IIASA

Long-Term Energy Futures: The Critical Role of Technology

Arnulf Grübler

RR-00-02
March 2000

REPRINT
RESEARCH
REPORT

Long-Term Energy Futures: The Critical Role of Technology

Arnulf Grübler
International Institute for Applied Systems Analysis, Laxenburg, Austria

RR-00-02
March 2000

Reprinted from *Revue de l'Énergie*, **508**:373–384, 1999.

International Institute for Applied Systems Analysis • Schlossplatz 1 • A-2361 Laxenburg • Austria
Tel: (+43 2236) 807 • Fax: (+43 2236) 71313 • E-mail: publications@iiasa.ac.at • Web: www.iiasa.ac.at

Reprinted with permissin from *Revue de l'Énergie*, **508**:373–384, 1999.

LONG-TERM ENERGY FUTURES : THE CRITICAL ROLE OF TECHNOLOGY

BY ARNULF GRÜBLER (1)
International Institute for Applied Systems Analysis. Laxenburg, Austria

The paper briefly reviews the results of a 5-year study conducted by IIASA jointly with the World Energy Council (WEC) on long-term energy perspectives. After summarizing the study's main findings, the paper addresses the crucial role of technological change in the evolution of long-term energy futures and in responding to key long-term uncertainties in the domains of energy demand growth, economics, as well as environmental protection. Based on most recent empirical and methodological findings, long-term dynamics of technological change portray a number of distinct features that need to be taken account of in technology and energy policy. First, success of innovation efforts and ultimate outcomes of technological change are uncertain. Second, new, improved technologies are not a free good, but require continued dedicated efforts. Third, technological knowledge (as resulting from R&D and accumulation of experience, i.e. technological learning) exhibits characteristics of (uncertain) increasing returns. Forth, due to innovation - diffusion lags, technological interdependence, and infrastructure needs (network externalities), rates of change in large-scale energy systems are necessarily slow. This implies acting sooner rather than later as a contingency policy to respond to long-term social, economic and environmental uncertainties, most notably possible climate change. Rather than picking technological « winners » the results of the IIASA-WEC scenario studies are seen most appropriate to guide technology and R&D portfolio analysis. Nonetheless, robust persistent patterns of technological change invariably occur across all scenarios. Examples of promising groups of technologies are given. The crucial importance of meeting long-term energy demand in developing countries, assuring large-scale infrastructure investments, maintaining a strong and diversified R&D portfolio, as well as to devise new institutional mechanisms for technology development and diffusion for instance through the flexibility and Clean Development mechanisms of the Kyoto Protocol are highlighted. The paper concludes with some methodological lessons to capture the essence of above outlined characteristics of technological change in energy models and long-term scenarios.

I. — INTRODUCTION

This paper summarizes a five-year study on long-term global and regional energy perspectives conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) reported in detail in Nakicenovic et al. (1998). A distinguishing feature of the study arising from its long-term (2050 and beyond) time horizon is that technological change emerges as a key determinant of long-term energy systems development. Resulting uncertainties are explored through a scenario approach highlighting the critical role of near – to medium-term R&D and investment decisions into resource extraction, conversion, and end-use technologies in yielding alternative outcomes in terms of future resource availability, energy supply structures as well as environmental impacts.

(1) Environmentally Compatible Energy Strategies Project, IIASA, A-2361 Laxenburg, Austria. E-mail : gruebler@iiasa.ac.at

An abridged version of this paper is presented at the IAEE/AEE Conference « Technological Progress and the Energy Challenges » September 30 - October 1, 1999, Paris. Unless specified otherwise all graphical material presented in this paper is from Nakicenovic et al., 1998. Further details on the studies results are also available directly through the internet (see Appendix E in Nakicenovic et al., 1998, for details).

Section 2 gives an overview of the scenarios developed in the IIASA-WEC study and summarizes its main conclusions. Section 3 briefly reviews theoretical and empirical aspects of technological change and how they were incorporated into the scenarios. Section 4 discusses patterns of technological change and resulting innovation opportunities that emerge from the IIASA-WEC scenario study. Section 5 concludes, highlighting policy implications in particular in the domains of R&D and niche market development (and their combination into RD&D, i.e. research, development *and* demonstration efforts) and technology portfolio diversification strategies. In essence, the picture that emerges is that the long-term future of the global energy system is largely *technologically constructed.* Generic areas of technology innovation and diffusion opportunities can be identified. But at the same time, the dangers of « forgetting by not doing » and of prematurely picking « winners » (that may turn out as « losers » later on) lurk large.

II. — AN OVERVIEW OF THE IIASA-WEC SCENARIOS

The joint IIASA-WEC study developed three alternative cases of economic development that are further subdivided into six scenarios of the long-term evolution of the global energy system. The principal focus for all cases is on the period up to 2050, but results are also presented to 2100. In brief, Case A presents a future of impressive technological improvements and consequent high economic growth. Case B describes a future with less ambitious, though perhaps more realistic, technological improvements, and consequently more intermediate economic growth. Case C presents a « rich and green » future. It includes both substantial technological progress and unprecedented international cooperation, including major resource transfers from North to South, centered explicitly on environmental protection and international equity. Key characteristics of the three cases are summarized in Table 1.

TABLE 1 - Summary of the three cases in 2050 and 2100 compared with 1990

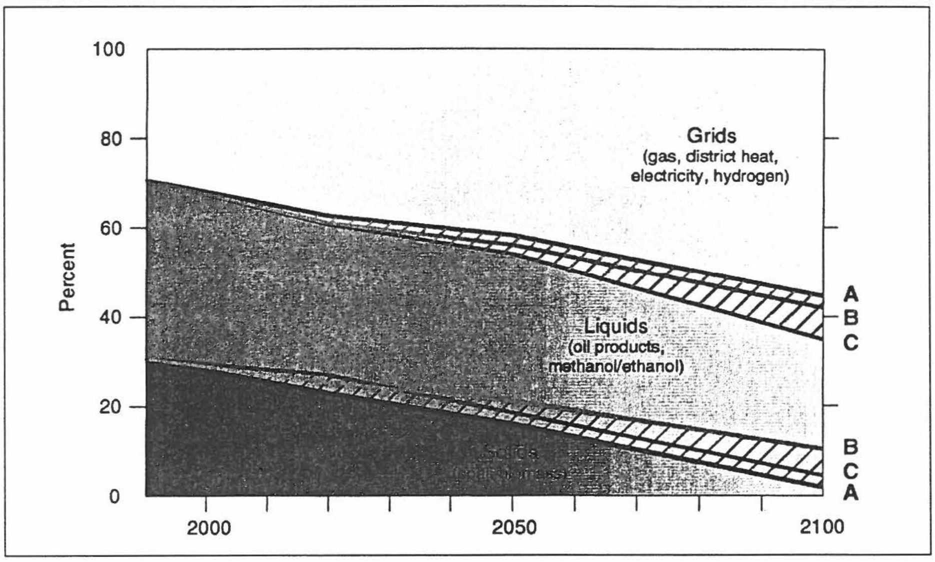
	Case		
	A High growth	B Middle course	C Ecologically driven
Population, billion			
1990	5.3	5.3	5.3
2050	10.1	10.1	10.1
2100	11.7	11.7	11.7
GWP, trillion US (1990) $			
1990	20	20	20
2050	100	75	75
2100	300	200	220
Global primary energy intensity improvement, percent per year	Medium	Low	High
1990 to 2050	-0.9	-0.8	-1.4
1990 to 2100	-1.0	-0.8	-1.4
Primary energy demand, Gtoe			
1990	9	9	9
2050	25	20	14
2100	45	35	21
Resource availability			
Fossil	High	Medium	Low
Non-fossil	High	Medium	High
Technology costs			
Fossil	Low	Medium	High
Non-fossil	Low	Medium	Low
Technology dynamics			
Fossil	High	Medium	Medium
Non-fossil	High	Medium	High
Environmental taxes	No	No	Yes
CO_2 emission constraint	No	No	Yes
Net carbon emissions, GtC			
1990	6	6	6
2050	9-15	10	5
2100	6-20	11	2
Number of scenarios	3	1	2

Abbreviations : GWP = gross world product ; Gtoe = gigatons oil equivalent ; CO_2 = carbon dioxide ; GtC = gigatons of carbon

The key message from the long-term scenario exercise is that it is easier to anticipate the forms in which energy will be demanded by consumers in the future than to estimate the absolute level of energy demand, or which energy sources will supply that demand. With increasing per capita incomes around the world, people will demand higher levels of more efficient, cleaner, and socially and environmentally less obtrusive energy services. Thus, one can see reasonably well the direction in which energy consumers are headed : high quality fuels, especially grid-dependent energy carriers are growing in importance, irrespective of the inherent uncertainties involved in projecting future levels of income and energy demand (see Table 1). Thus, there is little variation in terms of the structure of final energy across the three Cases and their six Scenarios explored in the IIASA-WEC study (see Figure 1). That message is robust across a wide range of energy (supply) futures – from a tremendous expansion of coal production to strict limits, from a phaseout of nuclear energy to a substantial increase, from carbon emissions in 2100 that are only one-third of today's levels to increase by more than a factor of three. Yet, for all the variation explored, all alternatives manage to match the expected demand pull for more flexible, more convenient, and cleaner forms of energy. The odds are thus good that consumers will indeed get what they want – flexibility, convenience, and cleanliness. Who their suppliers will be, which energy sources will be tapped, which infrastructural and technological means will be deployed emerges as main uncertainty of the future. Yet, it is a different kind of uncertainty : it is not exogenous to energy and technology policy and to resulting investment decisions, but rather being a matter of deliberate *choice*.

Another robust finding of the IIASA-WEC scenario study is that a major geopolitical energy shift towards the « South » is underway. Irrespective of the uncertainty in future levels of energy demand, future energy markets, including that of energy supply and end-use technologies move progressively to the currently developing countries. This raises the critical question of the international diffusion of new and advanced energy supply and end-use technologies. Historically technological knowledge and innovation capability (both in terms of supply « push » as well as demand « pull », i.e. R&D resources and market potentials), have resided mostly in the industrialized countries of the « North », and many decades will pass, before developing countries can build up comparable technological knowledge capital.

FIGURE 1 - World final energy by from : solids, liquids, grids (in percent)



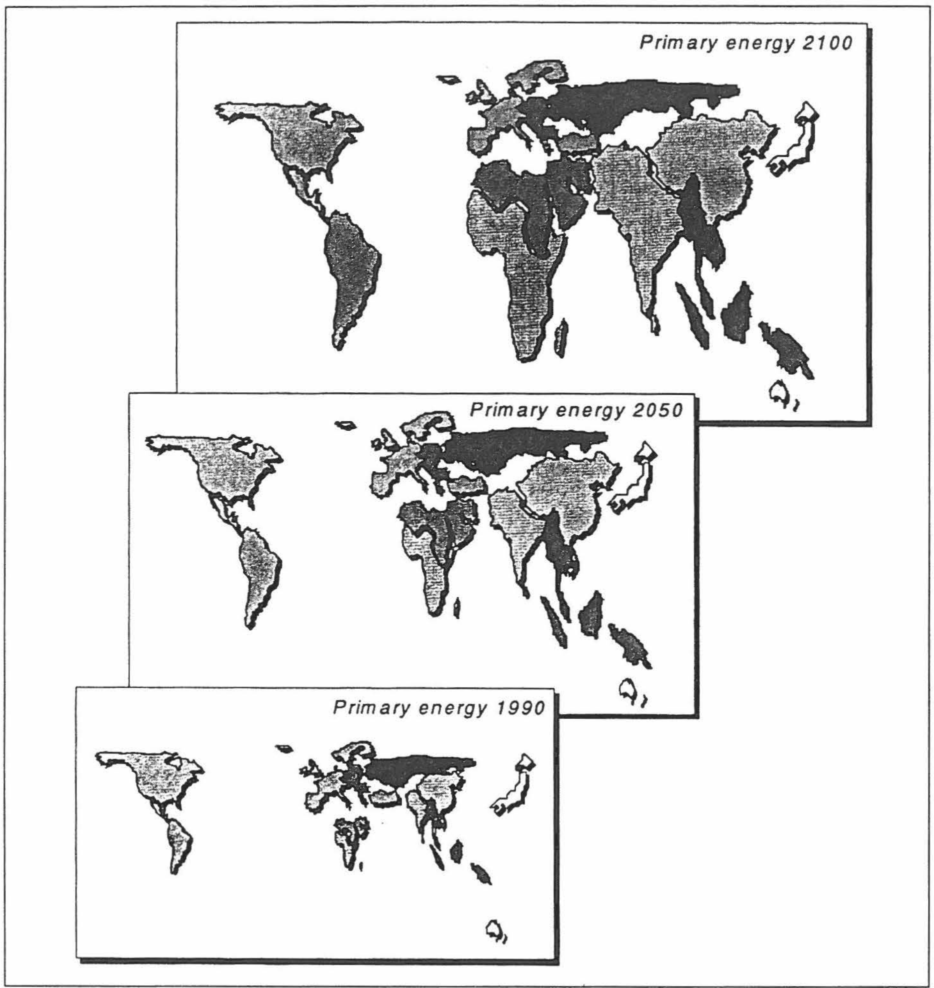
Levels of future energy demand projected in the IIASA-WEC study are different across scenarios. Rates of economic growth, structural change, technological developments, and (environmental) policies are the four most important long run determinants of energy demand. (Energy prices are an important determinant for the short – to medium term. In the long-term however, technology and policy are more important determinants, although important feedback mechanisms, e.g. in form of induced technical change exist.) As a result, future levels of energy demand can vary widely, even for otherwise similar scenario characteristics in terms of population and level of economic development. The study expects a 1.5 to 3-fold increase in global energy needs by 2050, and a 2 – to 5 – fold increase by 2100 (see Table 1 above).

Current developing countries at present account for about one third of global primary energy use, while accounting for three quarters of global population. Over the long-term, the IIASA-WEC scenarios indicate a dramatic shift. By 2050, developing countries account for between 57 to 67 percent of global energy use, a share that could increase to well over 80 percent towards the end of the 21st century.

The changing geography of global energy use is illustrated in Figure 2 for Case B, the scenario of the IIASA-WEC study that deploys the most conservative assumptions concerning pace and level of development « catch up » of the developing countries. In Figure 2, the size of individual world regions are rescaled in proportion to their 1990 primary energy use. As a result of the inequitable access to energy services, levels of energy use in the populous developing regions are comparatively small compared to the affluent industrialized countries of the « North » (compare for instance the respective energy sizes of Japan with that of the Sub-Indian and African continents in Figure 2). Over the long-term (2050 and beyond) however, current energy imbalances gradually are reduced and the « energy map » of the planet starts to resemble the geographical maps we are all familiar with.

Ever since the classical studies of Tinbergen (1942) and Solow (1957) it is widely recognized that technological change drives productivity growth and economic development. Across all scenarios the role of technological progress is therefore critical, both

FIGURE 2 - The changing geography of primary energy use, Case B 1990, 2050, and 2100
Areas of world regions are proportional to 1990 levels of primary energy use



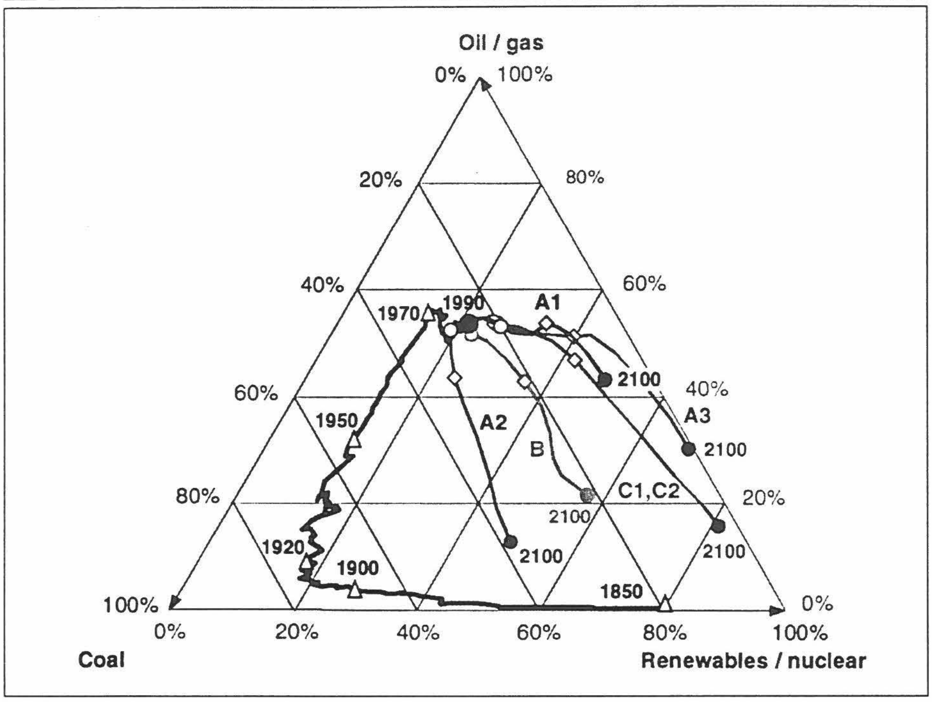
at the level of the economy at large as well as at the level of the energy sector. According to the findings of the IIASA-WEC study, it is the RD&D investments of the next few decades that will shape the technology options available after 2020. These near – to medium – term choices will determine which technology options will become available for widespread diffusion in the 21st century, and which options will be foreclosed due to a lack of anticipatory innovation and investment efforts. In essence, the study finds that future energy systems are *technologically constructed.*

A significant finding of the IIASA-WEC study is therefore that there is a wide range of supply structures that can successfully match the persistent final energy trends depicted in Figure 1. Long-term global energy futures are no longer seen as geologically preordained. The imminent resource scarcity as perceived in the 1970s did not materialize. With continued exploration efforts and continued technological progress, accessible and affordable reserves have increased and this trend will continue to at least 2020. However, after 2020 all scenarios move away from their current reliance on conventional oil and gas. However, very different resource and technological options can be drawn upon to meet the drive to cleaner energy demanded by ever more affluent consumers worldwide. These are matters of choice : near-term R&D and investment decisions will drive the long-term evolution of the global energy system into alternative, largely mutually exclusive directions. In the words of systems science : future developments of the energy sector portray features of *path dependency* (see e.g. Arthur, 1983 and 1989). This puts additional importance on near-term actions that can initiate long-term changes with technology and infrastructure investments being the most prominent examples.

The possible long-term divergence of energy supply structures is illustrated in Figure 3. Each corner of the triangle in Figure 3 corresponds to a hypothetical situation in which all primary energy is supplied by a single source : oil and gas at the top, coal on the left, and non-fossil sources (renewables and nuclear) on the right. In 1990 their respective shares were 53 percent for oil and gas (measured against the grid lines with percentages shown on the right), 24 percent for coal (measured against the grid lines with percentages on the left), and 23 percent for non-fossil energy sources (measured against the grid lines with percentages at the bottom). Historically, the primary energy structure has evolved clockwise in two « grand transitions » (black line in Figure 3) : traditional renewables were replaced by coal between 1850 and 1920. Coal reached its maximum market share shortly before 1920 and was then progressively replaced by oil and natural gas between 1920 and 1970. Since then, structural change in the global primary energy mix has been comparatively modest.

Because of the long lifetimes of power plants, refineries, and other energy investments, there is not enough capital stock turnover in the scenarios prior to 2020 to allow them to diverge significantly. But the seeds of the post – 2020 divergence in the structure of energy systems will have been widely sown by then based on RD&D efforts, intervening investments, and technology diffusion strategies. It is these decisions between now and 2020 that will determine which of the diverging post – 2020 development paths will materialize. The transition away from oil and gas progresses relatively slowly in Scenario A1

FIGURE 3 - Evolution of world primary energy structure : shares of oil/gas, coal, and renewables/nuclear. Historical development 1950-1990 (triangles) and scenarios to 2020 (open circles), 2050 (diamonds) and 2100 (closed circles). For explanation see text.



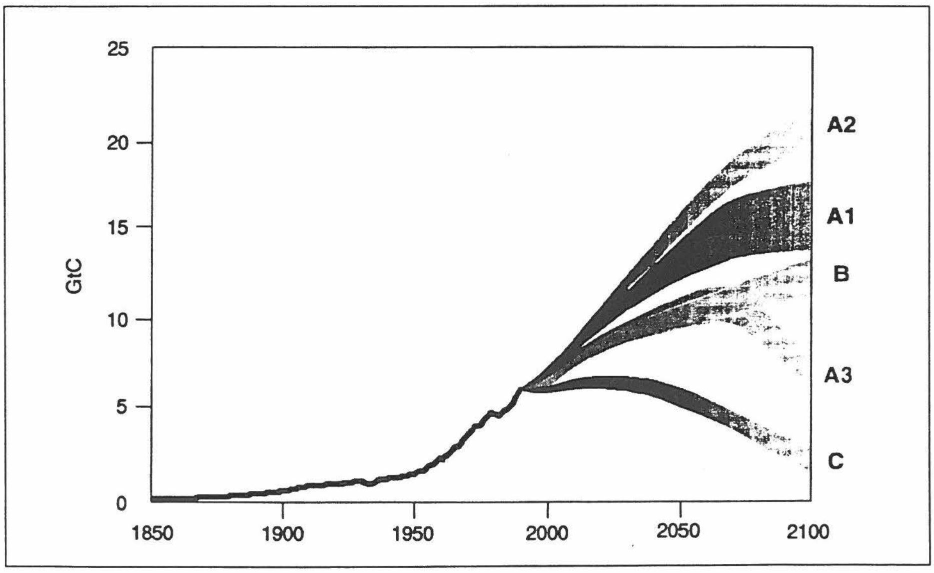
where oil and gas are assumed to be plentiful as a result of technological progress in recovery and economics of unconventional oil and gas resources. In Scenario A3 and Case C, it progresses more rapidly due to faster technological progress in post-fossil technologies (« bio-nuc » Scenario A3) or because energy and environmental policies favor the development of non-fossil alternatives and energy conservation (Case C). In these cases the global energy system could come almost full circle by the end of the 21st century. As in 1850 at the beginning of the Industrial Revolution, it relies predominantly on non-fossil energy forms, but these are high-technology renewables and advanced nuclear power rather than the traditional biomass fuels used 250 years earlier. In Scenario A2 and Case B, the transition away from conventional oil and gas includes an important contribution from coal, whose long-term market share after 2050 ranges between 20 and 40 percent. Nonetheless, little of this coal is used directly. Instead, it is converted to the high-quality energy carriers (electricity, liquids, and gases) demanded by the high-income consumers of the second half of the 21st century.

For each of the six scenarios, the level of energy use and the structure of energy supply, as summarized above (Table 1 and Figure 3), determine future carbon emissions. Figure 4 shows the results in terms of both gross and net carbon emissions from fossil fuels (2).

As shown in Figure 4, gross and net energy-related carbon emissions vary substantially among the scenarios. The range of emissions is particularly large in the three Case A scenarios. In Scenario A1, they reach 14 GtC (net) per year in 2100, and in the

(2) One of the (many) methodological refinements represented by the IIASA-WEC scenarios is an improved accounting of energy-related carbon emissions differentiating between « gross » and « net » emissions (for a discussion see Grübler and Nakicenovic, 1996). « Gross » fossil carbon emissions in a given year include all CO_2 associated with fossil energy resources extracted and used in that year irrespective of the conversion process chosen and whether the CO_2 is really emitted to the atmosphere. Conversely, « net » fossil carbon emissions refer to CO_2 released immediately to the atmosphere through burning fossil fuels. Net emissions are calculated by deducting CO_2 associated with non-energy purposes (feedstocks) and CO_2 that is « scrubbed » during electricity generation and synthetic fuel production and subsequently stored permanently (e.g., in depleted gas fields), as occurs in Case C, or that is sequestered through reinjection for enhanced oil recovery (as occurs already at present in the USA, and happens on a large scale in Scenario A1).

FIGURE 4 - Global carbon emissions from fossil fuel use, 1850 to 1990, and for scenarios to 2100 (inGtC). For each scenario, the range shows the difference between gross and net emissions (see text for explanation)



coal-intensive Scenario A2, they reach 20 GtC per year. In the « bio-nuc » Scenario A3, as a result of significant structural change in energy supply, they come to only 6 GtC per year, roughly the level of emissions today. The difference is that energy consumption in Scenario A3 in 2100 is five times greater than in 1990, with approximately the same level of emissions. Case B's emissions are very close to those of Scenario A3 up to about 2050 but then increase to nearly twice the Scenario A3 level by 2100. The two Case C scenarios as a result of climate policies stabilize global emissions at 1990 levels by the mid-21st century in order to reach emission levels of some 2 GtC by 2100. As such, only the Case C scenarios describe a long-term emission path leading to stabilization of atmospheric CO_2 concentrations at some 450 ppmv by the end of the 21st century. Scenario A3 also could reach stabilization at 550 ppmv towards the middle of the 22nd century assuming a continuation of its downward sloping emission trend after 2100.

It should be emphasized that emissions in the six scenarios are in most cases below levels of typical « baseline » or « business-as-usual » scenarios developed within the climate community. Only in Scenario A2 are cumulative (1990 to 2100) carbon emissions above those in the IPCC's IS92a reference scenario (Pepper et al., 1992). The generally lower emissions in the scenarios presented here are due to technological dynamics in the energy sector that are incorporated when the analysis is done in greater technological detail. From this perspective, typical baseline scenarios appear more as contrived, special cases than as potentially likely outcomes. They combine optimism about high economic growth with general pessimism about technological change and resource availability, except for coal production. The IIASA-WEC study concludes that the scenarios describe more consistent possible futures. They match high economic growth with technological changes that enlarge the resource base (particularly in the case of clean conventional oil and gas), that improve alternative energy supply sources, and that permit structural changes toward clean energy carriers. As such, the widely differing CO_2 emissions depicted by the IIASA-WEC scenarios perhaps illustrate best the powers of technological change in lessening or amplifying humanity's ecological « footprint » on the planet. This raises anew the question of a better understanding of the mechanisms and patterns of technological change before ultimately venturing to design policies to influence it in a particular, e.g. ecologically more benign, direction.

III. — INSIDE THE « BLACK BOX » OF TECHNOLOGY

A review of the literature (e.g. Freeman, 1994) and historical, empirical observations (e.g. Grübler, 1998) suggest the following simplified taxonomy of most salient characteristics of technological change as : *dynamic, cumulative, systemic,* and *uncertain.* Their consideration enables to begin to open the « black box » (Rosenberg, 1982) of technology. A brief summary is given below how above major characteristics of technological change were incorporated into the IIASA-WEC scenarios.

Foremost it is important to emphasize that the IIASA-WEC study – contrary to most (short-term) energy studies – treats technological change as inherently *dynamic.* This results both from the long time horizon adopted as well as recent methodological advances achieved at IIASA. These include the large energy technology inventory CO2DB (Messner and Strubegger, 1991) that enables a statistical representation of technological uncertainties (Strubegger and Reitgruber, 1995) as well as novel mathematical and algorithmic approaches in the modeling of endogenous technological change (for a review see Grübler et al., 1999). Adopting a Schumpeterian (1934) perspective, the technology life cycle is conceptualized as consisting of four successive phases : *invention* (discovery of principal feasibility of a new solution), *innovation* (first establishment of an organized market), *niche market* applications, and in case all earlier stages prove successful, potential for pervasive *diffusion.* Recognizing the considerable time lags involved, energy options that are not technically feasible today (i.e. have even not reached their invention stage) are excluded in the study. Nuclear fusion, for example, is excluded, while hydrogen is included as an energy carrier because it can be produced with current technologies, although not yet at competitive costs. New and emerging technologies were also kept as generic as possible in the study, both out of modeling economy as well as to avoid the trap of prematurely picking winners. With exception of mature technologies (e.g. conventional steam-cycle coal fired power plants) *all* technologies are treated as dynamic, with rates and direction of technological change adopted being *scenario specific.*

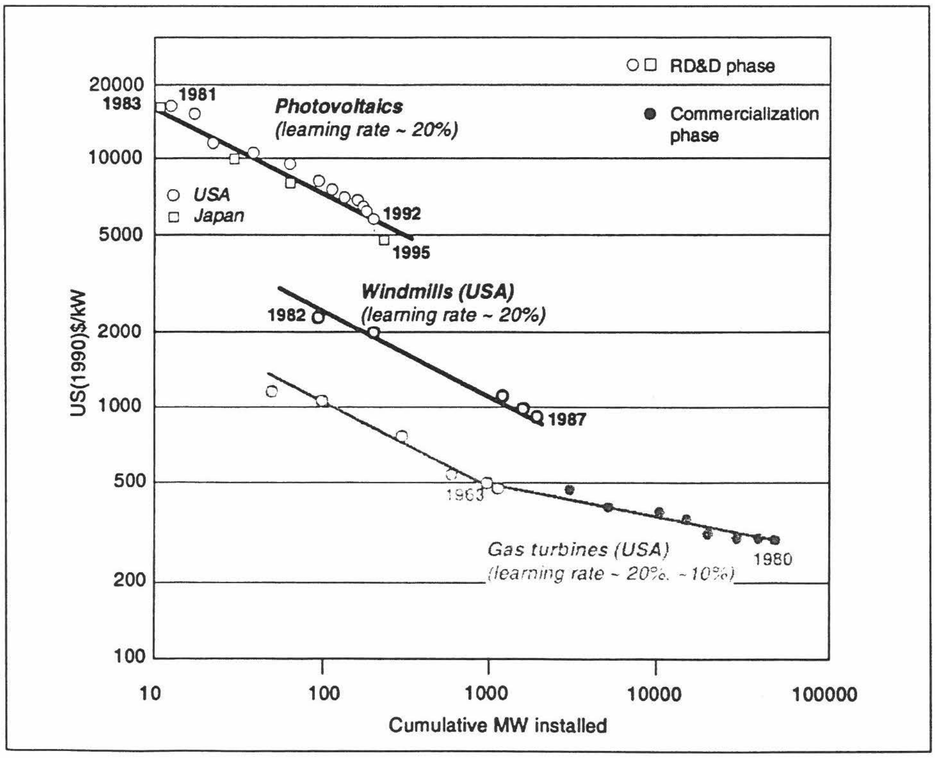
Secondly, the scenarios reflect the *cumulative* nature of technological change. A new technological artifact, like a new biological species, is seldom designed from « scratch ». New technology is deeply rooted in the experience and knowledge gained by designing its predecessors. Technological knowledge is thus largely cumulative (subject however to knowledge depreciation discussed below). Knowledge as applied in production also exhibits cumulativeness : initial defects become progressively eliminated as production volumes progress, costs fall, model varieties and regional product differentiations are introduced, etc. In short, cumulativeness implies the possibility of *increasing returns.* The most popular example in the technological literature being manufacturing « learning » or « experience » curves (Argote and Epple, 1990, Christiansson, 1995, Goldemberg, 1996, Neij, 1997) as illustrated in Figure 5. In essence, the scenarios of the IIASA-WEC study emphasize that improved technology does not come as a free good. It requires continued dedicated efforts and investments into both the disembodied (R&D) and embodied (new plant and equipment) aspects of technology.

It is important also to recall that whilst technological knowledge is cumulative, it also depreciates if not applied (or applied in a « stop and go » fashion). To paraphrase Rosegger (1996) : the corollary of « learning-by-doing » (Arrow, 1962) is « forgetting-by-not-doing » as empirical examples from the aircraft (Epple et al., 1996, Michina, 1999) and energy industries (e.g. Watanabe 1995 on solar PVs, and Cohn, 1997 on nuclear reactors) demonstrate.

In each scenario of the IIASA-WEC study, technological change reflects the scenario's distinctive choices, leading to an increasing divergence of development paths among the six scenarios. Both the high-growth Case A and the ecologically driven Case C contain multiple scenario branches within a single pattern of overall development. In each case, the difference between branches leading to different directions of technological change is path dependent ; early investments and initial steps in one direction reduce the costs and obstacles of continuing in that direction. The performance and competitiveness of future technologies, and indeed the path that the global and regional energy systems take, is thus shaped by RD&D choices and early investments in new technologies and infrastructures. Future development depends on the path of technological learning, experimentation, and cumulative experience taken in each scenario. In each, the future becomes increasingly locked into a particular technological development paradigm – some are resource intensive, some are environmentally benign.

No technology is an island, as depending on numerous other technologies both up- and downstream and especially on infrastructures. The IIASA-WEC study considered the systemic aspects of technological change, or *technological interrelatedness*, through a systematic exploration of the most important technology linkages in the energy sector. This was done using the detailed, bottom-up energy systems model MESSAGE III, developed at IIASA (Messner and Strubegger, 1995). As a result, the study identified in particular important infrastructural bottlenecks as of critical importance such as the need to develop extensive gas and electricity infrastructures in the rapidly growing coal economies of Asia (see also Nakicenovic, 1998). The study also argued that such long-term infrastructure investments that aim to avoid technological « lock-in » in carbon and sulfur intensive energy systems should be prime candidates for targeted investment under the flexibility and Clean Development Mechanisms of the Kyoto Protocol.

FIGURE 5 - Technology learning curves : improvement of investment costs ($/kW) as a function of accumulated experience (cumulative MW installed)



Due to innovation – diffusion lags, technological interdependence, and infrastructure needs (network externalities), rates of change in large-scale energy systems are necessarily slow. This implies acting sooner rather than later as a contingency policy to respond to long-term social, economic and environmental uncertainties (Grübler and Messner, 1998).

Finally, the IIASA-WEC study considered *technological uncertainty* (Rosenberg, 1996) through a scenario approach. A novel approach was adopted in which all available technology data were pooled into a single data bank, the CO2 DB technology inventory containing some 1,600 technologies. These data were then analyzed statistically to obtain empirical measures of representative ranges of cost variations of current and future energy technologies (Strubegger and Reitgruber, 1995). Near-term technology costs assumed for the three cases were derived from the medians of the empirical cost distributions. Lower ranges from the statistical frequency distributions defined the scope for future cost reductions that occur at different rates in the three cases (optimistic in Cases A and C, and more cautious in Case B). At the time of performing the modeling work underlying the IIASA-WEC study, methodologies and models were insufficiently developed to deal with the large scale computational problems (11 regions, 11 time steps, and treatment of hundreds of different technologies) involved in the endogenous treatment of technological change and uncertainty. (In the meantime, algorithmic and computational limitations have been largely overcome, cf. Gritsevskyi and Ermoliev, 1999.) Thus, uncertain future technology improvements were considered in the IIASA-WEC study primarily via varying exogenous technology assumptions. An iterative modeling procedure was applied to assure consistency between a scenario's technology dynamics and the underlying investment and diffusion profiles (see Grübler et al., 1999), consistent with the conceptual model of technological learning curves outlined above. As a result, all scenarios display features of short-term anticipatory investments into technological innovation and gradually expanding niche market applications of technologies that have considerable long-term market potentials. The scenarios also aim to minimize depreciation of technological knowledge, i.e. « forgetting-by-not-doing », in the short-term for options that are of strategic importance in the long-term. This aspect of the scenarios is perhaps the one in most stark contrast to customary short-term to medium-term energy studies (e.g. IEA, 1998). It is also the area where the scenarios differ most from the current dominant business ideology, emphasizing short-term profits and investments into mergers and acquisitions, rather than the build up of long-term strategic options and investments into technological innovation.

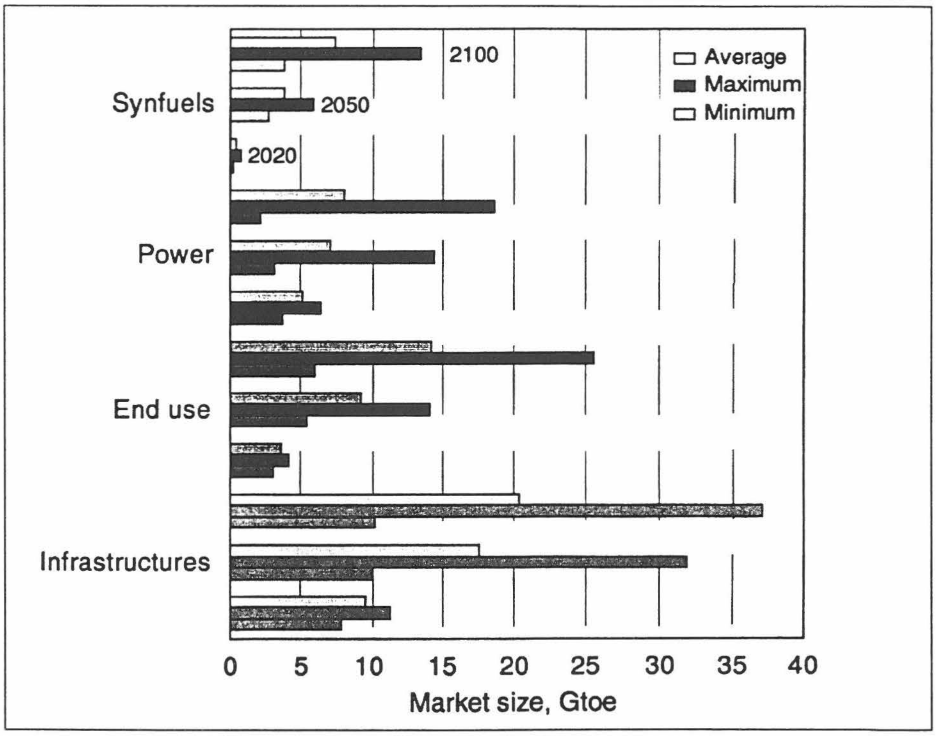
IV. — ENERGY TECHNOLOGIES IN THE 21ST CENTURY

Innovation and technology diffusion require that both opportunities are perceived and that the entrepreneurial spirit exists to pursue them. Long-term scenarios cannot forecast future technological « winners », but they can indicate areas of technological opportunity. Figure 6 illustrates for 2020, 2050, and 2100 the global market potential in the IIASA-WEC scenarios for four classes of energy technologies : new end-use energy devices (e.g. PVs, fuel cells, heat pumps), power plants, synfuel production (from biomass, coal, and natural gas), and energy transport, transmission, and distribution infrastructures. For each of the four classes, the minimum, maximum, and average market potential for the six scenarios are shown. (Greater technological detail is shown in Figure 8).

Across the wide variation in possible energy developments depicted in the six scenarios, the importance of energy infrastructures grows persistently. Even in the low-demand scenarios of Case C, energy infrastructures deliver at least 10 Gtoe per year by 2050. By the end of the century they average 20 Gtoe per year across all six scenarios, reaching close to 40 Gtoe per year in the highest scenarios.

Infrastructures are the backbone of the energy system, and the IIASA-WEC study indicates that requirements for new infrastructures will be vast indeed. Urban and rural poor need to get connected to energy grids in order to have access to modern energy services. New decentralized energy options can help to reduce costs in rural areas, but currently high costs need to be brought down through R&D efforts as well as stepped-up experience gained in niche market applications. Improved interconnections of energy grids for natural gas and electricity on a continental scale remains a task ahead for many regions in particular Asia, Latin America, and in the longer-term, also Africa. A recent IIASA study (Nakicenovic, 1998) has investigated the energy infrastructure needs in Eurasia based

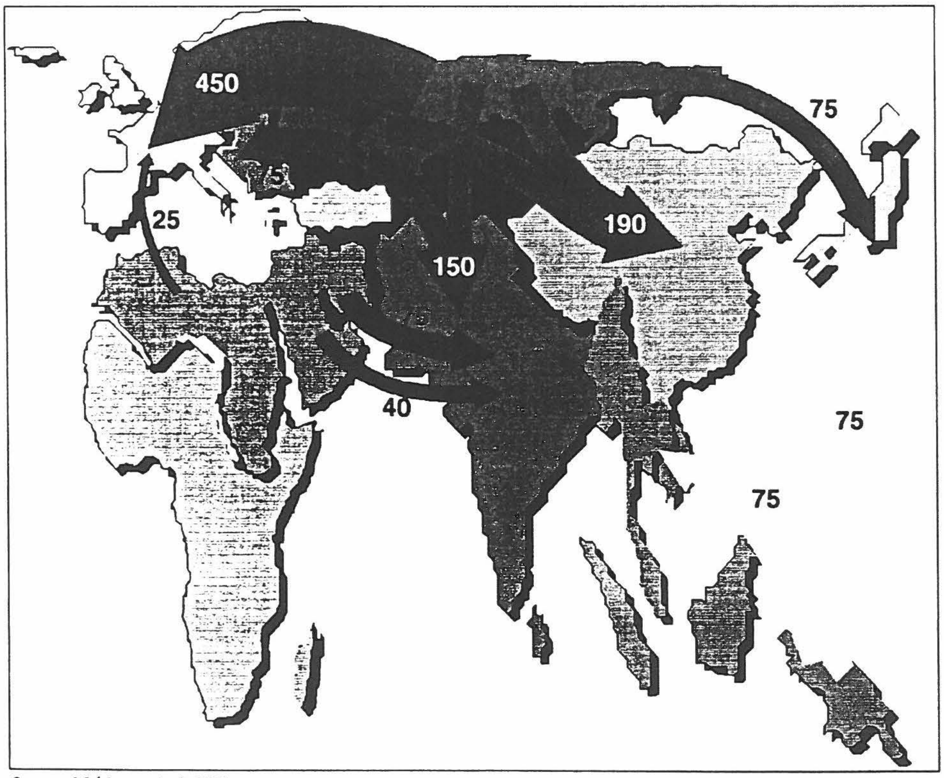
FIGURE 6 - Global market potential for four clusters of energy technologies by 2020, 2050, and 2100 (in Gtoe). Minima, maxima, an average across the six scenarios



on the demand projections of the IIASA-WEC scenarios. New infrastructures are needed in Eurasia, in particular, to match the large available resources of oil and gas in the Caspian region and Siberia with the newly emerging centers of energy consumption in Asia. The trade implications of new energy infrastructures in Eurasia are illustrated for natural gas in Figure 7 for 2050. To put these illustrative trade flows into perspective : gas imports to Western Europe in 1995 amounted to some 90 million tons oil equivalent (Mtoe), compared to possible trade flows of up to 500 Mtoe (Europe) and 700 Mtoe (Asia) that could be realized with a new continental gas infrastructures. Realization of such infrastructure projects will take many decades and multi-billion investments. Without a long-term perspective, both potentials, as well as realization horizons of such big energy infrastructure projects, cannot be studied. The flexibility and Clean Development mechanisms of the Kyoto Protocol could provide new opportunities in financing new energy infrastructures and development of cleaner energy supply structures, in order to avoid a technological « lock-in » in carbon and sulfur-intensive coal based economies, particularly in Asia.

The markets for power sector technologies also grow substantially, with a wide spread between the maximum and minimum scenarios (see Figure 6 above). By 2050, the range is between 3 toe per year (energy delivered) and 14 toe per year. Part of this spread relates to uncertainties about demand growth, but part of the spread arises from energy end-use innovations in the form of new, on-site decentralized electricity generation technologies such as photovoltaics or fuel cells. The potential for end-use technologies in the long term outgrows that of the power sector. The most important customers for energy technologies would no longer be a limited number of utility managers but rather millions of energy consumers worldwide. Synfuels also emerge in the long term as a major technology market (cf. Figure 6 above). An orderly transition away from conventional oil and gas translates into large technology markets for synliquids, syngas, and, in the long term, hydrogen produced from both fossil fuels (coal and natural gas) and renewables (biomass). By the end of the 21st century the global synfuels market could be at least 4 Gtoe per year, comparable to the current oil market.

FIGURE 7 - Natural gas trade within Eurasia in 2050 assuming high demand growth and the availabiliy of transcontinental infrastructure grids. Flows denote pipelines (blue) and LNG (yellow) routes. Width of trade « arrows » are proportional to gas flows (in Mtoe), areas of regions are proportional to primary energy use in 2050 (see figure 2)

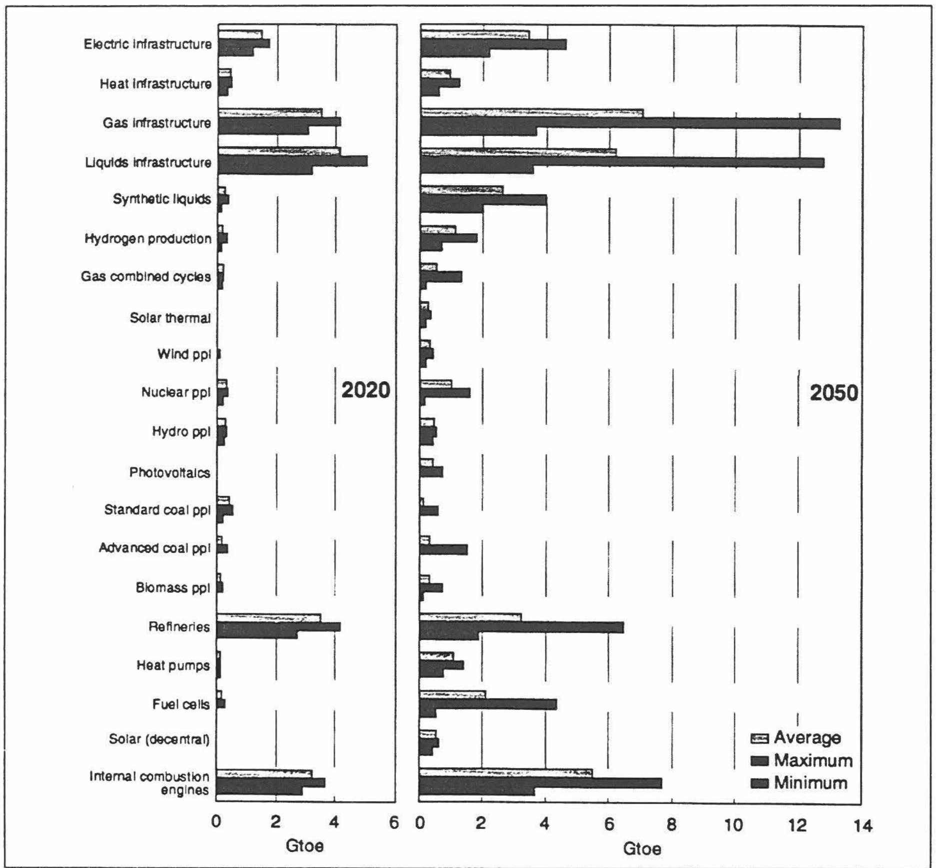


Source : Nakicenovic (1998)

The market potential in the 21st century for energy technologies in the form of infrastructures, power plants, synfuel production, and decentralized end-use devices is thus indeed large. Yet, the IIASA-WEC study indicates that the diffusion of new energy technologies will take many decades, with only modest and gradual deployment up to 2020. In that respect, the study confirms the overall S-shaped pattern of technological diffusion (Rogers, 1983 ; Marchetti and Nakicenovic, 1979 ; Grübler, 1998) : slow growth at the beginning, followed by massive market penetration, eventually leading to market saturation. Ranges for individual technologies are illustrated in Figure 8 for 2020 and 2050. Mindful of the dangers of trying to « pick winners », and consistent with the aggregate representation of technology in the IIASA-WEC study, only generic technologies are listed in Figure 8. For instance, the study does not distinguish between solid oxide, molten carbonate, phosphoric acid, and solid polymer fuel cells. Opportunities for hybrid and transitional technologies are also wide open – on-board steam reforming, for example, or partial oxidation could provide hydrogen for fuel cell vehicles while continuing to use existing oil distribution infrastructures.

The conclusion, that the point of final energy use is where the IIASA-WEC scenarios expect far-reaching technological

FIGURE 8 - Market potentials for energy technologies (in Gtoe) by 2020 and 2050



improvements to occur, has two additional implications. First, it weakens the argument for extensive R&D investments in large, sophisticated, « lumpy », and inflexible technologies such as fusion power and centralized solar thermal power plants. Improvements in end-use technologies, where millions, rather than hundreds, of units are produced and used, are more amenable to standardization, modularization, mass production, and hence exploitation of learning-curve effects (read : cost reductions and performance improvements). Second, institutional arrangements that govern final energy use and supply are critical. Deregulation and liberalization of electricity markets can create incentives in this direction as service packages are tailored to various consumer preferences and especially as traditional consumers can sell electricity back to the grid. But there are also concerns that liberalization will discourage long term R&D by emphasizing short-term profits as indeed seems to happen in a number of OECD countries. Private R&D is declining along with public R&D, with private sector investments in energy-related R&D, for example, falling by nearly a third in the USA in the past five years (Yeager, 1998). In the UK, the privatized offsprings of the Central Electricity Generating Board (CEGB) combined spend less than half of the R&D of the previous CEGB (Cunningham, 1998).

CONCLUSION

The IIASA-WEC study has identified technology as a crucial variable for long-term energy systems development. The most important challenges include meeting long-term energy demand growth in developing countries, assuring large-scale infrastructure investments, maintaining a strong and diversified RD&D and technology portfolio, as well as to devise new institutional mechanisms for technology development and diffusion for instance through the flexibility and Clean Development mechanisms of the Kyoto Protocol. In essence, it is only through improved technology that the imperatives of social and economic development as well as environmental preservation can be reconciled. Three technology-specific conclusions from the IIASA-WEC study deserve particular attention :

Technological change drives productivity growth and economic development. Drawing on human ingenuity, technology is a man-made, renewable resource, as long as it is properly nurtured. But progress has a price. R&D of new energy technologies and the accumulation of experience in niche markets (and their combination into RD&D) require upfront expenditures of money and effort. These are increasingly viewed as too high a price to pay in liberalized markets where the maximization of short-term shareholder value and investments into mergers and acquisitions take precedence over the build up of long-term strategic options and investments into technological innovation. Yet, it is the RD&D investments of the next few decades that will shape the technology options available after 2020. A robust hedging strategy focuses on generic technologies at the interface between energy supply and end use, including gas turbines, fuel cells, and photovoltaics. These could become as important as today's gasoline engines, electric motors, and microchips according to the IIASA-WEC study.

Capital turnover rates in end-use applications are comparatively short – one to two decades. Therefore, pervasive changes can be implemented rather quickly, and missed opportunities may be revisited. Conversely, the lifetimes of energy supply technologies, and particularly of infrastructures, are five decades or longer. Thus, at most one or two replacements can occur during the next century. Betting on the wrong horse will have serious, possibly irreversible consequences. The RD&D and investment decisions made now and in the immediate future will determine which long-term options become available after 2020 and which are foreclosed. Initiating long-term changes requires action sooner rather than later, as rates of change in global energy systems are slow.

Despite energy globalization, market exclusion remains a serious challenge. To date, some two billion people do not have access to modern energy services due to poverty and a lack of energy infrastructures. Many regions are overly dependent on a single, locally available resource, such as traditional fuelwood or coal, and have limited access to the clean flexible energy forms required for economic and social development. Policies to deregulate markets and get « prices right » ignore the poor. Even the best functioning energy markets will not reach those who cannot pay. Evidently, energy policies cannot fully address this issue. But what energy policies can accomplish is the improvement of old infrastructures – the backbone of the energy system – and the development of new ones. New infrastructures are needed in Eurasia, in particular, to match the large available resources of oil and gas in the Caspian region and Siberia with the newly emerging centers of energy consumption in Asia. Extended interconnections are also needed in Latin America and Africa. New, more decentralized energy technologies may lessen the economic burden of constructing traditional infrastructure grids, but they require their own « infrastructure » : most notably a strong science and technology base in developing countries. New institutional arrangements, drawing for instance on the flexibility and Clean Development mechanisms of the Kyoto protocol, should be explored to further infrastructure investments that are by their very nature, huge, risky, and with long-term payback only.

Finally, the results of the IIASA-WEC study also provide for some methodological lessons for future generation of energy models and scenarios. First, the study results question the commonly used practice of assuming « business as usual » type of developments, that technologically most often simply translate into devising a future that simply is just « more of the same » as existing today. Second, uncertainties need to be explicitly considered. Whereas scenarios, such as those described here, elucidate the impacts of alternative technological developments, they offer only limited guidance of « robust » strategies vis à vis uncertainty. Technology portfolio analysis, hedging strategies, and models of decisions under uncertainty are methodological next steps. For the latter, new methodologies are being developed at IIASA including advances in stochastic programming (e.g. Messner et al., 1996, Grübler and Messner, 1996). Finally, it is important to recognize that technology does not come as a free good. In addition, although a methodological nightmare for traditional deterministic planning models, there is overwhelming evidence that technological innovation can exhibit features of increasing returns (implying non-convexities in the language of optimization models). Fortunately again new methodologies are becoming available to consider these in energy models (e.g. Messner, 1995 and 1996), including a new generation of models that treat technological learning phenomena as highly uncertain (e.g. Grübler et al., 1999 ; Gritsevskyi and Ermoliev, 1999).

The elements of progressively opening the « black box » of technology are thus there : now it's the task of the analytical and policy community to revisit traditional approaches and conceptions. Abandoning the linear model of innovation, explicit considerations of uncertainty, and a better understanding of the mechanism that govern increasing returns to technological innovation may be good first steps ■

See bibliography, next page

REFERENCES

Argote, L., and **Epple, D.**, 1990. « Learning curves in manufacturing ». *Science* 247 : 920-924.

Arrow, K.J., 1962. « The economic implications of learning by doing ». *Review of Economic Studies* 29 : 155-173.

Arthur, W.B., 1983. « On Competing Technologies and Historical Small Events : The Dynamics of Choice under Increasing Returns ». WP-83-90, IIASA, Laxenburg, Austria.

Arthur, W.B., 1989. « Competing technologies, increasing returns, and lock-in by historical events ». *The Economic Journal* 99 : 116-131.

Christiansson, L., 1995. « Diffusion and Learning Curves of Renewable Energy Technologies ». WP-95-126. IIASA, Laxenburg, Austria.

Cohn, S.M., 1997. « Too Cheap to Meter : An Economic and Philosophical Analysis of the Nuclear Dream ». New York State University Press, Albany.

Cunningham, P., 1998. « Science and Technology in the United Kingdom », 2nd Edition. Cartermill Int., London.

Epple, D., **Argote, L.**, and **Murphy, K.**, 1996. « An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing ». *Operations Research* 44(1) : 77-86.

Freeman, C., 1994. « The economics of technical change ». *Cambridge Journal of Economics* 18 : 463-514.

Goldemberg, J., 1996. « The evolution of ethanol costs in Brazil ». *Energy Policy* 24(12) : 1127-1128.

Gritsevskyi, A., and **Ermoliev, Y.**, 1999. « An Energy Model Incorporating Technological Uncertainty, Increasing Returns and Economic and Environmental Risks ». Paper presented at the IAEE 1999 European Energy Conference, September 30 - October 1, Paris, France.

Grübler, A., 1998. « Technology and Global Change ». Cambridge University Press.

Grübler, A., and **Messner, S.**, 1996. « Technological uncertainty ». In : N. Nakicenovic, W.D. Nordhaus, R. Richels, and F. Toth (eds), « Climate Change : Integrating Science, Economics, and Policy ». CP-96-1, IIASA, Laxenburg, Austria, pp. 295-314.

Grübler, A., and **Messner, S.**, 1998. « Technological change and the timing of mitigation measures ». *Energy Economics* 20 : 495-512.

Grübler, A., and **Nakicenovic, N.**, 1996. « Decarbonizing the global energy system ». *Technological Forecasting and Social Change* 53(1) : 97-110.

Grübler, A., **Nakicenovic, N.**, and **Victor, D.G.**, 1999. « Dynamics of energy technologies and global change ». *Energy Policy* 27(5) : 247-280.

IEA (International Energy Agency), 1998. World Energy Outlook. IEA/OECD, Paris.

Marchetti, C., and **Nakicenovic, N.**, 1979. « The Dynamics of Energy Systems and the Logistic Substitution Model ». RR-79-13, IIASA, Laxenburg, Austria.

Messner, S., 1995. « Endogenized Technological Learning in an Energy Systems Model ». WP-95-114. IIASA, Laxenburg, Austria.

Messner, S., 1996. « Endogenized technological learning in an energy systems model ». *Journal of Evolutionary Economics* 7(3) : 291-313.

Messner, S., **Golodnikov, A.**, and **Gritsevskyi, A.**, 1996. « A stochastic version of the dynamic linear programming model MESSAGE III ». *Energy* 21(9) : 775-784.

Messner, S., and **Strubegger, M.**, 1991. « User's Guide to CO2DB : The IIASA CO_2 Technology Data Bank Version 1.0 ». WP-91-31a, IIASA, Laxenburg, Austria.

Messner, S., and **Strubegger, M.**, 1995. « User's Guide for MESSAGE ». WP-95-69, IIASA, Laxenburg, Austria.

Michina, K., 1999. « Learning by new experiences : Revisiting the Flying Fortress learning curve ». In : N.R. Lamoreaux, D.M. Raff, and P. Temin (eds), « Learning by Doing in Markets, Firms and Countries », National Bureau of Economic Research Conference Report, Chicago University Press, pp. 145-179.

Nakicenovic, N., 1998. « Energy Perspectives for Eurasia and the Kyoto Protocol ». IR-98-067, IIASA, Laxenburg, Austria.

Nakicenovic, N., **Grübler, A.**, and **McDonald, A.** (eds), 1998. « Global Energy Perspectives ». Cambridge University Press.

Neij, L., 1997. « Use of experience curves to analyze the prospects for diffusion and adoption of renewable energy technology ». *Energy Policy* 23(13) : 1099-1107.

Pepper, W., **Leggeh, J.**, **Swart, R.**, **Wasson, J.**, **Edmonds, J.**, and **Mintzer, I.**, 1992 « Emission scenarios for the IPCC, an update ». IPCC, Geneva.

Rogers, E., 1983. « Diffusion of Innovations ». 3rd Edition. The Free Press, New York.

Rosegger, G., 1996. « The Economics of Production and Innovation : An Industrial Perspective ». Butterworth, Oxford.

Rosenberg, N., 1982. « Inside the Black Box : Technology and Economics ». Cambridge University Press.

Rosenberg, N., 1996. « Uncertainty and technological change ». In : R. Landau, T. Taylor, and G. Wright (eds), « The Mosaic of Economic Growth ». Stanford University Press, pp. 334-353.

Schumpeter, J.A., 1934. « The Theory of Economic Development : An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle ». Harvard University Press.

Solow, R.M., 1957. « Technical change and the aggregate production function ». *Review of Economics and Statistics* 39 : 312-320.

Strubegger, M., and **Reitgruber, I.**, 1995. « Statistical Analysis of Investment Costs for Power Generation Technologies ». WP-95-109. IIASA, Laxenburg, Austria.

Tinbergen, J., 1942. « Zur Theorie der langfristigen Wirtschaftsentwicklung ». *Weltwirtschaftliches Archiv* 1 : 511-549.

Watanabe, C., 1995. « Identification of the role of renewable energy ». *Renewable Energy* 6(3) : 237-274.

Yeager, K., 1998. « EPRI and the Success of Collaborative R&D », testimony the Subcommittee on Energy and the Environment and the Committee on Science of the US House of Representatives, March 31. US Government Printing Office, Washington D.C.

Ordering Information

Orders must include the publication number and should be sent to the Publications Department, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria.

Telephone: +43 2236 807
Telefax: +43 2236 71313
E-mail: molina@iiasa.ac.at

A full list of IIASA publications is available at www.iiasa.ac.at

International Institute for
Applied Systems Analysis
A-2361 Laxenburg, Austria