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A Contribution to the Methodology of Long-Term Energy Scenarios

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Résumé — Contribution à l'élaboration des scénarios énergétiques — Notre objectif de contribution à l'élaboration des scénarios énergétiques s'appuie sur un mode de représentation graphique global et un cadre d'analyse des évolutions énergétiques reposant sur les séries statistiques longues (1850-1997). Nous adoptons une représentation graphique, dite *f/c*, consistant à croiser les historiques des consommations et des parts de marché d'une énergie primaire donnée. Cette représentation *f/c* suggère de retenir un cycle de vie énergétique de nature à préciser le potentiel de développement de chacune des énergies. Nous complétons cette approche en montrant, grâce à l'usage de données filtrées et de la représentation en phase, que toute évolution de long terme est courbe et ne peut être correctement traduite par un taux de croissance constant. Nous proposons en conclusion deux scénarios énergétiques globaux à l'horizon 2020 construits sur cette méthodologie.

***Abstract* — *A Contribution to the Methodology of Long-Term Energy Scenarios* —** *Our objective of contributing to the methodology of energy scenarios relies on a global mode of graphical representation and a framework for analyzing energy dynamics, based on long-term statistical series (1850-1997). We use a graphical representation, the* f/c *graph, which consists of plotting the history of consumption against that of market share for a given primary energy. This* f/c *graph leads to the adoption of an energy life cycle that can be used to specify the development potential of each kind of energy. Through the use of filtered data and a phase representation, we round out this approach by showing that all long-term evolution is curved and cannot be correctly described by a constant growth rate. In conclusion, we propose two global energy scenarios for the 2020 horizon, built on this methodology.*

INTRODUCTION

This article continues the authors' research work devoted to energy forecasting, which was presented in *Revue de l'Énergie* and the ENSPM's *Cahiers Économie* (*ENSPM* is the *École Nationale Supérieure du Pétrole et des Moteurs*, part of *Institut français du pétrole*). In the first paper (Alba and Rech, 2000), we highlighted the variety of problems, linked either to statistics (*i.e.*, precision, equivalences) or to methodology, whose inadequacies, in the latter case, were largely the result of not considering acceleration/deceleration phenomena when analysing the trends of the main variables.

Using a new methodological approach that we will present in detail and broaden in this article, we were led to emphasize:
- The inadequacy of parameterizing with a fixed rate of change (which is always contrary to what the past has shown us).
- The disruptive nature of some scenarios, which imply real economic utopias.
- The insufficient precision of certain studies as regards the data used, the reference dates, the coefficients of equivalence between energy forms, or even the methods used. We shall not return to these problems here, which are a matter for the "client" organizations of these studies, as well as for statistical institutes.

Here, first of all, we present our methodological approach, which further develops the principles laid out in our previous work on total energy consumption and its determinants, and extends this to primary energies. To lighten this presentation, we have transferred to the appendices various matters concerning the methodology and points that we consider secondary, relative, that is, to energy phenomena.

Then we attempt to explore the field of energy scenarios to demonstrate the flexibility of our method, without claiming that it is some kind of magic bullet, which, moreover, as the experience of economic analyses shows, is not likely to exist.

The problem of energy scenarios is at the heart of policies that have striking characteristics, including the size of investments, the lifetime of installations, the critical nature of the needs to be fulfilled, geopolitical considerations, and, last but not least, the prima facie limited nature of fossil fuels. It is clear, therefore, that energy scenarios are important factors for the policy choices they influence.

Here, we will not return to the problems of statistical quality or the coefficient of equivalence. The latter problem, although critical, only intervenes in mathematical terms in a linear way, without distorting observed or predicted dynamics. Everyone is familiar with these questions, though many publications can be criticized for omitting to mention their sources and the equivalences they use. The precision of data is unknown; in a world balance of 8 Gtoe, the "per thousand" ‰—if we take this as the reference for extreme precision—represents 8 Mtoe, while the "per cent" (%) represents 80. It might be estimated that our data precision is better than 1%, but can anything be concluded as to an annual variation of 2 or 3‰? Whatever the case, and even if all economic data are liable to such remarks, we must make do with what we have.

1 ORIGIN: FAILURE OF THE MARCHETTI's MODEL

At the root of our work is an attempt to update Marchetti's work (Marchetti and Nakicenovic, 1978). Why? Because, as far as we know, he is the only author to have sought a global representation of energy dynamics. In 1978, using a dispersion model, Marchetti proposed a quasi deterministic approach with a coordinate system of time/log*(f/1-f)*", where *f* is the market share *(Fig. 1)*: "*Observation of the past, from the Industrial Revolution in the 18th century, seems to indicate that the various sources of energy inexorably follow each other at unavoidable rates that can be precisely calculated and confidently extrapolated. According to the idea developed by Marchetti, a succession of energy waves follow each other with an almost fatalistic periodicity, establishing an obligatory schema that the world cannot escape."* (Percebois, 1989).

Although this model was summarily accepted by Peterka and Fleck (1978), it has proved to be too ambitious, and its predictions have only rarely been verified, particularly when the model is applied to a given country. However, this attempt showed that energy dynamics is not just an empty notion, and that representation can facilitate comprehension. Moreover, interesting parallels were drawn between different energies, as we will identify and explain.

To obtain an initial view of the problem of energy dynamics, very long-term data can be used *(Table 1)*. Although hydraulic energy use in the distant past has been greatly underestimated, and solar and wind energy come from the depths of time, we will maintain that the historical order of appearance is as follows: biomass, coal, oil, hydroelectric, natural gas, geothermal, nuclear, solar/wind. The "other renewable energy sources" (geothermal, solar, wind) are shown according to the best available data, whose precision is low, which means that the accuracy of their time series cannot be ensured, except through a sort of harmony with the overall schema. The data in the Table 1 leads to various questions that show the limits of Marchetti's (esthetically attractive) approach. These data not only show the dynamics of global consumption, but also the dynamics of each type of energy as regards its *quantity* and *market share*, while Marchetti only considers market share. The case of coal is remarkable, as the quantities cross, while the market share increases and then decreases. The data in Table 1 are shown again in Figure 2 (consumption) and Figure 3 (market share).

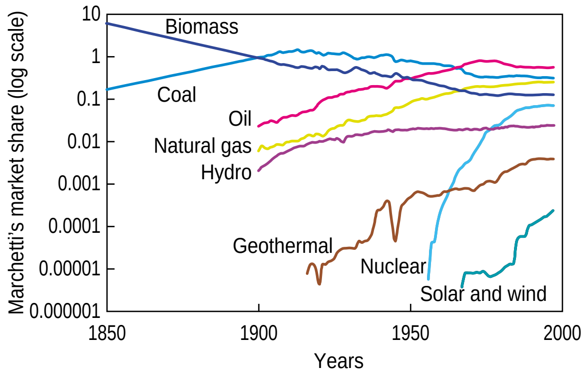

Figure 1

History of energy dynamics 1850-1997.

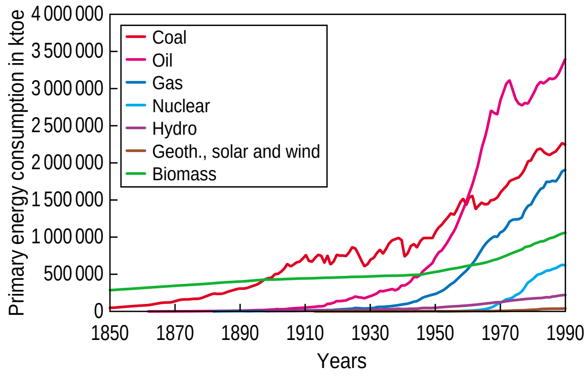

Figure 2

Evolution of primary energy consumption.

TABLE 1

Raw data for worldwide consumption of primary energies (in Mtoe)

	Coal	Oil	Gas	Nuclear	Hydro	Geothermal	Solar and wind	Biomass	Total
1700	3	–	–	–	–	–-	–	144	147
1750	5	–	–	–	–	–	–	180	185
1800	11	–	–	–	–	–	–	217	228
1850	48	–	–	–	–	–	–	288	336
1900	440	20	5	–	2	–	–	429	896
1950	945	492	162	–	41	1	–	495	2137
1997	2255	3409	1911	624	221	37	2	1062	9521

Source of data: see Appendix A1.

We felt that it was not unreasonable to try to arrive at a system of representation that is more suitable than Marchetti's. It was therefore with the aim of building an efficient system of representation—one that allows full freedom for scenarios, which is not the case of Marchetti's approach—that we undertook the work which lead to the proposals described below.

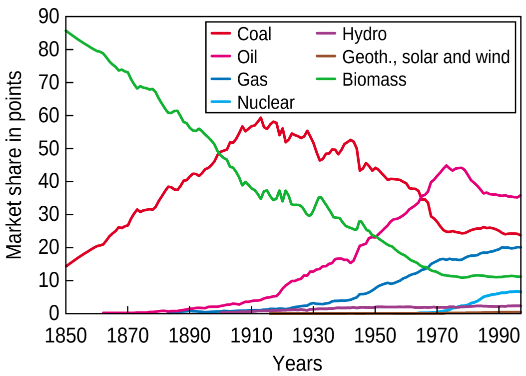

Figure 3

Market share history.

Before going on to develop the approach described above, we find it useful, based on experience, to specify certain elements of vocabulary.

- Growth rates (energy, GNP, population) are generally expressed in %/year. Although the time reference is generally omitted, that is not a reason to ignore it.
- We calculate and use a dynamic, which is the relative variation of rates *(see Appendix A3)*. It is also expressed in %/year, with the proviso that the dynamic is the %/year of a rate that is itself expressed in %/year. For example, a dynamic of 10%/year applied to a rate of 1.5%/year means that this rate becomes 1.65%/year.
- Traditionally, market shares are expressed in %. In order to avoid any confusion between the rate of growth (in %/year) of a market share (itself expressed in %), we have decided to express market share in points, with a scale from 0 to 100. For example, an energy source could have a market share of 30 points, with a growth rate of –1%.

This means that the market share goes from 30 points to 29.7 points. Of course, that related to the dynamic also applies.

2 PRINCIPLES OF THE PROPOSED METHOD

Although what follows is the result of thorough analytical work, we believe it logical that, as this article proposes a method, we first explain the principles before illustrating them.

2.1 Use of Filtered Data

The way we represent the phenomena we study must be coherent with a fundamental characteristic of energy investments, *i.e.*, their underlying consumption. We are in a long-term context, which implies using historical series that go far back in time. In order to stand far enough back, we are brought to the beginning of the century, because of the world wars, the massive appearance of oil after 1920, the rather less massive onset of nuclear energy after 1950, and the oil crises.

We therefore assume that neither the inevitable statistical imperfections nor the volatility of fluctuations mask secular trends. Our analysis relies on these trends, which are indicators of the profound dynamics that are characteristic of each energy source.

We therefore use classic time series, which we filter *a priori*. Even if the time series do not have a confidence interval that is optimally adapted for statistical use, we can nevertheless observe that all economic models effectively filter the data they use, both during the econometric phase of reconstructing the past, and during the projection phase. Consequently, we have decided to work with filtered data. For this, we use the classic Hodrick-Prescott filter (1997). Appendix A2 provides some details on this method.

2.2 Examining Phase Dynamics

Appendix A3 describes the principle of phase representation, which is not new. The interest of this representation is to naturally show the elements linked to rates of change, particularly the dynamic, which is the relative variation of a rate that is linked to the trajectories' curvature. From this analysis, we discover some noteworthy elements that can be used to characterize dynamic scenarios, or, in an equivalent formulation, to show which values of rates and dynamics (rate variations) should be used to attain a certain objective in a certain time. Examples 1 and 2 (developed hereafter) illustrate the properties of phase representation.

The interest of the phase representation as applied to energy dynamics resides in the fact that, beyond simple graphical use, this plotting integrates the economic dimension of energy development, by summarizing and illustrating the degree of tension between supply and demand.

2.2.1 Example 1: The Evolution of Coal's Market Share

In Figure 4, the evolution of coal's market share is plotted in the logarithmic phase plane (where the log of the market share is the abscissa, and rate of growth is the ordinate). The dynamic, which was slightly negative for 40 years, becomes sharply negative from 1900. The trajectory goes into the lower half-plane, forming a normal to the abscissa axis, at the time of World War One. Attempts to maintain market share, marked by trajectories that rebound upwards (in 1938, 1956 and the beginning of the 1980s), never succeed in crossing with sufficient energy to sustain growth.

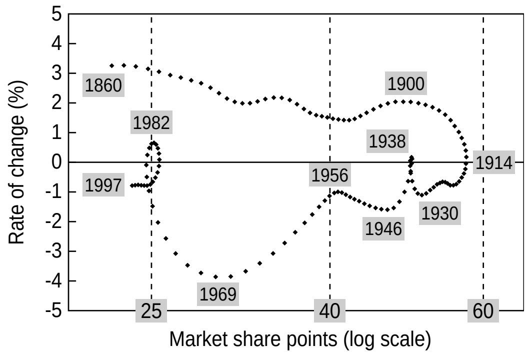

Figure 4

Coal market share cycles.

Table 2 gives the values of average growth rates (variations) and of the dynamic (rate of change) for noteworthy periods of the coal market share trajectory.

TABLE 2

GR and dynamic indexes evolutions of coal's market share

Period	GR*	Dynamic
1860-1900	2.10	–2.45
1900-1913	1.29	–6.89
1914-1930	–0.72	27.39
1946-1956	–1.29	–4.05
1956-1969	–2.45	12.08

* *GR = growth rate*

2.2.2 Example 2: The Evolution of Coal Consumption

In Figure 5, coal consumption is plotted in the logarithmic phase plane (log consumption as the abscissa, growth rate as the ordinate). The trajectory shows various cycles, for which

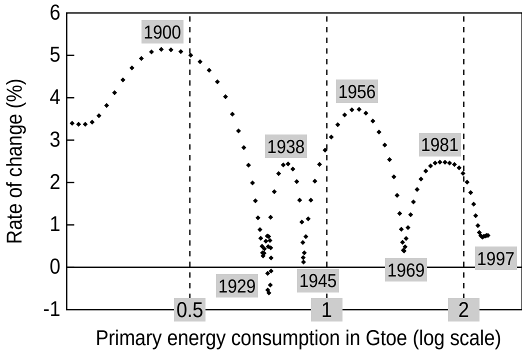

Figure 5

Coal consumption cycles.

the high and low points have been dated. The pseudo-cycloid structure is clear. Note the virtual symmetry between the growth phases and the decline phases.

Table 3 gives the values of average growth rates (variations) and the dynamic (rate of change) for noteworthy periods of the coal consumption trajectory.

TABLE 3

GR and dynamic indexes evolutions of coal consumption

Period	GR	Dynamic
1900-1927	2.08	–7.38
1945-1956	2.24	47.29
1956-1969	2.05	–8.93
1969-1981	1.73	22.12
1981-1997	1.38	–7.31

2.3 Plotting *f/c*: Market Share *vs.* Quantity

The characteristics of the evolution of the different energies sources are shown through a phase representation. As this history clearly shows that consumption and market share must simultaneously be taken into account, we decided to represent energy history by correlating these two variables, even though they are related through total consumption.

The property of this representation is that, **at each instant, the points representing the different forms of energy are aligned on a straight line, called the energy demand line**[(1)]. Thus, for each type of energy, by definition:

$$f_i = c_i/C$$

where f_i is the market share of energy *i*, c_i the consumption of energy *i*, and *C* is total energy consumption.

1 The consequence of using filtered data is that the sum of the filtered series of each primary energy source is not strictly equal to the filtered series of total consumption. However, the small deviation observed is not sufficient to question the conclusions generated by this mode of representation.

This shows that, for a given *C*, the points (c_i,f_i) are aligned. This is true whether the scale is logarithmic *(Fig. 6a)* or Cartesian *(Fig. 6b)*. We will use the logarithmic scale, because the slopes of the trajectories are then simply linked to the ratio of the growth rates of each energy form and of total consumption.

Besides the analytical elements this representation provides, which we will present below, we will use this context later on to formulate specific scenarios that are characteristic of each primary energy source. We call a specific scenario a trajectory in the *f/c* plane. Energy evolution is thus represented by the set of specific scenarios. This implies that the total energy consumption level must be considered as intrinsically exogenous. We then put the specific scenarios back in their respective phase representations in order to evaluate more precisely the consequences in terms of the rate of change of consumption and market share.

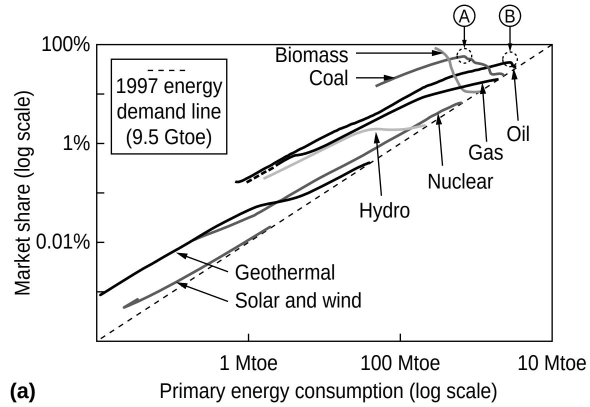

Figure 6a

Primary energies in the *f/c* plane 1850-1997.

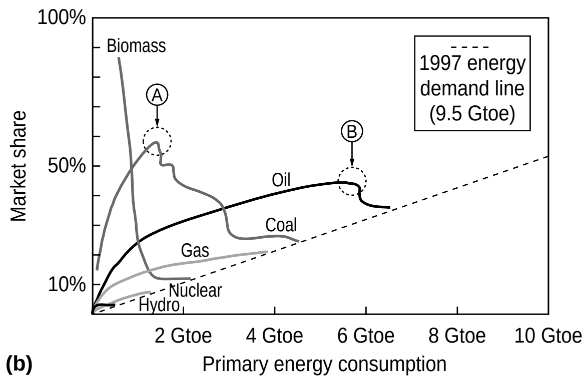

Figure 6b

Primary energies in the *f/c* plane 1850-1997 (Cartesian scale).

Once a scenario has been established in the *f/c* plane and evaluated in the phase representation, one can, if need be, for the purpose of illustration, return to classic representations that use time series by decomposition into variable *f* and variable *c*, even if this approach is ultimately of little interest either in the analysis of the past, or in the process of building a scenario.

3 ILLUSTRATION OF THE METHOD

3.1 What the History of Consumption Teaches

When plotting the time series of the rates of change of energy consumption, one is struck by the variability of those rates *(Figs. 7 and 8)*. If smoothed data are used *(Figs. 9 and 10)*, a remarkable phenomenon is revealed: the appearance of each energy form is accompanied by very high rates, which then drop fairly rapidly. There is no miracle here, but simply the consequence of definitions that were adopted, as we shall see with the help of a very simple theoretical approach.

Consider an economy with energy form c_1. Total consumption is C and the market share is f_1/C. At a given time t_i, we decide to introduce a new form of energy c_2:

for $t < t_i$, $c_1 = C$; for $t > t_i$, $f_1 = c_1/C$, $f_2 = c_2/C$,
and, obviously, $df_1/f_1 = dc_1/c_1 - dC/C$ (respectively, f_2)

– df_1/f_1 expresses the growth rate of market share f_1 of energy 1 (respectively, f_2) as the difference between the rate of growth of consumption of this energy and of total energy consumption. This applies to an energy form already on the market. We could conclude—wrongly—that an energy source could not be put on the market at a low rate. Indeed if dc_2/c_2 is $< dC/C$, df_2/f_2 becomes negative. But, by definition, df_2/f_2 is zero at first and cannot become negative. Here, we are in a discontinuous situation, which can be illustrated as follows: at time 0, dc_2 goes from 0 to a certain value through an impetus

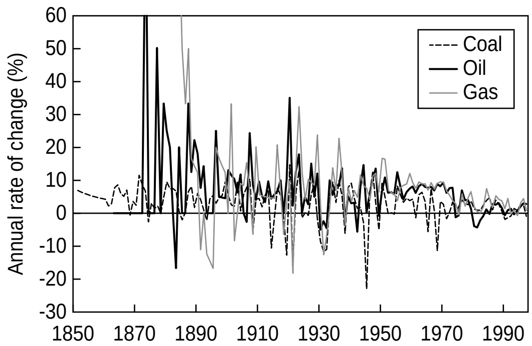

Figure 7

Time series of annual rate of change in primary energy consumption for coal, oil and gas (raw series).

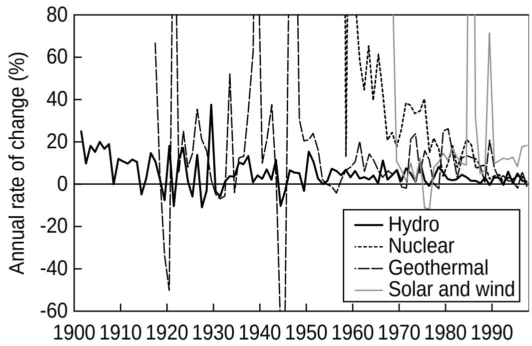

Figure 8

Time series of annual rate of change in primary energy consumption for hydro, nuclear, geothermal, solar and wind (raw series).

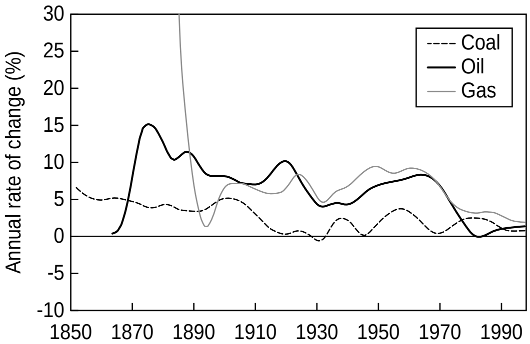

Figure 9

Time series of annual rate of change in primary energy consumption for coal, oil and gas (filtered series).

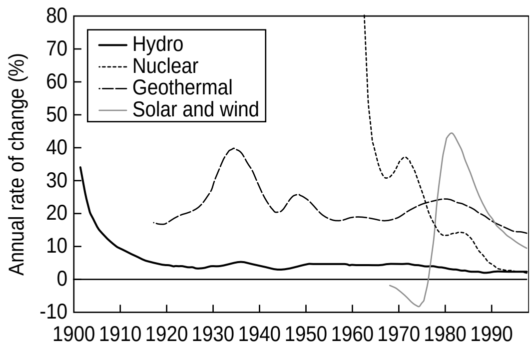

Figure 10

Time series of annual rate of change in primary energy consumption for hydro, nuclear, geothermal, solar and wind (filtered series).

(acceleration) of the second difference. dc_2 therefore appears as a jump, whose derivative is mathematically expressed by a Dirac delta function. Arithmetically, any introduction is associated with an instantaneous, almost infinite growth rate, which makes df_2 positive. The new energy source will see that growth in its market share (which simply expresses the high rate of consumption) will continue as long as its intrinsic properties or the aid it is provided are sufficient. What must be clearly understood is that the appearance of a new energy source is accompanied by very high rates, without this reflecting miraculous qualities.

This **introductory effect** is a feature of all the most recent energy sources. The effect is clearly lessened by a very prudent market launch strategy, but it cannot disappear, except by transferring the starting point way back in time. Without further elaborating, we may conclude that, at the launch of each energy source for which we have adequate statistics, we are not in the presence of this kind of process. It should also be remembered that interference between energy sources only appears at the end of the introductory phase, when the new arrival looks for an acceptable market share that will pay for its development.

We will now examine the dynamics of each energy form:

– Coal *(Fig. 11a)*: the dynamic is currently (1997) very slightly positive, at the limit of errors of measurement, and recent rates remain low, less than 1%/year. The maximum rate reached in 1980 was 2.5%/year, a favourable period for coal (with the price of oil at its historic high, and no concern for the greenhouse effect).

– Oil *(Fig. 11a)*: the big winner until 1969, oil has since suffered a change in status, with its rate of 8%/year before 1969 dropping to 0 in 1982. Since then, a dynamic, which although positive is constantly decreasing, has limited oil to around 1.5%/year, such that a return towards 0 is not impossible over the next 20 years.

– Natural gas *(Fig. 11a)*: the dynamic, which has been negative since the mid-1960s, appears now to be moving towards 0, and may even become positive, if we take into account gas reserves, the good geographic distribution of those reserves and the ecological popularity of the product. The latter point could encourage electricity production, which can rely on the remarkable progress made with combined cycle gas turbines. It is therefore reasonable to think that the natural gas rate might increase. Here, we are in a domain that offers a large number of degrees of freedom to establish future scenarios.

– Nuclear *(Fig. 11b)*: it can be assumed that nuclear energy has passed its introductory effect, but has not yet found a secure place in the energy mix. Here again, we are in a domain where various scenarios are possible.

– Hydro *(Fig. 11b)*: the dynamic fluctuates around 0, for a rate that is clearly almost constant, at 2 %/year. But having seen some good times since the 1950s, slightly better rates are possible over the long term.

– Biomass *(Fig. 11b)*: the consumption dynamic is negative, and the rate is virtually identical to that of worldwide demand. This is perhaps due to a statistical problem, but we will consider it nonetheless. Note that historically, a slight recovery in consumption during the 1980s led to a rate of only 2%/year. This clearly indicates that we should not expect revolutions in this domain.

– Other renewable resources: geothermal, solar and wind *(Fig. 11b)*. After a rebound at the end of the 1970s, the geothermal trajectory resumed its long-term trend, which shows consumption is winding down. For solar and wind energy, we'll confine ourselves to noting that the current growth rate remains the highest of the various energies. However, the quantities are so small that a definite conclusion cannot be drawn as to the trajectory's direction, given the difficulty in assessing the quality of

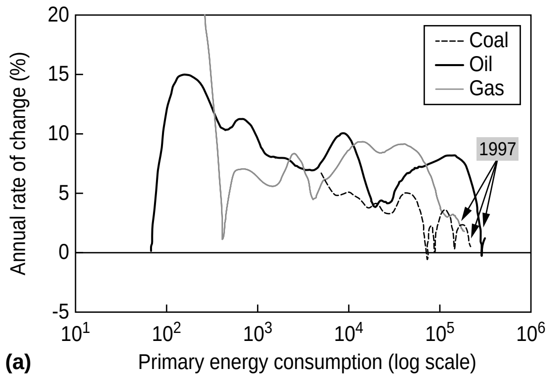

Figure 11a

Phase representation of primary energy consumption for coal, oil and gas (filtered series).

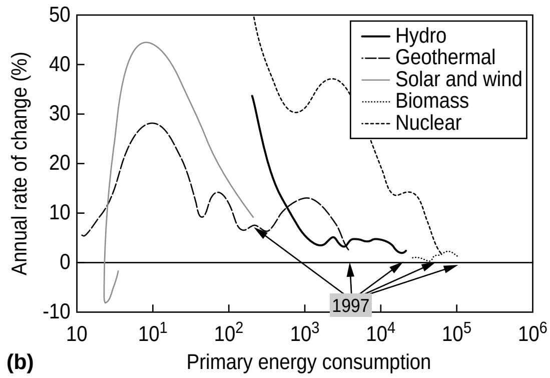

Figure 11b

Phase representation of primary energy consumption for hydro, geothermal, solar and wind, biomass and nuclear (filtered series).

TABLE 4

Annual growth rates of primary energy consumption (smoothed series (%))

	Coal	Oil	Gas	Nuclear	Hydro	Geothermal	Solar and Wind	Biomass	Total
1900	5.1	8.1	6.8	–	–	–	–	0.5	3.0
1930	–0.6	4.2	5.0	–	4.0	18.8	–	0.3	0.5
1950	2.0	7.0	9.3	–	4.5	12.6	–	0.8	3.4
1960	3.2	8.0	9.2	–	4.3	7.5	–	1.4	5.0
1970	0.5	6.5	6.5	36.2	4.6	7.7	–3.5	1.5	4.2
1985	2.2	0.3	3.3	12.6	2.4	10.3	32.4	2.0	2.0
1997	0.7	1.3	1.9	2.1	2.2	2.8	9.5	1.5	1.4

the statistics that we present, but without attaching great importance to this.

The Table 4 summarizes this information (rates in %/year).

Very different rates can be noted in the past. These are growing closer today, as seen by the convergence around low rates of change of market share, an unstable situation. The particular case of nuclear energy is striking: in 25 years, it has lost all its introductory effect. From this brief presentation of the history of consumption, we may conclude that, **unless the introductory effect is renewed (which can always happen through outside intervention)**, normal energy dynamics cannot hope to achieve very high values and regain their youth to meet the needs of some scenario.

3.2 What the History of Market Shares Teaches

Here we will also use a phase representation:

- Coal *(Fig. 12a)*: declines rapidly, tries to stabilize at 25 points, then resumes a slow, but fairly constant decline of between –0.5 and – 1%/year.
- Oil *(Fig. 12a)*: following the oil crises, declines with a very strong negative dynamic, then resumes a positive dynamic after the counter-shock of 1986. The phase diagram suggests a possible recovery of market share above 35 points, with a possible bifurcation: either a recapture of the market (which would require a growth rate that is not supported by the history of consumption (see supra), or an attempt at stabilization, perhaps like that of coal (slight recovery, then slow decline).
- Natural gas *(Fig. 12a)*: the growth rates of this fashionable energy source are not very high, and the dynamic fluctuates. To bring natural gas to a worldwide market share above 25 points (as foreseen by a simple extrapolation of the current trend) will require an effort that is perhaps underestimated today. In any event, natural gas is a key element for future scenarios. We note that natural gas “maintained” a growth rate of 3.5%/year in the past, which represents a sort of maximum long-term rate.
- Nuclear *(Fig. 12b)*: negative dynamic, bringing nuclear energy, whose market share is still slightly growing, into a critical phase, as it is nearing the crossing from the growth area to the decline area.

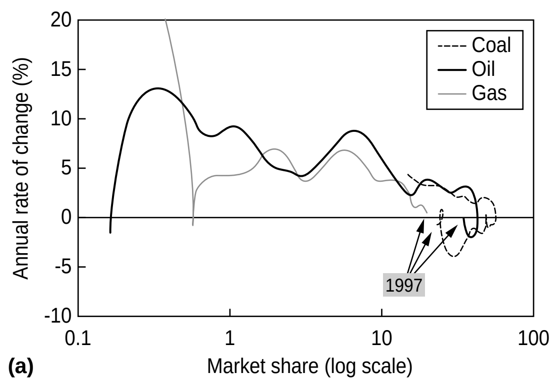

Figure 12a

Phase representation of coal, oil and gas market shares (filtered series).

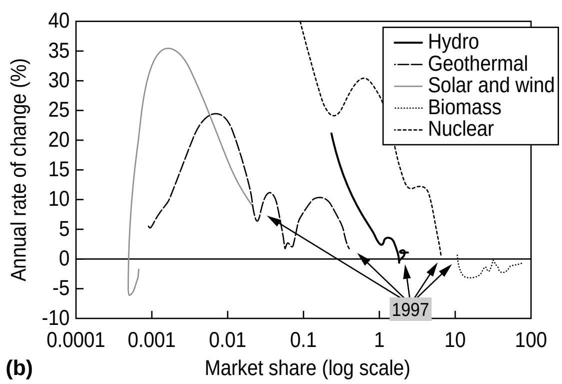

Figure 12b

Phase representation of hydro, geothermal, solar and wind, biomass and nuclear market shares (filtered series).

TABLE 5

Annual growth rates of primary energy market shares (smoothed series)

	Coal	Oil	Gas	Nuclear	Hydro	Geothermal	Solar and wind	Biomass
1900	2.0	4.9	3.5	–	–	–	–	–2.3
1930	–1.1	3.8	4.7	–	3.4	16.7	–	–0.2
1950	–1.4	3.4	5.7	–	1.0	9.3	–	–2.4
1960	–1.5	2.7	3.8	–	–0.5	2.3	–	–3.4
1970	–3.7	2.4	2.4	28.4	0.3	3.1	–3.3	–2.7
1985	0.3	–1.8	1.2	9.8	0.4	8.1	29.0	0.0
1997	–0.8	–0.1	0.5	0.5	0.8	1.6	8.7	0.0

– Hydro *(Fig. 12b)*: market share continues to grow, at a low rate (between +0.5 and 1%/year). Worldwide, it represents a market share on the order of 2 points, which eliminates a major role.
– Biomass *(Fig. 12b)*: a gradually slowing decline today is leading biomass to stabilize at around 11 points.
– Other renewable resources: geothermal, solar and wind *(Fig. 12b)*: geothermal's market share follows a trajectory very similar to that of its consumption. It seems that only an external crisis, such as during the 1970s, could revitalize the market penetration power of this energy source. For solar and wind energy, market shares—like consumption—are so low they require a different approach than that used for other energy sources.

Table 5 summarizes this information (rates in %/year).

3.3 The *f/c* Graph

In the light of the major trends in quantity and market share that are characteristic of each primary energy source, Figure 6a shows a highly interesting configuration that identifies two large families of energy, *according to their stage of development*: independent and competing energies.

3.3.1 Independent Energies and the Introductory Effect

As long as consumption and market share are fairly low, there is an almost linear relationship between the logarithm of market share and that of consumption. The slope is independent of the energy concerned, within the limits of the data precision. It is therefore clear that:

– As long as dc/c (primary energy) is much larger than dC/C (total consumption), we should obtain a relationship similar to that shown in Figure 6a. Thus, if dc/c is much larger than dC/C, we can assume that the latter quantity is constant. Integrating then gives $\log f = \log c$ – a term that is linear in time. This explains the growing gap (as the slope is less than 1 observed between $\log f$ and $\log c$. Experimentally, we have $\log f = a \log c + b$ (where f is market share, c is consumption, a and b are constants). If we introduce C, total energy consumption, then $f = c/C$, and we may write:

$$(1-a)\log c = \log C + b, \text{ and finally: } dc/c = (1/1-a)*dC/C$$

This relationship says that the market launch of a new energy form occurs at a constant rate, the fraction $1/(1-a)$ of the energy market's growth rate. This expresses the introductory effect that we have shown and explains the parallelisms shown by Marchetti (Marchetti and Nakicenovic, 1978). The measured values for "a" are as follows *(Table 6)*.

TABLE 6

Measurement of the introductory effect for primary energy sources (value of "a" for smoothed series)

Coal	Oil	Gas	Nuclear	Hydro	Geothermal	Solar and wind
0.79	0.79	0.73	0.84	0.70	0.75	0.86

These values can be taken to be virtually identical, given the precision of the measurements. Their interest, when plotting *f/c*, is to supply an initial reference point that is common to all energy forms, which can then be differentiated more easily. Virtually everything happens upon their introduction, as if the development of these energy sources were independent of the existence of other energy forms, and located in a specific area of the *f/c* plane. We will use the name independent energies for those that are still in this area of the *f/c* plane; these are also the renewable energies.

3.3.2 Competing Energies

For noteworthy values of market share and consumption (*i.e.*, those above 100 Mtoe and about 2 points market share), the energy trajectories level off and reflect inter-energy reaction behaviours, which are highly differentiated. We are in a competitive area, where we observe a complementary form of differentiation:

– market share: growing (natural gas), stagnating (oil, hydro, biomass) or declining (coal);
– consumption: growing or declining.

Although consumption is currently not declining for any energy source (note, though, that our series breaks off in 1997), it is reasonable to foresee this eventuality, which is therefore incorporated in certain scenarios *(see Section 4)*. Referring to the *f/c* diagram, we note that these configurations correspond to trajectories that have well-differentiated forms.

3.3.3 The Energy Life Cycle

The preceding considerations have encouraged us to propose the notion of an energy life cycle. We will consider two groups of elements: the curvature of trajectories in the logarithmic *f/c* plane and the evolution of consumption and market share. This very simple approach allows us to distinguish the periods shown in Table 7.

The "hard core" phase refers to a residual market share of technological or sector-based nature that may appear at the end of the "decline" or "withdrawal" phase.

Geothermal and solar energy are in the introductory phase; natural gas and nuclear energy are in maturity. Coal and oil have lost market share and seen a drop in consumption, such that withdrawal is undeniable. Biomass is in the hard-core phase. Hydraulic energy is somewhere between maturity and withdrawal. This classification is not irreversible, except for the introductory effect. What can be said is that the visual aspect of the coal and oil phase planes clearly distinguish them from the others. For example, in the market share phase plane *(Fig. 12a)*, they have moved into the lower half-plane, which is the withdrawal space (where biomass is still to be found, hanging on to its current market share), while the other energy forms are in the upper half-plane.

3.4 Conclusion: Knowing where we Came From

On the quantitative level, the following information in Table 8 supplements Tables 4 and 5.

We have described our model for energy system dynamics. We use the same method in this model to examine consumption and market shares and then to represent these dynamic phenomena in the coordinate system defined by the variables *(f/c)*. Past experience shows there are two distinct domains: one marked by the introductory effect, where competition has virtually no role (and which is thus called the independence area in the *f/c* graph), and another domain, which is marked by competition between energies.

The major fact that emerges from this examination of past trends is the observation that there are limits to energy dynamics. Whatever the situation of the energy considered (*i.e.*, whether it is independent or competitive), it seems clear *a posteriori* that even during the period that was most favourable to it, the variations in market share only very rarely attain 1 point/year. Moreover, it appears that the growth rates of consumption of competing energies only vary with great difficulty from the growth rates for global demand. Without creating a dogma in this regard, the conclusions that can be drawn from these observations tend to specify the relative likelihood of various energy scenarios. *Under what conditions will something that has never been observed in the course of history be seen in the relatively near future of 10 to 20 years?*

4 APPLICATION TO THE DEVELOPMENT OF ENERGY SCENARIOS

We are now going to take a simple case: if worldwide demand is specified, how can it be satisfied? In our representation, this means determining which trajectories are reasonably likely, without invoking rates of change, of consumption or of market share that are implausible, even if we could imagine anything we want. In the past, there was no better example than the first oil shock to modify consumption. Certainly, oil took a hit, but it fairly rapidly regained a significant role, even before the misguided attempts of *Opec* restored its pre-eminence and served as a lesson.

We therefore chose two reference points for worldwide energy consumption. The first, 12 Gtoe, was chosen because it seems highly probable that this level of consumption will be attained by the horizon of the year 2020. The second, 14 Gtoe, was selected because it places a limit on our frame of reference, as we believe that this level of consumption will

TABLE 7

Energy life cycle periods

Energy life cycle phase	Evolution of consumption	Evolution of market share	Curve of the trajectory in the *f/c* plane
Introduction	Growth	Growth	Very slight (marginal?)
Maturity	Growth	Growth	Noticeable
Withdrawal	Slowed growth	Stable	Very noticeable
Decline	Decline	Decline	Very slight (opposite direction)
Hard core	Weak growth	Stable	Zero

TABLE 8

Historical summary (gains and losses of market share in points per year)

Worldwide energy consumption*	Coal	Oil	Gas	Nuclear	Hydro	Geothermal	Solar and wind	Biomass
From 1850 to 1914/1918. 2% annual growth. Moderate dynamic	Increasing gains of 0.6 to 1	Steady gains of 0.1 maximum	Weakly increasing gains < 0.05	–	Regular gains on the order of 0.04	–	–	Losses on the order of –0.8
From 1914/1918 to the beginning of the 1930s. Annual growth close to 1%. Weak dynamic	Losses of –0.4	Gains on the order of 0.5	Gains on the order of 0.1	–	Regular gains on the order of 0.3	Weak gains	–	Losses on the order of – 0.2
From the mid-1930s to after World War Two. Annual growth close to 2%. Disrupted dynamic	Stability then increasing losses until –0.7	Increasing gains of 0.3 to 0.8	Increasing gains of 0.1 to 0.4	–	Declining gains of 0.5 to 0.2	Weak gains	–	Losses on the order of –0.5
From the end of the 1940s to the start of the 1960s. Annual growth above 4% Strong dynamic.	Losses on the order of –0.6	Gains on the order of 0.8	Gains on the order of 0.4	–	Weak, declining gains until	Weak gains	–	Losses on the order of –0.6
From the start of the 1960s to the start of the 1980s. Annual growth close to 3%. Negative dynamic	Increasing losses until –1.2, then return to stability	Rapid gains until 1.2 then heavy losses until –0.8	Erosion of gains from 0.4 to 0.2	Rapid gains from 0 to 0.4	Weak gains < 0.05	Weak but rapid gains until 0.02	Not significant	Erosion of losses from –0.6 until stability
From the start of the 1980s to the end of the 1990s. Annual growth close to 2%. Weak, negative dynamic	Declining gains then increasing losses until –0.2	Erosion of losses from –0.8 to –0.1 Tending to stability	Slight erosion of gains from 0.2 to 0.1	Rapid erosion of gains from 0.4 to less than 0.1	Very weak gains < 0.01	Very weak erosion of gains until stability	Very weak gains	Stability

** NB: a positive dynamic expresses an acceleration, while a negative dynamic expresses a slowdown.*

probably not be reached by 2020. We could use other values, but, when presenting a method, it's best to illustrate it with a realistic example. We make no hypothesis as to the growth dynamic for global demand.

4.1 Initial Approach by Linear Trend Scenarios

As a first approach, we will limit ourselves to trend scenarios based on linear extrapolation in the logarithmic *f/c* plane. In this frame of reference, that means creating a basic scenario that maintains sufficiently long-term trends and thus does not undermine the position of any energy form in the life cycle scheme, as we assume that the trajectories do not follow their natural tendency to level off. We will now consider our two reference points. On the graph in Figure 6a, we superimpose two lines that are parallel to the first bisector and to the 1997 demand line (9.47 Gtoe). These new lines represent demands of 12 and 14 Gtoe, respectively. By liner extrapolation, we attempt to determine the contributions of the various energies, both in absolute (Gtoe) and relative (market share) terms. (See Figures 13a and 13b on next page for renewable and fossil fuels, respectively.). We leave aside nuclear energy, whose trends cannot be easily extrapolated because of a very pronounced starting curve and inherent uncertainties.

The coordinates of the point of intersection between the total demand line and the primary energy trajectory depend on the period we select for linearly extrapolating the trajectory. As Figures 13a and 13b show, each energy form constitutes a special case, which we will treat as such:

– In spite of increasing consumption, coal shows a continuous decline in market share since 1913. The period on which we base the linear trend calculation is therefore 1913-1997 *(see Fig. 13b - Point 1).*
– Oil's trajectory suffers a sharp drop-off since 1975, similar to that observed for coal at the start of the century. The reference period is 1975-1997 *(see Fig. 13b - Point 2).*
– In contrast to coal and oil, the gas trajectory shows no turning point. We nonetheless observe an increase in the curve. The reference period is 1971-1997 *(see Fig. 13b - Point 3).*

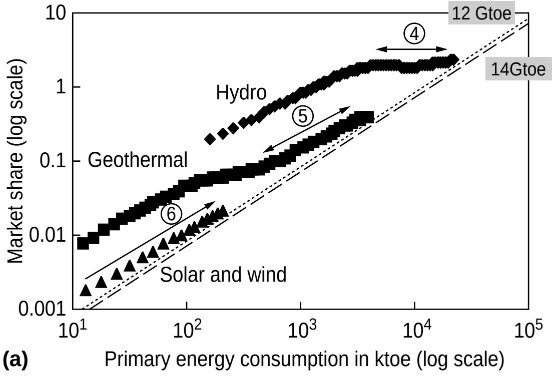

Figure 13a

Position of renewable energies plotted in the *f/c* plane for 2020 scenarios (12 and 14 Gtoe).

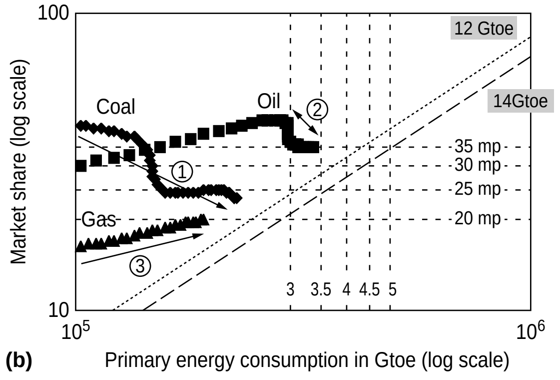

Figure 13b

Position of fossil fuels plotted in the *f/c* plane for 2020 scenarios (12 and 14 Gtoe).

– Hydraulic energy has managed to maintain and slightly increase its market share over the past several decades, but its growth potential appears to be almost exhausted. The reference period is 1951-1997 *(see Fig. 13a - Point 4)*.
– Geothermal energy seems to have regained some dynamism, as shown by the inflection point in the middle of its trajectory. The reference period is 1974-1997 *(see Fig. 13a - Point 5)*.
– Solar and wind energies show the characteristic trajectory of a "new" energy form: the straight line trajectory demonstrates the introductory effect, where gains in market share are almost proportional to consumption growth in the initial period. The reference period is 1976-1997 *(see Fig. 13a - Point 6)*.
– For biomass, a hypothesis is made that its market share will remain stable. This hypothesis is simplistic but not unreasonable, given the trajectory of the past 20 years. The effect is to determine its consumption.

The linear regression equation, which we will calculate for each reference period, provides the consumption (in Gtoe) and the market share for the energy under consideration *(see Tables 9 and 10)*. This equation is supplied by intersection with the total demand line parallel to the first bisector (in our case, 12 and 14 Gtoe). Figures 14a to 14f show the trajectories for each energy in the *f/c* plane, including the various acceleration/deceleration phases implied for the 2020 horizon.

The intersections for geothermal and solar/wind energy are obviously imprecise, as the linear trend scenarios here produce lines with slopes of almost 1. The interest in the calculation is to supply a nonarbitrary order of magnitude.

In both cases, for a worldwide consumption of 12 Gtoe or 14 Gtoe, the sum of the contributions of the seven primary energy sources that we have studied reaches 10.62 or 12.20 Gtoe, respectively. Setting aside nuclear energy, there will be a supply shortfall of 1.38 Gtoe for a demand of 12 Gtoe, and of 1.80 Gtoe for a demand of 14 Gtoe.

TABLE 9

Contribution of primary energy sources to a worldwide consumption of 12 Gtoe by a linear trend scenario

	Coal	Oil	Gas	Hydro	Geothermal	Solar	Biomass
Consumption in Gtoe	2.50	3.63	2.73	0.27	0.13	0.01	1.34
Market share (in points)	20.85	30.22	22.77	2.24	1.11	0.08	11.2

TABLE 10

Contribution of primary energy sources to a worldwide consumption of 14 Gtoe by a linear trend scenario

	Coal	Oil	Gas	Hydro	Geothermal	Solar	Biomass
Consumption in Gtoe	2.73	3.85	3.43	0.32	0.27	0.03	1.57
Market share (in points)	19.50	27.50	24.53	2.29	1.93	0.21	11.2

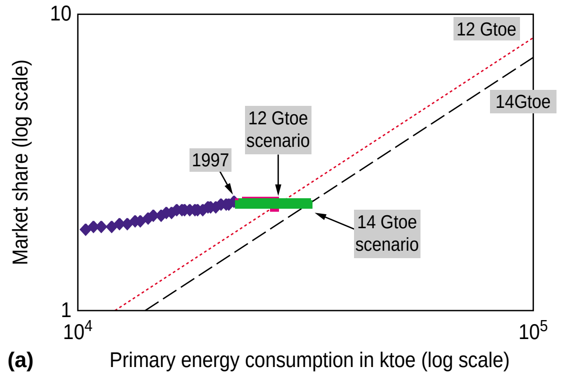

Figure 14a

2020 hydro scenarios - *f/c* plane.

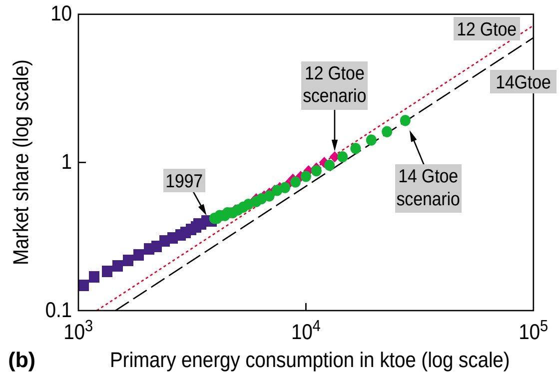

Figure 14b

2020 geothermal scenarios - *f/c* plane.

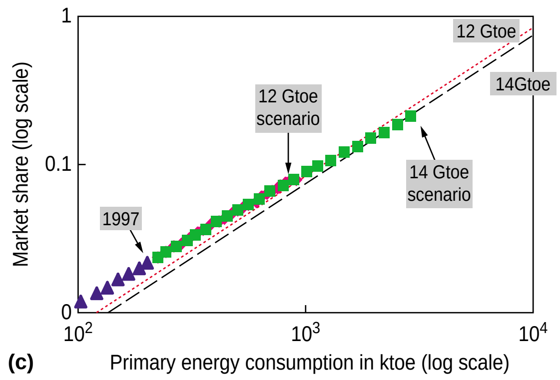

Figure 14c

2020 solar wind scenarios - *f/c* plane.

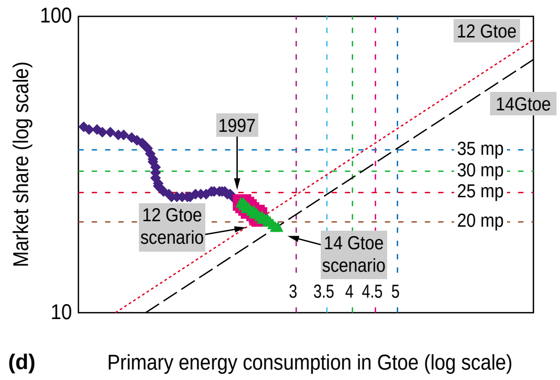

Figure 14d

2020 coal scenarios - *f/c* plane.

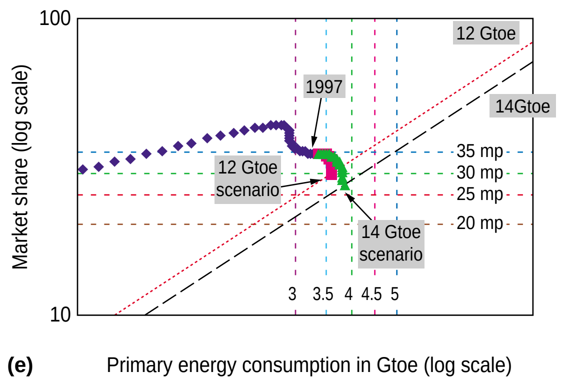

Figure 14e

2020 oil scenarios - *f/c* plane.

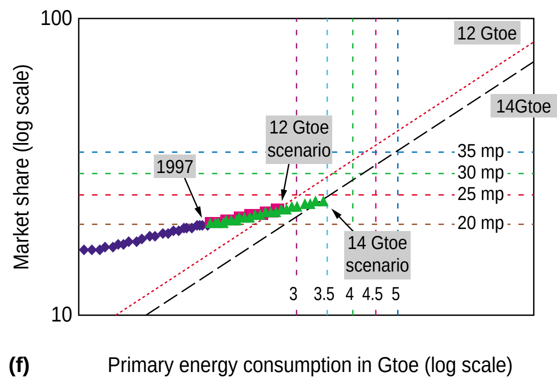

Figure 14f

2020 gas scenarios - *f/c* plane.

This very simple model has the advantage of quantifying several classic questions that are often marred by passionate feeling:

– Can we technically expect that CO_2-based energies will continue to advance to almost 10 Gtoe from the current 6.7 Gtoe?
– Does the break in the oil trajectory presage a similar decline to that suffered by coal since the beginning of the century? For the linear trend calculation, therefore, should we select the period starting in 1975 or rather an earlier date? Oil's potential contribution would, in the current case, be clearly underestimated.
– The natural gas trajectory is levelling off. Will the future bring an uneventful extension of this trend or a brutal drop-off such as we have seen for coal and perhaps oil *(see Fig. 6a - Points A and B)*?
– For the time horizon under study, is the contribution of renewable energy sources (excluding biomass) fated to remain less than 5% of worldwide consumption?
– Can we anticipate that nuclear energy will triple in the next 20 years from its current contribution of 0.6 Gtoe to almost 2 Gtoe?

To take this further, it is useful to bring out the implicit contents of the linear extrapolation in the logarithmic *f/c* plane. The linear extrapolation in the *f/c* logarithmic plane amounts to supposing that the ratio of the growth rate of each energy to the growth rate of worldwide demand is constant:

Thus, if $\log fi = ki^{*}\log ci + \text{constant}$,

then $dfi/fi = ki^{*}dci/ci$

and as $dfi/fi = dci/ci - dC/C$, then: $ki = 1 - (dC/C)/(dci/ci)$

The extrapolation takes the average ratio over the reference period and projects it onto the selected global demand. But we haven't made any hypothesis concerning the growth rate of global demand. For the linear extrapolation, this amounts to saying that the rate for a given energy source will, in the future, be in the same proportion that it was during the reference period. For this, it is not necessary to know the global demand rate; only the position of the demand line counts.

In spite of its convenience, the use of a linear extrapolation is nonetheless debatable on two levels:

– On the first level (which relates to long-term trends), the *f/c* representation shows that a nearly linear evolution only reflects a very particular, temporary phase of an energy source: its introduction. Except for this period, the trajectory shows a more or less pronounced curve, which is negligible in the near term, but unavoidable for the time horizon that interests us, when the trajectories will curve more than they do today, as we shall see below. Here, linear extrapolation can only be satisfactory if the energy universe is only slightly "curved", *i.e.*, in the short term.
– On the second level (which relates to short/medium-term trends), linear extrapolation must be supplemented, because of the existence of phases with variable dynamics (accelerating/decelerating growth/decline). These concern changes in tonnage and market share whose main characteristic is that it cannot be described in linear terms (Alba and Rech, 2000).

Nonetheless, as a first approximation, given that two dimensions (tonnage and market share) are simultaneously taken into account, the use of linear trend scenarios can supply the elements for questions concerning energy demand. This is particularly true as regards the major issue: the apparent shortfall in energy supply, which seems likely to reach a minimum of close to 1 Gtoe by 2020. The problem that then emerges is to determine which economic and/or technological conditions would enable this deficit to be covered, and, later, what would be the consequences if this were not done. With linear scenarios, we can ask fundamental questions based on a few quantitative elements.

4.2 The Scenario Space

Our methodological problem of how to improve scenario design clearly requires using more parameters than are available in the simple log-linear extrapolation. This means proposing trajectories for each energy.

To do this, while remaining simple, the first element to consider is the dynamic (which cannot be subject to linear extrapolation). But this degree of freedom imposes the restriction of not suggesting dynamics that historical analyses would show to be unrealistic. Finally, for the old energy forms (oil, coal and natural gas), it seems natural to set limits to consumption values, limits that are related to what we know about reserves and the constraints that affect these substances.

Regarding trajectories in the phase planes, we should also remember that a scenario can not be expressed by a straight line, to remain simple, without forgetting what happens afterwards, as, in this particular space, trajectories must approach the horizontal.

As it cannot be denied that energy trajectories slowly level off *(Fig. 6a)*, it is therefore clear that the problem of scenarios, besides that of linear extrapolation, is to place limits on the trajectories, given the constraints of rates, of dynamic that we discussed earlier in this paper.

More concretely, the initial framework is composed of the logarithmic "quantity *c*/market share *f*" graph, on which we plot the energy histories and the 12 and 14 Gtoe **demand lines** (Figure 13a for renewable energy and Figure 13b for fossil fuel). We then add **boundaries**, which are presumed limits for production (3 to 5 Gtoe) and for market share (20 to 35 points) for coal, oil and gas, as it is not unreasonable to believe that these fossil fuels will one day be **limited**, either by **geological difficulties** or by constraints (*e.g.*, CO_2 emissions, cartelization). The demand lines and the boundaries serve as *framework parameters* for the various scenarios. The scenarios themselves are the trajectories selected for the different energy forms. The **scenario space** is the delimited area of the plane in which trajectories can be found.

Scenarios are established using the phase representation, as both dynamic elements (the rate, the dynamic) and quantitative elements (quantity, market share) must be incorporated.

The final objective of our proposals is to evaluate more precisely the *minimum* energy supply shortfall for the frame of reference we selected as being very likely for the horizon of 2020, *i.e.*, a worldwide consumption of 12 to 14 Gtoe. We will proceed by first dealing with the case of renewable energies and then that of fossil fuels, it being understood that we again set aside nuclear energy. This is justified by the fact that the uncertainties that surround nuclear energy belie rational handling of this case.

4.2.1 Evaluation of the Contributions of Renewable Energies

Biomass, which is the leading renewable energy in terms of contribution to total consumption, combines traditional uses with the most sophisticated ones, such as reclamation of industrial, vegetable and animal wastes. The preponderance of traditional uses, along with the absence of complete data on modern uses, prompts us to handle the entire group without distinction and to formulate a hypothesis based on the stability of its market share over the last 20 years (about 11 points).

Hydro, geothermal, solar and wind energy show contrasting profiles when their long-term trajectories are considered *(Fig. 6a)*. On the one hand, for geothermal, solar and wind energies, the long-term trajectory promises potential growth. On the other hand, hydraulic energy has now reached maturity, its introductory effect exhausted. In the latter case, this means that hydraulic energy does not appear to be able to deviate in any significant way from the rhythm for total consumption growth. This, moreover, is related to the very long lifetime of its installations.

The natural trajectory in the *f/c* plane clearly shows that the gains in market share are less than proportional to consumption growth as the energy considered enters into the area of competition with energies that we consider established. The history of renewable energies shows two exceptions to this rule, although of different nature:

– The trajectory of geothermal energy shows a decline between the early 1950s and the late 1960s, before returning in a lasting way to a slope characteristic of a "new" energy source. This phenomenon is the graphical expression of the interest aroused by renewable energies beginning with the first oil crisis.
– The trajectory of hydraulic energy admittedly shows the transition from the introductory phase to maturity starting in the 1950s. However, as was the case for geothermal energy, the oil crises period was the source of a new dynamic.

The linear approach could therefore occasionally lead to an underestimate of the contribution of certain energy forms under particular circumstances. Keeping in mind these two exceptions, we build our proposal around the energy life cycle *(described in § 3.3.3)*. Figures 15a to 15c and 16a to 16c use a phase representation to project the contributions and market shares of the various renewable energy sources at the horizon of the year 2020.

Hydraulic Energy

At this point, we should distinguish and emphasize the nature of the two reference periods that characterize the trajectory of hydraulic energy. The period 1951-1997 refers to the energy life cycle (a joint development of consumption and market share), while the period 1970-1997 marks a continuous deceleration in consumption growth (a negative dynamic), except for a brief turnaround in this trend between 1989 and 1994. The contribution that we have calculated by linear extrapolation for the period 1951-1997 is based on a dynamic for consumption growth that is close to the 1970-1997 historical trend (which is the case of the 12 Gtoe scenario) or less than it (which is the case of the 14 Gtoe scenario) *(see Fig. 15a)*. This trajectory nonetheless leads to a collapse of the market share growth dynamic, which declines in absolute value in both cases (from 2.32 market share points (mp) in 1997 to 2.24 mp in the 12 Gtoe scenario and 2.29 mp in the 14 Gtoe scenario). We cannot plot this trajectory on Figure 16a because of our percentage change approach, in contrast to an absolute change approach *(see Appendix A3)*, unless we arbitrarily choose the coordinates of the intersection of the phase trajectory and the abscissas.

The likelihood of a consumption trajectory associated with an upheaval that affects the market share trajectory opens up two possibilities. Either the market share dynamic is greatly underestimated, which would lead us to revise the consumption dynamic upwards, or the dynamic of hydraulic energy is definitively exhausted, even if this may not necessarily lead to the very pessimistic scenario of an immediate, continuous decline in market share. As our objective is to determine the maximum "reasonable" contribution, we make the ambitious hypothesis, which is certainly beyond what could be expected, that the growth in market share for hydraulic energy will remain at 0.02 mp/year to reach 2.78 mp in 2020, or 334 Mtoe for the 12 Gtoe scenario and 389 Mtoe for the 14 Gtoe scenario.

Geothermal Energy

The geothermal energy contribution of 0.13 Gtoe to worldwide consumption of 12 Gtoe or the contribution of 0.27 Gtoe to consumption of 14 Gtoe by 2020 appears overestimated. This trajectory requires a brutal reversal of growth and market share dynamics, until it reaches a higher

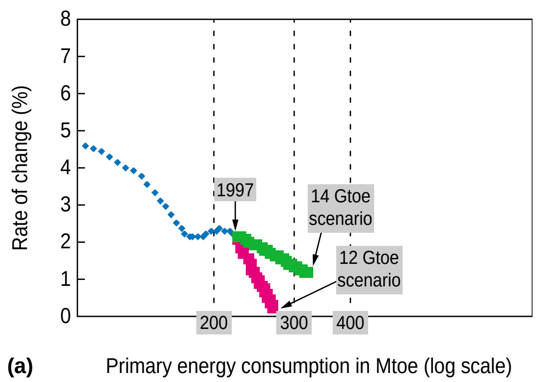

Figure 15a

2020 hydro scenarios - phase plane.

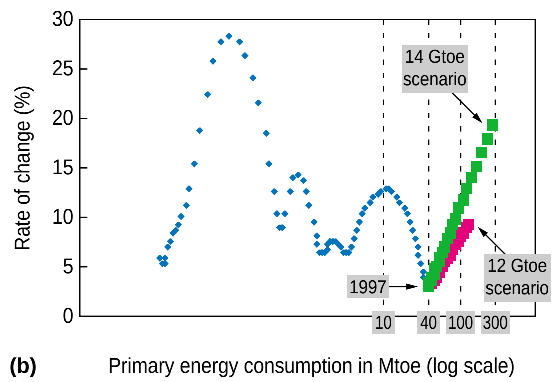

Figure 15b

2020 geothermal scenarios - phase plane.

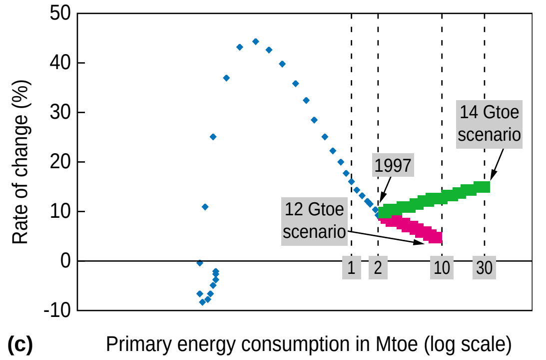

Figure 15c

2020 solar and wind scenarios - phase plane.

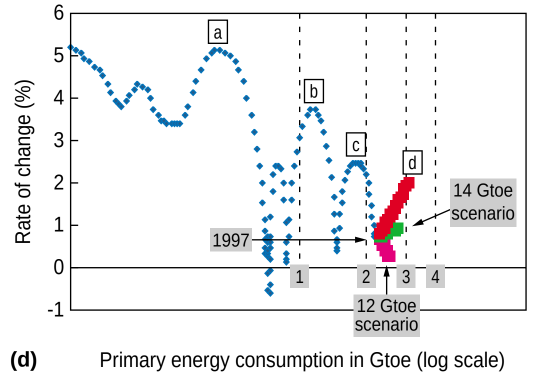

Figure 15d

2020 coal scenarios - phase plane.

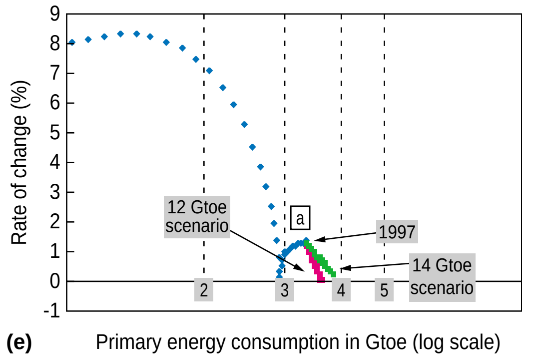

Figure 15e

2020 oil scenarios - phase plane.

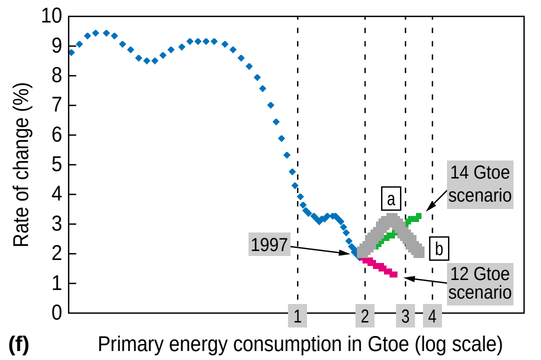

Figure 15f

2020 gas scenarios - phase plane.

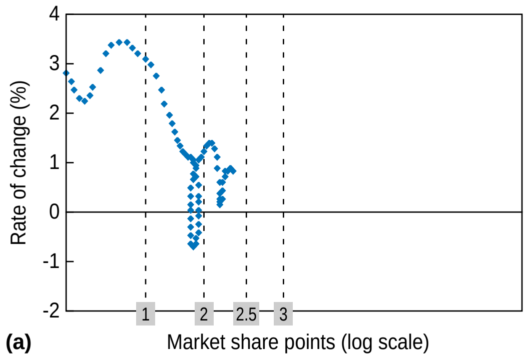

Figure 16a

2020 hydro scenarios - phase plane.

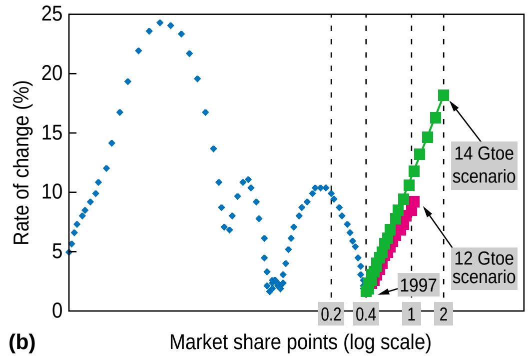

Figure 16b

2020 geothermal scenarios - phase plane.

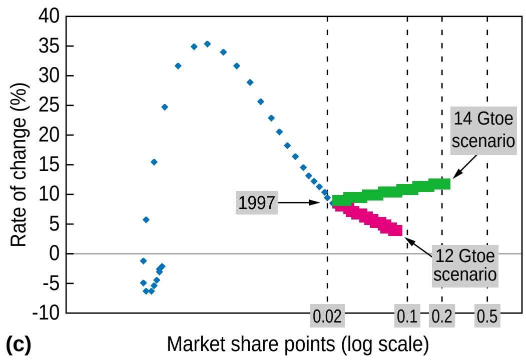

Figure 16c

2020 solar and wind scenarios - phase plane.

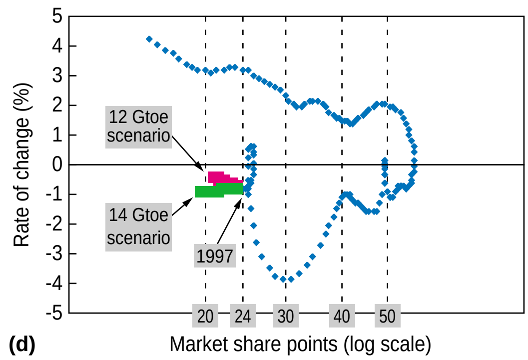

Figure 16d

2020 coal scenarios - phase plane.

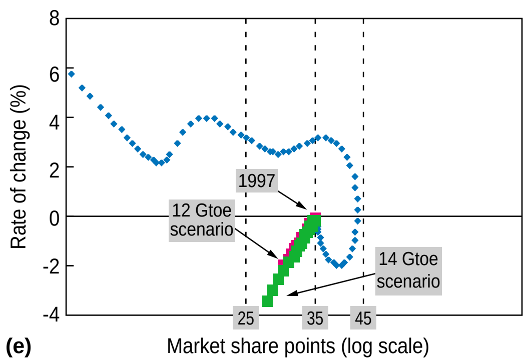

Figure 16e

2020 oil scenarios - phase plane.

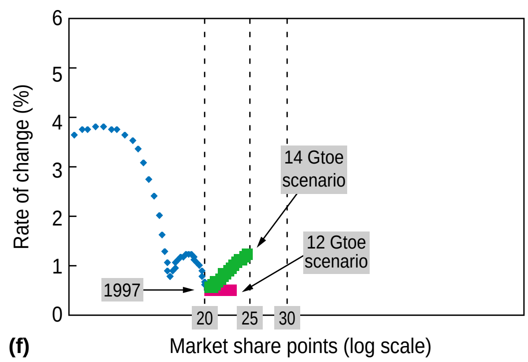

Figure 16f

2020 gas scenarios - phase plane.

level than that observed over the last 50 years, which includes the period of decline evoked previously as well as the oil crisis years, which were particularly favourable to renewable energies *(see Figs. 15b and 16b)*. Nonetheless, we make the resolutely optimistic hypothesis that this trend reversal will peak in 2020 at the maximum level of the preceding growth cycle (10%), for a market share of 1.17 mp, which is equivalent to a 140 Mtoe contribution for the 12 Gtoe scenario and 164 Mtoe for the 14 Gtoe scenario.

Solar and Wind Energies

Among the renewable energies, the most promising outlooks are attributed to solar and wind energy. Because of their very recent development (at least in their "modern" form) and the statistical approximations that are associated with them, our method of correlating the energy life cycle trajectory with that of the medium-term dynamic only offers a very approximate estimate of their future contribution.

When plotted in the *f/c* plane, the trajectory does not show any decline. The consumption dynamic leads to almost proportional increases in market share. From then on, the question of the future of solar and wind energies depends on the medium-term dynamic. In this regard, the phase representation shows a clearly perturbed trajectory due to the about-face of the main consuming countries during the mid-1980s as regards research and support for these energies. Thus, in spite of a growth rate of almost 10%, the dynamic declines.

Our linear extrapolation in the *f/c* plane is expressed as a contribution of 9 Mtoe for the 12 Gtoe scenario and 29 Mtoe for the 14 Gtoe scenario, implying a continued deceleration (9 Mtoe) and a slight reversal of the dynamic trend (29 Mtoe), respectively *(Figs. 15c and 16c)*. We select the high-end hypothesis for dynamic reversal of market share, which brings growth to a level that we arbitrarily set at 20% in 2020, namely *the most ambitious that can be anticipated over a period of 20 years.* We thus obtain a contribution of 51 Mtoe for the 12 Gtoe scenario and 60 Mtoe for the 14 Gtoe scenario. It doesn't appear "reasonable" to expect a higher contribution, in view of the continuous acceleration of growth needed to reach this level. We must face the fact that solar and wind energies will contribute only very modestly to the worldwide energy balance at the 2020 horizon. If perchance our method has caused us to underestimate this future contribution, the upward adjustment will only involve a few Mtoe at the most.

Table 11 summarizes the hypotheses for the contribution of renewable energies, which we formulate after analysing and correcting the linear trend scenarios in the *f/c* plane. These hypotheses are deliberately optimistic, and certainly go beyond what the "natural" development of each of these energies could supply. Only under exceptional circumstances such as oil crises could the values we select be exceeded.

4.2.2 Evaluation of the Contributions of Fossil Fuels

Now we apply our approach—which consists of a simultaneous examination of the trajectories in the *f/c* plane (energy life cycle) and in the phase representation (growth dynamics for consumption and market share)—to fossil fuels: coal, oil and natural gas.

Coal

Coal's situation is characterized by the following elements: a trajectory in the *f/c* plane that has been declining for several decades *(see Fig. 6b)*, a growth dynamic for consumption composed of successive cycles whose peaks are decreasing *(see Fig. 15d - Points a, b and c)* and a strongly declining market share dynamic. This latter dynamic seems likely to keep coal in a depressed situation over the long term, despite the fact that the trajectory has moved to near the stagnation area (abscissa) over the last 20 years *(see Fig. 16d)*.

Simply extrapolating the trajectory in the *f/c* plane *(see Fig. 14d)* leads to a limited reversal of the consumption dynamic for the 14 Gtoe scenario and, for the 12 Gtoe scenario, a continuation of the current cycle of growth slowing until it reaches a very weak level (under 0.5%/year) *(see Fig. 15d)*. The market share phase plane indicates that, even when applied to a 14 Gtoe scenario, coal will continue to lose ground to other energies *(see Fig. 16d)*. Only a reversal in consumption trends similar to that of previous cycles could interrupt the losses in market share. It should be remembered that these cycles correspond to two favourable periods for coal: the immediate post-war period and the oil crises period. *A priori*, we can legitimately doubt whether this kind of cycle will reoccur in the absence of equivalent circumstances.

We deliberately push our optimism as far as supposing that the *f/c* linear extrapolation underestimates coal's

TABLE 11

Estimate of the contribution of renewable energies in 2020

	Hydro		Geothermal		Solar and wind	
	Market share in mp	Contribution in Mtoe	Market share in mp	Contribution in Mtoe	Market share in mp	Contribution in Mtoe
12 Gtoe scenario	2.78	334	1.17	140	0.43	51
14 Gtoe scenario	2.78	389	1.17	164	0.43	60

potential, and make the hypothesis that the peak of an upcoming cycle will reach the growth threshold of 2%/year in 2020, for a contribution of 3036 Mtoe *(Fig. 15d - Point d)*. The inevitable descending phase of the cycle, which is almost symmetrical to the ascending phase, will only bring coal consumption towards 4 Gtoe in an additional period of about 20 years. *We therefore uphold our analysis and judgement as to the unrealistic nature of most published scenarios* (by the *IEA*, *WEC* or even *Shell*), which attribute consumption outlooks on the order of 4 Gtoe, namely an almost two-fold increase over the next 20 years.

Oil

Based on Figure 14e, the linear extrapolation of the trajectory in the *f/c* plane, the outlook for oil that emerges confirms the decline that began during the era of the oil shocks. The trajectory's disturbing downward curve might appear exaggerated, giving rise to the question: is oil's potential significantly underestimated by our approach?

An examination of the consumption and market share phase plane provides part of the answer. Consumption currently appears to be at the peak of a growth cycle that began at the time of the counter-shock *(Fig. 15e - Point a)*. The phase representation of the linear extrapolations shows that the trajectory is indeed heading down, whether total energy consumption reaches 12 or 14 Gtoe. While the descending phase of the cycle seems rather abrupt for the 12 Gtoe scenario, we note that even for the 14 Gtoe scenario, oil consumption never reaches 4 Gtoe (only 3.85). In terms of market share, the situation appears clear *(Fig. 16e)*: the trajectory never crosses the abscissa, which is the synonym of a new era of growth. Rather, it heads unequivocally into a new downward phase.

To the question of whether oil's contribution as calculated by the *f/c* linear extrapolation is underestimated, we respond: "perhaps". But it seems undeniable that this contribution will not be able to significantly exceed the boundary of 4 Gtoe by 2020 (or about 90 Mbbl/day). Subsequently, oil would seem to enter a growth cycle, whose amplitude is reduced compared to the current cycle. We should remember a characteristic common to the growth dynamics of all energy sources, and particularly to dominant energies: the rhythm of growth is never constant, but rather follows cyclical variations; the successive cycles tend to diminish in amplitude. A limited rebound in oil consumption growth after 2020 would be perfectly coherent with the market share trajectory. The latter, which is currently on a path of accelerated decline, will also ultimately reach a maximum and then dive into the next phase of decelerated decline (which expresses the new cycle of consumption growth).

Natural Gas

The evaluation of gas's contribution to total consumption certainly constitutes a controversial subject on the same scale as hopes for development of consumption of this energy in almost all the world's regions. Our intention, however, is to look at the characteristics of all energy forms without preconceptions, in order to best delimit the space used by the various graphical representations, within which the trajectories are most likely to be found.

In contrast to oil and coal, the *f/c* linear extrapolation for the gas trajectory augurs well for its continued growth in the world energy balance *(see Fig. 14f)*, and in this it reflects the very nature of this approach. Is it plausible to hypothesize that the trajectory in the *f/c* plane will stop levelling off over a period of around 20 years, although (without adopting the Marchetti's extreme thesis evoked above) this levelling off is a crucial element in long-term trends?

The phase planes provide new elements for this assessment: gas consumption reaches 2730 Mtoe in the 12 Gtoe scenario and 3430 Mtoe in the 14 Gtoe scenario. Figure 15f shows that the difference between these two values cannot be simply reduced to the 700 Mtoe spread, but rather delimits the field of possibilities:

- Gas will surely reach at least 2730 Mtoe in 2020, as this requires no deviation from its long-term trajectory and does not call into question its behaviour when growth slows down.
- On the contrary, consumption of 3430 Mtoe requires an immediate reversal of this trajectory, namely a continuous acceleration of the growth rate, which has not been observed in the past, except, of course, during the energy's introduction when growth rates are as high as the quantities are low. If we return to Figure 14f, this means assuming that the gas trajectory in the *f/c* plane *does not level off at all* (in our linear extrapolation) over a period of more than 20 years, which contradicts energy history. As we did for coal, we confirm our outlook that consumption will necessarily be below 3.5 Gtoe in 2020 and maintain our criticism of scenarios that give gas the lion's share, going so far as anticipating consumption above 3.5 or even 4 Gtoe.

Figure 16f confirms these conclusions; the market share trajectory is similar to that of consumption. Nevertheless, we note that 2730 Mtoe in the 12 Gtoe scenario means that the current cycle is interrupted and that gas enters a phase of stable growth in market share. But, all our observations clearly demonstrate that a rectilinear trajectory is implausible; all evolution is definitely curved. The most likely trajectory consists of a new cycle composed of an upward phase of accelerating growth (in consumption and market share), a peak and then a descending phase of decelerating growth, where the two successive phases are basically symmetrical.

If we assume that the maximum possible value (*i.e.*, 3430 Mtoe) is reached in 2020 at the peak of the cycle, the descending growth phase during the following 15 to 20 years would inevitably lead to consumption at levels that are hard to imagine, nearly 6000 Mtoe. The "maximalist" hypothesis we formulate is that the 3430 Mtoe value is reached at the end of the full cycle. The key to the problem resides in the level at the peak, which we put at the middle of the cycle, *i.e.*, in 2009. In this case, the consumption trajectory must reverse direction immediately, reach its peak at the threshold of 3.17% growth in 2009 *(see Fig. 15f - Point a)* and then decelerate to return at the bottom of the cycle to a growth level identical to that of 1997 *(see Figure 15f - Point b)*. We'll use this scenario in our effort to calculate the potential minimum supply "deficit", even though we believe it to be improbable, as it supposes that:

– The trajectory reverses direction immediately and durably, which requires a strong impetus.
– The peak of this cycle reaches the level of the preceding cycle (3.2%), which is never the case (as shown by the phenomenon of progressively decreasing cycle amplitudes).
– At its lowest point, the descending phase remains above the threshold of 2% (the current level of consumption growth).

Our observations and analysis show that all energy forms — fossil fuels even more than renewable resources — go through phases of maturity and then decline during their history. Gas's trajectory does not escape this rule and must *inevitably* level off. If the trajectory does not level off much (or at all) in the coming years, then there is a real possibility of a *brutal drop* such as happened to coal and oil *(see Fig. 6a - Points A and B)*. This situation should help guide our analysis regarding the causes and economic consequences of natural gas's move into the withdrawal/ decline phase. This hypothesis takes on particular importance in light of the considerable hope placed in the development of this energy form.

The contributions of all fossil energies to the 12 and 14 Gtoe consumption scenarios are summarized in Table 12. We deliberately use identical values for consumption in both scenarios, as we consider them to be maximum amounts that will not be exceeded by 2020.

4.3 World Energy Outlook for 2020

Our method of evaluating the future contributions of primary energy sources enables us to estimate the potential surplus or deficit in supply for a given level of demand.

In the framework of the 12 Gtoe scenario, the sum of the contributions of all energies except nuclear equals 12.33 Gtoe *(Table 13)*. Taking the conservative hypothesis, where nuclear energy's contribution remains at its current level of 0.6 Gtoe, it seems that the risk of tension over supply can be dismissed. It should be remembered, however, that *the apparent surplus of almost 1 Gtoe* (0.33 + 0.60) is the result of very optimistic scenarios, particularly as regards renewable energies and gas. If we use more restrained, less ambitious scenarios, this surplus would necessarily be reduced to a less comfortable level.

In the framework of the 14 Gtoe scenario, we obtain the opposite result. The sum of the contributions causes a deficit of almost 1.6 Gtoe *(Table 14)*, excluding nuclear energy, for

TABLE 12

Estimate of the contribution of fossil fuels in 2020

	Coal		Oil		Gas	
	Market share in mp	Contribution in Mtoe	Market share in mp	Contribution in Mtoe	Market share in mp	Contribution in Mtoe
12 Gtoe Scenario	25.3	3036	33.3	4000	28.6	3430
14 Gtoe Scenario	21.7	3036	28.6	4000	24.5	3430

TABLE 13

Contribution of primary energies to a worldwide consumption of 12 Gtoe

	Coal	Oil	Gas	Hydro	Geothermal	Solar	Biomass	**Balance**
Consumption in Gtoe	3.04	4.00	3.43	0.33	0.14	0.05	1.34	**+0.33**

TABLE 14

Contribution of primary energies to a worldwide consumption of 14 Gtoe

	Coal	Oil	Gas	Hydro	Geothermal	Solar	Biomass	**Balance**
Consumption in Gtoe	3.04	4.00	3.43	0.39	0.16	0.06	1.34	**–1.58**

a net deficit of 1 Gtoe, based on an identical contribution for nuclear energy (0.6 Gtoe) as in the 12 Gtoe scenario. The same remark as above regarding the "minimal" nature of this deficit applies here. The inevitable tension around supply that would result from this total level of consumption could be all the more underestimated in that (except perhaps for coal, and to a lesser measure for oil) we are considering the other energies at the maximum level of their contributions in 2020, and probably beyond that for some.

5 RECENT DEVELOPMENTS AND CONCLUSIONS

5.1 Short Term and Long Term: a Mutual Enlightenment

Our work covers the period 1850-1997. We now have more recent statistics available that can shed light on the trends we have highlighted and on our conclusions regarding the growth potential of primary energies. These confirm that the oil scenario we formulate is out of kilter with the orders of magnitude that are generally recognized for worldwide consumption, as shown by *IEA* and *American DOE* scenarios that forecast about 115 Mbbl/day in 2020. We could even cite the opinions of some experts who expect an even higher level of consumption.

We will conclude this presentation of our analytical method and results by putting into perspective the growth rates for oil consumption recorded for 1998, 1999 and 2000, *i.e.*, 0.56%, 2.30% and 0.74%, respectively (variations on raw series). In Figure 17, we project the years 1998 through 2000 after data filtering. It appears that the growth cycle that started in the early 1980s (positive dynamic), which we predicted would peak soon, before beginning a deceleration phase, is indeed headed in the direction we expected. The nearly zero dynamic (peak) appears to be tipping over towards a negative value, which presages a sharply slowing growth phase. Although we should remain prudent in this regard, we observe that most current predictions for oil consumption for 2001 (+0.1 Mbbl/d) and 2002 (+0.7 Mbbl/d), which was heavily affected by a world economy in virtual recession, confirm this trend (raw data).

Our two key comments that result from this work should help go beyond the debate that solely concerns the level of energy consumption that will or will not be reached at a given date:

– In the phase representation, all evolution is *curved* by the succession of acceleration and deceleration phases. The use of average growth rates alone to describe the past, and even more so the future, ignores these successive phases and is therefore inadequate, prone to the risk of wrong analyses and unrealistic projections.
– To support any value proposed in the context of a scenario at a given date, an energy projection must specify the growth rate associated with this value. In other words, it is more important to specify *the sign of the dynamic and the position in the cycle* and the end of the projection period than a unique, absolute value for consumption (or market share), which will only be the result of these two elements. Tables 13 and 14 (contributions of primary energies at a consumption of 12 and 14 Gtoe) do not mention these elements, as we have not made a hypothesis regarding the dynamic of global demand.

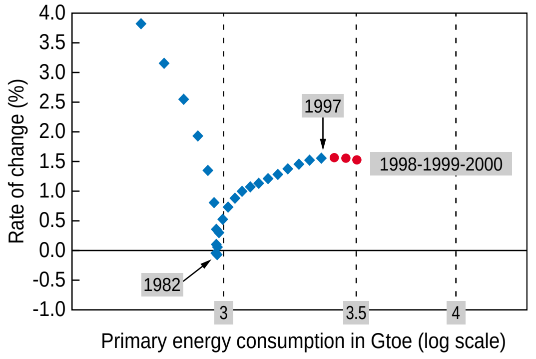

Figure 17

Oil consumption cycles and rates of change for 1998-1999-2000.

5.2 General Conclusions

1. We have not handled the problem of statistical inadequacy. This important question, particularly as regards equivalences, does not undermine our presentation. We can only urge that such an effort be undertaken, without being marred by considerations that push the scientific approach into the background.
2. Our work concerns the possibility of improving energy forecasts. An initial report published in May 2000 sketched out a methodology that we develop here in greater detail. The essential point is to consider dynamic elements and relational elements, as follows:
   - Dynamic elements consider the rates of change of consumption and market share, independent of consumption and market share.
   - Relational elements use the phase space to naturally associate the variables with their variations and the *f/c* space (market share/consumption space) to show relations between the energies.

   The properties of these spaces are described in detail in the Appendix. What is important is that the use of these spaces enables us—by merely considering the *morphology* of possible trajectories—to restrict the forecasts, limiting the areas in which the trajectories may be found. This does not limit the construction of dynamic models, but rather supplies boundaries that the solutions must not cross.

3. We have attempted to apply our method to a simple case that concerns two hypotheses for worldwide demand (12 and 14 Gtoe in 2020). It can be shown that the energy trajectories are sufficiently limited (in the sense of the space used) to supply realistic energy scenarios. In order to complete our work, which concerned data limited to 1997, we supplied, for oil, graphs obtained by adding data for 1998, 1999 and 2000, based on filtered series. The points obtained clearly demonstrate that no major modification of the dynamic appears.
4. Beyond our initial results, the construction of scenarios for each primary energy source requires the formulation of a hypothesis for the *global demand* dynamic. Our work will now develop towards accounting for general economic factors and attempting to integrate geographic aspects. The narrowing of the range forecast, which is central to our approach, appears to require the use of fundamental elements, which we have voluntarily left aside (*e.g.*, demographics, production). Nonetheless, it should not be thought that the trajectories of the various energies could free themselves from the constraints that we have highlighted, which remain in any event.

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APPENDIX

1 STATISTICAL SOURCES

1971-1997 period: Reviews and statistics of nonmember countries, *OECD/IEA*, 1999.

1950-1970 period: Etemad and Luciani, *La production mondiale d'énergie 1800-1985*, *CNRS* and *CHEI*, 1991, World Energy Supplies, UNO, 1976.

1850-1950 period: Etemad and Luciani, *La production mondiale d'énergie 1800-1985*, *CNRS* and *CHEI*, 1991; Marchetti and Nakicenovic, *The Dynamics of Energy Systems and the Logistic Substitution Model*, IIASA, 1978.

J.M. Martin data (biomass in 1850 and 1900, coal in 1850).

2 FILTERING

We chose the Hodrick-Prescott's filter (1997), which is regularly used in analysing the cyclical properties of macroeconomic variables. This technique is based on the idea that a trend must be sufficiently smooth so as not to follow all the inflections of the series, without deviating too much from the movements of the initial series. The method consists of seeking a filter such that the filtered series is a solution to the following problem:

$$\text{Min } \Sigma\, [y_t - \mu_t]^2 + l\, \Sigma\, [(\mu_{t+1} - \mu_t) - (\mu_t - \mu_{t-1})]^2$$

where μ_t is the trend component, $y_t - \mu_t = c_t$ the cyclical component. The first term measures the fit of *c* to *y* while the second indicates the degree of variability of the trend. The parameter λ represents the weight assigned to the second objective relative to the first. The larger this parameter is, the smoother the trend. For an infinite λ, we obtain a linear trend. Hodrick and Prescott (1997) recommend setting the value of the parameter λ to 100 for an annual series.

3 PHASE REPRESENTATION, DYNAMIC AND CYCLES: MATHEMATICAL ELEMENTS AND FUNDAMENTAL REMARKS

NB: The examples that illustrate the text below are shown as Examples 1 and 2 in the main text.

Consider a positive, continuous, differentiable function. The phase representation is based on a coordinate system in which the function is the abscissa and its first derivative is the ordinate. The term phase representation comes from the phase space of particle mechanics, in which the positions and momenta (the product of velocity and mass) are considered.

This kind of representation has a number of properties:

1. In the y plane, y', the slope of curve y is dy'/dy, or y''/y'. This shows that near an extremum ($y' = 0$), the slope becomes undefined and that the trajectory is governed by the second or higher-order derivative. Generally speaking *(see infra)*, the trajectories are normal to the abscissas, either flat (crossing) or with a turning point.
2. A special case is associated with $y'' = 0$, an increase at a constant rate (as y' is a constant). In this case, the trajectory is parallel to the abscissas in a linear representation and is a decreasing exponential asymptotic to the abscissas in a logarithmic representation.
3. The y,y' plane has a direction, as the sense of the variation of the function determines the sign of the derivative.
4. If we use a log y, dy/y representation (logarithmic phase representation), the slope of the curve equals the dynamic, *i.e.*, the relative variation of the rate (a standard term in economics for dy/y)
5. If an economy is cyclical, its growth rate must show a component that is almost constant, to which a periodic term is added. Limiting ourselves to a simple example, we would then write:

$$dy/y = k\,(1 + a \sin bt)$$

or again $\log y = kt - (ak/b) \cos bt + \text{constant}$.

In a logarithmic phase representation, these equations define three different types of curves, depending on whether a is >,=,< than 1. In particular, a cycloid is obtained for $a = 1$. In practice, reversals or more generally, turning points, should be found near the abscissa. These turning points mark the low points of the cycle if it is in the growth phase ($k > 0$), or the high points if it is in the decline phase. It should be noted that the phase representation amplifies the cycle signal (low point and high point).

3.1 Interest of the Phase Representation and Dynamic

A simple observation of time series, even before filtering, shows that the rates are never constant and show strong variations. Filtering eliminates some of these fluctuations while keeping the important changes, but lessening their abruptness. It is apparent, therefore, that rates vary and it is critical to take this aspect into account for the phenomena under study. As the phase representation offers the ability to clearly represent rate changes, it is a mathematical tool that is well adapted to studying the dynamic. The dynamic is the relative variation of the rate. It is expressed mathematically by $(d(dy/y))/(dy/y)$, or again by $(y''/y') - (y'/y)$.

3.2 Limits to the Use of the Dynamic

We improve on the simple calculations of rates (average annual growth rates) observed in the past by taking into account variations in the dynamic across long-term trajectories. It should be noted, however, that the numeric calculation demands intervals that do not cross the abscissas, because of discontinuities. For the same reason, it cannot even handle a minimum in the cycle (if the rate is > 0). In sum, the dynamic must be calculated on intervals for which the sign does not change.

It is therefore necessary to associate the notion of the dynamic to an examination of the historical trajectory over a long period. The thought process must focus more on the analysis of the trajectory's turning points, which constitute strong reference points, than on the rate of change, which hides subtle but essential variations over the long term. The economist's argument in this context is to take a position regarding the value of the dynamic and on the future existence of possible turning points.

Finally, the calculation of the dynamic includes an arbitrary part that depends on the degree of smoothing that is applied to the raw series, as the adoption of a stronger or weaker parameter modifies the value of the dynamic.

3.3 The Problem of Filtering

Observed time series can be smoothed through filtering, allowing at least first-order differences to be calculated and highlighting the nonmonotonic features of the systems studied. Filtering is thus essential in the phase representation for calculating the dynamic and bringing out the cycles. The effect of filtering should nonetheless be studied. We have worked with $\lambda = 100$. However, further analysis is needed to determine, for each case, the correct l parameter, which does not create statistical or graphical artefacts, and which enables the phenomena to be clearly read.

As an indication, the Table 15 gives the different values of the dynamic for global energy consumption over the period 1961-1997 (a homogeneous phase of slowing growth, *i.e.*, with a negative dynamic) as a function of the following values for the parameter λ: 25, 50, 75, 100, 125, 150 (*i.e.*, from a slightly filtered to a heavily filtered series).

The average growth rate for the period 1961-1997 is 2.80%/year. For the parameter $\lambda = 100$, the negative dynamic shows that it is tending to decrease at rate of –3.38%/year. Without affirming that this constitutes a real demonstration, we note that the value of the parameter λ does not significantly change the value of the dynamic. The conclusion remains that global consumption growth is clearly slowing down since the early 1960s. We can therefore state that the phenomenon we have highlighted is not an artefact that has resulted from statistical filtering of the raw series.

TABLE 15

Values of the dynamic for global energy consumption over the period 1961-1997

Parameter λ	25	50	75	100	125	150
Dynamic	–3.33	–3.35	–3.37	–3.38	–3.38	–3.39

4 ENERGY SUBSTITUTION AND THE LOGISTIC MODEL

Marchetti has contributed an interesting attempt to represent energy dynamics by fitting a diffusion equation. This model leads to a linear relation between log $(f/1-f)$ and time, where the relation is different during the market share's growth phase and decline phase. Despite its elegance (which is never negligible), a closer study brings out various inadequacies:

– The logistic fitting is not satisfactory, as shown by the linear phase representation. The logistic equation is $df/dt = A\, f(1-f)$, which defines a parabola. The energy decline thus calculated makes the implicit hypothesis that each energy form will totally disappear. This is a fundamental error, as it can be reasonably assumed that irreducible market shares ("hard cores") will subsist for each energy. Under these conditions, the variable associated with time is no longer $f/1-f$, but $f/f1-f$, with $f1$ the market share limit. As $f1$ is characteristic of each energy, a unique representation no longer exists.
– The model is almost deterministic, which constitutes rather a sin against the macroeconomic approach.

The same criticism can moreover be addressed to the work of King Hubbert (1956), who uses the fitting on a logistic curve to predict an extremum. This type of work postulates a growth/decline symmetry (for production of natural substances), which has no basis in fact and ignores all macroeconomic considerations.