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MODELLING LONG RUN SCENARIOS: METHODOLOGY LESSONS FROM A PROSPECTIVE STUDY ON A LOW CO₂ INTENSIVE COUNTRY

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Abstract

This paper intends to draw overall lessons from a long-term study on CO₂ emission in France, a country with a rather low energy/GDP ration and in which transition to non-fossil based production of electricity has been achieved. More generally, it points out the importance of possible bifurcation effects, and draws methodological and policy implications from these statements. It discusses modelling approaches to the linkages between energy and the rest of economy, and addresses the issue of difficulties in cost assessment analysis in the presence of several baseline scenarios. Finally, it proposes a more encompassing definition of no regrets policies.

Keywords: Long-run scenarios; Modelling; CO₂ emissions

In a context of enormous uncertainty, discussions on the costs of climate change policies are deadlocked by two critical difficulties: the assessment of the short and long term flexibility of our consumption and production systems and the choice of incentive instruments to trigger this flexibility and abate anthropogenic GHGs emissions at a minimum economic cost. The connection between these two points of contention is obvious in the classical debate on the relative role of price induced and "autonomous" technical progress in the past decrease in energy intensity:ⁱ to adopt a high value of autonomous energy-efficiency improvements minimizes the cost of the abatement strategies and emphasizes the influence of non- pricing policies on energy demand trends. Conversely, a conventionnal model assumes price signals to be the sole policy variable and concludes that abatement costs will be high in the absence of cheap supply-side solutions.

A satisfactory conclusion to this debate requires some methodological progress and no doubt it will be brought by on-going works. I would like to elaborate here some ways to approach these issues, based on the lessons drawn from a prospective study carried out in the context of the Atelier de Prospective Energétique (APE) of the French Commissariat Général du Plan (CGP).ⁱⁱ

In order to examine the long-term flexibility of our economies the "French case" is of some interest:

- As regards to the ultimate limits of energy-growth decoupling and the role of nuclear energy as a substitute for fossil fuelsⁱⁱⁱ, France is characterised by one of the lowest energy/GDP ratio among the OECD countries, and by a dominant share of carbon free energies (nuclear and hydro) in the production of electricity,
- Methodologically, because the evidence of the role played by the transportation in the long run raises questions until now overlooked in current costing studies of the preventive strategies and substantially moves the terms of the debate on the no regrets concept.
- In this paper, I shall not seek to go into all the details of the "French case", but to use it as an occasion for arguing in favour of some new research priorities. For clarity, I shall explain briefly the reasons for some key methodological choices of our study before giving the main numerical results and, in a third section, coming back to some general lessons.

I. METHODOLOGICAL OPTIONS FOR DEALING WITH FLEXIBILITIES AS A FUNCTION OF LONG TERM EXPECTATIONS

I.1. Brief insights on the institutional background

The French CGP does not aim to take mandatory command and control decisions. Bringing experts, business and trade union representatives together with the public administration, it tries to reveal some consensus on which to base

long- term policies. This procedural constraint partly determined the methodological choices for the study since they had to obtain some consensus in the commission.

In the energy field, the controversies about long-term technological and consumption patterns that lie energy behind energy demand, and the dramatic uncertainties about external parameters such as the political stability of the Middle East and Eastern Europe, US energy policy and environmental concerns^{iv}, engendered a consensus about the necessity of resorting to contrasted prospective scenarios. The aim was to sketch the boundary of the possibility set in the future and to facilitate discussions about the strategic hypotheses and their implicit assumptions by providing consistent pictures of competing views of the future.

This led to the use, for the 2005 scenarios, of a disaggregated bottom-up model of the French energy system with 165 end energy uses, a precise description of vintages of equipment for each category of energy consumer and a modelling of induced investments.

The 2005 balances, which derive from a consensus on the relevant scenarios which need to be constructed for strategic analysis, provide numerical picture of the range of opinions of experts about the international background, the technical degrees of freedom available and the social and political constraints which will ultimately determine the viability of any scenario.

The climatic change issue, which requires the consideration of timescales far beyond the following decade, made it necessary and possible to partially relax this political acceptability constraint. Taking the 2005 balances as starting points, the long- term scenarios (2030) are consequently strictly exploratory, and aim to answer two sets of questions:

- After 2005, will France, having exploited the maximum possible substitution between carbon based electricity and nuclear energy, be faced with limits to further reductions of energy intensity, making it unable to accept any commitment to substantially reduce its CO₂ emissions; if not, how far can technical innovation push these limits?
- What could be the impacts of a carbon tax of FF1000 per tonne of carbon, as proposed by the Groupe Interministériel sur l'effet de serre?^v

The high level of this tax is meant to give a strong enough price-signal enough to change both the consumption patterns and the technical innovation trends; it aims to stabilize long-term expectations and to counter the inherent instability of the energy markets. This level implies that the tax will be offset by a decrease in income tax, value-added tax and any other social contribution, so as to offer fiscal neutrality; its implementation will depend on a prior commitment involving the main OECD countries, to avoid distortionary effects on international markets.^{vi}

Beyond the greenhouse issue, this proposal is part of a movement tending to envisage taxation of environmental externalities as a partial solution to the problem of raising revenue. Today, income taxes above a certain level provoke strong opposition and the internationalization of capital markets has reduced taxation on profit and capital; value added is then becoming the main fiscal base, which has a negative impact on both economic activity and employment.^{vii} It is consequently timely to study whether taxation of bads (negative externalities) and not goods could be a possible answer.

The economic models currently available, which were built to describe the short- and medium-term macroeconomic impacts of oil shocks and energy policies were not able to address these new issues. The problem was no longer one of describing economic behaviour with a given set of techniques, but accounting of accounting for the changes in expectations likely to generate a new set at $t + n$. This carbon taxation scheme, complemented by accompanying measures, is not meant to be an external shock on a system characterised by a given elasticity, but a signal aiming to upgrade this elasticity by improving the efficiency of energy markets and shifting technical innovation and consumption behaviour on to a more energy saving path.

- Unlike the situation after the past oil shocks, the fiscal neutrality principle means that the product of this tax is immediately recycled in the national economy via the lower cost of other production factors (labor and capital) so as to reallocate investment decisions towards technology and consumption patterns with a lower carbon content.
- A modelling structure, called IMACLIM, was designed to cope with these issues. This is not the occasion to go into the details of the methodological solutions adopted ^{viii} but we will nevertheless elaborate

briefly on two critical points: the description of technological paths and the linkages between macroeconomy and technology assumptions.

I.2. Technological trajectories between engineering optimism and macroeconomic pessimism

It is now common knowledge that engineers and economists disagree about the abatement cost issue.^{ix} The use of cost curves based on engineering data enables optimization models, like EFOM or MARKAL, to write low-cost medium-term scenarios^x because they rely yet on untapped energy-efficiency resources. Over the long term, the use of optimistic hypotheses on new technology vintages^{xi} leads to the same conclusion. As pointed out by Manne and Richels,^{xii} economists tend to counter this engineering optimism about the "efficiency gap" by listing the following arguments:

- Nothing is said about the costs and political feasibility of removing the market imperfections explaining the gap between the economically sound energy consuming practices and those that are currently employed,
- The feedback between technical progress and consumer behaviour is ignored: an improvement in motor efficiency lowers the cost per kilometre driven and has the perverse effect of encouraging more trips;
- It is a mistake to take into account technical progress on the production of existing goods and services but to ignore the endless process of the discovery of new needs and the development of new goods and services, some of them with a high energy content (holidays in tropical areas for example).

However, the economists' answer' to capturing these contradictory factors is mainly to rely on "top down" models. Econometrically calibrated over the past, these models are useful for describing an aggregated outcome over the short and medium term, but are less suitable for dealing with the long term, since we cannot robustly model feedbacks between economic incentives (prices, interest rates and funding policies) and technical change.

Indeed, even if the distinction between autonomous and price-induced

technical progress is highly enlightening, its measure relies on a pure econometric artefact. First, oil shocks have historically been systematically accompanied by measures such as incentives for investment on energy conservation, standards, information and training and have also been contemporaneous with structural changes in the industry. Second, some confusion arises from the fact that the autonomous trends is not strictly related to mere efficiency: it compounds structural changes, (saturation of certain energy uses, decrease of energy intensive industries...), non-price induced technological progress, and non-price policies designed to enhance the uptake of energy-efficient techniques. Third, these difficulties are exacerbated by the theoretical necessity of separating, in the price effect, the relative weight of short-term optimizing behaviour (the substitution effect) and that of innovation spurred by changes in long-term expectations; experience to date shows, indeed, that even a sudden change in these expectations can induce technological irreversibilities whose impact is far greater than the expected effect of a mere short-term and reversible response to price variations ^{xiii}.

- In order to bridge, to whatever extent is feasible, the gap between engineering perspective and economic perspective, while designing a tool able to explore alternative assumptions on technical progress, structural changes in industry and lifestyles, we tried to design an instrument which adhere to three basic principles:
- To treat the assumptions about technology, structural change and behaviour not as grounded uniquely on current trends but as depending on controversy expert statements, and to be able to test the impact of current controversies on the results of the scenarios.
- To distinguish explicitly the needs likely to reach saturation levels in the future from consumption trends with linear or exponential growth, at least given our current knowledge.
- To avoid the risks of a mere multiplication of technical assumptions by accounting for the effect of institutional inertia on the diffusion of technical and behavioural changes, verifying the consistency of the technological and structural assumptions with economic parameters such as personal income and the relative prices.

- We adopted a solution which may seem simple, but tried to take advantage of the institutional context of this study, for which we had access to detailed exogenous expertise. It consists in using logistic functions in $y = f_k(r,p)$ and $y = g_k(t,p)$ with personal income (r) and prices (p) as arguments for the segments of demand expected to reach saturation ($dy/dr > 0$) ^{xiv}, and time (t) and energy prices (p_e) for the energy-efficiency coefficients of each technology ($dy/dt < 0$). In the latter case, the role of time is to encompass capital turnover effects arising from the progressive diffusion of new technologies.

The external expertise determines the asymptotes "k" for these logistic curves, which means that they can be changed in case of non consensus. Given the value of saturation levels, ^{xv} each curve can be benchmarked for the corresponding techniques or end use, based on past observations (1973-1988) and on future data, in this case, APE's 2005 scenarios. For a given set of experts statements, the price of energy acts mainly as an accelerator in the technical diffusion (see Figure 1), and the benchmarking of the curve catches the non-economic and non-technical inertia observable in the past and accounted for (or expected) by the of the APE expert in their 2005 scenarios.

Figure n° 1

I.3. Macroeconomic costs: relaxing production functions

The key limitation for a sound assessment of the long-term deadweight costs of emission abatement is the lack of homogeneity of the current treatment of the technical progress in the energy and non-energy sectors by energy-macro-economy models. Technical change in macroeconomics is, indeed, whatever the level of disaggregation of the model, a "proxy" which encompasses several factors: technical innovation in the engineer sense, intersectoral and intrasectoral structural changes, business cycles, strategic behaviour departing from simple representations of microeconomic rationalities over the short and medium term (eg pursuit of investments in sectors with excess capacity to discourage competition).

This makes it very hard to establish explicit links between production functions in economic models and technology projections.^{xvi} Therefore, unlike in the energy sector where it is possible to explore a wide range of alternative expert statements, the current practice in macroeconomic modelling (in general also for equilibrium and macroeconomic models) is to use fixed production functions for all sectors other than energy. This method is sound and reliable for the short-term analysis, but there are few logical grounds for assuming that a set of price or non-price long-term incentives to innovation would be of no effect on the production functions of the non-energy sectors in the long term. Consequently, in the case of a nested CES Cobb-Douglas for example,

$$Y_t = [a(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + b(E_t)^{\rho\beta}(N_t)^{\rho(1-\beta)}]^{1/\rho}$$

a carbon tax would not simply result in movement along a function characterized by a given set of coefficients a , b , α , β ; it would induce new expectations leading to a production function with new coefficients a' , b' , α' , β' , ρ' ^{xvii}.

Because of the scarcity of factual findings about the possible range of variation of those coefficients with time, we used a backward induction procedure connected with a general equilibrium approach. Each scenario is considered consistent with a long-term static macroeconomic equilibrium (absence of public deficit, balance between income and expenditure for all sectors), this equilibrium being the result of non-specified production functions for non-

energy sector (a single composite good in the first version of the model). The macroeconomic context of the scenario is then fully explained by our assumptions about technology, structural change and demographics. Then the coefficients of the implicit production function can be calculated at the margin by interpreting (with a very *few ad hoc* hypotheses) the results of the taxation scenarios at constant economic growth as giving the partial derivatives to prices (see the appendix).

Only one additional hypothesis is necessary to solve the equation system and assess the impact of a carbon tax on the equilibrium of each scenario ^{xviii}), the impact of higher prices of fossil fuels on the cost of the composite good. This in turn depends on the coefficients of the new production function. It is then possible to carry out sensitivity tests on the impact on the macroeconomic equilibrium of a wide range of values for resulting total productivity: the production cost of the composite good is increased of the total value of additional energy costs in the case of technical inflexibility, and remains constant in the case of an efficient long-term response to the price signal.

II. II. ALTERNATIVE SCENARIOS AND THE EVIDENCE OF POSSIBLE BIFURCATIONS

II.1. Three baseline scenarios

In the spirit of the above, three baseline scenarios were built, for the period beyond 2005, describing various expectations over the long term and different development strategies; the choices underlying each of them (in industry, building, and transport) were made without any particular connection with environmental concerns or with domestic energy policy. A carbon tax was then applied to each of these baseline scenarios, progressively increasing to FF1000 per tonne carbon (tC). Tables 1 and 2 give energy consumption figures for 1988.

Reference scenarios (REF, REF1). These scenarios extrapolate the trends of the central APE scenario for 2005, with a 2.5% GDP growth rate between

2005 and 2030. The REF1 scenario assumes the implementation of a carbon tax without accompanying measures.

- These scenarios project current trends in France's energy supply (Tables 4-7), an increase in the share of the nuclear power, a decline in coal production, and no particular emphasis on the development of renewable energy sources. On the demand side, the decreasing energy content of goods and services reaches an asymptote as a result of no specific incentives for energy efficiency; at the same time, some components of the consumption pattern (space heating, utilities, number of cars per household) tend to saturation. By contrast, no saturation was taken into account in other transport sectors such as freight, air and public transport since there is currently no evidence for such trends in France.
- An oil price of US\$40/bbl was chosen since both economic growth and energy intensity are on a rather high trend, therefore accelerating the pressure on depletable resources (we implicitly assume that all major industrialized countries are on the same path). The price of electricity was assumed to remain constant, implying that technical progress will offset the cost of nuclear plant dismantling and renewing installed capacities.

Energy-efficiency scenarios (ME, ME1).^{xix} These scenarios (Tables 8-11) follow the same development pattern as the REF scenarios, but with a strong policy in favour of energy efficiency. In our scenarios, this is reflected in the use of lower asymptotes for the energy intensities. In the ME1 scenario, the trickling down of this technical progress is accelerated by the carbon tax.

Structural change scenarios (MS, MS1). These scenarios (Tables 12 and 13) describe a different development pattern while adopting the same assumptions for energy efficiency as those of the ME scenarios. They envisage a context where, for reasons unconnected with the greenhouse concerns or energy security, new orientations are taken in two fields: growth is based less on energy intensive industries, and there is a reduced demand for freight and passenger transportation.

These scenarios begin in 2005 because our focus was the possible saturation in the decoupling between GHG emissions and economic growth over the long term, and because climate policies were not considered in the possible baselines for 2005. In order to check the possibility of meeting the TORONTO

targets^{xx} without structural and more controversial policies, a third version of ME and MS scenarios was also constructed (ME2, MS2) assuming ME1 policy to be launched earlier, namely in 1992 (Tables 14-17).

II.2. The reversal of the current trend in decreasing CO₂ emissions: a high probability risk?

The REF scenario points to the possibility of a sharp increase of the CO₂ emissions between 2005 and 2030. The CO₂/GDP ratio decreases by about 46%, but this does not prevent a reversal of the decreasing trend in total CO₂ emissions as observed between 1973 and 1988 (Figure 2 and 3).

This reversal is clearly related to the nuclear programme reaching some kind of steady state: electricity exhausts all its niches in the absence of technological break-through in biofuels or hydrogen. The REF scenario allows for a strong additional penetration of electricity on the industrial markets (Table 4): by the year 2030 electricity meets 60% of industrial energy needs (feedstocks excluded), compared with 53% in 2005 and 47% today. Despite this penetration, the French energy strategy hits a hard core of fossil fuels consumption in motor fuels and chemical uses, both among of the most dynamic increasing end-uses. In addition, the penetration of natural gas is squeezed between the non substitutable uses of oil and the increase of electricity use.

In fact, the overall result is quite noteworthy: France would be able, simply by continuing its current energy trend, to reduce its CO₂/GDP ration significantly, an achievement which, if generalised to all industrialized countries, would stabilize the world emissions of CO₂ by the middle of the next century. This perspective is nevertheless unsatisfactory; first, an efficient preventive strategy requires more ambitious abatement levels; second, during a negotiation process, France cannot expect special treatment by putting forward its present achievements and asking for other countries to act first.

II.3. Controlling CO₂ emissions: a wide range of possible policies

II.3.1. The limits of the French model on the supply

- Because of the conservative technical change hypotheses of the REF and ME scenarios the carbon tax merely succeeds in limiting the use of coal to coke in the steel industries, in slightly increasing the use of gas and in fostering combined cycle plant to meet peak demand for electricity.
- More important evolutions could be envisaged such as industrial cogeneration and district heating; but they are not triggered in these scenarios by a carbon tax only. Some reform in the price and financing policies of the French electric utility is a prerequisite to facilitate self-generation. The MS and MS1 scenarios simulate this evolution as a result of the progressive harmonisation of rules in Western Europe and the pressure of some industries in favour of cogeneration.
- Despite the rather low support to date in France for new and renewable energies, the APE agreed upon taking into account their possible development beyond the current 6,5 Mtoe of wood fuel ^{xxi}. Maximum technical potentials for the penetration of these energy sources were then adopted in the MS and MS1 scenarios (see Tables 12 and 13).^{xxii}.

The results are unsurprising and confirm the narrowness of the remaining penetration margins for carbon free energies; hydroelectricity remains stable, the new renewable energies bring only additional 9.4 Mtoe and the continuing penetration of electricity into its market niches is only sufficient to stabilize the weight of nuclear power in the primary balance and to offset the increasing role of the end-uses linked to oil and gas (gasoline, feedstocks).

Residential and commercial sectors. The main result is that, without drastic assumptions on energy efficiency and without allowing for possible evolutions in lifestyles and consumption patterns, the ME and MS scenarios succeed in

stabilizing the energy of these sectors and in decreasing the emissions by 43% from the REF scenario.

The energy-efficiency policy succeeds in lowering average consumption by 30% of the 2005 levels in old buildings with conventional heating, by 10% in old building with electric heating, and by 33% for new buildings with conventional heating, and by from 15% for new buildings with electric heating. Moreover, significant progress is expected, and has been assumed, in lighting^{xxiii} and most electrical appliances.

Our scenarios show a rather good reaction to the carbon tax in these sectors since, between REF and REF1, energy consumption decreases by 23 Mtoe (Tables 4 and 6). This flexibility may be unexpected since many studies have demonstrated the low reaction to prices over the short and medium term,^{xxiv} the APE projections to 2005 follow this conclusion since between the two scenarios are distinguished only by the energy price hypotheses (US\$22/bbl and US\$35/bbl in 2005), residential and commercial energy consumption decreases only by 12% compared to 20% in the transportation sector and 33% in industry (steel excluded). This seemingly contradictory result can easily be explained by the slow rate of capital turnover in this sector. In the long term, this rigidity disappears and about 80% (17 Mtoe) of the reduction is due to the pure price induced acceleration of existing techniques.

The stabilization of the final energy demand around 78 Mtoe (equal to that of 1988), combined with the on-going penetration of electric heating, the moderate substitution of gas for oil, and a moderate increase of solar energy brings about an abatement of 43% of the direct emissions from this sector in MS1 compared to the REF scenario. This figure does not include the indirect emissions in the electricity sector due to the use of fossil fuel to produce peak load electricity. The steepness of the low duration curve is clearly linked with the development of electric heating in winter. The question whether this could be reversed is controversial, but is not likely to change the orders of magnitude of our results.

Industry. Using the accounting framework

$$E/VA = \sum_i (VA_i/VA) = \sum_i \alpha_i (E_i/O_i \times O_i/VA)$$

the evolution of energy intensity in industry has been analysed as resulting from structural mutations (α_i), from technical progress (E_i/O_i) and from a tendency, slight but without apparent saturation effect, towards increasing value added per unit of material product (O_i/VA). From 2005 onwards the most significant technical improvements are expected in the steel industry (increasing use of electric furnace limited only by tensions on the scrap iron markets), and in the chemical industry (through recycling of plastic products, use of natural gas and biomass-based fuels as feedstocks, and substitutes for oil).

- The energy saved in the industrial sector between REF (the non-taxed business as usual scenario) and ME1 (the taxed energy -efficient scenario) is equivalent to the quantity saved in the residential and commercial sector (43 Mtoe, namely 29% of final consumption). However this reduction results from a quite different process.
- First the savings between REF and REF1 are modest (5 Mtoe). The weak reaction to the carbon tax can be explained by a much better use of available technologies in the year 2005 (according to the APE results) than in the residential and commercial sector. This reflects a higher sensitivity to more efficient equipment, spurred by industrial competition and principally to a higher rate of capital turnover (between 10 to 15 years in the industrial sector, more than 30 years on the residential and commercial sector, as far as buildings are concerned).

The only degree of freedom left lies, then, in energy saving innovations. With the moderately optimistic technical hypotheses adopted in ME for 2030 we get a reduction of 22% from the REF scenario. This larger set of available technologies gives greater scope for the carbon tax to work: between ME and ME1, it delivers a further 7% reduction in energy consumption.

Nevertheless, contrary to the results of the residential and commercial sector, the mix of non-price incentives and carbon tax does not prevent a 65% increase of final energy consumption and a 39% increase in the consumption of carbon based energy sources between 1988 and 2030 in scenario 2030 ME1. If we take into account the fact that, over the same period, the industrial value-added grows at a 2.5% per year, these gains are by no means negligible. But they do not suffice in stabilizing CO₂ emissions in the long term.

More optimistic results come from the MS and MS1 scenarios where the rather industrialist perspective of the REF and ME scenarios is ruled out. An elastic-

ity of 0.6 (in MS) instead of 0.8 (in REF and ME) between industry and GDP^{xxv} brings an additional 24% reduction in final energy demand between ME1 and MS1. Such a growth pattern enables to reach a 4% decrease in industrial sector CO₂ emissions between 1988 and 2030. But it must be underlined that a sizeable part of this result is due to the partial relocation of some energy intensive industries outside France.

As a whole, the analysis shows that the existing trend towards lower energy intensities in the industrial sector is unable to offset the growth of output; additional flexibility is conditional upon an innovation specifically directed to energy efficiency, and on structural change involving a possible shift from material based to information based economic growth.

Transportation. In this sector, scenario ME1 achieves only a 7.2% decrease in energy consumption compared to the REF scenario, and a corresponding 9% decrease in CO₂ emissions. The rigidity of this sector is easily explainable by three factors:

The impact of a carbon tax on consumer prices is far lower for fuels in transport than in other sectors because of the existing level taxation in France: an increase of 8.6% of the price of gasoline due to the carbon tax must be compared to 260% for coal, 34% for the industrial use of natural gas and even 9% for electricity.

- The gains in energy efficiency observed between 1973 and 1988, and the additional progress expected until 2005, have taken advantage of the technically easiest improvements. Beyond these easy improvements, factors such as the increase in the power of cars and the worsening of traffic conditions are expected to offset most of the additional gains in motor efficiency (see Figure 4). The rail for road or rail for air substitutions are both slow and insensitive to pure price incentives, unless measures are taken to enhance consumer interest in railways.
 - The high rigidity of the transport sector is all the more unfortunate since substitution between non-fossil fuels and oil based fuels is far more difficult here than in other sectors. Indeed, some technological breakthroughs may occur (electric cars for urban transport, hydrogen), but the economic ad-

vantage of oil based fuels has been judged high enough to prevent a great diffusion of these solutions by the considered time horizon of 2030.

- Consequently, only structural changes in transportation policy are likely to lower the emission profile of the sector. In the absence of tools for a convincing model of this type of policies, the following normative hypotheses were adopted for illustrative purposes in the MS and MS1 scenarios:
- reduction of 20% in individual transport needs and of 30% for the air transport, because of the saturation of available flying routes,
- Intermodal substitution of rail transport for freight, long-distance inter-urban transportation and urban public transportation.
- Moreover, a 15% increase in vehicle efficiency was assumed, arising from improvements in traffic conditions.

This set of hypotheses is necessary to reach an abatement of CO₂ emissions of the same order of magnitude than in the other sectors, 29% between REF and MS1.

II.4. Some first lessons about price incentives, non-price policies and structural issues

- As was shown in Figure 2, the range of possible French CO₂ emissions in 2030 is quite wide, between 92 Mt C pa in MS1 to 183 Mt C pa in REF; but not surprisingly so. It is more noteworthy that without structural change France fails in to meet the Toronto targets (20% abatement in 2005, 50% in 2030), even in the best case (MS2), with only a 17% abatement in 2030. Obviously, more satisfactory results could be obtained via more optimistic hypotheses on carbon free technologies and on development patterns; but this analysis demonstrates that these targets will not be reached without important additional efforts or technological breakthrough.

In terms of policy implications, the challenging conclusion is that shifting from the highest to the lowest scenario requires a combination of price signals, non-price incentives, and changes in long-term development patterns.

- The implementation of the carbon tax alone (from REF to REF1) leads to a 21% abatement of CO₂ emissions, but that does not prevent a 7% increase in the absolute level of emissions between 2005 and 2030 (a 40% increase from the 1988 level). The limitations of the tax policy come partly from the low flexibility of the industrial sector if a saturation of energy saving technical progress is assumed in the long run; but they come mainly from the fact that, in the French context, the carbon tax has too slight an impact on current trends in the transport sector.
- An energy-efficiency policy relying on incentives other than taxation (subsidies, information, standards, research and development programmes, etc) would be able to stabilize the emissions at the 1998 level, but only if they were implemented in combination with a carbon tax. This policy triggers technical progress towards energy efficiency and accelerates its diffusion, but, in the end, its effect is linked with the energy price level. However, efficient in promoting energy savings through technical progress in the industrial sector, the ME1 scenario (non price measures + carbon tax) fails to drastically lowering total emissions because of rigidities in the transport sector.
- A more ambitious abatement of total emissions can only come from additional structural changes, as described in the MS family scenarios. The critical point is that the choices between different structural paths *are likely to be taken for reasons unconnected with energy and climate change issues, and that the mechanical impact of any carbon tax is likely to be small.*

The case of gasoline provides a good illustration. On the one hand the increase of the final price due to a FF1000 tC tax is too marginal to really hamper its progressive domination of the sector; on the other, the competitive advantage of the oil based car fuels is high enough to discourage the automobile and refining industries from taking the risk of a large-scale production of alternative motors and fuels. This does not rule out the possibility of technological breakthroughs; it simply means that these breakthroughs would be fostered by other factors than a concern for the greenhouse effect. The electrical car could be a solution to local pollution in the big cities, biofuels could be an attempt to secure new markets for agricultural production and to rely less on imported energy and so on.

The above remarks, far from minimizing the interest of a carbon tax, help to highlight two key issues. First, taxation is only one part of the issue; in order to assess its effects, it is critical to specify in which context its implementation is being considered (accompanying measures, structural trends etc); second, we should not just focus on the mere allocative effects of the tax but also on its impact on collective expectations.

In the case of France, one of the side effects expected from the carbon tax is to remind certain sectors of public administration that current energy prices do not reflect the long-term cost of energy supply, and ward off the permanent temptation to rescind energy-efficiency measures, for short term reasons. Similarly, in a context where the perspective of taxing bads instead of goods would be broadly accepted, it would be easier to take up measures to internalize the costs of traffic congestion in current urban planning and transport policies.

- These considerations have direct implications in terms of assessing the macroeconomic costs of greenhouse policies. A majority of the available studies start from an optimized baseline projection: they then compute the shift induced by a taxation policy; and consequently cannot but conclude that they will be net macroeconomic costs. But measures in non-energy sectors unconnected with the greenhouse issue are likely to have strong consequences for the flexibility of our productive systems and therefore on the shape of the underlying production functions.
- The high sensitivity of macroeconomic results to assumptions on the production function of the non-energy sectors is illustrated in Table 18 with two sets of scenarios, REF and MS ^{xxvi}. The macroeconomic effect of the carbon tax is the product of a quasi-Keynesian effect of lower taxes on labour and production, and of the regressive effect of any reduction of the average productivity reflected in the price of the composite good (see the appendix for the role of parameter χ in capturing technical progress).

Macro-economic impacts of a compensated FF1000/t C carbon tax sensitivity tests

REF Scenario

χ	0	0,5%	1%	
Δ GDP	+1,65%	+0,94%	+0,24%	-2,15%
Δ N in million	+574 000	+325 000	+83 000	-745 000

MS Scenario

χ	0	0,5%	1%	
Δ GDP	+0,88%	+0,18%	-0,4%	-2,81%
Δ N in million	+305 000	+64 000	-172 000	-970 000

- χ denotes the increase of the production cost of the composite good due to the carbon tax in the case of non-substitutability between energy and other production factors; the macroeconomic cost is between 2.5% and 2.6% of the GDP, and it falls to between 1% and 1.5% if the substitution parameter between energy and the other input to production is assumed to be the same in the baseline and taxed scenario.^{xxvii}. But a very slight change in this function is enough to create a situation where the benefits of decreasing other taxes offset the deadweight costs of the carbon tax. The cost of the composite good could remain constant in the case of a higher but reasonable optimism; in that latter case, the positive effect of the taxation scheme would lead to a slight increase of GDP.

Those results are too preliminary to conclude that a response to the greenhouse issue could be achieved at no cost or at negative cost, but we would like to point out:

- to what extent the current results of current models can be reversed without drastic assumptions on the potential effect of a high tax on the long-term innovation process in the non-energy sectors;
- to what extent it will be impossible to go beyond these precautionary remarks until we try to bridge the gap between the macroeconomic description of production^{xxviii} and a fuller description of the long-term perspectives for technology and development.

III. SOME METHODOLOGICAL ISSUES: COST ASSESSMENT, IRREVERSIBILITIES AND BIFURCATIONS IN THE DEVELOPMENT PATTERNS

The flexibility that determines the global costs of climate policies depends a great deal on behaviour unconnected with energy policy or climatic change. This statement should be trivial but it was, at first, overlooked as long as the focus was on the impact of a carbon tax on the energy system, on final energy prices and on the macroeconomic impacts of the increase of these prices.

Once an economy has achieved the substitution between fossil and non-fossil fuels in the electricity power sector, and improved the efficiency of the whole energy system (from primary energy to end use, the key role of some structural factors becomes obvious: the substitutability between materials (steel, non ferrous, chemical products, cement, biomass products), shifts between material based industries and information-based activities, and transport.

This requires us to seek new approaches to link the energy sector to the rest of the economy. The task is to better capture the relationship between development patterns and the behaviour of the macroeconomic box, keeping in mind the fact that the environmental disruptions are not caused by the amount of value-added itself but by the technical and material counterpart of this value-added. Some examples from the transport sector help to illustrate the recurrent research directions. These directions are articulated around the concept of bifurcation, the reliance on several baseline scenarios for cost-assessment, and a broadening of the no-regrets concept.

III.1. Bifurcations; towards the use of several baseline scenarios

Two trends can be observed in France in the freight sector which would lead to a doubling of road freight on highways within 15 years: a shift towards road transport (by trucks) and an increase in the total volume of freight, under the influence of the single European market. Reversing these would obviously require decisions on infrastructure, and also on pricing and taxation systems in order to account the full cost of road transport as opposed to rail or water.

The key issue arises from the fact that, if these decisions are not taken before, say, the year 2000, we will certainly have gone beyond a bifurcation point and engaged in an irreversibility process, which can be analysed in two ways:

- First, as an extension of the lock in process analysed in the literature;^{xxix} learning curves, economies of scale, informational increasing returns, and above all positive network externalities, will act in favour of the system promoted by today's decisions, and market forces will close a self-reinforcing loop. Moreover, their localizational implications (attraction of services or activities around their proximity), induced investments (attraction of services or activities around their proximity), induced investments (doubling of a tunnel), the nature of skills and the degree of interests involved, will produce an inflexible system which will be hard to change over a reasonable timescale.
- Second, each of the possible pictures of the freight system in the long term will unequally narrow the range of available choices and the flexibility of the economy to both price or non-price incentives. They will entail drastically contrasted economic and political costs in the case of future actions to slow global warming. In the worst case action could become impossible.

This bifurcation issue is not limited to choices between means of transport; it also encompasses innovation choices on motor fuels and, surely the most difficult, the evolution of demand for transport induced by alternative town planning patterns. More generally, it encompasses many network industries where market forces tend, beyond a bifurcation point, to reinforce the first choice instead of correcting it, in a self-fulfilling process.^{xxx}

The first implication is that, at the date t , there are still several possible market equilibria at $t+n$, and several states of the world characterised by different technical contents, and not easily predictable from current trends. Trying to use some probability distribution is both difficult and misleading since the realization of one or other of the states of the world" in $t+n$ depends on the very decisions made in t , and in fact on the collective expectations at that time t ^{xxx}. The only sound answer is to work on the basis of several baseline scenarios, not scenarios with high, medium or low versions, but characterized by alternative assumptions on development patterns and innovation.

III.2. Implications for cost assessment analysis and new research directions

A conventional cost-benefit approach may not be helpful in choosing the optimum scenario; it would require some reliable information on several (and mutually exclusive) baskets of goods, services and techniques, and a complete set of preferences, with partial ordering and transitivity, formulated by the agents, not on each good for a given context (the utility attached to driving a car to go to work) but on each good for alternative states of the world: to be obliged to cross Ile de France in the absence of new RER lines, or to benefit from high investments in metro infrastructures and from a reversal of tendencies towards increasing distances between residential and business districts.

Similarly, the technological cost curves used for ranking mitigation options depend heavily on the long-term marginal development cost of each technique, whose cost in turn depends on today 's decisions and on the context it will be used. It is possible to picture, within the next 40 years, an electric motor, a 2 l/100 km gasoline motor, and a biofuel motor produced at the same, or even at lower, costs than current motors, thanks to economies of scales and learning curves. But, given the high research and development costs involved in a new motor ^{xxxii}, nothing ensures that equivalent research and development risks will

be incurred on these three technologies and that it will be possible to have at $t+n$ three large-scale technologies competing on the same markets ^{xxxiii}.

A cost assessment analysis can be consequently meaningful only at the margin of each scenario, where each is the result from observed trends, technological facts, future expectations, willingness to defend one's view on a given technology, arbitrary beliefs, political choices and value judgements. For each of these points, the longer the time horizon, the more controversial are the hypotheses.

This context of decision under controversy^{xxxiv} does not imply that the economist is not in position to inject some objectivity into the discussions. But, departing from professional reflexes to maximize the predictive value of models, the economist must accept the fact that scientific controversies and disagreements on value or political judgments mean that several possible stories are plausible. But, for an economist, it will be obvious that the viability of each scenario is conditional upon its economic consistency at two levels, macroeconomic equilibrium and microeconomic behaviour. The task is to try to supply the appropriate tools for bridging the gap between economics, engineering and political sciences. In order to achieve this bridge, two research lines are likely to be fruitful.

First, a more systematic use of the properties of the general equilibrium concept can be helpful for describing the final picture of each set of expectations, as illustrated modestly in the above attempt ^{xxxv}: a set of economic hypotheses can be associated with each set of technical hypotheses, ensuring the economic consistency of the resulting scenario. The obligation to make the values of these economic parameters clear is enough to rule out the most inconsistent combinations. Moreover it becomes possible to take into account the feedback effects to be expected from the implementation of each set of hypotheses. In other words, the economist accepts that many parameters are exogenous and controversial but, once the consistency between the set of non-economic assumptions and the economic signals and flows is established, these relationships become endogenous. The economist is then in a position to give the de-

cision makers the logical implications of each set of assumptions, of each vision of the long term.

Second, some additional work is required to model technical trajectories, their response to the economic and non-economic signals, and their sociopolitical viability. This call for additional work on behavioural submodels adapted to each sector and technique ^{xxxvi} lies beyond the simple solution adopted here i.e. in a specific institutional background. For example, countering the intuitive idea of higher capital requirements for rail systems, some experts ^{xxxvii} point out that total investment is of the order of FF0.3/t km for trucks and 0.12 for rail if we include investments in vehicles. ^{xxxviii} But investments decisions are made by very different agents with different economic behaviour and it could be misleading to carry out any cost assessment of rail-road substitution without any simplified description of this behaviour.

III.3. About the no regrets concept

The debate on no regrets strategies, linked today to the "efficiency gap" controversy, must be broadened to encompass bifurcation issues. In that case we are not in a situation in which consumers are supposed to adopt suboptimal behaviour because of market imperfections or incomplete information. Theoretically a road dominant system, or a rail/canal dominant system, can be assumed to be without any slacks, moving at its efficiency maximum, and consumers can be assumed to be totally rational; but they are faced with either basket of goods and services, resulting from a long and cumulative process, and characterized by very different energy contents.

Manne and Richels are right to underline the risks of technological forcing involved in a mere engineering vision of energy efficiency: beyond market imperfections (which undoubtedly exist in the case of energy markets), seemingly irrational choices may take place, since consumers have a far more com-

plex objective function than the minimisation of energy costs. Here we have another type of technological forcing. In network industries and infrastructure activities, public intervention is always necessary, prior to the realization of technical projects (whatever this intervention may imply - investment outlays on infrastructure , funding, standards, building licences, laws etc); this will in fact determine, directly or not, the range of options (often a single one) at the disposal of consumers.

Since these public choices determine in the long run a good part of the energy path, embedded in transport and urban structures impossible to replace overnight, it is legitimate to question their underlying collective preference function. In France's freight system for example, the long-term shift from rail to road arises from the flexibility of road transport - the door to door service - but also from the underpriced infrastructure for trucks, and the risks of strikes in the railway sector. But, having experienced, last July, the ease with which the truck drivers' union was able to block traffic all over France, and faced with local protests against the extension of highways, the public authorities (broader than the national government) may be persuaded to introduce security and local environment as arguments of the collective preference curve and to review some components of the present incentive structure.

From that perspective, climatic risks must be discussed as a new argument of this function. The no-regret concept goes further than the mere accounting of the negative costs of improved energy efficiency of a specific equipment; it encompasses the fact that the abatement of greenhouse gases becomes a by-product of improvements on other dimensions of the collective preference function.

The research on no regret strategies should therefore be focussed on the core of actions where this byproduction of positive externalities is possible. In this core, a specific attention must be given to measures enabling economies to avoid bifurcation (1) leading to fossil fuel intensive development patterns and technological paths, and (2) and also likely to have long-term unexpected negative impacts on the social welfare.

CONCLUSION

As a conclusion, I would like to sketch here some ideas on the collaboration between energy and transport economists which has been proved to be necessary to address the key issues of the long-term development-environment analysis.

In the past two decades, energy economists have brought about a paradigmatic revolution: they focused on energy-growth decoupling and elaborated demand-side approaches to complement the supply-side optimization, studying the external determinants of end-use demand. It seems that this type of questions has not yet reached the core of transport economics which focuses on the difficult problem of the choice between means of transport and the optimization network infrastructures.

With the opportunity provided by climate change issues, energy modelling could play a provocative role asking, for the sake of its own models, about the long-term determinants of transport needs, simply because the projection of their current exponential growth would drastically reduce the chance of the success of preventative policies. Freight transport does not raise the most difficult theoretical problem; it can be solved on the one hand by a better understanding of the geographic trends of economic activity, on the other, by a study of incentive structures which are better able to reflect the external costs of this sector (congestion, security, infrastructure maintenance). The issue of individual transport (for work or leisure) is quite different because we are confronted by the risk of imposing undue normative constraints on the consumer.

Similar to the transition in the energy field from measures aimed at minimizing the cost- of a given tonne of oil equivalent or kilowatt hour to the cost-minimization of end-use energy as a whole, the first stake is to substitute the maximization of accessibility for the maximization of mobility as the key argument of the collective objective function in infrastructure policies: indeed, an increase in transport needs can either reflect an increase in welfare, or a

response to new, unexpected constraints, unfolding as a result of development patterns. The substitution between transportation and telecommunication is but a partial response, since the first trends observed in the 1980s indicate that the explosion of new telecommunication tools has increased geographical extension and the number of business contacts, which has induced higher rather than lower transport requirements.

That is why we cannot avoid a thorough description of constraints likely to enable us to discover possible long-term saturation effects which the current trends does not reflect. Given uncertainty about these constraints, the time budget of the citizen could provide us with a solid accounting system which captures the ultimate constraints on the demand for individual transport. There is a long way before any reliable result will be in sight on that issue. However, linked with economic balances and the energy balances, this accounting could be the most efficient way to connect three types of expertise and to understand better some of the ultimate development issues raised by climate concerns.

Bibliography

Arthur, B., "Competing technologies, increasing returns and lock-in by historical events". **Economic Journal**, 99, pp. 116-131.

(^{xxxix})Commission des Communautés Européennes, "CO2 Study, Crash Programme, Cost effectiveness analysis of CO2 reduction options, "Bottom-up" approach. Document de travail, oct. 1990

Giraud, P.N., "France - Energie 2010". **Futuribles**, juill.-août, 1991.

Godard, O., Hourcade, J.C., "Some instruments for collective management of climatic risks: an analysis focusing on the means for making a price signal appear". Intergovernmental Panel on Climatic Change (IPCC), "Seminar on Economic and Financial Measures", Paris, avr. 1990, 8 p.

Goldenberg, J., Johansson, T.B., Reddy, A.K.N., Williams, R.H., **Energy for a sustainable World**. World Resources Institute. Washington, DC, 1987.

Grubb, M., "Climate Change Policies: the CO₂ heresis". Forthcoming in the **Energy Journal**.

Hourcade, J.C., "France", in W. U. Chandler, ed., **Carbon emissions control strategies. Case studies in international cooperation**. Baltimore, World Wildlife Fund, 1990, pp. 129-153.

Hourcade, J.C., "Calcul économique et construction sociale des irréversibilités: leçons de l'histoire énergétique récente", in R. Boyer, B. Chavance, O. Godard, **Les figures de l'irréversibilité en économie**. Paris, Editions de l'EHESS, 1991, pp. 279-310.

Hourcade, J.C., Baron, R., "L'intérêt paradoxal de l'équilibre statique dans la modélisation des liens environnement - développement à long terme: illustration à partir du modèle IMACLIM". Communication au XXXIIe Colloque International **Modélisation des marchés internationaux de l'énergie**, Montpellier, 24-25 oct. 1991, 26 p.

Hourcade, J.C., Ben Chaabane, N., Baron, R., **Politique énergétique et effet de serre. Une esquisse des marges de manoeuvre à 2030**. Paris, CIRED, Rapport pour l'Atelier Prospective énergétique du Commissariat Général du Plan, 1991, 36 p.

Jorgenson, D.W., Landau, R., **Technology and Capital Formation**. MIT Press, Massachusetts, 1989, 525 p.

Lucas, R. E. "Econometric Policy Evaluation : A Critique" in K. Brunner, A. Meltzer (eds), **The Philips Curve and Labor Markets**, Carnegie - Rochester conference Series, vol. 1. Amsterdam, North Holland, pp. 19-46.

Manne, A., Richels, R.G., **Buying Greenhouse Insurance - the Economic Costs of COP2 emissions limits**. MIT Press, Stanford University, Jan. 1992.

Martin, Y., **Rapport au Premier ministre du groupe interministériel sur l'effet de serre**, nov. 1990.

(ⁱ) Williams, R.H., "Low cost strategies for coping with CO₂ emissions limits (a critique of "CO₂ emission limits: an economic cost analysis for the USA", in A. Manne, R. Richels, **The Energy Journal**, vol. 11, n° 4, **International association for energy economics**, 1990; and Manne, A., Ri.

chels, R.G., "Global CO₂ emission reductions, the impacts of rising energy costs", **The Energy Journal**, 1991.

(ⁱⁱ) *CGP Energie 2010*. Rapport du Groupe Pecqueur. Paris, La Documentation Française, févr. 1991.

(ⁱⁱⁱ) Nuclear energy is considered here as a carbon free energy, with a positive externalities as regards to the climate change. Concerns about nuclear risks will not be dealt with; they would require a more comprehensive study and to overcome the theoretical difficulties in assessing two types of major and non commensurable risks.

(^{iv}) Giraud, P.N., "France - Energie 2010". **Futuribles**, juill.-août, 1991

This perspective is similar to the aborted proposal of the EC. It remained exploratory and was never adopted officially at the political level.

(^v) Martin, Y., **Rapport au Premier ministre du groupe interministériel sur l'effet de serre**, nov. 1990.

(^{vi}) This perspective is similar to the aborted proposal of the EC. It remained exploratory and was never adopted officially at the political level.

(^{vii}) Godard, O., Hourcade, J.C., "Some instruments for collective management of climatic risks: an analysis focusing on the means for making a price signal appear". Intergovernmental Panel on Climatic Change (IPCC), "Seminar on Economic and Financial Measures", Paris, avr. 1990, 8 p.

(^{viii}) Hourcade, J.C., Baron, R., "L'intérêt paradoxal de l'équilibre statique dans la modélisation des liens environnement - développement à long terme: illustration à partir du modèle IMACLIM". Communication au XXXIIe Colloque International **Modélisation des marchés internationaux de l'énergie**, Montpellier, 24-25 oct. 1991, 26 p.

^{ix} M. Grubb, *Energy Policies and the Greenhouse Effect*, Vol 1, *Policy Appraisal*, Royal Institute of Foreign Affairs, Aldershot, 1990.

^x *COHERENCE: cost-effectiveness analysis of CO₂ reduction options, synthesis report*, CED DG XII report, 1991.

^{xi} Goldenberg, J., Johansson, T.B., Reddy, A.K.N., Williams, R.H., **Energy for a sustainable World**. World Resources Institute. Washington, DC, 1987.

^{xii} Manne, A., Richels, R.G., **Buying Greenhouse Insurance - the Economic Costs of COP2 emissions limits**. MIT Press, Stanford University, Jan. 1992.

(^{xiii}) For example the drastic decrease of the price of gasoline in the middle of the 1980s did not reverse the progress in average efficiency of motor cars during the preceding decade.

(^{xiv}) For the other segments, we worked with usual log-linear functions to income and prices

(^{xv}) In the case of energy efficiency, the long term saturation levels resulting from the reaction of the innovation process to drastic increases in energy prices can be changed if necessary.

^{xvi} In the same way, this makes it hard to explain the gap between the findings of Jorgenson (D.W.Jorgenson, 'Energy, prices and productivity growth', in S. Schurr, S. Sonenblum and D. Wood, eds, *Energy, Productivity and Economic Growth*, Oelgeschlager, Gunn and Hain, Boston, MA, 1983, pp 133-153) and Hogan-Jorgenson W.W. Hogan and D.W. Jorgenson, *Productivity Trends and the Cost of Reducing CO₂ Emissions*, Global Environmental Policy Project, Discussion Paper E-90-07, Harvard University, 1990) about the negative correlation between technology change and energy prices in the US economy (the same approach gives the same result for France (J.G. Devezeaux de Labergne, *Croissance économique et consommation d'énergie, essai d'approche économique et économétrique*, PhD thesis, University of Paris I, 1986) and the observation of acceleration of innovations at a technical level; in fact the slowing of productivity growth is correlated with many more factors than mere

technology (excess capacity resorption, growing uncertainties, monetary instability etc).

(^{xvii}) In a quite different context Lucas (R.E. Lucas, ‘Econometric policy evaluation: a critique’, in K. Brunner and A.Meltzer, eds, *The Phillips Curve and Labor Markets*, Carnegie-Rochester Conference Series, Vol 1, Amsterdam, North Holland, 1976, pp 19-46) has demonstrated the importance of this problem and the fact that, to date, econometrics fails to solve it.

(^{xviii}) This tax is applied not as a shock disturbing a given equilibrium in 2030, but is applied today in order to switch towards another stabilized growth path.

(^{xix}) ME is for *maîtrise de l'énergie*, literally energy mastership, a concept whose origin lies at the name of a state agency: Agence Française pour la Maîtrise de l'Energie

^{xx} Toronto Conference on the Changing Atmosphere, Implications for Global Security (27-30 June 1988) recommended a 20% reduction in each country up to 2005 and a 50% reduction up to 2050.

(^{xxi}) This use is about 3% of France's total energy demand in 1988.

(^{xxii}) 20% in the residential and commercial sectors (wood, urban and agricultural wastes, solar heating, geothermal energy), 10% in the industry (combined cycle, waste, and use for biomass as a chemical feedstock), 5% of biofuels for motors.

(^{xxiii}) Under the assumption that, in 2030 the problems with the use of the high efficiency lamps have been overcome and their costs lowered thanks to economies of scale and learning process.

^{xxiv} R. Kalaydjian, *Evolution des consommations énergétiques des ménages de l'industrie sur la période 1970-1988*, Study for AFME (Agence Française pour la Maîtrise de l'Energie), September, 1990.

(^{xxv}) These industrial scenarios were built by BIPE, Bureau d'Information et de Prospective Economique

(^{xxvi}) Computed under the assumption that all other OECD countries adopt a similar tax policy.

(^{xxvii}) These results are of the same order of magnitude as most of the assessment studies for OECD countries (2% in Manne and Richels (op cit, Ref 1, 1991) for the European Countries).

^{xxviii} For example, see D.W. Jorgenson and R. Landau, *Technology and Capital Formation*, MIT Press, Massachusetts, 1989.

^{xxix} Arthur, B., "Competing technologies, increasing returns and lock-in by historical events". **Economic Journal**, 99, pp. 116-131.

^{xxx} The USA could pass a bifurcation point if the target zero emission vehicles mandated as 10% of the 2003 market in California is respected: with the first, say, 5% of the market taken by a carbon intensive vehicle (standard electric) or a carbon free one, the ultimate technological paths could be totally different, with an important impact on long-run US emissions: Hourcade, J.C., Ben Chaabane, N., Baron, R., **Politique énergétique et effet de serre. Une esquisse des marges de manoeuvre à 2030**. Paris, CIREN, Rapport pour l'Atelier Prospective énergétique du Commissariat Général du Plan, 1991, 36 p.

(^{xxxi}) Since the works on the "sunspot theory" (C. Azeriadis and R. Guesnerie? 'Sunspots and cycles', Review of Economic Studies, Vol 53, 1986, pp 725-737), the plurality of equilibria induced by different sets of expectations leading to self-fulfilling processes has been demonstrated in other fields of economic research than the economics of technology.

(^{xxxii}) In past history, it is noticeable that only one technological path received the main of the R and D efforts, ensuring the dominance of the four-stroke engine on the two-stroke engine, and that the promising rotary motor failed because it did not succeed in attracting innovation efforts during sufficient period of time. See J.P. Bardon, J.J. Chanaron, P. Fridenson and J.M. Laux, *The Automobile Revolution: The Impact of an Industry*, University of North Carolina Press, Chapel Hill, NC, 1982.

(^{xxxiii}) except obviously for some specific markets for electrical vehicles.

^{xxxiv} O. Godard, 'Social decision-making under scientific controversies: a descriptive model of the conventional construction of global environmental risks

as economic stakes, and some consequences for the choice of a policy-mix', Communication for *Autumn Workshop in Environmental Economics, Managing the International Commons*, Venice, September-October 1991.

(^{xxxv}) An extended version of this approach is developed in *NEXUS: cadre générique pour une modélisation des liens énergie, développement, environnement*, CIRED 1992, forthcoming.

(^{xxxvi}) This behavioural perspective is adopted by J. Edmonds, 'Long term modelling of the links between economics, technical progress and environment: evolution of approaches and new trends', Communication et Séminaire du PRISTE – CNRS et du Programme ECLAT du Ministère de l'Environnement, *Modélisation prospective, critères de décision et négociation internationale d'un développement durable : le cas des risques climatiques*, Paris, 28 October 1992

(^{xxxvii}) We are indebted to J.P. Orfeuil, research director at the Institut National de Recherche sur les transports (Paris), for this point.

(^{xxxviii}) This gap is mainly due to the relative densities of the two networks, but it remains that the aggregate investment of the two transport systems are comparable.

(^{xxxix}) This perspective is similar to the aborted proposal of the E.E.C. It remained exploratory and was never shouldered officially at the political level.