# An energy R&D fund for energy paradigm transitions: Macro and micro scale analysis

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## ABSTRACT

Human civilizations are historically distinguished by their dominant pattern of energy harvesting, called the *energy paradigm*. The energy history of human civilizations may be shortly described as the successive transition from one energy paradigm to another. As the transition of our civilization from its fossil-fuel energy paradimg lies at the top of the global sustainability agenda, the paper develops a model of a global *Research & Development* (R&D) *fund* as a financial instrument that will institutionalize the global finance of energy technology innovations for the implementation of a global energy transition. Based on that, a generalized dynamic model of energy paradigm transitions is developed. At the macro-scale, energy paradigm transitions incorporate the combined effect of two main resources that also work as the two major *limiting factors* that necessitate perpetual technological progress; (a) the energy paradigm's fuel availability and (b) the ecosystem's pollution capacity. As both factors are thermodynamically depleted across the energy paradigm's lifetime, the *Scarcity Rent* (SR) is introduced as a fund that best reflects their depletion rate. The SR derives immediately from the 2nd Law, expressing the compensation for resource or carrying capacity depletion. Reduced in economic values the SR consists in the lost net benefit when one unit of resource is currently consumed and is no longer retrievable (because of the validity of the 2nd Law) in the future. For renewable fuels and ecosystem carrying capacity, the SR is reduced by their renewal rate. The SR is embodied in prices –thus connecting consumption with depletion and the SR size- and is re-invested as a minimum fund in ambitious energy technology R&D programs, aiming at the overall limiting factors' mitigation through the transition to a more abundant and sustainable world energy paradigm. Innovation ability is the evolutionary engine of human civilizations, of which the core process is R&D. However, R&D needs funding –as a fraction of the society's income- and time to yield results. Thus, it is necessary to discount a desired future innovation level, which must have been achieved by a predefined time. At the micro-scale, R&D is modeled as a Schumpeterian *information accumulation* process that involves uncertainty on the innovation's exact arrival time, expressed by a Poisson model. This conception of R&D as accumulating information, is methodologically useful as it allows us to assume that uncertainty eventually dissolves; however turning the main question to "when"; This makes "time" a factor of primary importance in the model as the innovation must have been implemented in time, so that its social deployment and massive adoption will be achieved before any of the limiting factors is exhausted. Consequently, the relation between the increase of the financial investment and the increase of the innovation's average expected rate of arrival is mathematically examined through various elasticity measures, where relative SR management schemes are also proposed.

**Keywords:** energy paradigm, transition, sustainability, finance, R&D, innovation, limiting factor, Scarcity Rent, information accumulation, Poisson model

## Introduction

The foundations of human societies consist in the bidirectional flows of matter and energy with the natural environment. From these flows derive material and energy quality losses. In an integrated socio-environmental context, technology is conceptualized as the measure of the quality of flows between nature and human societies. In relation to that, White (1959) postulated the idea that *social systems are determined by technical systems*. His view highlights the importance of the means of energy harvesting from nature (energy technology) for the course of human civilizations across time. To White's extent, the anthropologist Joseph Tainter developed a special economic theory, based on marginal energy productivities, in order to identify the energy shortages that led to rapid

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collapse, sixteen past human civilizations (Tainter 1988). However, both the above studies substantiated a very important point of view; that the amount of available energy does not constitute by default a condition for ensuring a society's sustainability, unless it is accompanied by an efficient mechanism of technology transition that will revitalize its fuel budget and secure its energy availability in order to continue to exist and evolve across time. This conclusion has directed integrated socio-ecological research to the study of the endogenous factors of a social system's energy structure; and more specifically to the organization of Research & Development (*R&D*) as its primary core mechanism of energy transitions.

## 1. Fundamental concepts

The paper develops a model that is designed to reflect a society's energy transition pattern in two basic scales: **(a)** macro, which concerns the society's overall (macroscopic) picture of energy consumption life-cycle and **(b)** micro, which concerns the endogenous (financial) mechanisms that accelerate transitions via energy technology innovations. Mathematical representation is based on fundamental notions that classify the energy transition's most important variables and also comprise the model's fundamental assumptions.

### 1.1 The Energy Paradigm

The energy paradigm is the society's dominant pattern of energy harvesting. The energy history of human civilizations may be described shortly as the successive transition from one energy paradigm to another. The energy paradigm defines fundamentally the society's fuel availability. For example, hunter-gatherer civilizations were limited by the availability of muscle-energy. Their natural successors were the first agricultural civilizations that were based on crop energy, and so on. Energy paradigms begin with an *event of structural change*, which usually manifests intensively near the saturation of the current fuel resource. Structural change events constitute the factors that trigger energy transitions throughout human history. The most recent example of structural change was the Industrial Revolution, which ignited the –until today- fossil fuelled civilization.

### 1.2 Pollution Carrying Capacity

The Pollution Carrying Capacity (PCC) variable can generally be defined as the ecosystem's stoichiometric ability to tolerate a specific population of pollutants, just as ecological carrying capacity refers to the number of individuals with specific minimum energy needs that an ecosystem of specific primary productivity can support. PCC is the maximum toleration of a pollutant on behalf of the ecosystem, or the upper acceptable limit of pollution where the effects are predictable. The overshoot of that limit causes extreme degradation conditions of which the cost (economic, social and environmental) is not acceptable; hence it must be avoided. PCC is different for every pollutant just as every pollutant consumes a different amount of carrying capacity at different environments (i.e. the atmospheric $CO_2$ capacity consumption is different than the hydrospheric). As the numbers of both the pollutants produced by the industrial world and of biological species with different decomposing abilities are extremely high, it is obvious that the full introduction of all the relationships concerning ecosystem pollution would make the analysis extremely complex. The issue is resolved with the introduction of the Limiting Factor concept presented below.

### 1.3 The Limiting Factor

This quite abstract but vitally important notion is based on Justus Von Liebig's *Law of the Minimum*, which traditionally refers to the determinant of a biological system's growth. According to the law, a system's growth determinant is the nutrient found in maximum relative scarcity; meaning the nutrient with the highest "demand/natural availability" ratio. Liebig initially set the LF as a relationship between the quantities of three chemical elements; Carbon (*C*), Nitrogen (*N*) and Phosphorus (*P*), concluding that they are utilized in strictly specific ratios of $C/N/P = 41/7/1$.

However, Liebig's Law may very well be expanded to apply in human societies as well; and is of extreme importance for modelling energy paradigm transitions because it provides significant methodological conveniences by reducing the complexity. Fuel resources and pollution carrying capacity are actually fundamental biophysical surpluses (*BSs*) that determine the economy's growth potential. Just as in ecosystems the energy utilized will be determined by the surplus found in maximum relative scarcity. For instance, if the fuel reserve can provide 1000 barrels of oil, the PCC –say of $CO_2$ as the most important pollutant- equals to 1000 kg and each barrel emits 3 kg of $CO_2$, then the economy's LF is the PCC, as the upper limit will have been reached after the consumption of ~333,3 barrels of oil. This means that the system will utilize only 33,3% of the available oil as well; hence leaving the rest unutilized. Generally, from a total of BSs that are used as inputs to the economy, we can define as the LF the one with the highest relative scarcity, which is the one with the highest demand/natural availability ratio. Specifically from an *n* sum of BSs:

$$(X_1 / BS_1)/(X_2 / BS_2)/.../(X_{n-1} / BS_{n-1})/(X_n / BS_n) \qquad (1.1)$$

The $BS_i$ is a specific biophysical surplus and $X_i$ is its demand. The LF is for $Max(X_i/BS_i)$. Natural resource availabilities should always be examined in relation to the demand for them. Hence, even a resource with the highest natural availability may actually be the LF if its demand is also high enough to deplete it fast. The LF concept releases a model from excessive complexity. In relations that include complex dynamics between the variables (i.e. the pollution dynamics described above) there is no need for fully detailed modelling. As the LF determines fundamentally the overall system growth the rest variables are of secondary importance. It is obvious that the LF is not constant in the long-term. Energy transitions consist in the shift of the energy paradigm, which is quite expected to be limited by a different LF. However, in the short and mid-term, the LF might be considered to be constant.

## 1.4 The Scarcity Rent

The Scarcity Rent (*SR*) derives immediately from the 2nd Thermodynamic Law, expressing the payment for a resource's thermodynamic depletion. This kind of opportunity cost constitutes an endogenous account, which in order to be economically effective it must be disposed exclusively in *some form* of replacement of the resource consumed in a past time. Reduced in economic values, this opportunity cost consists in *the net benefit that's lost when one unit of resource is consumed today and is not available in the future*. This concerns also renewable resources of limited quantity that have a small regeneration ratio in comparison to their consumption ratio (such as the PCC). Consequently, besides the extraction cost, the price of a resource should embody the SR as well, which is *the pure scarcity effect from a resource's consumption intensity*.

Furthermore, the SR is conceived in the model as minimum payment for natural services to human societies. While it's easy to comprehend other forms of payment -such as wages for human labor- the same is very difficult to apply for the environment's services towards human societies as the formation of raw materials in the environment does not emanate from human work. Since a consumed non-renewable fuel resource cannot be recreated (because of the 2nd Law), the SR is to be re-invested *qualitatively*; meaning in energy technology transition via R&D as *a promissory title of avoidance to need the resource in the future*. This monetary deposit is actually an investment on the mitigation of the society's dependence on the resource (or at least on its maintenance at sustainable level). Even if the resource's demand remains constant, the society's relative dependence (demand to availability ratio) on it is increasing as the resource is depleted in time. From the time that society achieves the innovation and begins to cease the use of the depleting resource, begins the *resource loan settlement* towards the natural environment. In a few words, what the SR actually does is to *enhance the transition stability*, by connecting directly energy consumption with minimum energy transition investment, primarily via the *ex ante* information provision on the resource's increasing scarcity along its use and secondarily by setting a payment framework for it.

### 1.5 Information accumulation

R&D is conceived as a process where knowledge always increases; hence it may actually be considered as an *information accumulation* process. R&D programs work as a social investment in information accumulation. The particular attribute of information is that it is always positive, irrespective of the R&D program's result –its failure or success. From a purely *Information Theory* (*IT*) approach, information is always positive because of the natural *irreversibility* of information processes (Shannon 1948). R&D programs are always targeted; meaning that they primarily aim at answering positively or negatively to a scientific or technological question. However, their probable failure by no means decreases the *per se value* of the process, as -in any case- something has been learned by it. In many cases gathered knowledge from failed R&D programs has comprised the information basis for the success of future R&D programs; many times *accelerating* the social deployment of their results (to know exactly what *not to do* has the same value with knowing exactly what to do). Hence, the most important question should be "how fast is society able to accumulate information" via an R&D program and how can it accelerate its accumulation rate under the pressure of resource depletion. The last part of the paper examines this issue as well.

## 2. Modelling the energy transition macro-dynamics

This part develops a model of an energy paradigm's life-cycle with the integration of the fuel reserve consumption, the PCC consumption and the SR increase dynamics.

### 2.1 Fuel reserve consumption dynamics

Fuel resource consumption is expressed as a function of time. It is assumed for simplicity that the energy paradigm is comprised only by a single fuel resource. It is also assumed that the initial fuel reserve is not regenerated (via new discoveries etc.). In turn, the intensity of energy use -on behalf of the society- gradually defines the reserve *consumption path*. Consumption begins from an initial intact reserve –say- $A_0$. Its temporal reduction is a complete function of its use, of which the general pattern is expressed by a parabolic curve (an inverse U-shaped curve). Society may choose to consume the reserve rapidly but deplete it in a short period of time or choose a smoother consumption path that provides the energy paradigm with increased longevity. Mathematically, these attributes are expressed by the general consumption trajectory, which –in turn- depends on the *average* consumption/substitution ratio. The general shape of the curve indicates that initially -during the absence of any substitute fuel- the resource use is increasing, while after a specific time it begins to decline as a result of accumulated information (via R&D) and social deployment of the new energy technology. In any case, the complete transition to the new energy resource must have been achieved before the complete exhaustion of the current energy paradigm's fuel reserves. According to the above, the fuel consumption level at each specific time $t$ may be found by:

$$c_t = a \cdot t - b \cdot t^2 \text{, with } a>0,\ a>b,\ 1\geq b\geq 0 \text{ and } t>0 \qquad (2.1)$$

We set *a, b* as two antagonistic parameters with *a* as a parameter of *energy use intensity*, defining the net growth of energy use, while *b* defining the *average* substitution ratio that mitigates partially the effect of parameter *a*. Their ratio defines mainly two features of the curve: (a) its slope, which primarily defines the steepness of the consumption path's trajectory and (b) the time where the reserve becomes zero. We may further analyze the Eq. (2.1) as:

$$c_t = a \cdot t \cdot \left(1 - \frac{b}{a} t\right) \qquad (2.2)$$

According to Eq. (2.2) the energy use intensity parameter *a* is multiplied with a diachronical energy use limitation factor $(b/a)\cdot t$. The *(b/a)* part is an endogenous *substitution efficiency* ratio that expresses how much of the energy use intensity is substituted per unit time. Respectively, the total fuel consumption $C$ at any certain time $t$ is equal to the sum of all individual fuel consumptions up to that certain time:

$$C_t = \int_0^t \left(at - bt^2\right)dt \leq A_0 \qquad (2.3)$$

From the inequality part of Eq. (2.3) derives the conclusion that the total fuel consumption can in no case exceed the amount of the initial fuel reserve $A_0$. This conclusion is in accordance to the First Thermodynamic Law (*FTL*), which dictates that energy can neither be created nor destroyed, but only change form. Indeed, the energy stored in the chemical bonds of the fuel reserve (i.e. hydrocarbon) can only be transformed –upon ignition- into kinetic energy that fuels machinery and eventually heat. However, in any case the total amount of energy after a complete cycle of transformations remains constant. Hence, as long as the fuel is consumed the remaining fuel reserve $A$ at the beginning of each year $t$ will be:

$$A_t = A_0 - C_t \qquad (2.4.1)$$

$$\text{Or } C_t + A_t = A_0 \qquad (2.4.2)$$

Eq. (2.4.2) is a clearer expression of the FTL. However, although equations (2.3) and (2.4) set the limits of the total energy use across a specific time-path, they do not provide any information on the distribution of energy use within this time-path; meaning the maximum limits in energy use that are set in every year from the fuel consumption of the previous year. In a few words, energy availability must be ensured in every year. Hence, for every discrete time we may write:

$$A_t = A_{t-1} - C_{t-1}, \text{ with } 0 \leq A_t \leq A_{t-1} \leq A_{t-2} \leq \ldots \leq A_0 \qquad (2.5)$$

While equations (2.3) and (2.4) are related to the FTL, eq. (2.5) is related more with the Second Thermodynamic Law (*STL*). As the initial fuel reserve is consumed across time, its initial chemical energy is increasingly converted into kinetic energy and finally into heat -dissipated in the environment- which is no longer usable for work production or recoverable from the environment. This reduces future availability. Thus, eq. (2.5) implies that in order for society to avoid a rapid collapse, the remaining reserve must always be enough to support the energy use of the successive year. By further analyzing eq. (2.5), if $A_t=0$ then society has consumed all its fuel resources and the energy paradigm has reached to its end. This is a very marginal situation, where it cannot be known in advance if the transition has been achieved or if the society has suffered an energy default. Contrarily, if $A_{t-1}=A_t>0$, it means that society has not only achieved the transition in time, but has left a fraction of the initial reserve unutilized in its biophysical form. Finally, if $A_{t-1}>A_t>0$ it means that the energy paradigm's life-cycle is not yet complete and society is still on the transition path.

## 2.2 Pollution Carrying Capacity (PCC) dynamics

It is assumed for simplicity that a single pollutant is considered to be responsible for the PCC's consumption and that its production is a direct function of the fuel reserve consumption. Hence, it follows the same pattern with the latter (see equations 2.1 - 2.3); furthermore multiplied by a coefficient $p$, which is the pollutant production per unit of fuel reserve consumption. It is also assumed that the pollutant is accumulating; meaning that the reduction of the fuel consumption does not decrease the pollutant accumulation in the environment (in reality atmospheric $CO_2$ pollution is considered to reduce with significant time-hysteresis; thus, for simplicity we might as well assume that it is accumulating). According to the above, the pollutant production at each specific time $t$ is:

$$p_t = p \cdot \left(a \cdot t - b \cdot t^2\right), \text{ with } p>0 \qquad (2.6)$$

Just as in Eq. (2.2), the total pollution production at any specific time $t$ will be the sum of pollutant productions up that that certain time:

$$P_t = p \cdot \int_0^t \left(at - bt^2\right) dt \leq p \cdot A_0 \qquad (2.7)$$

The PCC might be considered as a product of the total biological stock (i.e. forests); hence it might be considered to be renewable via the continuous solar inputs that maintain forest biomass relatively constant –contrarily to the fuel reserve, which is diminishing across its consumption. However, it is not infinite as the growth of the biological stock is limited by natural availabilities -such as nutrient constraints or natural limited space; hence after a period of growth biomass stabilizes around a maximum value –say- $B$. In order to determine the overall PCC, biomass $B$ has to be multiplied by a pollution absorption coefficient $m$, which expresses pollutant absorption ability per unit biomass. To simplify the analysis, it is assumed that all various biological species have the same pollutant absorption ability. Hence:

$$PCC = m \cdot B \text{, with } m, B > 0 \qquad (2.8)$$

For simplicity it will also be assumed that $B$ is not oscillating at all across time. Hence, the overall PCC consumption dynamics may be expressed as:

$$m \cdot B - P_t = m \cdot B - p \cdot \int_0^t C dt \geq 0 \qquad (2.9)$$

The $m \cdot B$ term of Eq. (2.9) is the upper limit of the PCC consumption term $(p \cdot \int C dt)$ that should not be overshot. Furthermore, based on the same equation, the LF could be identified as well. According to the model's structure, there are two alternative LFs; either the fuel reserve or the PCC. The relation between the fuel reserve and the PCC that reveals which of the two factors is the LF, is expressed as:

$$k = \frac{p \cdot A}{m \cdot B} \qquad (2.10)$$

According to Eq. (2.10), k expresses how many times each factor is more limiting than the other. More specifically, if $k>1$ the LF is the PCC as the total pollution production is higher than can be absorbed by the biological stock. This allows only a ratio $A/k$ consumption of the fuel reserve. If $k=1$ then both resources have the same limitation gravity. In that case, from a purely mathematical point of view society is indifferent, as it must have achieved the transition before the depletion of the fuel reserve in order to avoid both energy shortages and environmental collapses (although in reality the LF should be considered to be the PCC as it usually embodies a higher degree of unpredictability and oscillating behavior). Finally, if $k<1$ the limiting factor is the fuel reserve as the PCC is able to sustain pollution even if the latter is entirely consumed and still have a surplus; hence the transition must have been achieved before the fuel reserve's entire depletion.

The ratio $(b/a)$ fixes the transition speed, as in time $t=a/b$, the variable $c_t$ is zero. It is obvious that the transition speed is a positive function of the substitution efficiency ratio (and more specifically of parameter $b$). This has a significant natural meaning as it signifies that the society gets ahead quite early to dedicate funds in energy R&D in order to make the transition in time. Contrarily, low $(b/a)$ ratios embody the risk that the fuel reserve is depleted before the society shifts completely its energy paradigm. Low $(b/a)$ ratios imply that the society does not possess efficient endogenous mechanisms (i.e. financial, administrative, legislative, political etc.) in order to achieve the transition in time; thus having a greater risk of experiencing an undesirable collapse. This will lead to a rapid collapse of the energy use curve –that actually comprises an energy default- because of the overshooting of the society's limiting factor. This signifies the importance of the society's availability of endogenous limitations of energy over-consumption and self-alarming mechanisms. Societies that possess mechanisms like that are more likely to avoid an energy paradigm default. An indicative conceptualization of the above two cases is presented in figure 2.1 below.

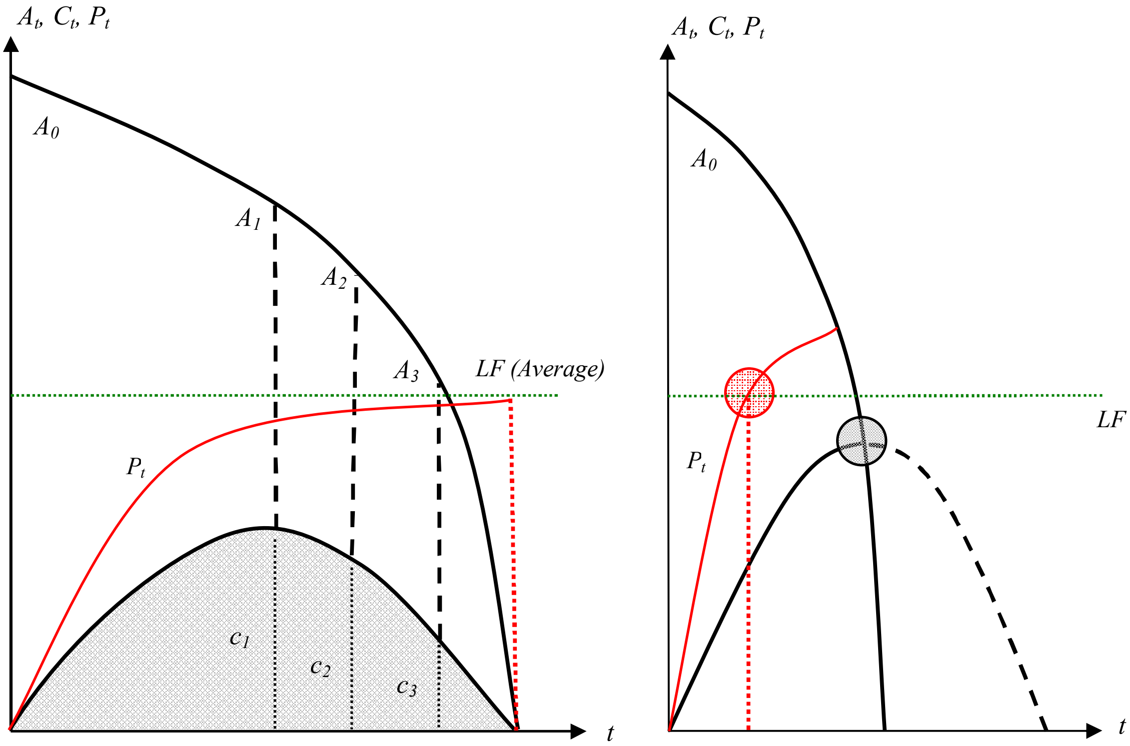


**Figure 2.1:** Representation of the energy transition dynamics based on the fuel reserve and the PCC consumption. In figure **(a)** the LF is considered to be neutral ($k=1$) and the energy paradigm completes its life exactly when the fuel reserve is depleted ($A_t=0$). Contrarily, in figure **(b)** the LF is considered to be the PCC. Figure (b) also aims at clarifying the possible consequences of a very low *b/a* ratio: as the fuel reserve is rapidly consumed it crosses the consumption curve at some non-zero point. After that, the energy consumption falls rapidly to zero as society actually faces an energy default. However, this is not the worse; the rapid fuel consumption increases pollution at a proportionally rapid ratio at such a degree that society will have faced an environmental collapses much before the energy default.

Fig. (2.1), presents two indicative scenarios of energy use. One can think various other combinations; however in any case, the bottom-line is to highlight the high risks that are embodied in very high energy use intensities without being accompanied by a respective substitution ratio. Hence, according to what has been shown above, a high *(b/a)* constitutes a *necessary but not sufficient* condition for the society's transition to a new energy paradigm. It is important (in some cases more important) to examine the dynamics that are formed by the value of parameter *a* itself. One could think that high energy use intensities could drive society to a rapid economic growth and building of structures that would allow it to proceed faster to an energy transition. This point of view it is not very different from the rationale behind the environmental Kuznets curves that claim that high incomes derived from economic growth are a factor of environmental restoration and that the faster economic growth is achieved, the faster the restoration takes place. However, as shown in fig. (2.1), if there is a tighter limitation (i.e. the PCC) this rationale might very well prove to be destructive. Generally, it could be postulated that in cases where the limiting factor is other than the fuel reserve, the energy use intensity parameter should be thoroughly examined as well.

## 2.3 Scarcity Rent (SR) dynamics

The transition speed is determined by the proportion of parameters *a* and *b* that fix the ratio between *use* and *substitution*; thus there must be a relation that couples the consumption of the fuel reserve (and its consequent depletion) with investment in R&D. A more thorough examination of the short-term consumption dynamics of a non-renewable fuel resource reveals that even if the demand is constant in *absolute terms* the demand in *relative terms* is increasing. The Relative Demand (*RD*) is defined by the ratio between the absolute demand (*D*) and the remaining reserve ($A_t$). More specifically:

$$RD = \frac{D}{A_t}\text{, with } \frac{\partial D}{\partial t} = 0, \frac{\partial A}{\partial t} < 0\text{, hence } \frac{\partial (D/A)}{\partial t} > 0 \qquad (2.11)$$

According to Eq. (2.11) the constant demand of a decreasing non-renewable fuel reserve is equivalent to demand growth. Hence, besides the cost of resource extraction ($M$) that comprises a fraction of the fuel's final price ($N$), there should be introduced a Scarcity Rent ($SR$) that reflects *exclusively* the net cost of the resource's thermodynamic exhaustion, which should be also included in the fuel's price. Fig. (2.2) below, conceptualizes this idea:

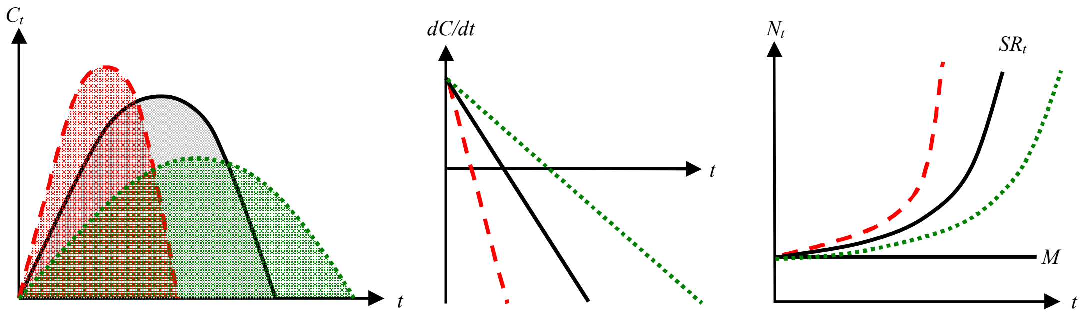


**Figure 2.2:** The short-term evolution of the SR: **(a)** three alternative trajectories of the fuel reserve consumption, with different energy use intensity parameters. It is assumed that the LF is the fuel reserve itself, **(b)** the derivatives of these three trajectories (from the derivation of Eq. (2.1)); it is clear that the higher the energy intensity the sooner society will meet the peak of its energy paradigm *(dC/dt=0)*, **(c)** the SR dynamics in relation to each of the trajectories. In the short-term, the extraction cost *M* of a resource may be assumed to remain constant. However, the thermodynamic depletion effect SR must be embodied in the resource's price *N*. The higher the energy use intensity, the faster the SR increases.

According to the above, the ratio of the fuel's price increase should be proportional –but not necessarily equal- with the SR ratio of increase. Hence, there is established a clear and *continuous* price-based connection between the fuel's consumption and its depletion, *irrespective* of extraction cost increases. We could also imagine more complex combinations –for instance that the extraction cost increases. This would motivate by itself the economizing of the resource, limit its extraction and fund research for other energy resources. However, although these examples are realistic, they do not provide with clear and –above all- continuous information between the thermodynamic depletion of an energy resource and the increase of its price, as the increased extraction cost is an indication that the resource's reserve is significantly reduced. Although very interesting, further analysis on the evolution of the SR under variable (increasing) cost of extraction does not belong to the purposes of this paper. According to the above, the final price of a fuel resource must be:

$$N_t = M + \mu \cdot SR_t\text{, with } \mu>0 \qquad (2.12)$$

In Eq. (2.12) the coefficient ($\mu$) is actually a multiplier that expresses the derived limitations from each reduced unit of the fuel reserve. Across the use of the resource, the SR's main purpose is to be invested in R&D that will eventually mitigate the society's limitations from the fuel's reserve depletion. However, it is possible that substitution is very difficult or very slow across the fuel reserve's depletion; hence it should be accelerated via increased funding. The (probable) difficulty of implementing a sufficiently high information accumulation ratio via the R&D process and move in time to an energy transition is reflected by the multiplier ($\mu$). That is why it is mentioned that the price increase must be proportionally but not necessarily equally ($\mu=1$) to the SR increase. These issues are further explained in the next section.

Finally, it has to be mentioned that the SR has a generalized application; meaning that it must apply simultaneously for renewable resources as well, like the PCC. As said, natural resources are biophysical surpluses of which the consumption reduces future availability. This reduced availability for future generations must be compensated with some form of investment. A renewable resource of which the consumption rate is higher than its regeneration rate (i.e. fisheries) suffers from the same depletion effects as a non-renewable resource. PCC is n indicative example related to the paper's model. The use of the fuel reserve consumes PCC via the production of pollutants. The environment's capacity to sustain an amount of pollutants is finite; hence the increasing production of pollutants is exponentially consuming this kind of biophysical surplus. The only actual difference of the SR between renewable and non-renewable resources is that in the first case the SR is reduced by the resource's net regeneration ratio (if positive). Although very interesting, further analysis on the evolution of the SR for renewable resources does not belong to the purposes of this paper.

## 3. Modelling the energy transition micro-dynamics

Granted that society is aware of its limiting factor and has taken all necessary measures to avoid potential risks from overshooting them, by influencing the (*b/a*) ratio it is possible to speed-up the substitution process via increased R&D funding. The key point of the society's intervention is the acceleration of the average innovation arrival ratio, which eventually leads to the faster implementation of the R&D program's results and social deployment of the new energy technology. As R&D is a process dominated by uncertainty, the following section develops a theoretical model between the increase of available funding and the increase of the average innovation arrival ratio.

### 3.1 R&D as a Poisson Process

R&D is modelled as a Poisson process. Poisson processes are discontinuous and focus on the desirable event probability within a specific time interval (Ott 1995). In this case the desirable event is the successful implementation of the R&D program (Anghion & Howitt 1998). According to the Poisson model, at some time in the future the desired R&D event time will arrive with absolute certainty at least once. The question is simply at what particular moment this will happen for the first time (the success of the R&D program needs to succeed only once in order for the new energy technology to start deploying and the substitution-transition process in the macro-scale to begin). The expression of the event's arrival probability (*P*) in the classical Poisson distribution is:

$$P = e^{-\lambda t}, \text{ with } 0<P<1 \qquad (3.1.1)$$

Or based on the complementary probability $1 - P = 1 - e^{-\lambda t}$ (3.1.2)

It is obvious from eq. (3.1.1) and (3.1.2) that the model is a form of exponential decay. The classical probability (*P*) refers on the evolution of the possibility that the desirable event *does not arrive*. As (*P*) decreases by a ratio expressed by parameter ($\lambda$), this probability diminishes across time with intensity proportional to the absolute value of ($\lambda$). Contrarily, the complementary probability (*1-P*) refers to the possibility that the desirable event *arrives*. It is obvious that both views are absolutely equivalent. The parameter ($\lambda$) of the Poisson distribution refers to the average arrival frequency of a desired event within a selected time interval *t* (i.e. if the desired event arrives once within one year, then the average –say monthly- rate of arrival is 1/12=8,33%). Within this time there must have been achieved a total of ($\lambda \cdot t$) arrivals. Although the notion of the average rate has no profound practical utility, its usefulness consists in estimating the average speed of the event's arrival. This is extremely useful when attempting to increase that speed.

For very long time intervals the probability (*P*) approaches asymptotically the value *0* over time (almost absolute certainty of at least one arrival) but it never acquires precisely that value. In infinity the curves theoretically meet (see fig. 3.1, $limP=limP^*$ as well as $lim(1-P)=lim(1-P)^*$ when $t \to \infty$), but what matters is the distance between the curves much before that point, which is expected to be positive. As after some specific time *t*, the derivative *dP/dt* becomes extremely low – although non-zero- we are actually concerned with at what probability *P* and after, the function begins to have more output of innovation arrivals per unit time. Generally, the less is the probability value change, the more "stiff" (or inelastic to the funding increases) is the new function considered to be. Horizontal curves are more inelastic than steep curves. This is a very significant indication on the limits of manipulating R&D via purely monetary terms, in order to economize funds for other more productive means of manipulation. In a few words, R&D manipulation via monetary means does not work after a point and it should be known in advance what this point is. Generally, it could be claimed that the funding is to take place where the derivative *dP/dt* is maximized. After R&D efficiency increases exhaust monetary means, other means of increasing the average rate of innovation arrivals (i.e. administrative is to follow). A Poisson probability distribution is presented below in Figure (3.1).

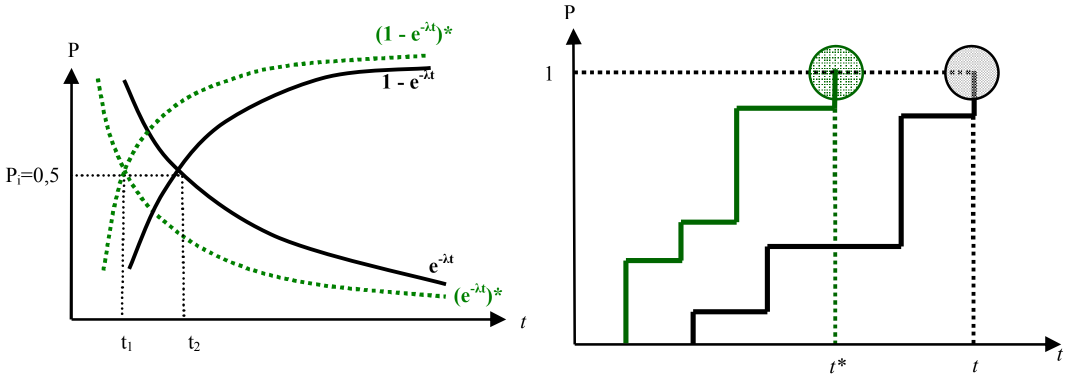


**Figure 3.1:** Probability distribution in a Poisson process: **(a)** the increase of the average rate of innovation arrivals - expressed by parameter ($\lambda$), moves the *entire* probability distribution curve (classical and complementary) to the left. A major consequence is that the whole process is accelerated. Statistically, this means that each probability corresponds to a shorter time, **(b)** internal structure of the process. Each successful step of the R&D program corresponds to a discontinuous bigger or smaller step closer to the complementary probability (*1-P*) equal to *1*. By accelerating the process the steps are implemented at a faster rate, resulting to the probability equal to *1* sooner (at *t**) than before.

### 3.2 Accelerating the transition

In relation to the above, the most important parameter of the model is ($\lambda$), which essentially provides information on the R&D's temporal efficiency. Additional funding comprises a factor of technological upgrades. The ($\lambda$) correspondence in the R&D financial inputs constitutes in practice an *innovation accelerator*. This allows society to upgrade its energy technology within a shorter time interval. This measure is very useful for providing a basic orientation to societies in which innovation is difficult to be achieved because of inadequate funding. For instance, if the endogenous development of a new energy technology proves to be very expensive for the society's budget standards, the society could turn to the international R&D market. If the cost of buying the energy technology is lower than the cost of development, it could use the SR funds for purchasing it. From this particular attribute can derive a measure of the correspondence of the R&D process towards increases in available funding. We may name it as the *Financial Accelerator of Energy Technology* (*FAET*), which is the average innovations increase ($\lambda$) per additional monetary input ($Z$):

$$FAET = \frac{\partial|\lambda|}{\partial Z} \qquad (3.2)$$

The parameter ($\lambda$) in eq. (3.2) is considered as an absolute value (without the sign) as we are purely interested in the parameter's reaction towards funding increases without being interested on the direction of that change (we logically assume in advance that it is positive). Thus we may write the new classical Poisson probability function as:

$$P = e^{-\lambda\cdot\left(1+\frac{\partial|\lambda|}{\partial Z}\right)\cdot t} \qquad (3.3)$$

Some economies are more efficient in transforming the available funding to innovative knowledge. Differences in that efficiency concern mostly the structural attributes of a society. Hence, if we wish to be more accurate in explaining this response as a structural element, we have to calculate the response of parameter ($\lambda$) *independently* of the effects of scale and assess the *FAET Elasticity*, which is actually the percent derivative. Thus, we may write:

$$FAET_{\varepsilon} = \frac{\frac{\partial|\lambda|}{\lambda}}{\frac{\partial Z}{Z}} = \frac{\partial|\lambda|}{\partial Z} \cdot \frac{Z}{|\lambda|} \qquad (3.4)$$

According to Eq. (3.4), the elasticity removes the effects from the variables of which the scale of values differs a lot. For example, if the ($\lambda$) takes values from 0,1 to 5 and the ($Z$) takes values from 100.000 to 1.000.000, the *FAET* will falsely give extremely small values. This gives the false impression that a lot of money must be spent for very small increases, which is a serious underestimation. Contrarily, the elasticity gives results in percentages; which is equivalent as if the two variables had the same value scale.

Furthermore, the *FAET Elasticity* provides more accurate information on the SR's multiplier ($\mu$), developed in the previous section. Specifically:

$$\mu = \frac{1}{FAET_{e}} \qquad (3.5)$$

According to Eq. (3.5), the multiplier examines how far is the relation between funding increases and ($\lambda$) increases from a one-to-one relation; meaning the relation in which the per cent increase of funding causes an equal per cent increase of the average innovation arrival rate. In this case the *FAET Elasticity* is equal to *1*. In this case ($\mu$=*1*) the total of the SR needs to be directed to funding the R&D program that aims at the energy paradigm's substitution. If *FAET Elasticity<1* then there is not sufficient correspondence of the parameter ($\lambda$) towards funding increases; hence in order to accelerate the process at an acceptable rate and avoid the fuel reserve's depletion before society has managed to substitute completely its current energy paradigm, the funding should be a multiple of the SR. Contrarily, a very elastic *FAET* signifies that the R&D process is very sensitive to financial inputs; meaning that small financial inputs suffice for a significant increase (higher per cent increase than the per cent change of the initial funding) of the average innovation arrival rate. In this case only a fraction of the SR is demanded to fund the R&D program.

## Conclusions

The paper develops a model of financing energy technology innovations, of which the primary vehicle is R&D. The model grounds its theoretical assumptions on the theories of the contemporary "energy sociologists" who primarily visualized the similarities that human societies have with energetic ecosystems and further argued that energy availability comprises the "primary function of culture"; meaning the fundamental condition for civilization evolution. Based on that, a society is viewed as a system that in order to sustain its structures and further evolve must bind "economically" energy from its natural environment. The dominant pattern of energy harvesting from the environment is called the "energy paradigm". The model focuses on the optimization of mechanisms that directly connect the consumption of the energy paradigm's fuel reserves with the magnitude of the necessary R&D investment in order to make a transition to a new one – consequently liberating society from its current energy use limitations. As energy use is the primary source of wealth production, a part of this wealth has to be re-invested in order for the transition – via energy R&D as the fundamental energy transition vehicle- to be successfully implemented. This part of the society's wealth must be equal to the scarcity that the thermodynamic depletion of the energy paradigm's fuel resources causes to society; expressed in monetary terms by the Scarcity Rent (SR). As the SR is invested to R&D as a qualitative form of compensation across time, relative management schemes based on the relation between increased financial investment and acceleration of the R&D process are examined. The model ends to the coupling -in a unified circular financial framework- of resource consumption with resource investment, as well as the micro and macro-scale of the energy transition dynamics.

**Bibliography and References**

1. Anghion, Philippe & Peter Howitt (1998), **Endogenous Growth Theory**, MIT Press
2. Borrelli, G. et al. (2001), **Socio-Economic Research on Fusion**, Summary of EU Research 1997 – 2000, EFDA
3. Dosi, Giovanni (1990), **Finance, innovation and industrial change**, Journal of Economic Behavior and Organization 13, p. 299-319
4. Foxon, Timothy J. (2003), **Inducing Innovation for a low-carbon future: Drivers, barriers and policies**, A report for The Carbon Trust
5. Gorman, Michael E. (2005), **Earth systems engineering management: human behavior, technology and sustainability**, Resources, Conservation and Recycling 44, p. 201–213
6. Hall, Bronwyn H. (2001), **The Economics of R&D Tax Credits**, University of California at Berkeley, Oxford University
7. Kemp, Rene (1994), **Technology and the Transition to Environmental Sustainability: The problem of technological regime shifts**, Futures, 26(10) 102331046
8. Ott, Wayne R., (1995), **Environmental Statistics and Data Analysis**, Lewis Publishers
9. Popp, David (2005), **Lessons from patents: Using patents to measure technological change in environmental models**, Ecological Economics 54, p. 209– 226
10. Shannon, Claude (1948), **A Mathematical Theory of Communication**, reprinted with corrections from The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656
11. Tainter, Joseph (1988), **The Collapse of Complex Societies**, Cambridge University Press
12. Tsur, Yacov and Amos Zemel (2002), **Growth, Scarcity and R&D**, The Department of Agricultural Economics and Management, The Center for Agricultural Economic Research
13. White, Leslie (1959), **The Evolution of Culture: The Development of Civilization to the Fall of Rome**, McGraw-Hill
14. Zachariadis, Marios (2002), **R&D, Innovation, and Technological Progress: A test of the Schumpeterian Framework without Scale Effects**, Louisiana State University