Appendices
Appendix 1

For a Physical Economy

“Natural riches are inexhaustible because if this were not the case, we would not be able to obtain them freely. Since they can be neither multiplied nor exhausted, they do not come under economic sciences”.

Jean-Baptiste Say
French economist (1767–1832)

A1.1. Foresight of a physical economy

On a finite planet, the management of resources should maximize the service provided per unit quantities of resources. From the point of view of energy, the ratio of useful outgoing flow to primary incoming flow is the yield. This measure should be a primary indicator in the direction taken by the economy.

The law of variation of the power as a function of the energy yield goes through a maximum for a yield of 0.5. The statistical data for France concerning primary and final energies since 1973 verify this law. As the decades go by, the power increases regularly, however, by a less and less significant amount, whereas the yield decreases.

The power can be expressed as a function of the apparent productivity of work and of the final energy intensity. As a result, an energy policy that proposes an inversion of the current trend, by prioritizing performance of the yield, would

1 Version 8.0 dated 2nd September 2015 (based on version 1.0 dated 19th March 2013, filed on 10th June 2013, with Copyright France under the number NF2W2D6).
set up a reduction of the global energy power, in other words a reduction in productivity.

Reinterpretation of the economy in the light of a physical point of view may legitimize certain degrowth scenarios.

### A1.2. Economy and energy

Energy is the fundamental reality which underlies all transformations, all activity. Living systems, anthropological systems and, in particular, economic activity can therefore be examined from the point of view of thermodynamics [ROD 12]. One of the principal pioneers of the physical approach to the economy, Nicholas Georgescu-Roegen [ROE 06], has soundly criticized the neoclassical economy by astutely invoking the second principle of thermodynamics, which stipulates that during a transformation, useful energy deteriorates and its availability reduces. True energy processes are therefore not reversible; yields inevitably decrease, etc. However, even regarding the primary principle of thermodynamics, there are major learning opportunities that have not yet been integrated into the economy.

National economies refer to the gross domestic product to evaluate their performance. This indicator represents the sum of the added values, in other words the counterpart of the energy contributed all along the activity chains. The GDP therefore expresses an annual flow. The priority objective is an increase in this flow. However, a flow presumes a difference in potential or, expressed in a more prosaic fashion, “reservoirs” at each end of the flow. At previous stages of the chain, these reservoirs are sources of energies, raw materials and biomass, and at later stages, they are humans and biomes that receive the products, and wastes from the activity. The previous reservoirs become empty when the exploited resources are not renewable or, for renewable resources, when the rate of sampling exceeds the rate of renewal. The reservoirs in later stages fill up when the flow of waste is greater than the resorption capacity of the materials by natural environments. Thus, oil becomes rarer in the Earth’s crust and the carbon dioxide produced by its combustion accumulates in the atmosphere.

The neoclassical economy does not integrate, in a physical sense, the capacity nor the status of the reservoirs in its approaches. Supply and demand, which calibrate prices, are not correlated with the potential of the resources, but to their instantaneous flow rate, which does not allow long-term evolution to be anticipated. The course set by the economy is too disconnected from physical contingencies, and pursuit of growth of the worldwide GDP leads at best to a dead end. Paradoxically,
the desire to free ourselves from nature has chained us to it, due to the dependence on resources and un-controlled pollution. In the same way as nature and from an ethical point of view, humans themselves are not at the center of economic thinking, whose priority is efficient allocation of resources: “They aim [the reactions of economists] to maintain conventional economic analysis of the financial system in the context of a thinking apparatus that is highly abstract and more and more disconnected from the empirical analysis of social and human behaviors” [DED 13].

The abundance, facility of extraction and use of fossil energies is behind (at least up until the present day) the exponential development of production and consumption, allowing belief in the inexhaustible nature of resources and an infinity that rational accounting therefore has no need to consider. Yet, it has definitely been shown that physical flows of energy are in fact a major deciding factor in economics for evolution of the GDP [JAN 12].

In an economy that sees itself as frugal and patrimonial, one suitable criterion to consider would be the notion of energy yield and the priority objective would be to maximize this yield, meaning to maximize production and services with a minimum of invested energy. National and international accounting practices obviously take an interest in energy, but not from this preferable physical point of view. It is symptomatic not to see included in national statistics, both for France and, for example, for the International Energy Agency, the tables of values showing the overall energy yield of economies. However, the energy intensity (see Figure A1.1 for France), in other words the quantity of energy dissipated per monetary unit of the GDP, is well-documented. However, the reference to the flow unit of a GDP euro does not restitute performance related to the previous and subsequent potentials of the economic system.

As an example, in its *Green Paper* on the climate strategy for 2030, the European Union is always questioning whether the consumption of energy normalized to the GDP would not be a better indicator. In the case of France, it is maintained that “today, in France, a third of a barrel of oil is required to produce one thousand euros of GDP, whereas in 1973 three times more was required to produce the same effective value” [ART 10], although the consumption of primary energy

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2 The energy equation expressed in dimensions is $\text{ML}^2\text{T}^{-2}$. The GDP expresses an annual flow of money, which has a counterpart in the material flow, with the dimension of a flow rate $\text{MT}^{-1}$. The dimension of the ratio that expresses the energy intensity is $\text{L}^{2}\text{T}^{-1}$, which is kinetic viscosity.

3 “It will also be necessary to consider if the metric for such a target should continue to be absolute energy consumption levels or whether a relative target related to energy intensity would be more appropriate (e.g. energy consumption relative to GDP or gross value added)” [COM 13].
and final energy is increasing in absolute value (albeit with a downturn since 2008), and in value per inhabitant, and despite a sharp increasing trend of the country’s energy bill [SER 15]. In an article on energy transition [BEL 13], the IDDRI (a French think tank, the Institute for Sustainable Development and International Relations) confirms for its part that “in the absence of significant measures to substantially improve energy intensity, all growth of the GDP leads to an increase in energy consumption”, invoking the energy intensity as a pertinent indicator and considering the cause and effect relationship between the GDP and the consumption of energy in the orthodox and nevertheless debatable sense of the point of view of the physical economy.

The ratio of the final energy intensity ($i_F = \frac{E_F}{\text{GDP}}$) to the primary energy intensity ($i_P = \frac{E_P}{\text{GDP}}$) automatically restitutes the overall energy intensity ($\frac{E_F}{E_P}$), but the economic analyses limit themselves to an interpretation of the energy intensity and not of the ratio of its two final/primary expressions.

![Figure A1.1. Evolution of the final energy intensity in France between 1981 and 2011 (kWh/€)](image)

**A1.3. Final energy yield of national economies**

Statistical data from the International Energy Agency reveals an overall energy yield that has been regularly decreasing since at least 1970 (Figure A1.2). In 40 years, it has gone from 0.75 to 0.68.
Figure A1.2. Worldwide energy yield ("world primary energy demand" over "world total final consumption") of countries around the world, according to the International Energy Agency. For a color version of this figure, see www.iste.co.uk/rossignol/climatic.zip

Comment on Figure A1.2.– For a given year, the values differ a little depending on the sources and one of the terms in the pair may be missing (primary energy $E_P$; final energy $E_F$). The graph shows, in red, the yields calculated when for a given source the two terms in the pair ($E_P$; $E_F$) are available and, in blue, the ratio of the annual average of primary energies available to the annual average of the final known energies (in this case, for certain sources, one of the terms in the pair ($E_P$; $E_F$) may be missing).

In France, for several decades, the consumption of energy has been increasing, more sharply for primary energy than for final energy (Figure A1.3), which led to a reduction in the overall energy yield (Figure A1.4) from 0.69 to 0.58 between 1981 and 2011 (in 1973, the yield was 0.74). This decrease is greater than the worldwide average, which is seen in countries which have intensified their economy the most.

For France, the data used come from the Pégase database, from the French Observation and Statistics Service (SOeS). A continuous series is available for the period 1981–2011. The energy data for 1973 come from statistics from INSEE (French National Institute for Statistical and Economic Studies) (the energy yield was 0.74 in that year).

4 The Pégase database does not provide figures for the period prior to 1981. The World Bank goes back to 1960, but only for the consumption of primary energy. The Eurostat database provides data for after 1990. INSEE does not provide a continuous annual series (only 1973 is available prior to 1990).
From the point of view of the physical economy, the performance of France is in decline. The reduction in energy intensity, which is *a priori* something to be celebrated, only demonstrates that the growth rate of the GDP (around 70% over 30 years) is higher than the growth rate of the energy consumption (40% for the same period) and confirms that this indicator does not provide useful information for the patrimonial management of energy resources.

**Figure A1.3.** Evolution of the consumptions of primary energy (in red) and final energy (in green) in France between 1981 and 2011 (Mtoe). For a color version of this figure, see www.iste.co.uk/rossignol/climatic.zip

**Figure A1.4.** Apparent worldwide energy yield for France between 1981 and 2011
A1.4. Energy yield and power: the case of France

The final power is the final energy consumed per unit of time: \( P_f = \frac{E_f}{t} \).

Figure A1.5. Final power (GW) of availability of energy for the French system

Figure A1.6. Theoretical curve of the variation of the power as a function of the yield of an energy system
The average energy yield ($\eta$) in France is given by the ratio of the final energy consumed to the primary energy provided previously:

$$\eta = \frac{E_F}{E_P}$$

A law relates the useful power (here, final, $P_F$) and the energy yield ($\eta$) of a system:

$$P = K (1 - \eta) \eta$$  \[A1.1\]

This law is governed by a second-degree function, represented by a concave parabola, which has a maximum for a yield of 0.5.

The constant $K$ can be explained in economic terms.

That is $\prod$ the apparent productivity of work\(^5\) and $T$ the cumulative volume of hours worked:

$$\prod = \frac{GDP}{T}$$  \[A1.2\]

The economic trend is to increase productivity, in particular the productivity of work. It is a case of increasing flows while reducing the time required to produce them. The apparent productivity of the work has been regularly increasing for decades, on a worldwide scale and in particular in France (Figure A1.7).

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\(^5\) According to INSEE: “In economics, productivity is defined as the ratio, in volume, between a production and the resources implemented to produce it. The production designates the goods and/or services produced. The resources implemented, and also denoted production factors, designate the work, technical capital (installations, machines, tools, etc.), invested capital, intermediate consumption (raw materials, energy, transport, etc.), in addition to factors that are more difficult to grasp although they are extremely important, such as accumulated savoir-faire. The productivity can also be calculated with respect to a single type of resource, work or capital. We therefore talk of apparent productivity. A measure that is often used is the apparent productivity of work. An apparent productivity of the capital can also be calculated […] the apparent productivity of the work only takes into account the single factor of work as the implemented resource. The term ‘apparent’ serves as a reminder that the productivity depends on all the production factors and on the way in which they are combined. The apparent productivity of work is usually measured by relating the wealth created with the work factor: the wealth created is measured by the added value (evaluated as a volume); only the volume of work implemented in the production process is taken into account and it can be quantified in several ways: 1) if the volume of work is measured by the number of hours worked, the term ‘apparent hourly productivity of work’ is used; 2) if the volume of work is measured by the number of people in employment (real people), the term ‘productivity per head’ is used”.
The final energy intensity of the economy ($i_F$) is the final energy per unit of added value produced:

$$i_F = \frac{E_F}{GDP}$$

According to [A1.2], it results that:

$$E_F = \prod i_F \cdot T$$

The final power is therefore:

$$P_F = \frac{\prod i_F \cdot T}{t}$$  \hspace{1cm} \text{[A1.3]}$$

By combining equations [A1.1] and [A1.3], it results that:

$$K = \frac{\prod i_F \cdot T}{t (1 - \eta) \eta}$$

Restitution of a constant value for $K$, from statistical data, is required to validate this interpretation. In fact, this is indeed more or less the case$^6$ (see Figure A1.8). For France:

$$K = 825 \text{ GW} \pm 10\% \text{ (standard deviation 46 GW)}$$

$^6$ K is a constant for a given energy “generator”. A more in-depth examination would be necessary to assess possible modifications of the eco-energy system which would explain the fluctuations observed for $K$. 
The final power expressed as a function of the yield, restituted by annual statistical data, approximately follows the theoretical law as shown in Figure A1.9.

**Figure A1.8.** Constant $K$ ($P = K (1 - \eta) \eta$) as restituted by statistical data for France (GW)

**Figure A1.9.** Final power (GW) as a function of the yield recalculated with the average constant $K$ (red curve) and with the annual values of the $K$ parameters. For a color version of this figure, see www.iste.co.uk/rossignol/climatic.zip
Since 1981, each decade that goes by sees an increase in the energy power of the French system to the detriment of the yield. However, as shown in Figure A1.9, this evolution is slowing, which suggests probable stagnation, or an inverting trend in the coming years, which would be beneficial from the point of view of the economic management of resources and synonymous with a reduction in productivity, for example.

A1.5. Case of other European countries

The Eurostat database provides series of data on energy for the period 1990–2011. Similar processing to that detailed above for France in the case of the three other top economic powers in Europe and for some countries with lower GDPs returns different values of $K$ that are roughly constant.

![Figure A1.10. Constant $K = K (1 - \eta) \eta$ restituted by statistical data (Eurostat) for some European countries (GW). For a color version of this figure, see www.iste.co.uk/rossignol/climatic.zip](image)

A1.6. Interpretation and physical justification of degrowth

With the decline of fossil resources and energy yields from exploitation on the horizon, and therefore of economic profitability, it has become fundamentally important to modify the economic reasonings that are based on the abundance of easy energy.
A patrimonial economy should prioritize energy yield, in other words renounce maximization of power. Due to the fact that the current global yield is higher than 0.5, its increase would be expressed as a reduction in power (Figure A1.11).

![Useful power vs Yield η](image.png)

**Figure A1.11.** Advanced economies must envisage inverting their productivistic thinking to improve energy performance. For a color version of this figure, see [www.iste.co.uk/rossignol/climatic.zip](http://www.iste.co.uk/rossignol/climatic.zip)

The power expresses the ratio of energy involved in the transformation, to the time required by the process. Consequently, reducing the power has the effect of slowing down the economy: producing less in absolute terms, but more for the same energy invested and for a longer duration of time, is a new principle which should prevail. Taking into account the processing times reveals, according to the “language” of the second principle of thermodynamics, that the slowing of transformations would come close to reversing and would therefore generate less entropy, in other words less deteriorated, unusable energy. Slowing of the economy, otherwise known as a certain type of degrowth, would be an improvement. The idea of economic degrowth has widely been introduced and justified [DIE 09] and insight provided by the physical approach is important, since the principles on which tangible material things are based necessarily govern all physical systems, even if they are anthropological and dedicated to the resources economy [FER 14]. Although they generally incite rejection and denial (due to the confusion between material degrowth and recession or regression), degrowth has, in fact, begun in developed countries. France is already showing a change of regime, as demonstrated by the accumulation of the points on the power–yield curve (Figure A1.9) and their increased dispersion which reveals instability, for recent years, on approaching a yield of 0.5. These conclusions about the pertinence of a certain form of degrowth, based on the physical approach, are added to those of a few economic studies which simulate various degrowth scenarios. Peter A. Victor has demonstrated that depending on the political economic options that have been selected, a scenario of
degrowth can lead either to a catastrophe or to an improvement of the economy from the point of view of the GDP, public debt, employment, poverty and greenhouse gas emissions (Figure A1.12) [VIC 08]. The conditions required for favorable degrowth are in particular:

– low growth of State expenditure;
– stabilization of the population;
– carbon tax;
– growth of State expenditure to combat poverty;
– reinforcement of the local economy;
– reduction in the consumption of space;
– low growth of investment and productivity;
– reduction of working time (with more equal sharing).

It is of interest to note that certain conditions that are conducive to economically favorable degrowth (low growth of investment, productivity, reduction of working time) comply entirely with the advice provided by the improvement in energy yield. To mitigate the lack of good sense, we take good note of the fact that the first principle of thermodynamics, in the same way as the second, dictates that infinite growth of anything is an ideal that needs to be assessed. While the economy continues to avoid getting tied up in tangible physical things, the unavoidable degrowth imposed by nature will create a recession, even a devastating regression, which is well-documented in the prospective scenarios given by Dennis Meadows et al. [MEA 12] for the 21st Century and by the considerations of François Roddier concerning the thermodynamics of evolution [ROD 12]. However, the return to physical “good sense” suggests deliberate unleashing of a degrowth which generates prosperity of another order, which is a new progress, according to Tim Jackson [JAC 10], based on an attention of human well-being and to the perennity of the environments. Reinterpretation of the economy from an energy point of view should now be prioritized, as advocated by P.P. Christensen, for example:

“Negligence of energy and material resources or their presumed aggregation in primary factors (for the functions K,L) constitutes a central weakness in the neoclassical theory of production. This difficulty will not be overcome simply by adding new production factors (functions KLE and KLEM) and new production relationships to the existing theory. The theory must be substantially reformulated. Considering energy and material flows in a manner that is compatible with physical principles will lead to a different theory” (author’s translation) [CHR 87].
Figure A1.12. Simulation of two degrowth scenarios in comparison with the trend scenario, by Peter A. Victor [VIC 08]. For a color version of this figure, see www.iste.co.uk/rossignol/climatic.zip
The postulate stated by Jean-Baptiste Say, which still prevails in the political imagination, is obviously void and invalid. It is in fact a matter of urgency to design a new vision of the economy directed by ethical, biological and physical indicators, in particular those involving energy, in order to orientate the future of our societies towards calm and harmony with the planet.

Over and above an energy transition alone, it is necessary to carry out a revision of economic theories, which are too disconnected from physical, ecological, anthropological, cultural contexts, etc., or are quite simply false [KEE 14], to reorientate the development model.