lantern) in silhouette against a sunset sky. The sun is a bright, glowing orb positioned low on the horizon, partially obscured by the structure of the pumpjack. The sky is filled with soft, wispy clouds, and the overall color palette is dominated by warm tones of orange, yellow, and light blue.

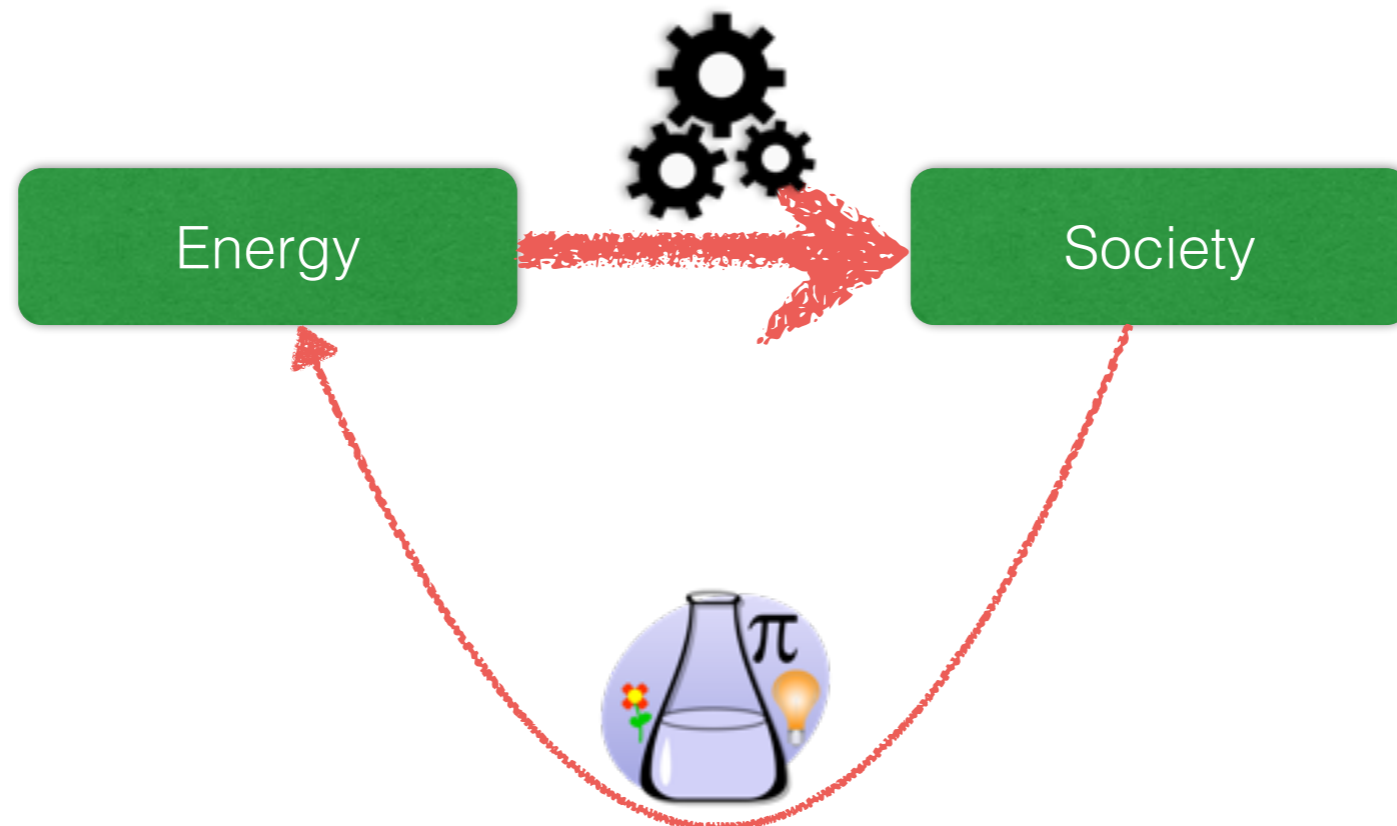
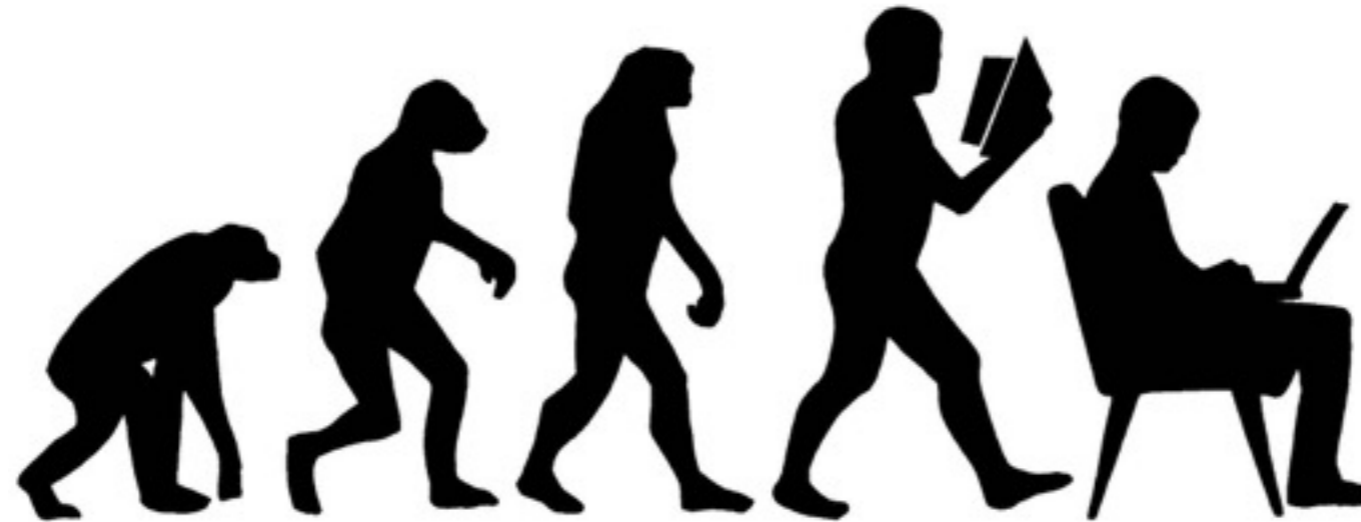
In Europe, almost 5% GDP growth per year during 30 years  
« The Glorious Thirty » - « Les Trente Glorieuses »

...

-> 1973 Oil Crisis

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

# Trajectories of Societies



# The Challenge



# The Challenge

Non renewable

> 80% - < 20%

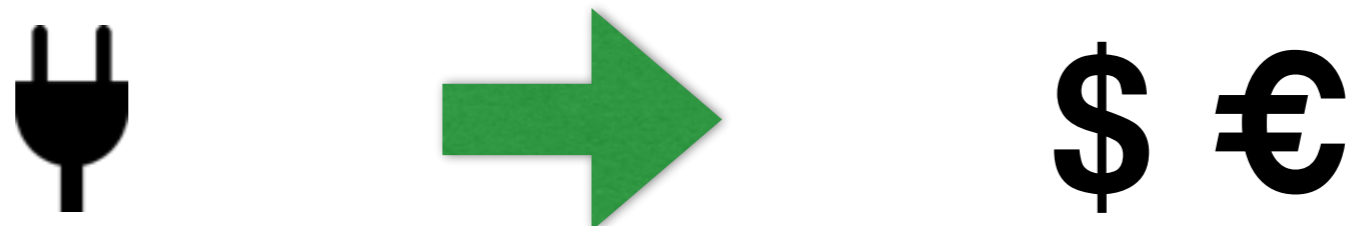
Renewable

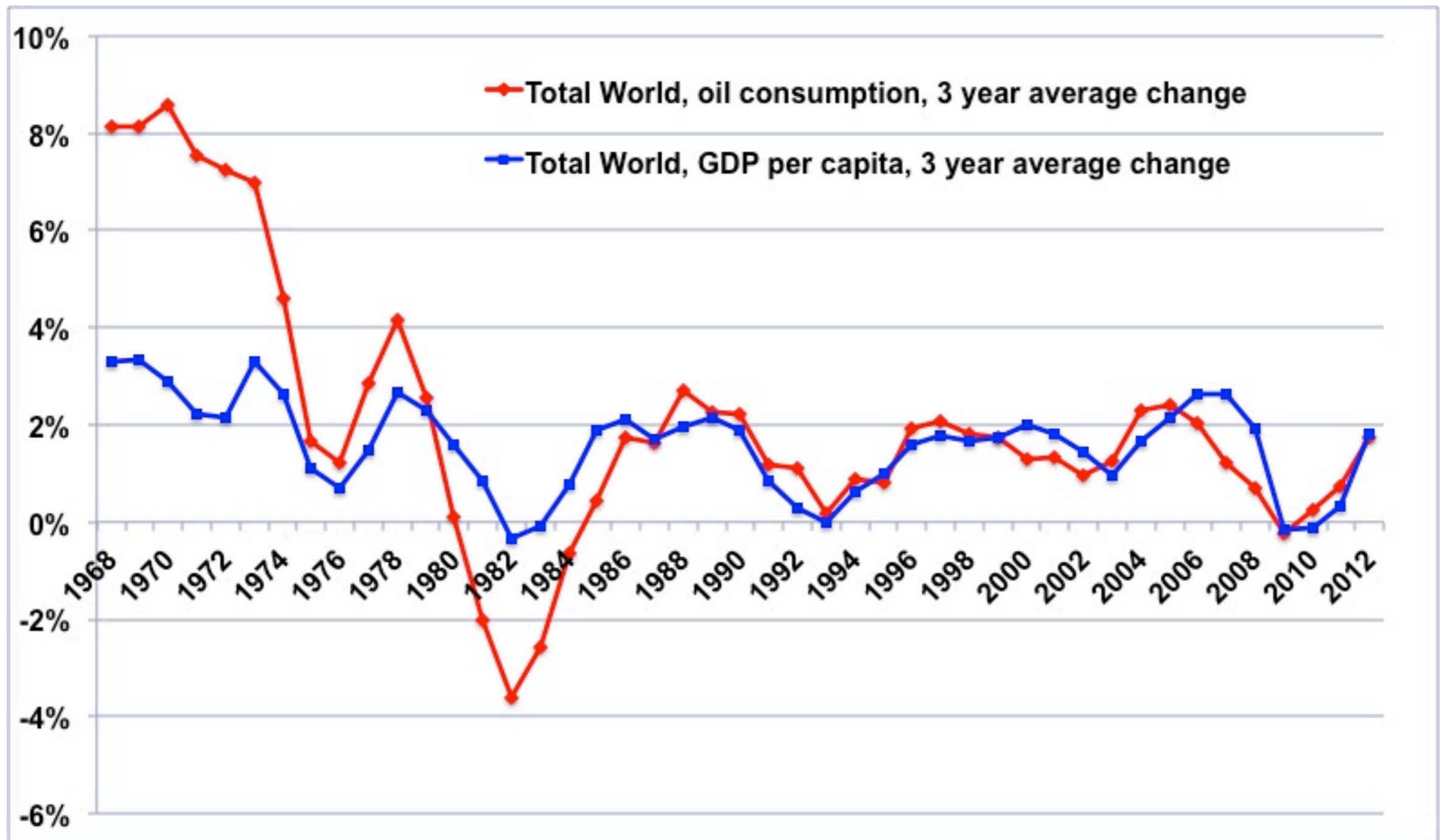
# The Challenge

- 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

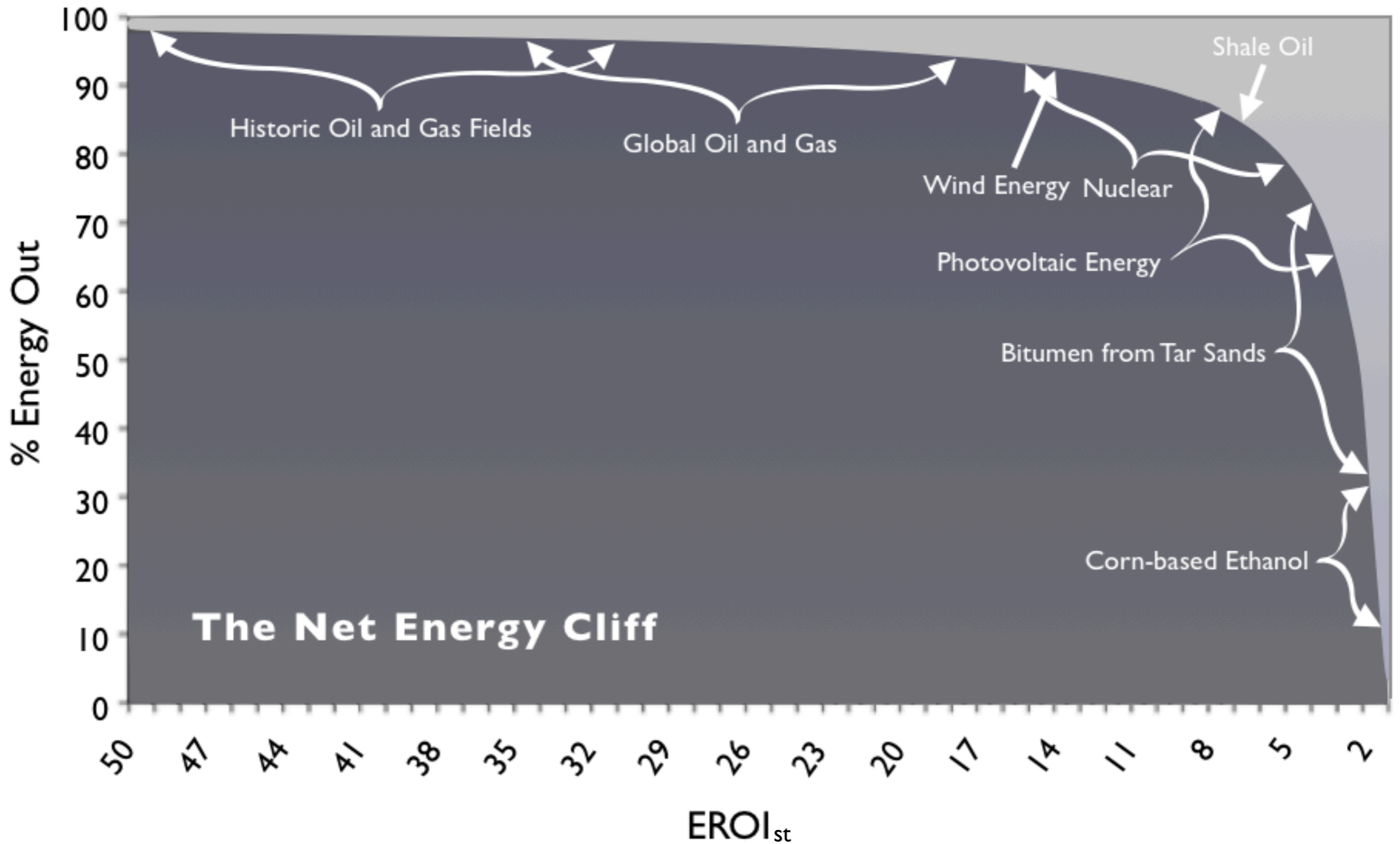
Modeling the  
transition?

# 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:

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

- 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

# Modeling the transition

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

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

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

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

# Modeling 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

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



# Modeling 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

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

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

# Modeling the transition

- Constraint on the quantity of energy invested for energy production

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

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

# Modeling the transition

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

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

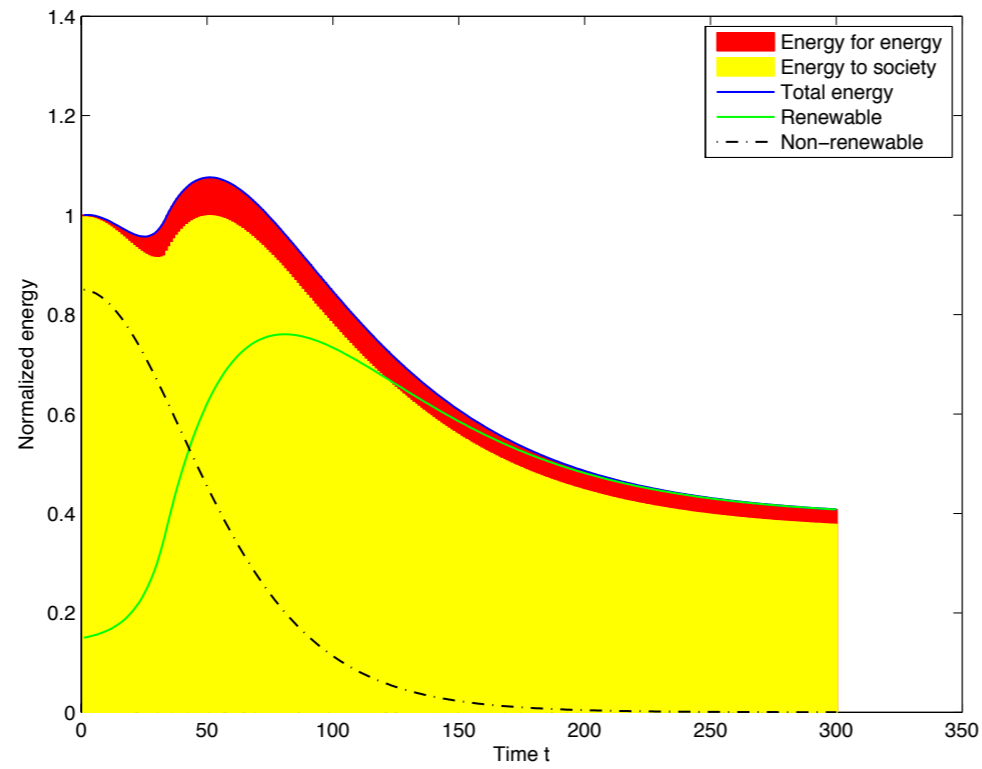
- Long-term replacement cost is (i) proportional and (ii) annualized

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

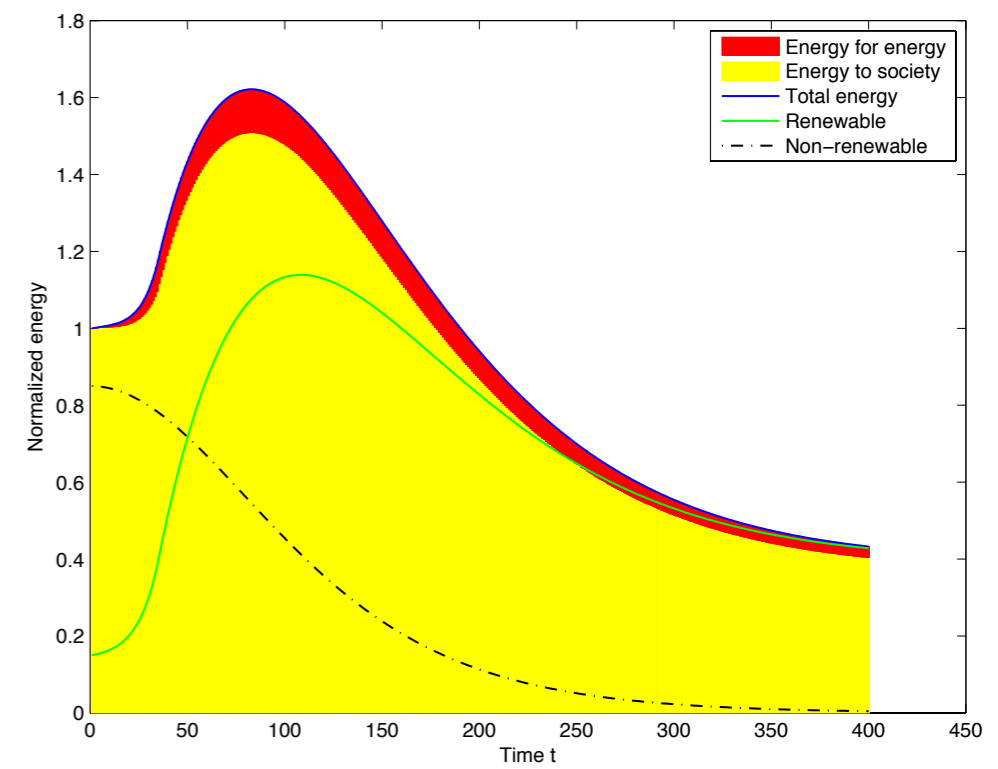
$$E_0 = 1$$

$$B_0 = 0.85E_0$$

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



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



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

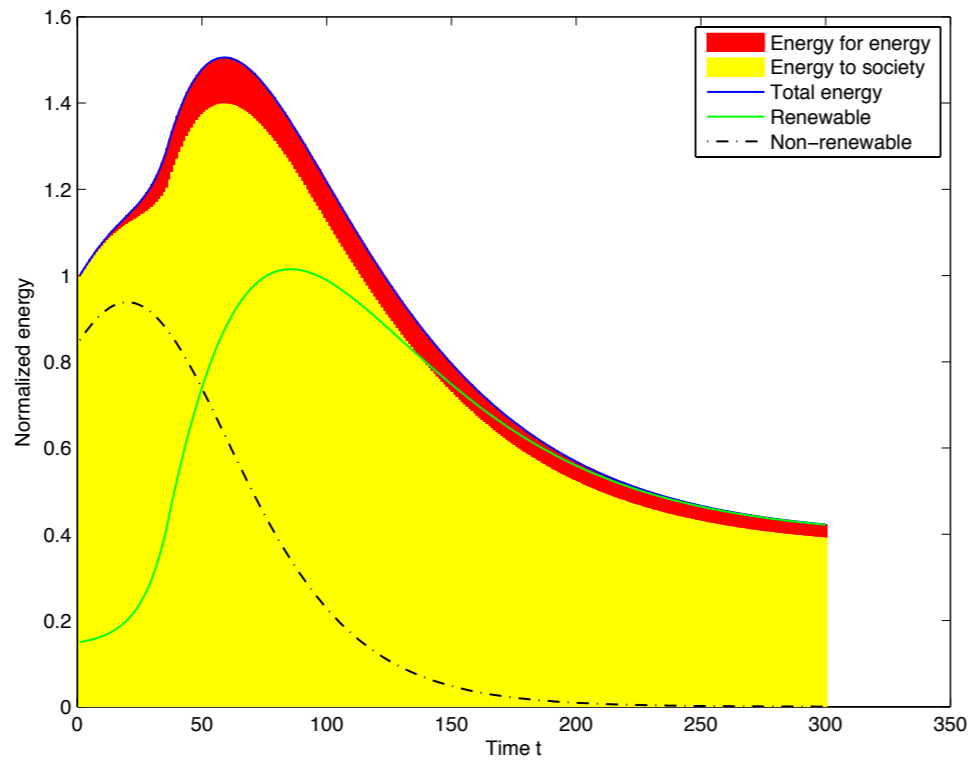
$$\sum_{n=2}^N R_{n,0} = 0.14E_0$$

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

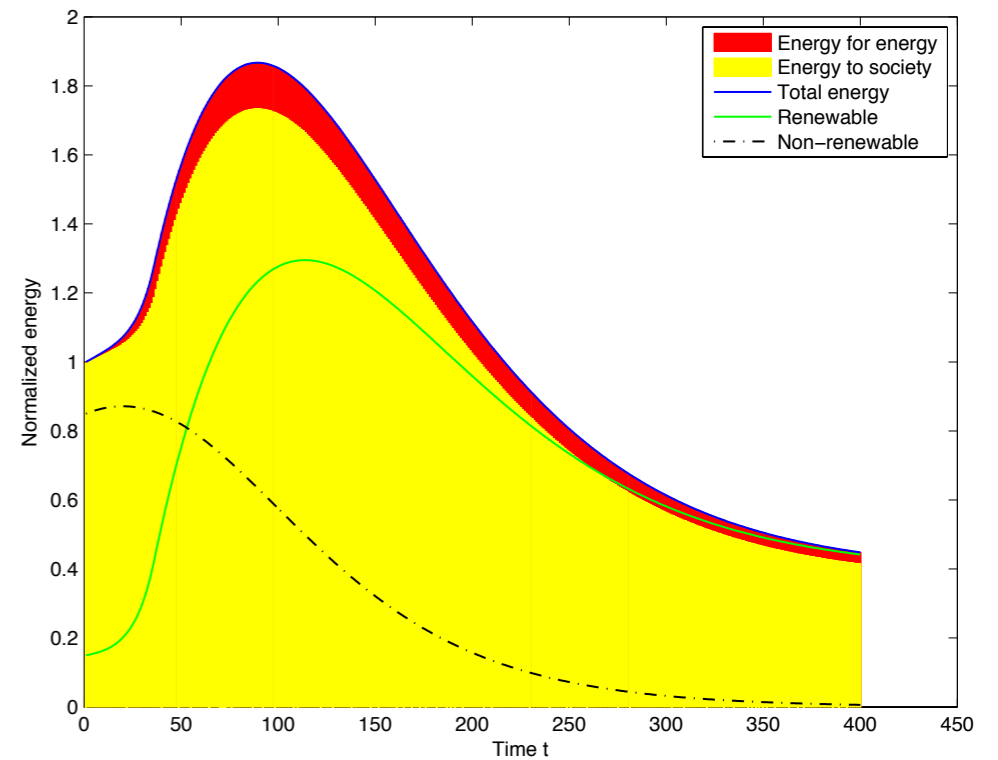
$$\Delta_{1,t} = 20$$

$$\sigma_t = 14$$

Constant growth  
if possible, else  
max admissible



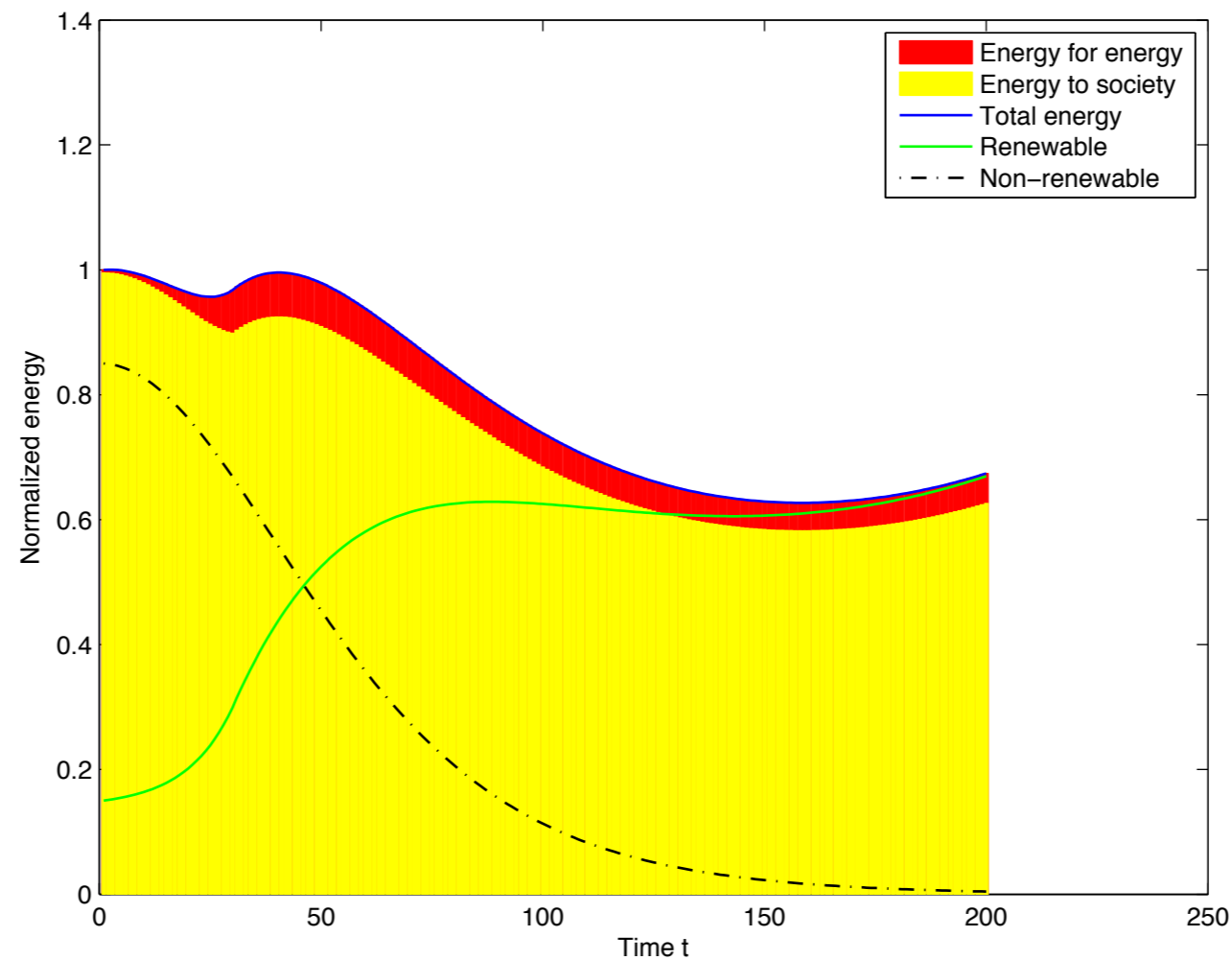
**Fig. 4.** Scenario “peak at time t=20”



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

# Modeling the transition

- Increasing the EROEI parameter



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

# A few suggestions

- What kind of decisions can be suggested by such a « rough model »?
  - Price may not always be a good indicator
  - Energy efficiency: « do better with less »
- > Lots of decision making under uncertainty problems to solve here
- For people interested in Smart Grids: below is link toward a simulator for Active Network Management (ANM) developed by my colleagues at the University of Liège:

<http://www.montefiore.ulg.ac.be/~anm/>

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**



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