Une histoire d’énergie : équations et transition

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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 l 13.11.2017 à 16h05 • Mis à jour le 14.11.2017 à 14h18 l
Par Stéphane Foucart et Martine Valo

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 l 15.11.2017 à 07h50 • Mis à jour le 15.11.2017 à 12h17 l
Par Guy Dutheil
Outline

Energy Stories

Modeling the Transition
Energy stories
About 1 million years ago:
Fire domestication: lighting, heating, cooking
-> improved health
About 10 000 years ago:
Agriculture: a ‘new’ way to ‘efficiently’ collect solar energy via photosynthesis
During the Roman Empire, agriculture provided food to humans (some of them are slaves) and animals: this was (almost) the only source of energy
Well, the Romans used to have another source of energy…

Andrei Nacu 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
« Een Wonder en is gheen wonder »
Simon Stevin
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.)
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.
After WW2, almost exponential growth of oil consumption opens the so-called « consumer society » era.
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
Trajectories of Societies
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 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
Energy & GDP

Total World

\[ y = 7,0399x - 15298 \]
\[ R^2 = 0.9855 \]

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.

Energy & GDP

1861–1944 US domestic first purchase price
1945–1985 Arabian Light posted at Ras Tanura
1986–2015 Brent Spot
Source: Energy Information Administration

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
The Challenge

> 80% - < 20%

Non renewable

Renewable
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
Importance of EROI

"The utility of a fuel depends upon not only its quality but also how much of it there is that is, its quantity." - Murphy et. al, 2010 [71]

For example, wind power may have a moderately high EROI, especially at very favorable locations. Nevertheless, the total quantity of electricity that is produced and delivered is typically small in comparison with energetic needs. This is slightly less true for some low population mountainous or coastal regions where wind power is prolific (e.g. Denmark). But, even there, fossil fuels remain dominant in the region's total energy profile, and current technology demands very expensive and energy-intensive backup systems [6].

Other non-traditional energy sources such as biodiesel and photovoltaics tend to have relatively low EROIs when compared to those of traditional fossil fuels (e.g. coal). To date, these alternative fuels claim an insubstantial portion of the total energy consumed by the majority of nations [6]. The total magnitude of alternative energy produced remains so very small that it is not likely to be a significant contributor to total global energy production for many years or even decades. Murphy et al., 2010 report that just prior to the financial collapse of 2008 [71], the annual global increase of each conventional fossil fuel (oil, gas, and coal) was greater than the total annual production of all non-conventional, solar-based (i.e., wind turbines and photovoltaics) energy [71]. What this means is that energy derived from non-conventional, solar-based, energy sources is not displacing fossil fuel use. Instead, it is merely contributing to the annual global energy growth.

Hierarchy of Energetic Needs

Certain thresholds of surplus energy must be met in order for a society to exist and flourish. The above hierarchy of "energetic needs" is somewhat akin to Maslow's "pyramid of (human) needs". It represents the importance of the quality of energy devoted to the production and maintenance of infrastructure required to support society. We analyze this using EROI analysis. If the EROI for oil was 1.1 to 1 (1.1:1) then one could pump the oil out of the ground and look at it. If it were 1.2:1 you could both extract it and refine it (Appendix B). At a 1.3:1 EROI it could also be distributed to where it is useful but, once again, all you could do is look at it. Hall and Klitgaard examined the EROI required to run a truck [6]. They found that an EROI of at least 3:1 EROI at the wellhead was necessary to build and maintain the truck and the roads and bridges required to use one unit, including depreciation (Appendix C) [6]. In a thought experiment Hall and Klitgaard found that in order to deliver a product in the truck, such as grain, an EROI of roughly 5:1 is required to include growing and processing the grain to be delivered. To include depreciation of the oil field worker, the refinery worker, the truck driver and the farmer, it would require the support of the families and an EROI of approximately 7 or 8:1. If the children of these families were to be educated an EROI value in the region of 9 or 10:1 would be required. If the families and workers receive health care and higher education then an EROI value of perhaps 12:1 at the wellhead is required. An EROI value of at least 14:1 is needed to provide the performing arts and other social amenities to these families and workers. In other words to have a modern civilization, one needs not simply surplus energy but lots of it, and that requires either a high EROI or a massive source of moderate EROI fuels.

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
  \[
  R_{n,t+1} = (1 + \alpha_{n,t})R_{n,t} \quad \alpha_{n,t} \in [-1, \infty[ 
  \]
Modeling the transition

- Energy costs for growth and long-term replacement

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

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

- Total energy and net energy to society

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

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

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

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

  \[ M_{n,t} (R_{n,t}) = \frac{1}{ERoEI_{n,t}} R_{n,t} \]
$E_0 = 1$

$B_0 = 0.85E_0$

$R_{1,0} = 0.01E_0$

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

$E RoEI_{1,t} = 9$

$\Delta_{1,t} = 20$

$\sigma_t = 14$

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
References