ENERGY TECHNOLOGIES AND SUSTAINABILITY: INSIGHT FROM MARKAL/TIMES BOTTOM-UP PARTIAL EQUILIBRIUM MODELS

TECHNOLOGIES DE L'ENERGIE ET DURABILITE: COMPREHENSION APPROFONDIE PAR DES MODELES D'EQUILIBRE ECONOMIQUE PARTIELS MARKAL/TIMES

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1. Introduction

Introduction

Present energy systems appear far from sustainable, at least until a transition reduces both emissions harmful to the local, regional and global environment and the dependence on concentrated energy resources. In the last two decades the former problem has been more central in the policy-making process than the latter. In fact, energy security is not less important. After the 1973 oil embargo, energy security was the topic of several studies, although not directly linked to sustainability. Energy economists tried to identify potential risks deriving from supply disruptions and assess their economic impacts. Policy analysts discussed advantages and disadvantages of a variety of actions intended to ensure energy supply security or to reduce the negative effects of disruptions.

Participants in the Energy Technology Systems Analysis Programme of the International Energy Agency (IEA/ETSAP) have for nearly 30 years now analysed sustainability problems from the energy system point of view. Their constant aim has been to quantify costs and benefits of possible actions under different assumptions and in diversified circumstances[1]. Hundreds of technical economic models of global, regional, national and local energy systems and their long-term development have been built with this purpose by means of the MARKAL/TIMES model generators.

This paper discusses the link between energy security and the more general sustainability concept. After a short summary of ETSAP evolution (Section 2) and methodologies (Section 3), the paper presents a security concept extended to a system-wide perspective including technologies (Section 4) and assesses the economic value of a more secure energy system in order to frame possible budget allocations to reduce energy security risks (Section 5). It then exemplifies quantitative assessments of energy technology options and actions which could reduce dependence (Section 6): more energy efficient end use devices, new technologies with learning potential and processes to transform coal into energy carriers with CO_2 sequestration. The conclusive remarks stress the potential advantage offered by a renewed commitment to energy R&D (Section 7).

2. Sustainability from an energy system perspective

Durabilité du point de vue d'une analyse de système

The goal of energy system analysts making use of ETSAP tools is to provide decision-makers with robust quantitative assessments of costs and benefits of each suggested or new policy action. While it is clear that all evaluations depend on the actual technical economic evaluation of energy markets and technologies, it is worth clarifying how strongly the results are influenced by the boundary of the systems, the options included and the weight of different policy objectives. In the nearly 30-year history of ETSAP, there has been a continuous evolution in terms of the analysis. Topics of studies and enhancements of ETSAP analytical tools reflected relevant energy and environmental issues. They included energy security analysis, optimal technology choices, environmental analysis of criteria pollutants, mitigation studies of criteria pollutants, analysis of flexible mechanisms in reducing carbon emissions and studying the role of technology learning in meeting multiple objectives. A brief description of these activities follows.

After the first oil embargo, the objective was to identify a new chain of technologies to satisfy the same demand for energy services by means of more secure primary energy supplies and to assess their cost. The starting tool has been the analysis of the technological content of energy balances across nations with static tools (1976-7). The natural evolution has been to use a pseudo-dynamic tool for scenario analyses[2]. Starting from energy systems existing at the time of the first embargo, studies were made of the possibility of ensuring a smooth transition to less vulnerable systems by investing in energy RD&D. In the early eighties the IEA suggested guidelines for national and cooperative energy RD&D programs and priorities to OECD governments, based upon energy technologies dynamic cost benefit analyses carried out by ETSAP [1].

In the following period, when oil prices started to decline, the analysis was revisited in order to assess the robustness of new technologies ranking under different price and demand development assumptions. The problem was to assess the range of demand and price conditions under which the transition to a new energy technology mix would still be profitable. The answers stressed the need of long time periods and of putting the highest effort in energy efficiency improvements, particularly in end-use devices [2].

When concerns about the effects of acid depositions became greater than those for oil embargos, the group switched to analyse the potential and costs for reducing emissions from the energy system of acid rain precursors. It was found that reduction potentials were generally high and possible in the short-medium term, because several technologies existed for preventing the formation of pollutants or for their abatement [3].

Local and regional pollution problems were then associated to the issue of global climate changes. The problem was then to assess possible synergies and conflicts between pollution reduction and climate change mitigation policies, together with the assessment of CO_2 emissions reduction potentials and costs. The initial assessments were far less positive than for emissions of acid rain precursors: potentials were small and achievable only in very long time-frames because abatement options were not examined [4].

Afterwards the group included in the analysis of mitigation policies the concern of fossil fuel suppliers and at the same time evaluated technical solutions for energy systems and the macro-economic effects of emissions reduction policies that went far beyond the direct costs. This required the development of new analytical capabilities and the transformation of a least cost model into a partial/general equilibrium model[3]. The average evaluation of costs (something less than one percent GDP loss in 2050) and potentials (one percent CO_2 emission reduction per year till 2050) were much diversified across countries [5].

In the following years (1996-98) the analyses extended to multi-regional models in order to assess interferences and synergies of international market mechanisms with domestic mitigation policies intended to foster a technological transition of energy systems. As expected, the studies concluded that the flexible mechanisms in the short-term bring economic as well as mitigation advantages to both sellers and buyers of emissions, because existing efficient supply technologies are deployed to replace obsolete ones. However, longer-term solutions are not affected significantly [6].

More recently the global market mechanisms in the model have been extended to include the choice between existing technologies, competitive in the short-term and new technologies that might become competitive in the long-term if their markets would become big enough to trigger 'learning' and 'experience' processes observed so frequently with new technologies in the past (endogenous technology learning models). The problem is to evaluate potential economic benefits for developers and users – depending on learning rations and international spill overs. If it is assumed that some of these technologies are capable of solving the main problems – security of a growing demand for energy services, climate change, local and regional pollution – at the same time, then governments may evaluate the possibility of advancing the costs of technology learning. Analyses are rather surprising, because negligible variations of the global utility imply divergent technological developments and policies [7].

3. Methods and tools to assess sustainable technologies

Méthodes pour l'évaluation des technologies durables

The objective of ETSAP is to assist decision-makers to assess new energy technologies and policies in order to meet the challenges of energy needs, environmental concerns and economic development. ETSAP's strategy in achieving the objectives is twofold. Through a common research programme, ETSAP establishes, maintains and enhances the flexibility of consistent multi-country energy/economy/environment analytical tools and capability (the MARKAL family of models[4]). ETSAP members also assist and support government officials and decision-makers by applying these tools for energy technology assessment and analyses of other energy and environment related policy issues.

It is a great advantage to analyse a global market such as energy with a 'global' tool, developed by an independent international agreement and used by several groups of different countries to analyse from different perspectives and points of view the same global market. Since the IEA approved the shared goals (1993), ETSAP has increased the capabilities of its tools in order to model free and open energy markets, where the impact of long-term energy security and environmental protection policies can be evaluated. The original bottom-up engineering least cost modelling tools have been merged with bottom-up economic approaches to provide full computable economic equilibrium tools, with explicit treatment of hundreds of energy technologies.

The first strong point is the group itself because it includes representatives of different countries, from independent research agencies and with different backgrounds. So far they have always maintained internally diversified points of view, although using the same quantitative methodology. Although using the same tools, similar assumptions can result in different conclusions due to the different national circumstances and constraints.

The second strong point is that participants carry out quantitative energy environment sustainability analyses with the same analytical tools, which quantify costs and benefits of energy security from a systems analysis point of view simultaneously. The same tool allows the exploration of solutions near the economic equilibrium and to calculate trade-offs with different policy objectives, as illustrated later. While the advantages of this approach in terms of environmental sustainability have been clarified often [6, 7], it is deemed important to make explicit here the less obvious advantages of using the same tool to quantify energy security problems and possible solutions.

4. Systems analysis approach to energy security

La sécurité énergétique du point de vue de l'analyse de système

The world total primary energy supply exceeds 10 billion tonnes oil equivalent in the last few years [9]. The share of oil decreased from 44 percent in 1973 to 33 percent in 2001, the share of natural gas increased from 15 percent to 20 percent in the same period. The international oil trade accounts for about 55 percent of the total yearly oil consumption. The market value of primary energy supply is in the order of 1.5 T$US2004. The market value of final energy purchased by economic producers and consumers is three to four times larger, reaching the order of 10 of 12 percent of GDP: six to seven percent paid by families to purchase household and transportation services, the rest appearing as intermediate expenditures of economic producers in industry and services.

Why then does this situation generate large security concerns? The supply of food and drink, which for human beings seems an economic sector more vital than energy, raises much lower security concerns. Seemingly, energy security problems stem from the centralised nature of energy systems: relatively few locations and companies supply oil and gas, infrastructure for electricity and fuels are largely centralised. The flexibility, distribution and variety of food and drinks chains are something unknown in the energy sector. Clearly, concentration of major suppliers in a few locations creates security concerns. In addition, the ability of energy markets in processing correctly information on production, consumption, and stocks also creates uncertainties. For a consuming country, diversification of sources of supply and increase of the use of different forms of energy can reduce the impacts of sudden changes in supply and prices.

In traditional analyses, energy security is dominated by concerns about oil imports, either by sudden physical reductions of flows or sudden price fluctuations. From an energy system point of view, however, this restricted frame has to be extended to include the markets for all energy commodities – from the crude oil in the reservoir or coal in the mine to the passenger kilometres or the warm water demanded by end users – as well as to all facilities and capital goods that transform one form of energy into another or into the energy services demanded by end users. This extended concept is a more powerful tool to identify different types of threats to energy security.

In this framework, the security of energy services is a concept much wider than securing the smooth behaviour of the global crude or natural gas markets[5]. What matters is the security of supplying the economic producers with the energy service necessary to maximise their profits, and the final consumers – families and community systems – with the energy service that maximises their utility. Further to the security of primary energy supplies, this requires the security of the technological chain that transforms primary supplies into energy services. Energy importing countries commonly discuss the problems of securing the constant and unrestricted supply of primary energy vectors at affordable prices. Technology importing countries sometimes face the problem of securing unrestricted imports of new energy technologies at affordable prices.

The major risk mentioned in the literature is the physical disruption of oil and gas supplies in general and imports in particular. Physical disruptions of primary supply are caused not only by wars or local instabilities from political unrest, but also by concomitant accidents, social problems in one or more supply countries and perturbations to international trades. The risk grows with the increasing share of oil and gas in the total primary energy supply of the country and with the dependence on imports. The economic impact associated to this risk gives a measure of the vulnerability of the national energy-economy system.

The second and more commonly felt threat to energy security is the sudden fluctuation of energy prices, sometimes referred to as price volatility[6]. This second risk has an economic relevance similar to the first one, when prices grow significantly. But it includes the discussion of consequences of price volatility without significant long-term average changes. Price volatility stems from several important structural weaknesses of energy systems. The first reason is the huge physical and economic dimension of the market, which is mostly global, with ramifications in all aspects of our daily life, and temporally continuous. The problem is caused by the narrow margins of the order of few percent points in terms of production capacity and fuel switching capabilities in the short-medium term. In other words the rigidity of the system exposes it to extreme price fluctuations.

Other risks are linked to the technical complexity of the energy chain. Most of us have experienced supply disruptions due to failures of the transportation or distribution network, mainly electricity, at the regional level, but also natural gas at the national level and at the local level also district heating. The risk is not negligible because different networks have to be interlinked, operational margins are narrow and demand has to be matched instantly with supply. And in fact the highest economic damages we have incurred in recent years were due to electricity blackouts.

Additional risks of energy service disruptions are caused by environmental problems. In several large cities private traffic is banned when the air pollution level caused by fuel combustion reaches levels dangerous for human health. Also plants and factories are sometimes obliged to change their operational schedule to avoid harmful emissions under special weather conditions.

It seems difficult to transfer those concepts into operational and quantifiable measures of energy systems security. At most some indicators are used, such as energy intensity of the GDP, total primary energy supply per person, percent dependence on energy imports, and in particular on oil and oil imports[7].

5. Evaluating the benefits of energy security

Avantages économique de la sécurité énergétique

It remains difficult to understand why after 30 years such a huge risk remains. Some actions have been taken so far, in single countries and sectors. But in general the action is inadequate to reduce security risks in the energy sector, which are growing so steadily and so much. The demand for energy services has grown continuously in the last two centuries, due to the increase of population (factor 6), life expectancy (factor 2) and income (factor 70); as a result the demand for mobility has increased by a factor of one thousand [10]. The demand for final and primary energy has grown much less: for instance, in the last 30 years the energy intensity of 11 OECD economies has reduced to 70 percent [11].

The first and fundamental point of view to be discussed is whether the system has to be left alone to an uncontrolled development (only the laws of the ‘market’, which is short-sighted by definition) or it is thought appropriate to plan a transition in common, anticipating long-term problems. Most analysts do not view the market as providing sufficient signals to address the problem of the disruption of energy service supply due to whatever type of reason [12]. It is recognised that oil imports have hidden costs on the economy that are not reflected in the market price of oil or in the private decisions regarding the use of oil instead of alternatives. Other known externalities are created by oil use in the form of environmental costs [13]. The security dimensions of energy supply have always been viewed as appropriate concerns of the government. Controversy appears about the degree of control to be exerted in the system and even more on the precise actions to be taken.

Several specialists have debated the issue of economic costs of insecure energy systems[8]. The major extra cost related to oil import stems from the monopoly of producing countries and, to some extent, of supply companies. To ensure the amount of oil necessary to satisfy the present global energy system, consumers presently pay for oil a unit price much higher than marginal production costs. The present oil prices of US$30 to 35 (2004) per barrel have to be compared to the present marginal production costs, which range between US$5 and 15 (2004) per barrel. This unit difference implies excess global outlays of the order of 0.5 TUS$2004 just for oil, equivalent to 1.5 percent of the global GDP.

Lower dependence would reduce several other externalities. Among the indirect cost of oil imports, specialists have mentioned economic costs deriving from depreciation of the national currency, inflation and military expenditures in the oil production regions. Also the debate on the macroeconomic effects of energy price shocks, both internalised and externalised, is still open: several experts have attributed to them the economic recessions experienced globally after 1973 and 1980. Although the specialists are still debating on the details, the majority of researchers give positive values to these costs. The GDP losses associated to the 1973 and 1980 oil crises have been measured in some percentage points.

The purchase of final energy absorbs six to seven percent of families' budgets. However, private consumers devote a much higher share of their budget to satisfy their demand for energy services. When the purchase and maintenance of end use devices and other capital goods necessary to transform the final energy into energy services is also included the expenditure amounts to 20 to 30 percent. Furthermore the willingness of final consumers to pay for energy services is even higher, because there is the clear perception that energy services are a basic component of quality and duration of life. It has to be remembered that in some countries consumers pay a price five times larger than the equivalent market price of oil for automotive fuels, without showing any sign of leaving automobiles in their garages.

An analytical framework such as the MARKAL model could compare the costs and benefits of alternative technology scenarios in meeting a fixed level of energy services. In the near term, the trade-off between reduced use of imported oil would be compared with the possible higher cost of energy services provided by alternative energy sources. In the long run, the benefits of alternative technology mixes would incorporate the benefits of technology learning. A system approach allows an analyst study of social costs and social benefits of different energy policies in achieving more diversified sources of energy supply and a level of energy security that is acceptable to decision-makers. The benefits of early adoption of new technologies can also be assessed in cases where supply of oil and gas become scarcer.

6. Technological options for sustainability

Options technologies durables

The initial exercises of cost-oil import trade-offs gave insight in terms of technological options [14]. The average discounted cost (over 45 years) of displacing permanently a barrel of oil through new technologies was US$25 to 30 (2004) per barrel, with variations from one to 100 dollars across countries. First on the list were primary energy supply technologies – enhanced oil and gas recovery, development of unconventional oil and gas resources – followed by more efficient end use devices in residential and transportation, then cogeneration in industry, electric power plants from nuclear and renewable sources and eventually coal liquefaction processes[9]. The most stringent policies, accepting the highest extra costs, had the effect of reducing oil imports of the 15 participating countries to one-third of 1980 levels, which was about 1.1 btoe per year.

After improving the characterisation of energy technologies – hundreds of them are explicitly represented in present models – and of the different energy markets, after switching from least cost to equilibrium models where different policy objectives are represented at the same time, analyses are more robust and scenarios are more flexible to the objectives. For instance, scenarios to 2050 for UK and Germany, find the possibility to reduce oil dependence and CO_2 emissions to about 30 percent of present values with a cumulative GDP penalty in 2050 of the order of 1.5 percent in UK and 0.6 to zero in Germany [15][10]. Three sets of technologies, which have been evaluated through energy technology systems analysis tools, exemplify hereafter the potential of technological options to trigger a transition to a new system.

6.1 Energy efficient devices

Appareil à haut niveau d'efficacité énergétique

Most energy analysts using technical economic models have experienced what may be called the 'paradox of the statistical year'. It happens that calculated equilibrium quantities and prices are far different from the statistical values and calculate a solution more competitive than the actual one. It most often happens that the competitive equilibrium model would prefer to choose a set of existing end use technologies much more efficient than the actual one. To adjust solution values to statistics, as necessary before looking for equilibrium projections, it is customary to increase the interest rate of private energy consumers in the residential and transport sectors far above the value of the national real discount rate, to reach values of 30 percent or more.

Without entering into the polemics of the possible energy efficiency gain factors that existing end use devices might bring to the global energy system without economic losses (factor two, four or even 10), every serious path towards more efficient end use devices improves the utility of the economic system[11]. A recent exercise carried out to evaluate the possibility of increasing 'white certificates' obligations in Italy above the threshold established by present regulations, brought positive conclusions, because such obligations are a way to overcome behavioural barriers [17]. These policies can reduce primary energy supplies and CO_2 emissions by a few percentage points, while increasing the GDP by a few thousandth of a percentage. Although effective in the short-term, this policy is promising also in the medium and long-term, because there seems to be scope for improving the energy efficiency through the use of new technologies for decades.

Throughout the years and the national circumstances, whatever assumptions are made on energy prices, demand developments, model time horizon[12], discount rates, energy efficient end use devices are always used more in the models than in the actual systems [1-7]. Particularly when the methodology is used to model large developing countries such as China and India, there seems to be no other way to satisfy a demand for energy service growing at a pace similar to GDP (four to five times in 40 years) without disrupting global oil and gas markets and financial markets to enable investments.

Several other analysts have asserted that an energy efficiency gap exists between actual and optimal energy use [18]. Without entering into the details of different notions of optimality[13], the actual gap can be explained through existing market and non-market failures, which explain why energy efficient technologies diffuse too slowly. Most market failures relate to inefficient and ineffective information. Non-market failures relate to uncertainties, inertia and undesired non-energy attributes, i.e. to insufficient communication of information.

6.2 New technologies with high 'learning' potential

Nouvelles technologie susceptible d'un haut niveau d'amélioration

On the supply side, there seems to be little scope for change. Business-as-usual projections show an absolute increase of global primary energy supply (a factor of two in 40 years) and little shifts among different fuels. This results most of the time from extrapolation prepared with econometric models whose parameters are estimated from historical data[14]. The picture changes when technologies are described one-by-one and their technical characteristic explicitly included in the models.

In fact technology learning in hydrocarbon exploration techniques has improved enormously the success ratio of oil and gas drilling, achieving a considerable reduction in overall production costs. If appropriate investments are made available to other energy technologies and just some of them continue to improve with a progress rate similar to the past until they achieve their full market potential, energy systems might experience the transition hoped for by most analysts [6, 7].

Since 1999, researchers of the ETSAP community, following other modellers, have developed their modelling tools to calculate cost and benefits of technologies with endogenous technology learning [19]. This analysis is not limited to the benefits for the country where scientific breakthroughs are achieved, but spreads to global markets. The most promising technologies identified so far are (their progress ratio is in brackets[15]): solar photovoltaic (0.81), gas fuel cells (0.82), wind (0.9), gas combined cycle (0.9), advanced coal (0.94), new nuclear (0.96). Electric supply system scenarios calculated by models including endogenous technology learning show results completely divergent from the non-learning case at the same cumulative discounted global system costs. By taking into account the expected technological progress, the same demand is satisfied in 2050 with negligible use of fossils fuels and CO_2 emissions [20].

The most important message of these model experiments is that the present energy supply systems, relying on century-old concepts, has the possibility to change. The transition needs appropriate investments, but not necessarily net additional costs. It reaches several objectives: in the field of security it reduces the need of fossils fuels, from the environmental point of view it reduces all forms of regional pollution and global climate change and from the system point of view it may trigger the transition to less centralised networks. In this sense, potential progress in some key supply technologies has to be supplemented by a transition of the system of infrastructures. More importantly, this type of analysis indicates the way to follow in order to avoid the risk of cutting the energy system out of technological progress (sometimes addressed as ‘technology lock-in’).

6.3 Coal transformation processes and new management of energy intensive materials
Processus de transformation du charbon, meilleur aménagement des matériaux a haute consommation énergétique

System analysis studies indicate further technological options and policies useful to increase security and reduce pollution.

One example is the set of technologies that transform coal into final energy carriers – electricity, process and district heat, liquid fuels and gas including hydrogen. R&D in coal transformation technologies started decades ago and received further attention after the two oil embargos. Although tens of processes have been developed and experimented, nowadays they are considered less important in pursuing energy security. Their competitiveness is linked to technological progress, to the availability of cheap coal and to the willingness to pay the resulting energy carriers more than their production cost with insecure fuels, but less than the amount final consumers pay now. Their development seems particularly important in countries such as China and India, where the oil and gas import bill to some extent would hinder economic growth, and worldwide to reduce strains in global oil and gas markets, which could create large security problems to all countries.

Therefore coal can continue to be the most important primary energy resource in countries endowed with this resource. However, to reduce local and regional environmental impacts and the contribution to global climate changes, coal use must rely on centralised gasification and liquefaction technologies, where particulate, acid deposition precursors and CO_2 can be removed and sequestered [21]. Liquid fuels from coal reduce the global pressure on oil markets, because they also can be used as a feedstock for several chemical industries.

In this same direction, systems analyses of the energy system extended to energy intensive materials has shown that oil imports and CO_2 emissions can be reduced by about 10 percent without scientific or technical breakthroughs by starting from alternative raw materials and managing in an energy conscious way the manufacturing chain [5, 6, 7].

7. Policy conclusion

Conclusions

From an energy security point of view, different analysts have suggested different governmental actions. So far most policy suggestions refer to actions to be taken in order to tackle the security of oil and gas imports. For instance, a recent analysis identifies four major themes relevant to the US energy security in the 21st century: new ways to manage growing dependence on oil imports (rather than aiming at achieving energy independence[16]), the need to diversify the geographic origin of energy, of pursuing a diversified fuel mix, and more energy efficiency. But the discussion concentrates on the first two, and argues that interdependence rather than independence is the cornerstone of contemporary oil security and warns that technology cannot make up for declining resources [22].

According to another less recent analysis, the problem of energy security is dealt with in the US by three main policies: improve the stability of the Persian Gulf region, establish government owned and controlled strategic oil stocks and establish a coordinated international response procedure. The main criticism to these policies is that they do not address the basic problem of oil price instability and dwindling energy reserves and they merely bolster the ability to respond to temporary disruptions once they have occurred, without reducing reliance on insecure oil supplies [23].

Sporadic attention has been devoted so far to proposals addressing energy security problems from the technology system point of view, which offer at the same time solutions to more general sustainability problems. Energy conservation and renewable sources, flexible energy system and fuel switching capabilities, are judged not sufficient to increase energy security in the US in the 1990s without a prior comprehensive solution of oil supply security [23]. The analysis summarised in this paper points to several additional and maybe more effective governmental actions[17].

The most appropriate answer to sustainability including energy security seems to be the development of a large variety of technologies, without which relevant energy mix changes appear unlikely. However, the allocation of resources to R&D in new energy technologies seems largely insufficient. Out of a total world R&D budget of about US$600 billion, the amount devoted to energy has remained stable in the last decade at about US$10 billion. While the present total R&D effort is about 1.5 to two percent of the global GDP and an increase to three percent is sought from many, the energy R&D is only about 0.3 percent of the value of the energy system. This percentage is not higher in industry. The international industry in software and IT, health, pharmaceuticals spend in R&D more than 10 percent of their sales, oil and gas industries less than one percent, as is the case for the beverages and tobacco industries. Only 1.5 percent of the venture capital investments in 1998 – nearly US$40 billion – has been used by energy industries [24].

Since the time necessary to trigger a transition from the present energy system, the design of which is basically a century old, to a new sustainable system appears very long, governments of knowledge producing countries are expected to finance large R&D programmes [12][18]. This goal also requires major contributions from those new science fields, which recently experienced huge progress and could inject new concepts into the energy sector. To be commensurate to the problem, energy R&D programs are expected to remain at the physiological level of three percent for decades, i.e. time scales similar to the lifetime of energy infrastructures[19].

Waiting for a transition, fast deployments of the most energy efficient end-use devices may reduce the weight of the problem. However, since market forces have not been able to reduce the ‘energy efficiency gap’ and energy supply companies will never contradict their core business and propose to their clients to consume less energy goods, the main responsibility for energy efficiency policies may be shifted to companies and markets that provide more energy efficient devices.

The success of both policies is heavily linked to non-energy sectors and factors [25]. A sign of political will to trigger a transition towards sustainability could be to attribute the responsibility of energy security and environment problems to the offices and groups that have to bear the costs of insecurity and pollution, instead of leaving the responsibility to the groups that profit from maintaining the status quo.

8. Endnotes

Notes

* Opinions expressed by the authors do not necessarily reflect the position of the related organisations.

1. Since 1976 many OECD countries – Austria, Australia, Belgium, Canada, Denmark, EC, Finland, Germany, Greece, Ireland, Italy, Japan, Korea, Netherlands, Norway, Spain, Sweden, Switzerland, Turkey, the UK and the US – have cooperated to make available to analysts across the world the MARKAL/TIMES methodology, a flexible tool that generates partial and general equilibrium expansion models of the most different energy systems (see: <www.etsap.org>).

2. Since none of the existing models was flexible enough to model different countries at the same time, the group developed the MARKAL model generator.

3. The non-linear MARKAL-MACRO general equilibrium version has been developed. Shortly afterward the partial equilibrium versions have been developed: the non-linear MARKAL-MICRO and the linearised MARKAL-ED. Both versions include taxes/subsidies; some versions include the treatment of stochastic events and damage functions. The extension of the MARKAL methodology used in this study combines with the energy model built with MARKAL the long-term macroeconomic growth model called MACRO, to provide a dynamic, neoclassical, applied general equilibrium model. The linkage between MARKAL and MACRO is based upon the concept of an economy-wide production function. The integrated model, which simultaneously solves energy and economic components using non-linear optimisation, is able to analyse separately price-induced energy conservation and autonomous energy efficiency improvements.

4. MARKAL is not a model, but a generator of economic equilibrium programming models of energy systems and their time development. Contrary to most economic equilibrium models, supply/demand curves of commodities are not represented by means of analytic functions with econometrically estimated parameters, but are specified by stepwise linearised functions. Each step refers to a different technology providing/consuming the commodity. The minimum and maximum length of each step (quantity) is imposed by the market potential of each input/output technology and fuel. The height of each step (cost) depends on the costs (investment, fixed O&M, variable O&M) of each input/output technology and fuel. Actual equilibrium cost of each step is the sum of costs incurred in primary extraction, transformation, transmission, distribution, including taxes and subsidies, taking into account the efficiencies of all intermediate technologies. Since technologies and values are interlinked, the actual supply/demand curves are fully resolved only in the solution. The construction of such stepwise supply/demand curves for each commodity represented in the model is made possible through the Reference Energy System approach. The entire energy system is represented by a graph, where each branch is an energy flow or material and each knot is a technology. In full-scale models each fuel appearing in detailed energy balances is represented by a separate flow, sometimes more than one if different environmental characteristics have to be accounted for. Each supply/demand technology is characterised by technical economic and environmental parameters, together with the graphical indication of the input commodities/output services. When the supply/demand curves are specified as linear stepwise functions, the equilibrium model is formulated as a mathematical program [8]. A Linear/Non Linear Program (LP/NLP) turns out to build equilibrium models when the Objective Function (OBJ) specifies the total surplus (partial equilibrium) or the utility (general equilibrium) of the system. The equilibrium over time is maintained through a substitution mechanism of one energy source/technology with a cheaper one.

5. The present analysis is restricted to the average security of large energy systems, such as national or regional ones; the analysis of energy service security from the national average to the local levels requires a different approach, which is not discussed here.

6. Since this analysis focuses on structural problems, the link of price volatility to financial markets is not discussed here.

7. A simple measure of supply security is given by the percent of endogenous supply: risks start when imports rise over 30 percent. In this sense several countries and regional aggregations (such as the EU) are at risk now and increasingly so in the future. There is no simple measure of energy service security. The first important indicator is the flexibility of the system, measured in terms of percentage of energy service that can be satisfied with more than one energy supply source; it is sometimes called fuel-switching capability. A second static indicator is the degree of dependence from a single source. A third indicator may be the reserve factors of the system. Also the reliability of energy services is useful.

8. A summary of discussion is reported in [13]

9. Thirty-one technologies were aggregated in four priority levels. 1 – Enhanced oil recovery, enhanced gas recovery, tar sands and oil shale for production; advanced converter nuclear reactors, alternative transport fuels, breeder reactors, coal liquefaction for conversion; conservation in automotive transport systems and in building equipment, industrial conservation, residential and commercial solar water heating for end uses; coal mining and environment-protecting technologies, nuclear reactor safety and fuel cycles for key supporting technologies. 2 – Geothermal, combined cycles, fuels from biomass and HCV gasification. 3 – Electric automobiles, geo-pressurised methane, wing power. 4 – Hot dry rocks, solar electric, ocean power, fuel cells, LCV gasification, MHD, hydrogen, underground coal gasification. Suggested actions were: exploratory R&D, pilot scale testing, demonstration and commercialisation, according to the technology.

10. Several authors have demonstrated the existence of synergies among different energy policy objectives (for a recent evaluation related to energy security and climate changes, see for instance [16].

11. Even taking into account all due rebound effects [5].

12. Other options, such as emission trades, are less robust: in short-term models they are chosen, but less in the long-term, where early investments in new technologies are preferred, because they ensure long-term advantages.

13. The economists' economic potential, the technologists' economic potential, hypothetical potentials, the narrow social optimum and the true social optimum [18].

14. It is quite frequently the case where energy system are judged rigid, because the model by which they are represented and that are used to produce scenarios are rigid and do not take into account new options.

15. The progress ratio is the coefficient by which investment costs have to be multiplied at every doubling of the market.

16. At a distance of 12 years a view completely different from the US Energy Independence bill is proposed.

17. Different supply mixes in different countries satisfy the same demand for energy services. It means that the same energy security problems have different solutions from a technology system perspective, although the present options are not sufficient so far.

18. Although coal-producing countries are expected to promote the development of coal specific technologies, all countries should participate actively, because all would benefit from diversification. Investments in R&D would allow knowledge production countries, which may be soon losing the present monopsony position in energy goods market, to maintain a leading role at least in the energy technologies market.

19. It seems appropriate that government maintain the main responsibility for investments in energy infrastructures, as it happens now for roads and other public goods. In fact adding to the existing system flexibility and reserve capacity, which are contrary to whatever market principle, enhances energy security.

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