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Article

Peaks and Cliffs:
An Example of the Power of Analogy Across Disciplines

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Abstract

The aim of this paper is to show how the studies in Energy field are intrinsically cross-disciplinary. Energy undergoes to the general Physics laws and, in particular, to the Thermodynamics ones, but often we think it like a separate field, regard, for example, to the Ecology. We show some example useful to see the analogy between those fields of study and how these analogies could enlighten the scientific explanation in both fields.

Keywords: Peaks; Cliffs; Analogy; Renewable and no renewable energy resource; Energy depletion; Energy return on investment (EROI).

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Introduction: The Power of the Analogy

One of the most powerful instruments for the development of a specific field of knowledge is, sometimes, look at other fields and try reasoning "outside the box" and using the analogy. In History of Science, there are many examples of this kind of "contamination" and a first way to distinguish them is the similarity that can be internal (the same field of study) or external (different field of study). We proceed with a couple of examples.

The internal one is, for example, the case of Pierre de Fermat (1601-1665) who announce the theorem: an equation in the form $x^n+y^n=z^n$ have no solution for n>2. Fermat wrote, in a book border, to have found the solution of this theorem (which from then on took his name), but this solution was never found.

Only in 1993, Andrew Wiles found the solution (and for that, he won the Fields' medal). In a popular science book (Singh 1997) is reconstructed the story who lead Wiles to this discovering and – without going down into details – the main point is that discovery it was possible thanks to the analogy between two fields of mathematics far from each other and

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without common points: the numbers' theory and the differential geometry. Both of them contribute to the solution:

> The value of mathematical bridges is enormous. They enable communities of mathematicians who have been living on separate islands to exchange ideas and explore each other's creations. Mathematics consists of islands of knowledge in a sea of ignorance. For example, there is the island occupied by geometers who study shape and form, and then there is the island of probability where mathematicians discuss risk and chance. There are dozens of such islands, each one with its own unique language, incomprehensible to the inhabitants of other islands. The language of geometry is quite different to the language of probability, and the slang of calculus is meaningless to those who speak only statistics. The great potential of the Taniyama-Shimura conjecture was that it would connect two islands and allow them to speak to each other for the first time. Barry Mazur thinks of the Taniyama-Shimura conjecture as a translating device similar to the Rosetta stone, which contained Egyptian demotic, ancient Greek and hieroglyphics (Singh 1997, 219-220).

This example shows the dynamic inside a single discipline: mathematics. Obviously, there are many examples of productive exchange, for example, between physics and mathematics. One of the most famous in recent times is the relationship between the tensor calculus and the general relativity theory. Indeed, the "engine" of Einstein's theory of general relativity, one of the most scintillating gems of twentieth-century science, is the work of an Italian mathematician: Gregorio Ricci Curbastro. Albert Einstein, after having been the victim of a real "block of the scientist", found in the Ricci tensor calculus the algorithmic apparatus that allowed him to transform an elusive intuition into a solid physical theory. That famous theory that represents the perfect condensation between Einstein's physical genius and the power, synthesis and elegance of mathematics created by Ricci Curbastro (Toscano 2004).

Another example of the powerful prediction involves mathematics and astronomy and it is quite famous: the discovery of Neptune. Probably the liveliest description of this episode comes from the Nobel Prize in Physics Richard Feynman:

> If we have confidence in a law, then if something appears to be wrong it can suggest to us another phenomenon. [...] Jupiter, Saturn and Uranus were big planets that were known, and calculations were made about how slightly different from the perfect ellipses of Kepler the planets ought to be going by the pull of each on the others. And at the end of the calculations and observations it was noticed that Jupiter and Saturn went according to the calculations, but that Uranus was doing something funny. Another opportunity for Newton's Laws to be found wanting; but take courage! Two men, Adams and Leverrier, who made these calculations independently and at almost exactly the same time, proposed that the motions of Uranus were due to an unseen planet, and they wrote letters to their respective observatories telling them – 'Turn your telescope and look there and you will find a planet'. 'How absurd', said one of the observatories, 'some guy sitting with pieces of paper and pencils can tell us where to look to find some new planet'. The other observatory was more… well, the administration was different, and they found Neptune! (Feynman 1965, 23-24).

A quite singular case, where the mathematics was better than a telescope.

In the following part of this paper, we show analogies between energetic resources, ecology, and a quasi-economic theory.

The concept of EROEI (or EROI) and what the EROEI means

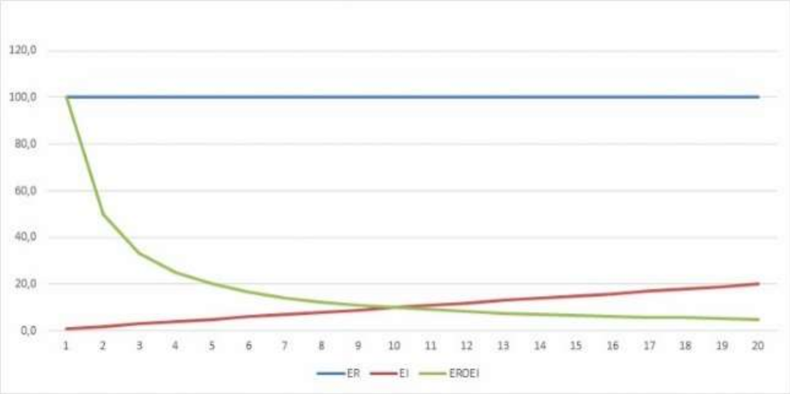
Inside of the Energy field study, one of the most important concepts is the EROEI (or EROI), the acronym of Energy Return on (Energy) Investment. The concept comes from the Ecology, it is relevant for many disciplines and Charles Hall developed it, in Energy field (Hall 2017).

The simplest example of this cross-disciplinary approach is about the case of hunter-croppers' tribe. We can imagine a tribe that arrives in a savanna. They establish their camp and the men go hunting. Initially, they find much prey but in few days the animals turn away from the camp and the men have the necessity to cover more distances to find new preys. How much time the camp remains in that piece of savanna?

The (qualitative) answer is quite simple: they remain there until the energy spent to hunt preys (for themselves and tribe) is balanced by the number of preys (and then the number of calories they have). In other words: the Energy Return (ER) must be greater than Energy Invested (EI) and, in particular, the value of EROI (= ER/EI) must be bigger than one.

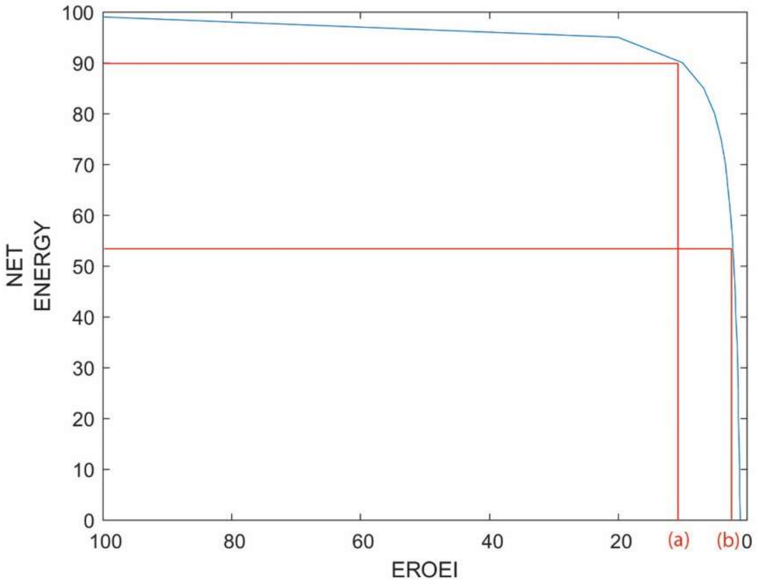
This concept can be applied to the tribe but also to the energy resource like oil, PV panels and so on. In the case of oil, the quality (and the slope) of the curve for declining about energy comes from the study on the EROI. Classical examples of this count are the extraction of oil. To have a qualitative measure of an implant is necessary having the net value of extraction (for example 100 barrels/day) and the value of energy necessary for the correct functioning of the implant (for example: 2 barrels/day). Therefore, the EROEI is 50.

If we imagine using simple numbers to show the quality of the curve, the results are the following (with ER = 100 and EI = from 1 to 20):



Picture 1: The hypothetical graph for a declining EROI, with Energy Investment from 1 to 20

However, to better understand "where we are" in the graph (always for the example of the oil extraction) a more useful parameter is the Net energy, defined as: Net Energy (NE) = Energy Return - Energy Investment. If we divide all terms for a single quantity ER, the result is: NE/ER = 1-(1/EROI), and, under the theoretical hypothesis of the ER always equal 100 for the society, the NE value can be expressed in percentage. So, the equation is: NE(%)= [1-(1/EROEI)]*100. Now, if we make a graph NE vs. EROEI the result is the following:



Picture 2: The "Net energy cliff" and the bias of perception about this

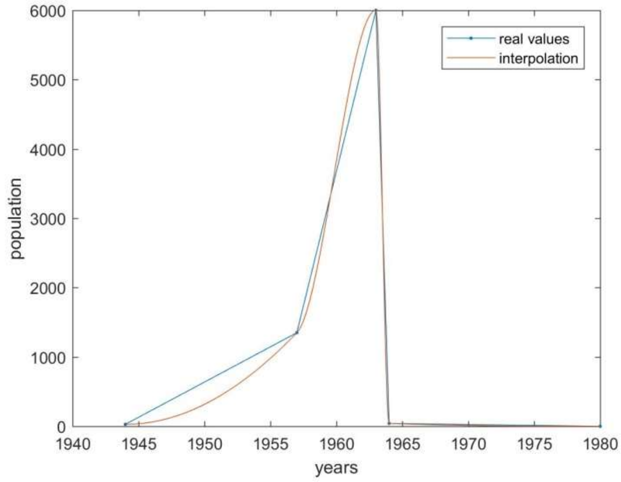
The red lines are precisely the meaning of the carrying capacity of the (eco)system: with EROI = 10 (more or less the point (a)) nothing seems to happen, but if EROI goes down again - from 10 to 2, for example: so more or less the point (b) - the decreasing of net energy is dramatic.

The (Real) History of St. Matthew Island' Reindeer Population: When the Renewable Resources become no Renewable

Some scientist uses the analogy between Mankind and what happened in this remote angle of the world since 1944. Almost at the end of WWII, the US Coast Guard colonized the St. Matthew Island for logistic reason. This Island – in the middle of the Bering Sea – before 1944 was deserted. Technicians and soldiers arrived to install a device useful for the navigation of ships around the area, and they brought with them 29 reindeer as food back up in case of bad weather or war problems.

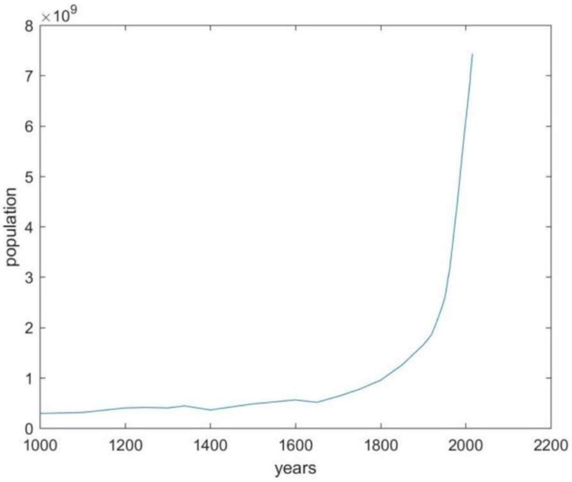
Some months later the war was finished: the people go home, and the reindeer are vacated in an optimal habitat for them, without natural predators. For years, the entire world forgets the reindeer and in 1957 some researchers go to the Island and found more or less 1,350 healthy animals. Only six year after, in 1963, there are 6,000 reindeers but their conditions were not a good one: they ate all lichen in the Island and they are only capable to grazing the sedge grass, but... also this resource of food is coming to the end.

In 1964 the population dramatically fell down and there are on the Island only 42 members: the entire population died for starving. The problem is that 41 are female and only 1 male, the last one infertile for the scarcity of food. So, in the Eighties, also the last reindeer died. Here, the curve of the population:



Picture 3: Trend of reindeer's population. This graph – made in Matlab with few points – shows the real values (broken line) and the interpolation (smooth line).

And here the graph of world population since 1000 b.C.[2]:



Picture 4: World population since 1000 b.C.

The analogy between reindeer' population and the Humankind is evident: our Island is the entire Earth planet, but, as what happens to the reindeer, we have no natural competitors for thousands of years. From the Industrial Revolution, the human population grows substantially linear to the availability of energy per capita with high EROI. What about our future? Something must change.

From the Hubbert's Peak to the Seneca Cliff

In 1956 Marion King Hubbert, a Shell geologist, in a meeting in Texas, had predicted the US oil crisis in 1973: many colleagues did not believe him, but he had all the elements to do this: the amount of oil extracted per year in the USA and the growing consumption of the society. He became famous for a kind of theory[3] that said something like this: "One day in the past we extracted the first oil barrel. One day in the future, we will extract the last one. In the

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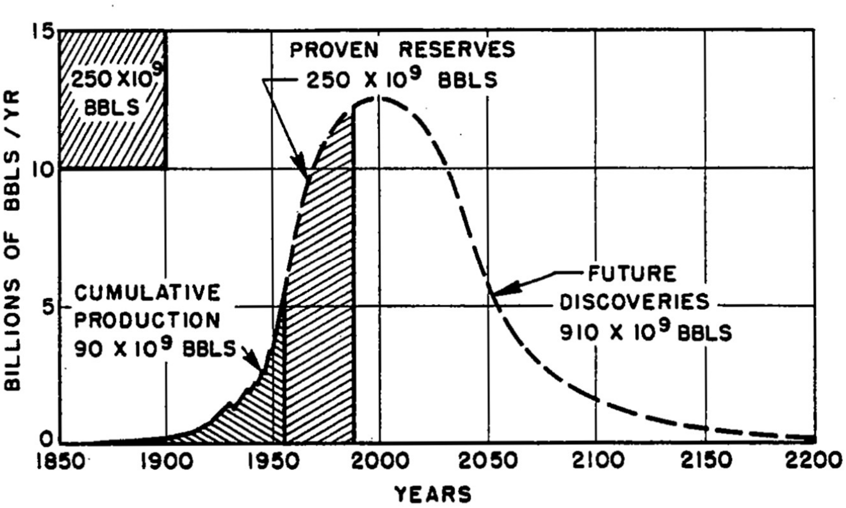
[2] Source: U.S. Census Bureau.

[3] Really closer to a formalization of a commonsense consideration than a theory *tout court*.

middle probably there is more or less a bell curve that indicates the maximum amount of oil extracted worldwide: the peak oil". The peak oil became the Hubbert's peak.[4]



Picture 5: Hubbert's peak oil and his depletion prevision

Could be the Hubbert prevision changed? Many things happened from 1973 and the world itself is changed, but focusing our attention on the curve, to what kind of force it is subjected? There is a force that transforms the peak into a cliff[5] because the consumption is faster than the past, and the main cause is basically the population growth. Another force (in the opposite direction to the previous) "extend" the time we have to make an energy transition: the technology enhancement. This happens with a greater ecological cost,[6] but all can be measured with the EROI index.

Fast or Not?

One of the most relevant aspects of our society is the tendency to grow up in terms of capacity and speediness (we have constantly under the eyes cars faster and bigger than thirty-forty years ago). Generally speaking, our society requires constantly a surplus of energy to perform jobs faster than before.

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[4] There is a little video clip where he personally explains, in a TV program, his theory: https://www.youtube.com/watch?v=usJoqXTvGZ0 (all links are checked on June 30th, 2018). In this brief video, he shows another important thing: if we take a graph with the *Human history from the 5000 BC to 5000 AC*, the oil peak becomes something more similar to a Dirac impulse that a peak. In other terms: our society has available a lot more energy than they have had the past societies (and probably the future one). Recently a young Australian scientific communicator, Stuart McMillen, wrote a comic about the life of Hubbert: http://www.stuartmcmillen.com/comic/peak-oil/. The picture comes from the original Hubbert's work, presented to the Geologists Congress in 1956 at Austin (Texas): *Nuclear Energy and The Fossil Fuels*.

[5] The cliff paradigm comes from Ugo Bardi and his intense activity of dissemination, in many blogs (http://thesenecatrap.blogspot.it/, http://cassandralegacy.blogspot.it/) and mailing list management (Energy Transition). Recently he reorganized his work in a new book (Bardi 2017).

[6] A way to have an idea of this ecological devastation is sufficient a brief search: with Google images look at "tar sands Canada".

Ugo Bardi, lecturer of Chemistry at University of Florence, uses a kind of paradigm to show his students this phenomenon: the higher will be the intensity in use of energy, the faster our society will fall down. In particular, Bardi has used a famous sentence that comes from the ancient philosopher Lucio Anneo Seneca: "It would be some consolation for the feebleness of ourselves and our works if all things should perish as slowly as they come into being; but as it is, increases are of sluggish growth, but the way to ruin is rapid"[7]. Useful cases, in both animal and human populations, show this: in the next paragraph, we will suggest a linguistic analysis about a best seller like *Collapse* (Diamond 2005).

Jared Diamond, famous for his previous book (Diamond 1997), in *Collapse* has analyzed the way in which ancient populations – often in uncertain balance with the environment – have faced the question of their survival and in which cases their strategies have had success or not.

The *leitmotiv* about the decline is the same of the growth: "fast" and "rapid". In particular: «Writers find it tempting to draw analogies between those trajectories of human societies and the trajectories of individual human lives – to talk of a society's birth, growth, peak, senescence, and death – and to assume that the long period of senescence that most of us traverse between our peak years and our deaths also applies to societies. But that metaphor proves erroneous for many past societies (and for the modern Soviet Union): they **declined rapidly** after reaching peak numbers and power, and those rapid declines must have come as a surprise and shock to their citizens» (Diamond 2005, 6, bold mine). And talking about events happened on the Easter Island, we have found:

> Around 1680, at the time of the military coup, rival clans switched from erecting increasingly large statues to throwing down one another's statues by toppling a statue forwards onto a slab placed so that the statue would fall on the slab and break. Thus, as we shall also see for the Anasazi and Maya [...], **the collapse of Easter society followed swiftly** upon the society's reaching its peak of population, monument construction, and environmental impact (Diamond 2005, 110, bold mine).

Again, along with the book, when he writes about the Anazasi population:

> That should make us modern Americans hesitate to be too confident yet about the sustainability of our First World economy, **especially when we reflect how quickly Chaco society collapsed** after its peak in the decade a.d. 1110-1120, and how implausible the risk of collapse would have seemed to Chacoans of that decade (Diamond 2005, 155, bold mine).

We don't give here extra examples, but it is relevant to underline that Diamond cannot avoid an explicit parallelism with our society:

> Like Easter Island chiefs erecting ever larger statues, eventually crowned by pukao, and like Anasazi elite treating themselves to necklaces of 2,000 turquoise beads, Maya kings sought to outdo each other with more and more impressive temples, covered with thicker and thicker plaster – reminiscent in turn of the extravagant conspicuous consumption by modern American CEOs. The passivity of Easter chiefs and Maya kings in the face of the real big threats to their societies completes our list of disquieting parallels (Diamond 2005, 177, bold mine).

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[7] Lucius Anneaus Seneca, *Letters to Lucilius*, n. 91. The complete description of this paradigm, called *The Seneca Cliff*, can be find online at:http://thesenecatrap.blogspot.it/2015/11/the-seneca-effect-why-decline-is-faster.html

In nature, societies of animals normally find a balance with the environment (1) for the normal prey-predator dynamics[8], or (2) for the particular hard condition of the environment itself. However, in some (not properly natural) cases, it is possible to find out that, without natural boundaries (weather conditions and prey-predator dynamics), the populations grow up until the limit of carrying capacity of the ecosystem, like the history of the reindeer in St. Matthew Island's suggests us.

There are also some independent researchers (Greer 2008) that thinking in another way the shape of declining. The society is more resilient than we expect and the time of transition between phases could be sufficiently long to allow a social adapting to the new phase.

Another Peak (and Cliff) in History of Science: The "Guano Age" in Peru

There are examples in History of Science (and maybe in History *tout court*) where we can see applied the Hubbert peak or/and the Seneca cliff? We have seen some cases (Diamond 2005) and we can see them from an energetic point of view when also the renewable resources can become no renewable because of the consumption intensity (Celi 2017).

One of them, not listed in Diamond and did not found elsewhere, is the "guano case". The socio-political condition of Peru in the mid-19th century knew a period of stability and prosperity thanks to revenues generated by the export of guano and the strong leadership of President Ramón Castilla, in 1845, when he started his first administration.

Guano, or bird droppings, had been accumulating on the coastal islands of Peru for hundreds of years when, due to scientific breakthroughs in Europe, it was suddenly discovered to have great value as a fertilizer. For forty years, the young Peruvian State knows the prosperity, but in the 1870s was for Peru's economy "a decade of crisis and change" (Greenhill, Miller 1973). Nitrate extraction rose while guano extraction declined and sugar cane dethroned cotton as the main cash crop. Guano exports dropped from 575,000 tons in 1869 to less than 350,000 tons in 1873 and the Chincha Islands and other guano islands were depleted or close to be so. Deposits elsewhere were of poor quality (Greenhill, Miller 1973) and the "guano era" ended. A typical case of (low) renewable resource depletion, similar to the whale case at the beginning of the 19th century[9].

A few years later, as in the whale case, the question was resolved by a technological discovery: the Haber process (also called the Haber-Bosch process), an artificial nitrogen fixation process and is the main industrial procedure for the production of ammonia and mainly used to produce fertilizer today. For the Peruvian State, according to government experts, to only way to cope with the guano depletion was to supplement this one with synthetic fertilizer. Foreign companies were brought in to construct plants, which used the Haber-Bosch process to create fertilizer. As a result, the Guano Administration Company was renamed the Corporacion Nacional de Fertilizantes (CONAFER).

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[8] See the Lotka–Volterra equations, explained also in an old book (D'Ancona 1942).

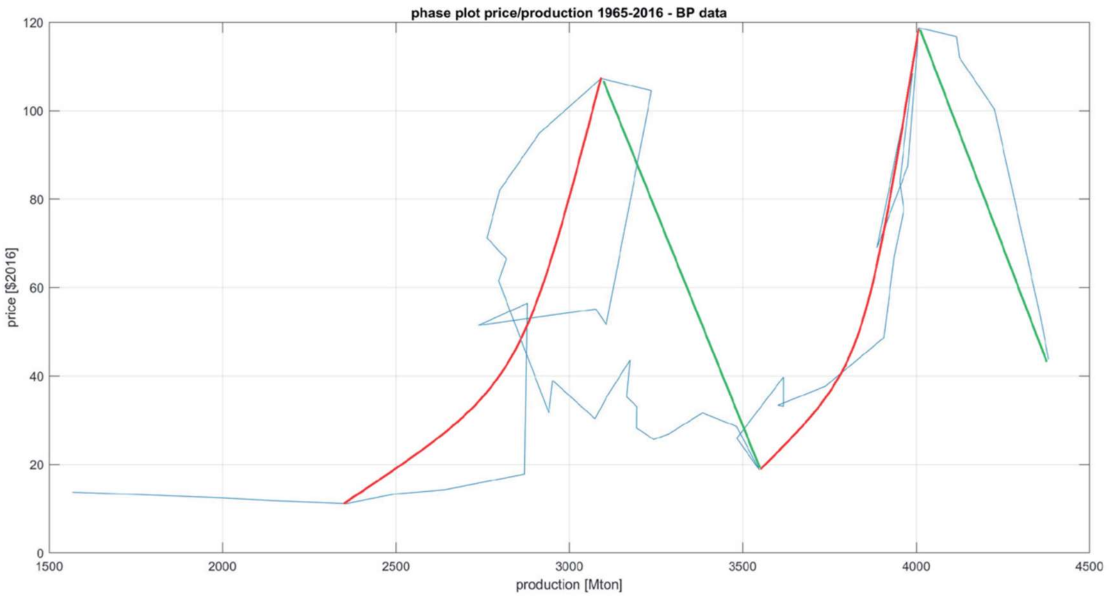
[9] This case is well described in a book (Bardi 2014) and ironically, the whales, hunted for the (whale) oil, are saved by the beginning oil production.

Last (Ecological) Example: Oil Dynamics Market and the North American Spruce Budworm[10]

The behavior of complex systems is one of the most intriguing phenomena investigated by recent science; natural and artificial systems offer a wide opportunity for this kind of analysis. The energy conversion is both a process based on important physical laws and one of the most important economic sectors; the interaction between these two aspects of the energy production suggests the possibility to apply some of the approaches of the dynamic systems analysis. In particular, a phase plot, which is one of the methods to detect a correlation between quantities in a complex system, provides a good way to establish qualitative analogies between the ecological systems and the economic ones, and may shed light on the processes governing the evolution of the system.

This section aims to highlight the analogies between some peculiar characteristics of the oil production vs. price, and show in which way such characteristics are similar to some behavioral mechanisms found in Nature.

In a previous study (Celi, Della Volpe, Pardi, Siboni 2017), we tried to show how a phase plot of oil production (vs. the price) has an irregular trend (*random walk*) with two important features that identify as inelastic the oil market (The two lines in red, in the following picture). The relationship, even if only qualitatively, shows two peaks upward where the oil price became very high in few years, and then rapidly decreases (green lines: obviously, we are looking at the general trend, without considering the "random walk behavior" in the middle).



Picture 6: Phase plot oil production vs. price, years 1965-2016

This kind of "swinging behavior" recalls some typical phenomena, investigated by some theories in the domain of complex systems. In particular, this is the case of Thom's catastrophe theory (Thom 1972, cited in Scheffer 2009). The behavior shown in the phase

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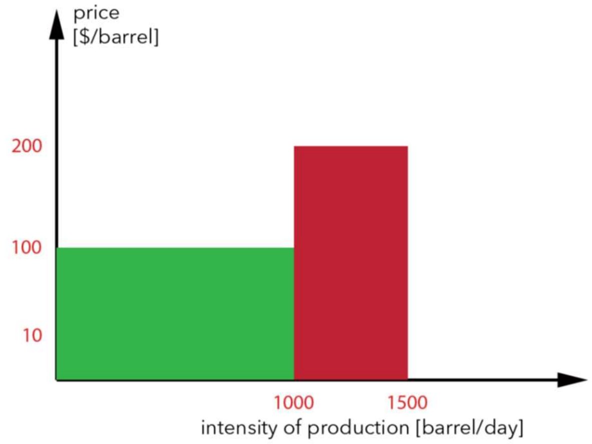
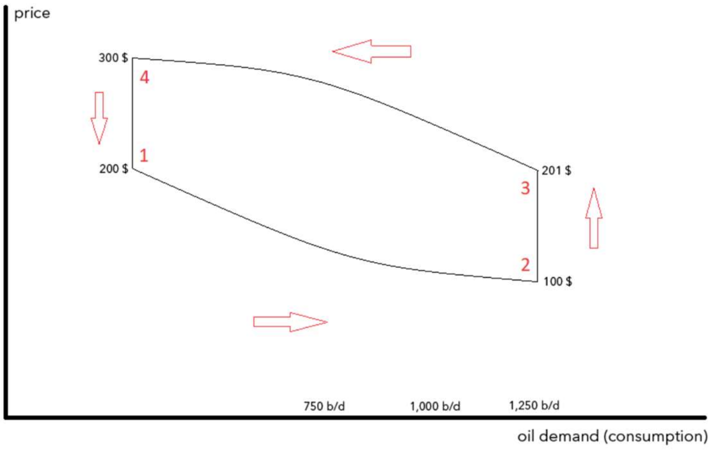
[10] This contribution was a part of the speech *Spruce budworm and oil price: a biophysical analogy* held in the Annual Conference of the International Society for BioPhysical Economics, *Developing Economics for a resource constrained world*, Wells College, Aurora, NY, USA, June 2018, 13-17th. This work had also the contribution of Claudio Della Volpe, Stefano Siboni (University of Trento) and Luca Pardi (Italian National Research Council, Pisa). It is also a part of Celi (2019).

plot (picture 6) in his simpler version could be represented as follows. We can imagine having two oil wells: one at a lower cost of extraction (i.e. 100 $/barrel) and one higher (200 $/barrel), as schematically shown in picture 7.



Picture 7: Intensity of oil production vs. price

If in our hypothetical world the consumption is in the range between 0 and 1,000 barrels/day, we use the oil at a lower price (green rectangle), with a price (ideally) inside the range 0-100 $/barrel. If the intensity of consumption grows, we need to use the second stock of oil at the higher price (red rectangle). In this case, the oil price increase quite rapidly, and the phase plot should be the following, in picture 8.



Picture 8: Phase plot consumption vs. price

The ecological model

The phase plot should be like this because in our ideal world we expect that, if the oil price increases rapidly, the consumption decrease and, sooner or later, the society come back to the previous range of intensity of extraction (so in the green rectangle, picture 7). The main characteristic of this simple oil-price dynamics, here described, is that there are two rapid movements on the cycle (rise and descent of the price: phases 4-1 and 2-3) and two slow (consumption that goes up and down, to adjust itself to the oil price: phases 1-2 and 3-4)[11].

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[11] The graph in picture 6 has higher prices because take into account the inertia of the social system.

The analogy between this characteristic of the oil market and some dynamics in Ecology (for example Kar, Batabyal 2010; Piltzy et al. 2017) is suggested at least by a model well studied (Royama 1984; May 1977), where we have three species in competition between them, following a variant of the Lotka-Volterra model:

1. prey: the American spruce, whose needles are the food of caterpillars of the species *Choristoneura Fumiferana* (this is the slow variable since the regeneration of the leaves – and not only - is a process that lasts several decades);

2. predator: the population of the caterpillars *Choristoneura Fumiferana*, considered able to vary rapidly (fast variable, since there are periodically observed demographic outbreaks of this species, considered a real scourge);

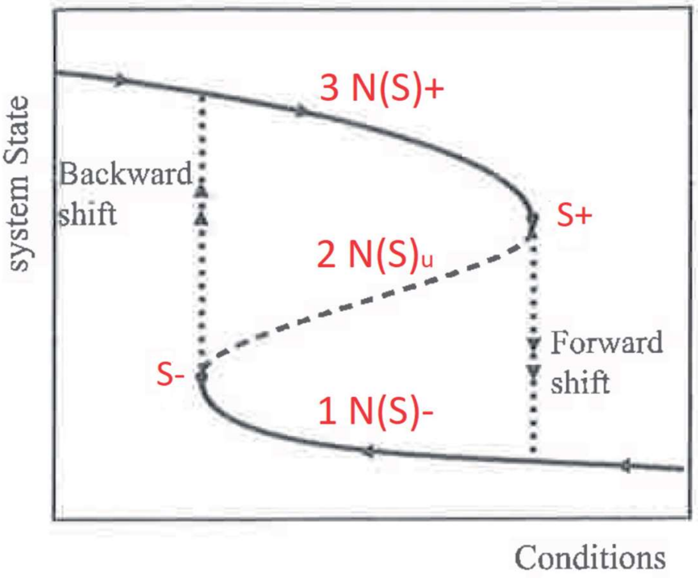
3. "super-predator": the population of birds, which eat the caterpillars, but do so at a rate that we can consider constant (identified as a "natural" rate of mortality of the caterpillars themselves) because this predator actually does not feed exclusively on these caterpillars. The demographic explosion of the latter, however, saturates the space for all prey (the needles of the spruce). In this sense, we will not take into account, in the following discussion, this variable.

In the construction of the ecological model, we start with a preliminary model in which the caterpillars' population N is the only variable, while the spruces' population S is introduced as an assigned parameter. We define a range $S- \leq S \leq S+$ of values for S, inside the caterpillars' population could have three state of equilibrium (indicated in picture 9):

1. a "low" value of equilibrium N(S)-, asymptotically stable;

2. an intermediate value of equilibrium $N(S)_u$, unstable, and

3. a "high" value of equilibrium N(S)+, also asymptotically stable.



Picture 9: Equilibria of the system.[12]

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[12] (Scheffer 2009, 20).

This notation recalls us that all equilibrium states are function of the parameter S. Because of its instability, the equilibrium level $N(S)_u$ is inaccessible to the caterpillars' population, inasmuch as any variation of the population determine a rapid leaving from equilibrium and a fast convergence of the system towards N(S)- or N(S)+. For S < S- only the stable equilibrium N(S)- is defined, while for S > S+ we have only the stable equilibrium at N(S)+. The preliminary model explains the outbreaks and collapses of caterpillars' population as imputable to slow variations imposed by the parameter S, which due to these variations "crosses" the critical values S- and S+. The variations of S are assumed "almost-static", i.e. so slow to ensure that almost instantly the population of caterpillars settles at the corresponding equilibrium value (the relaxation times at equilibrium of the N population of the caterpillars are considered much shorter than those of variation of the parameter S).

The typical cycle of outbreaks and collapses of the caterpillars' population N is described as follow:

1. The process can start from a value S < S-, for which the caterpillars' population corresponds to the equilibrium value N-;

2. Then, we increase the value of the parameter S, corresponding to an increment of the spruce biomass. The parameter reaches and overtakes the critical value S- and still grows up until the critical value S+. In this interval, the caterpillars' population grows up but stands to the asymptotically stable equilibrium level N(S)-, because of all the possible fluctuations are lessened and reabsorbed. The compresence of the equilibrium $N(S)_u$ is not relevant, because of its instability;

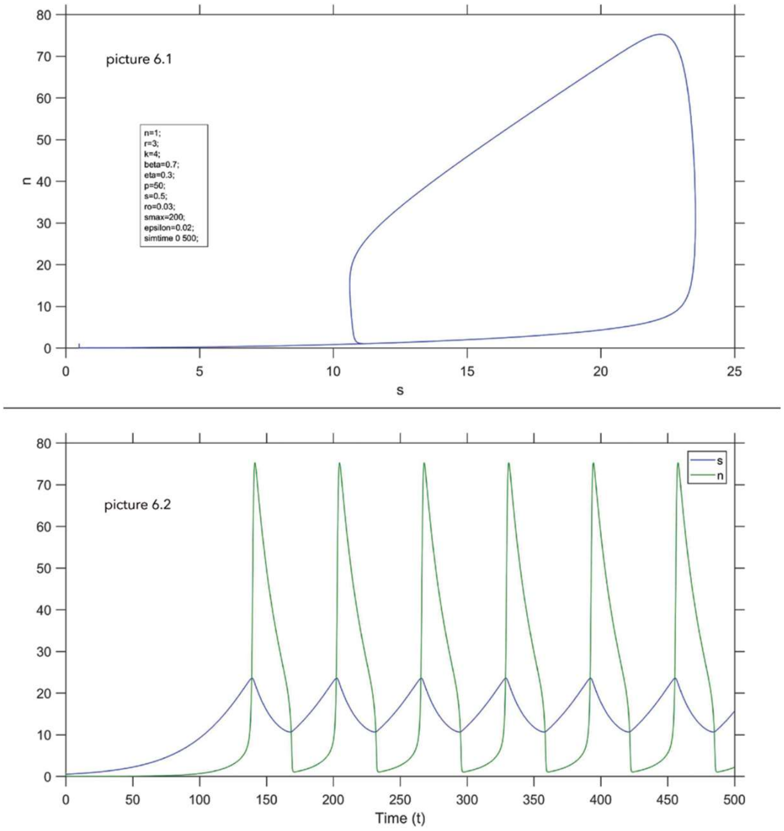
3. The parameter S overtakes the critical value S+. The equilibrium N(S)- suddenly disappears, along with $N(S)_u$, and the population rapidly grows up to reach the "high" equilibrium value N(S)+, the only available and asymptotically stable. Further increments of the parameter S determine a further, but contained, increase of the caterpillars' population, in any case always corresponding to the equilibrium value N(S)+;

4. The next step is reducing the parameter S, to simulate what in reality happens: the overpopulation of caterpillars depletes the spruce biomass and determines its reduction. The parameter S reaches and overtakes the critical value S+, following its decrease until S-. The caterpillars' population slowly decreases, maintaining itself, as long as possible, close to the asymptotically stable equilibrium point N(S)+,. Also in this part of the cycle the intermediate equilibrium $N(S)_u$, even if defined, does not play any role because of its instability;

5. The last step: the parameter S finally passes below the critical value S-. This results in the destruction of the equilibrium N(S)+, as well as that of $N(S)_u$, with a consequent rapid collapse of the caterpillar population to the only available equilibrium value N(S)-. Any further decrease in S leads to a reduction in the population of the caterpillars, which however remains at the equilibrium value N(S);

6. Now the caterpillars' population is at the minimum level, the spruces biomass can start to grow up again, so that the parameter S grows up in turn and the cycle restarts.

The previous model with a variable (N) and a parameter (S) suggests a more complex two-variable model in which the population of caterpillars and the biomass of spruces are considered both as dynamic variables, in mutual interaction. In the further differential equation that governs the dynamics of S the characteristic constant parameters are chosen to ensure that the variation of S over time remains relatively slow. In this way, we can consider that the trends observed in the preliminary model with a single variable persist also in the new two-variable model, giving rise to a stable limit cycle characterized by two rapid growth and decrease phases of the caterpillars' population N. These rapid variations of budworm population alternate with two relatively slow growth and decrease phases of the same population, while the biomass of spruces varies always rather slowly, both increasing and decreasing, throughout the cycle.



Picture 10: 10.1: The Matlab simulation for the phase plot caterpillars' population vs. spruces foliage and (10.2) the same values in time.

The Transition to Economics

The shift from Ecology to the Economy (oil price-EROI cycle) is suggested by the following qualitative considerations:

1. the price of oil is potentially able to undergo very rapid changes, being linked to the delicate balance between supply and demand. On the contrary, EROI presents itself as a parameter that changes slowly because its decrease naturally derives from the exploitation of deposits, while its increase can be obtained through the implementation of cultivation technologies already available (at best), the search for new deposits, or the improvement of the technologies themselves, operations that require time and significant investments;

2. a very low level of EROI can be associated with a rapid increase in average prices, due to the difficulty of extracting the resource at low energy costs; on the other hand, a very high EROI will favor high levels of production and a general decline in the price of the resource.

These observations suggest identifying: (a) the population N of the caterpillars with the average price of oil and (b) the biomass S of the spruces with the reciprocal of the EROI, variable that assumes low values when the EROI is high and vice versa. This is an index of the energy cost that must be borne to obtain a unit of useful energy.

The interesting aspect of the model is that the price is not described as a function of the EROI, because two different price levels correspond to the same value of EROI, according to the historical phase of the economic cycle where the system is placed. Basically, we are faced with two zones of stability, one with high content and one with a low content of "predators" (price), which are alternately reached. The reason why the sizes were chosen is that, in the oil model, the quantity that varies faster is the price, while both the total production and the EROI (which depends on technology and investments) are sizes with too many constraints to be able to vary quickly. EROI does not succeed because of the technical conditions of production, while production because of the constant energy hunger.

Conclusions

The concept of EROI here described is used to look at the quality of an energy resource (in the broader sense of the term). As shown, this is not only a good parameter of evaluation but also a way to compare different energy sources, because, from a mathematical point of view, the EROI is a dimensionless number.

This concept is powerful: we have shown its use in different fields of study and it could be seen as a method or a point of view to teaching science in a cross-disciplinary way, with the aim to enlighten with analogies, the typical dynamics of disciplines apparently far from each other.

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