Energy Transition: How Can We Succeed?

InsideOut - Scientizenship - BEST
Liège, July 22nd, 2014

Raphael Fonteneau
1. Preamble

2. Energy: facts and stories

3. Simulating the energy transition?

4. Epilogue
Preamble

Photo: Kurohito via Wikipedia
What do you use « energy » for?
When don’t you use « energy »?
What allows us to spend time discussing together now instead of growing our own food to survive?
Energy: facts and stories

Jacob van Ruisdael (1628/1629–1682)
Energy and Society

• Diversification of human activities was made possible by the growth of workforce productivity
  
  It offered to humans the opportunity to spend time completing tasks that are not directly related to farming, making clothes or building houses

• The growth of workforce productivity is mainly due to the use of « machines »

• These machines are powered by energy

• A virtuous circle can be observed, since the growth of available energy indirectly allows to increase the energy efficiency of these « machines »

• In particular, social progress can also be seen as a consequence of the access to abundant energy

• Having access to huge quantities of energy is at the basis of our society model
The example of the industrial revolution of the 11th-12th centuries in Europe

- GDP per inhabitant in Europe, around year 1000: around 400 $ eq. 1990 per inhabitant (compared to 450 in Asia at the same time)

- GDP per inhabitant in Europe, around year 1500: around 750 $ eq. 1990 per inhabitant (compared to 572 in Asia at the same time, and 566 world average)

- It is very likely that the massification of the use of watermills and windmills, each of these supplying as much energy as 40 men, has played a big role in this GDP increase

- This is also the case of the « Dutch Golden Age » (16th century), that relied on the supply of cheap energy from windmills and from peat, easily transported by canal to the cities. The invention of the sawmill enabled the construction of a massive fleet of ships for worldwide trading and military defense

Sources:
- Angus Maddison, « When and Why did the West get Richer than the Rest ? »
- (In French) "La Fabuleuse Histoire de la Science », episode 4/6, Qu’est-ce que l’énergie?
Variation of the world energy consumption (green) and GDP - constant $ (blue) - Data from the World Bank for GDP and BP stat for energy

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

From the economic point-of-view

- Recent research (Giraud et al.) has shown that the sensitivity (« elasticity ») of the GDP per inhabitant with respect to primary energy is in the order of 60% (world average)

- This research also shows that causality is univocal in the direction energy growth -> GDP growth

**Elasticity can be quantified as the ratio of the percentage change in one variable to the percentage change in another variable, when the latter variable has a causal influence on the former**

- This result is surprising because the energy industry « only » represents around 5% of the GDP

Source (in French): Gaël Giraud, CNRS : « Le vrai rôle de l'énergie va obliger les économistes à changer de dogme » : http://petrole.blog.lemonde.fr/2014/04/19/gael-giraud-du-cnrs-le-vrai-role-de-lenergie-vu-obliger-les-economistes-a-changer-de-dogme/ and other material redirected from this page.
The challenge

• About 80% of consumed final energy is from non-renewable origin

• A decrease of the quantity of available energy is very likely to imply a GDP contraction with potential unstable consequences

• Sustaining our lifestyle implies to maintain our access to huge quantities of energy (at least for a period of time during which we can increase energy efficiency)
Problem statement

• We have access to a **budget of non-renewable energy** (ex: oil, gas, coal,…)

• These resources are currently also used to build energy production means for renewable origin (such as wind turbines or photovoltaic panels, etc)

• How can we **efficiently allocate** such a budget so as to achieve an energy transition leading to a high level of energy availability?
The transition to a society that would not rely on the use of non-renewable energy requires the use of non-renewable energy.
Energy Return Over Investment

- EROI, for « Energy Return over Investment », also called ERoEI for « Energy Return over Energy Investment » 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
A few examples

- Oil in 1930 (USA): about 1:100
- Oil and gas (world) in 1999: 1:35
- Oil and gas (world) in 2006: 1:18
- Nuclear fission (USA): 1:5-15
- Photovoltaic panels: 1:6-12
- Wind turbines: 1:18
- Hydroelectricity: > 1:100

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 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.


---

**Minimum EROI for Conventional Sweet Crude Oil**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Minimum EROI Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arts and Other</td>
<td>14:1</td>
</tr>
<tr>
<td>Health Care</td>
<td>12:1</td>
</tr>
<tr>
<td>Education</td>
<td>9 or 10:1</td>
</tr>
<tr>
<td>Support Family of Workers</td>
<td>7 or 8:1</td>
</tr>
<tr>
<td>Grow Food</td>
<td>5:1</td>
</tr>
<tr>
<td>Transportation</td>
<td>3:1</td>
</tr>
<tr>
<td>Refine Oil</td>
<td>1.2:1</td>
</tr>
<tr>
<td>Extract Oil</td>
<td>1.1:1</td>
</tr>
</tbody>
</table>

---

**Society's Hierarchy of “Energetic Needs”**

- **Arts**
- **Health Care**
- **Education**
- **Support Family**
- **Grow Food**
- **Transportation**
- **Refine Energy**
- **Extract Energy**

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.

Figure 7: The "Net Energy Cliff" (figure adapted from Lambert and Lambert, in preparation [3] and Murphy et al. 2010 [71])

As EROI approaches 1:1 the ratio of the energy gained (dark gray) to the energy used (light gray) from various energy sources decreases exponentially [71]. High EROI fuels allow a greater proportion of that fuel's energy to be delivered to society (e.g. a fuel with an EROI of 100:1 (horizontal axis) will delivers 99% of the useful energy (vertical axis) from that fuel to society [71]. Conversely, lower EROI fuel delivers substantially less useful energy to society (e.g. a fuel with an EROI of 2:1 will deliver 50% of the energy from that fuel to society). Therefore, large shifts in high EROI values (e.g. from 100 to 50:1) may have little or no impact on society while small variations in low EROI values (e.g. from 5 to 2.5:1) may have a far greater and potentially more "negative" impact on society [71] (concept courtesy of Euan Mearns).
Exercise: «draw a picture» of the dynamical system «energy available to society» in an energy transition
Simulating the energy transition?

A Pascaline, an early calculator
Photo: David Monniaux via Wikipedia
Discrete-time Formulation

• We consider a discrete-time system, where each time-step corresponds to one year:

\[ t = 0 \ldots T - 1 \]

• The horizon is in the order of hundreds of years:

\[ T \sim 200 \]

• We consider a deterministic formalization (expected values)
Budget of non-renewable energy

- Each year, a quantity of non-renewable energy is available:

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

- We use Hubbert curves to model the depletion:

\[ \exists r > 0, \tau > 0, t_0 : B_t = \frac{1}{r} \frac{e^{-\frac{(t-t_0)}{\tau}}}{\left(1 + e^{-\frac{(t-t_0)}{\tau}}\right)^2} \]
Hubbert curves
Energy from renewable sources

• We assume that a constant quantity of renewable energy is available each year (mainly biomass):

\[ K \geq 0 \]

• We assume that we have access to a set of technologies producing an annual quantity of energy from renewable sources:

\[
\forall t \in \{0, \ldots, T - 1\}, \forall n \in \{1, \ldots, N\}, R_{n,t} \geq 0
\]
EROI, lifetime and growth

• Each of these technologies is characterized by two main parameters, EROI and lifetime:

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

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

• We do not consider fluctuation/storage issues
Growth and replacement of renewable production means

• The dynamics of the deployment of renewable technologies is formalized using a growth parameter:

\[ R_{n,t+1} = (1 + \alpha_{n,t})R_{n,t}, \forall t \in \{0, \ldots, T - 1\} \]

• We introduce the energy costs associated with the growth and the long-term replacement of the deployment of technologies producing energy from renewable sources:

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

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

\[ M_{n,t} (R_{n,t}) \geq 0. \]
Assumptions

• **Assumption**: the energy cost of the growth is proportional to the development of production means:

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

\[
C_{n,t} (R_{n,t}, \alpha_{n,t}) = \begin{cases} 
\gamma_{n,t} \alpha_{n,t} R_{n,t} & \text{if } \alpha_{n,t} \geq 0 \\
0 & \text{else}
\end{cases}
\]

• **Assumption**: the energy cost of replacement is proportional to the current size of the production mean:

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

\[
M_{n,t} (R_{n,t}) = m_{n,t} R_{n,t}
\]
Total energy and net energy to society

• We define the total energy available:

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

• We define the net energy available to society after energy investment:

\[ \forall t \in \{0, \ldots, T - 1\}, \quad S_t = E_t - \left( \sum_{n=1}^{N} C_{n,t} + M_{n,t} \right) \]
Constraints - Energy threshold

• We assume that the energy investment for growing renewable technologies and replacing them cannot exceed a given threshold (cf. pyramid of « energetic needs »):

\[
\forall t \in \{0, \ldots, T - 1\}, \exists \sigma_t > 0 : \sum_{n=1}^{N} C_{n,t} + M_{n,t} \leq \frac{1}{\sigma_t} E_t
\]

• In the following, we call « energy threshold » such a parameter

• Note that this constraint may induce a negative growth
Expressing growth and energy costs using EROI and lifetime

- A given set of production means is expected to produce over its lifetime the following quantity of energy:

\[ Q_{n,t} = R_{n,t} \Delta_{n,t} \]

- **Assumption**: the energy investment is done initially:

\[ \gamma_{n,t} = \frac{\Delta_{n,t}}{EROI_{n,t}}, \quad C_{n,t} = \frac{\Delta_{n,t}}{EROI_{n,t}} \alpha_{n,t} R_{n,t} \quad \text{if} \quad \alpha_{n,t} \geq 0 \]

- **Assumption**: the replacement cost is annualized:

\[ m_{n,t} = \frac{1}{EROI_{n,t}}, \quad M_{n,t} = \frac{R_{n,t}}{EROI_{n,t}} \]
Scenarios for fixed EROI, fixed energy threshold

• We consider 4 different scenarios for the depletion of non-renewable energy: (i) Peak now, (ii) Plateau now, (iii) Peak in 20 years, (iv) Plateau in 20 years

• We consider one technology (photovoltaic panels), with constant EROI:

\[ \forall t \in \{0, \ldots, T - 1\}, EROI_t = 6 \]

• The energy threshold is set to:

\[ \forall t \in \{0, \ldots, T - 1\}, \sigma_t = 15 \]

• For each scenario, we consider three growth configurations: « weak », « optimistic » and « max »

• The simulations are initialized with a 2014-like configuration
Peak now - weak growth
Peak now - optimistic growth
Peak now - max growth
Plateau now

Optimistic

Weak

Max
Peak in 20 years

Optimistic

Weak

Max
Plateau in 20 years

Optimistic

Weak

Max
Influence of EROI
Let us be optimistic!

- Max growth

\[ EROI_t = 12, \forall t \]
Last configuration: EROI greater than energy threshold

- Max growth

\[ EROI_t = 15, \forall t \]

- Growth is not anymore constrained by the energy threshold

- Other constraints should then be taken into account
And what about greenhouse gas emissions?

- We can enrich the model with a penalization of the consumption of non-renewable energy.
- Then, we can assume that, as technology progresses, dependency to non-renewable energy decreases.
- This defines a whole class of problems where the energy investment has to be optimized over time.
What to say about this model?

- Models are - almost - always wrong…

- Anyway, this model suggests that:
  - we should favor technologies with high EROI
  - even if we are currently building photovoltaic panels and wind-turbines, we may still be very surprised by our current dependence on non-renewable energy
Epilogue

Photo: Diliff, edited by Vassil via Wikipedia
A last story: the decline of the Roman Empire - The Theory of Complexity (J. Tainter)

- At the time of the Roman Empire, energy was mainly extracted from **photosynthesis** (via agriculture)

- Roman agricultural output slowly declined and population increased, **per-capita energy availability dropped**

- The Romans solved this problem in the short term by **looting**: conquering their neighbors to snatch their energy surpluses (metals, grain, slaves, etc.)

- For example, when Pompee acquired Syria, the budget of the empire increased by 70%

A last story: the decline of the Roman Empire - The Theory of Complexity (J. Tainter)

- However, as the Empire grew, the cost of maintaining communications, garrisons or civil government increased.

- Eventually, this cost grew so great that any new challenges such as invasions and crop failures could not be solved by the acquisition of more territory.

- At that point, the Empire fragmented into smaller units.

Two interesting elements:

- For centuries, the Roman administration never ceased to **deprecate the value of its currency**, slowly but surely reducing the amount of precious metals in coins.

- Archeological evidence from human bones indicates that **average nutrition improved after the collapse** in many parts of the former Roman Empire.

Take-home message

• Energy and economy are much more related than we used to think

• The energy transition should be considered as a decision making problem with budgeted actions (in terms of energy quantity)

• Net energy aspects of technologies should be better taken into account

• I believe that the energy transition is a challenge for the rising generation that may be really exciting!
Going further

- Work of Jean-Marc Jancovici (energy & climate expert) : [www.manicore.com](http://www.manicore.com), in particular:
  « Gérer la contrainte carbone, un jeu d'enfant ? » [http://youtu.be/KV33L5p7Zg8](http://youtu.be/KV33L5p7Zg8)

- Work of Gaël Giraud (Senior researcher at CNRS) : [www.gaelgiraud.net](http://www.gaelgiraud.net), in particular:


- Blog of lemonde.fr (by Matthieu Auzanneau) related to energy: [http://petrole.blog.lemonde.fr](http://petrole.blog.lemonde.fr)


- La diminution de l’énergie nette, frontière ultime de l’anthropocène - Benoît Thévard, Institut Momentum, December 13th, 2013

- Optimizing greenhouse gas mitigation strategies to suppress energy canibalism - J.M. Pearce, 2nd Climate Change Technology Conference, May 12-19 2009, Hamilton, Ontario, Canada
Many, many thanks to…

• Other people from the « Scientizenship team »: Damien Ernst, Steve Melon, Frederic Olivier, Aaron Qiu, colleagues and friends from the Montefiore Institute

• F.R.S-FNRS & University of Liège

• InsideOut

• BEST