International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 342 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

Interim Report **IR-99-17**

Towards New Energy Infrastructures in Eurasia: a background paper

Ger Klaassen (klaassen@iiasa.ac.at)
Arnulf Grübler (gruebler@iiasa.ac.at)
Leo Schrattenholzer (leo@iiasa.ac.at)

Approved by

Gordon J. MacDonald (macdon@iiasa.ac.at)
Director, IIASA

December 1999

Contents

Abstract

This study explores the concept of new energy infrastructures (in particular gas pipelines) in Eurasia and discusses its implications on future energy systems, gas trade, and the environment. Overall resource availability is not expected to be a real constraint in meeting growing energy demand within the next 100 years, but the geographical concentration of resources is. The expected increase in the use of domestic energy sources (coal) in Asia is associated with severe adverse environmental impacts causing significant damage to human health and the natural environment. In contrast, natural gas could offer an ideal bridge to the post fossil era, but requires the development of new Eurasian energy networks. Up-front investment in gas transit pipelines may constitute a significant portion of future energy investments. The financial risks appear significant and depend on factors such as demand and supply development, technological progress, geographical and political environments and prevailing regulatory regimes. Timely investments and associated cost reductions in the necessary infrastructure could create the potential for FSU gas exports becoming ten-fold as high in 2050 as otherwise would be the case. This would have significant positive impacts on the global, regional and local environment and also entail significant positive economic impacts. In addition, supply diversification would be promoted.

Acknowledgements

Financial support from the New Energy and Industrial Technology Development Organization (NEDO), Japan, for this study is gratefully acknowledged.

Towards New Energy Infrastructures in Eurasia: a background paper

Ger Klaassen
Arnulf Grübler
Leo Schrattenholzer

1 Introduction

Authoritative long-term energy development scenarios such as those developed by IIASA in collaboration with WEC (Nakićenović *et al.*, 1998) indicate substantial growth in Asian energy demand in the decades to come. Primary energy demand in Asia could overtake that of a larger Europe (Western and Eastern Europe, including the Former Soviet Union) as early as 2020, and by 2050 could be as high as 8.7 Gtoe (Gigatons oil equivalent). At present most of the Asian energy supply is based on traditional biomass uses and domestic coal production. Both pose a serious threat to local, regional and global environment. Coal emits sulfur leading to acidification, as well as CO_2 emissions causing climate change. Decarbonizing (reducing the carbon intensity) Asian energy systems could offer significant economic as well as environmental benefits in the long-term. But, decarbonization requires that new energy technologies and, foremost, new energy infrastructures, are available to match the potential supply of clean energy (natural gas and electricity), with the rapidly growing demand centers in Asia.

The objective of this report is to explore the concept of new energy infrastructures (in particular gas pipelines) in Eurasia. Such new infrastructures should extend and link anew the gigantic hydrocarbon energy resources in the Caspian region and in Siberia with the consumption centers in Western and Central Europe, Japan, China, India and the rest of Asia. The energy regions of a larger Europe and of Asia could mesh into a new "energy Eurasia" in which new infrastructures increase access to energy as well as promote environmentally sound development through further decarbonization of energy systems, particularly in Asia. The report illustrates some impacts of new Eurasian energy infrastructures on future energy systems, gas trade, and the improvement of the local and regional (i.e., sulfur) as well as global environment (i.e., CO_2 emissions).

The report has the following structure. Section 2 gives an overview of expected global and Asian energy developments and Section 3 sketches the environmental implications of these developments. Section 4 outlines possible new energy infrastructures and the associated investments and costs. Possible gas trade flows are quantified in Section 5. The illustrative environmental benefits of such expanded gas flows are discussed in Section 6. Section 7 concludes.

2 Overview of Current and Future Energy Developments

2.1 Introduction

In collaboration with the World Energy Council (WEC), IIASA explored long-term global and world regional energy prospects.

The joint IIASA-WEC study analyzed the prospects for improving the availability and quality of energy services, and the wider implications these improvements may have. The study explored a broad range of global energy developments and their consequences, such as likely financing needs and environmental impacts. The study's findings were presented in the joint IIASA-WEC report (Grübler *et al.*, 1995) and a number of related publications (Nakićenović, *et al.*, 1995; Grübler *et al.*, 1996; Nakićenović and Rogner, 1996; and Grübler and McDonald, 1995). The study findings were also extensively reviewed and evaluated by ten WEC regional expert groups. The final results were published in Nakićenović *et al.*, (1998). This section summarizes the global outlook presented in the IIASA-WEC scenarios and sketches the implications for Asia in particular.

2.2 Global perspectives

The IIASA-WEC study explored three cases (A, B and C) of future social, economic and technological development for 11 world regions. Case A represents a high growth future in terms of vigorous economic development and unprecedented rapid technology improvements; it includes three scenario variants reflecting alternative perspectives on resource availability and directions of technological progress.[1] Case B represents a *middle course*, with intermediate economic growth and more modest technology improvements. Case C is *ecologically driven*, incorporating challenging policies to simultaneously protect the environment and enhance North-South economic equity (Case C includes two scenario variants with alternative developments concerning nuclear power).

The key underlying elements that affect the outcome of the respective scenarios are the following: population and economic growth, energy intensity, technological advance and the energy resource base. These four clusters are usually exogenous assumptions that are combined in a consistent way in IIASA's integrated scenario assessment methodology. According to the scenarios, world population doubles by the middle of the 21st century, reaching 12 billion by 2100. The world economy would expand three- to five-fold from 1990 to 2050 and 10- to 15-fold by 2100.

In all scenarios, substantial reductions of energy intensities occur and economic development outpaces the increase in energy demand. As individual technologies progress, and as inefficient technologies are retired in favor of more efficient ones, the amount of primary energy needed per unit of gross domestic product (GDP) – the energy intensity – decreases. All other factors being equal, the faster economic growth, the higher the turnover of capital, and the greater the energy intensity im-

[1] The three Case A scenarios include: A1, ample oil and gas; A2, return to coal; and A3, non-fossil (bio-nuclear) future, in which natural gas provides for the transitional fuel of choice.

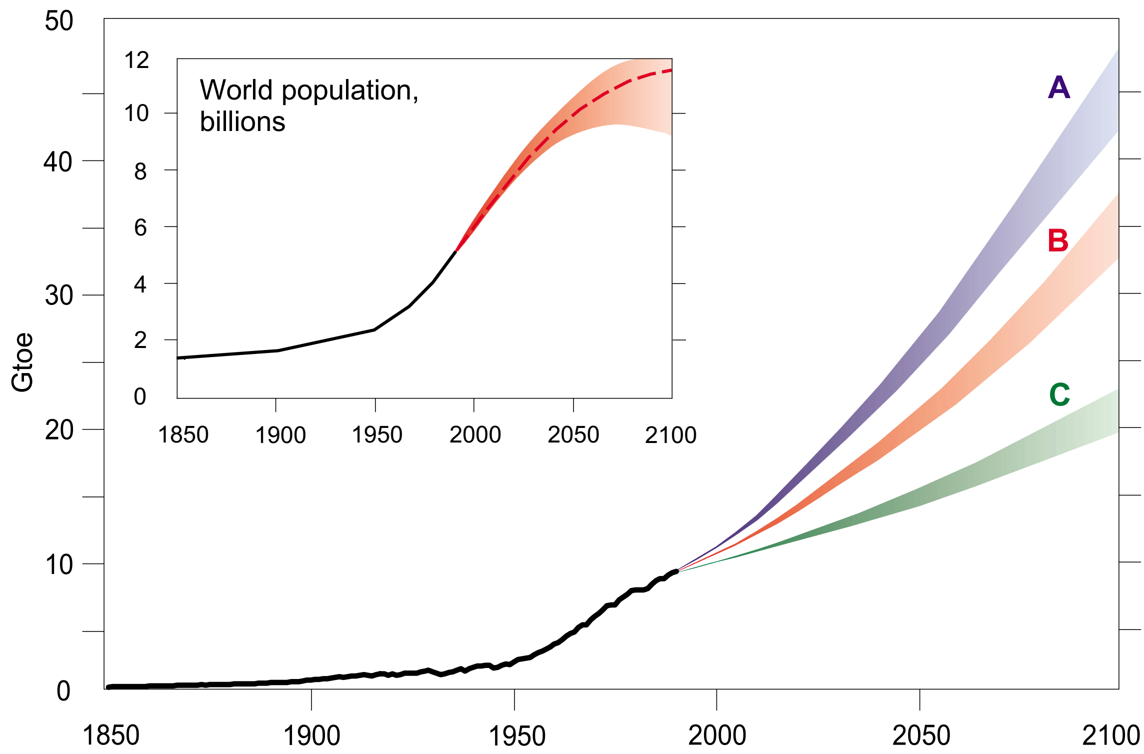

Figure 1. Global primary energy use, 1850 to present, and in the three IIASA-WEC Cases to 2100, in Gtoe. The insert shows global population growth, 1850 to present, and the central projection to 2100 (Bos *et al.*, 1992), in billion (10^9) people. Source: Nakicenovic *et al.* (1998)

provements. Improvements in individual technologies were varied across a range derived from historical trends and current literature about future technology characteristics. Combined with the economic growth patterns of the different scenarios, the overall global average energy intensity reductions vary from about 0.8 to 1.0 percent per year (Case B, respectively case A), to a high figure of 1.4 percent per year (Case C). These figures bracket the historical rate experienced by more industrialized countries during the last hundred years, which was approximately one percent per year as the long-term average. Efficiency improvements are significantly higher in some regions, especially over shorter periods of time.

The IIASA-WEC study envisages a 1.5- to three-fold increase in global primary energy use by 2050, and a two- to five-fold increase by 2100. The six scenarios are grouped into three different levels of primary energy consumption covering this wide range of alternative developments (see *Figure 1*).

A consistent finding across all scenarios, is the progressive shift of future energy demand towards the rapidly growing "south". Whereas in 1990 developing countries accounted for 34 percent of global primary energy use, their share is expected to pass 50 percent between 2020 and 2030 in all scenarios and reaches between 70 to 82 percent by the end of the 21st century. This shift in the geographical center of energy use is particularly visible when assessing the prospective developments in Asia (see discussion below). This shift also explains the need to explore technological, infrastructural, and investment strategies for a clean development of the anticipated rapid energy growth in developing countries.

The rates of technological change and the availability of energy resources also vary in a consistent manner across the scenarios in the IIASA-WEC study. For example, the high rates of economic growth are associated with rapid technological advance, ample resource availability and high rates of energy intensity improvement. Low rates of economic growth result in a more limited expansion of energy resources, lower rates of technological innovation in general, and lower rates of reduction in energy intensities.

The geophysical availability of energy resources is not a major constraint *per se*. Instead, the availability of energy resources and the rates at which they are converted into reserves are a function of the envisaged development strategies themselves. Key trends are resource exploration and production efforts, technological advance, and investments into energy infrastructures. Which, and how much resources thus become available for future energy systems is by and large a function of intervening development strategies and investment choices leading to different patterns of energy supply in the long-term. Part of the divergence in the structures of future energy systems also depends on policy choices. For example, the two Case C scenarios that assume successful international cooperation focused on environmental protection and international economic equity use much less fossil fuels than the other scenarios.

The IIASA-WEC scenarios indicate the possibilities for a wide range of energy supply alternatives, from a tremendous expansion of, to strict limits on, coal production from a phaseout of nuclear energy to a substantial increase in its use, from carbon emissions in 2100 that are only one-third of today's levels to emission increases of more than a factor of three. In spite of all the variations explored in the alternative scenarios, all manage to match the likely continuing push by consumers for more flexible, more convenient and cleaner forms of energy as incomes rise (*Figure 2*). Energy is thus increasingly transformed and converted into quality carriers such as electricity, liquids and energy gases. Hence, the issue of matching demand for high quality energy carriers with available supply and a diversified energy portfolio (including imports), assumes a growing importance for future energy systems. Because of rapid demand growth, the required changes will be most pronounced in Asia.

Alternative structures of future energy systems are capable of meeting these stringent demands for higher-quality energy end use and services. Despite all the variations, the scenarios look quite similar through 2020, and all still rely to a large extent on fossil fuels. However, after 2020 the scenarios start to diverge. Some become coal-intensive, replicating the "conventional wisdom" scenario for Asia on a global scale (Scenario A2, and with lower economic and energy demand growth also in Case B). In others, like the high-growth Scenario A3, gas provides the transitional fuel for a long-term structural shift towards post-fossil alternatives, or unconventional oil and gas resources allow an extension of the fossil fuel age well into the 21st century (Scenario A1). The ecologically driven scenarios of Case C are more renewable and nuclear intensive, albeit due to enhanced conservation efforts at lower levels of energy demand.

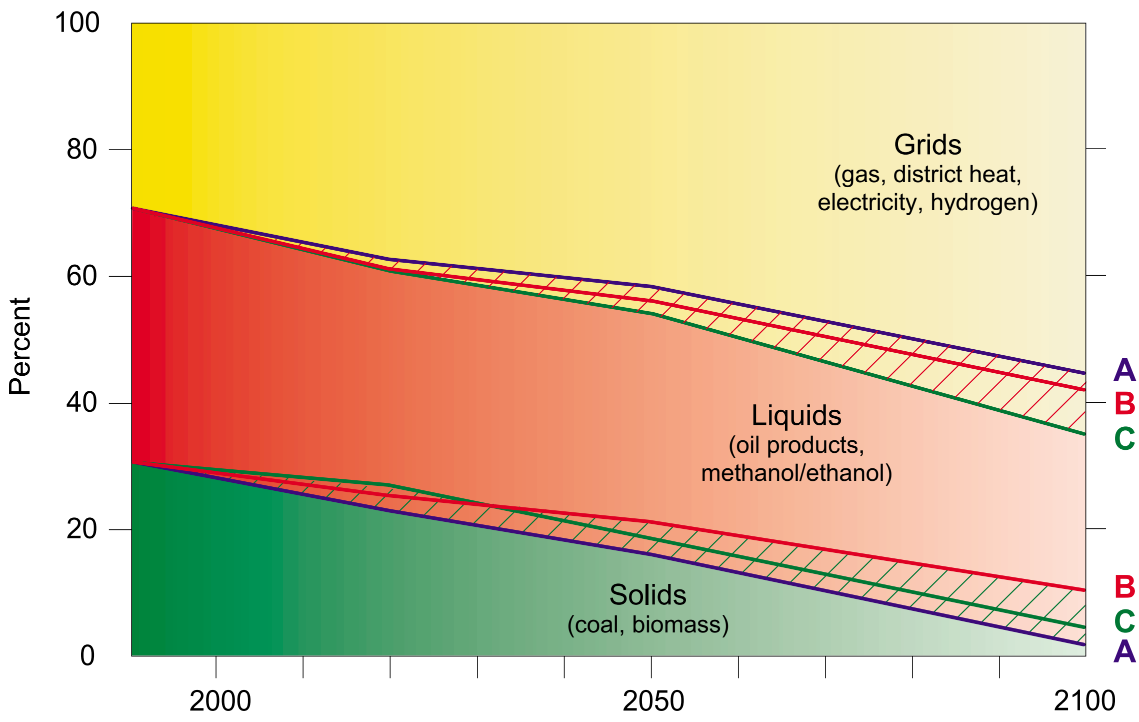

Figure 2. World supply of final energy by form: solids (coal and biomass), liquids (oil products and methanol/ethanol), and grids (gas, district heat, electricity, and hydrogen). Overlapping shaded areas indicate variations across the three Cases of the IIASA-WEC Study. Source: Nakićenović *et al.* (1998)

2.3 Prospects for Eurasia

The prospects for Eurasia[2] are ultimately determined by GDP increases, energy intensity changes, technology dynamics and resource availability. A summary of the main scenario results from the two illustrative high growth scenarios (A2 and A3) of the IIASA-WEC study is given in *Table 1*.

For all scenarios, percent GDP increases in Asia are, in general, a factor two to three times higher than the world average. Economic growth in a world region as inhomogeneous as Eurasia is difficult to adequately characterize in a few words. Overall growth in Eurasia is determined by adding the output of economies in transition, highly developed industrial countries, and rapidly growing developing countries. Doing this for Case A results in a more than five-fold increase of GDP in Eurasia between 1990 and 2050. The fastest growing economy within the region is China with a factor of almost 30 during these 60 years. This overall growth corresponds to average annual rates of 5.6 percent for China and 3.0 percent for Eurasia as a whole. The corresponding rates in Case B are 4.4 percent (China) and 2.3 percent (Eurasia). The FSU (Former Soviet Union) and Central and Eastern Europe (EEU) reach similarly high values after 2020.

[2]Eurasia consists of the following 6 out of 11 WEC study regions: CPA (Centrally Planned Asia and China), SAS (South Asia), and PAS (Other Pacific Asia) which together form ASIA as well as EEU (Central and Eastern Europe), FSU (Former Soviet Union), and WEU (Western Europe) which are called EUROPE.

Table 1. Population, GDP, primary energy supply by source in Eurasia for two illustrative high energy scenarios of the IIASA-WEC study; A2 conventional coal intensive scenario, A3 long-term shift to a post-fossil energy system using gas as transitional fuel.

	1990 EURASIA	2050 ASIA A2	2050 ASIA A3	2050 EUR A2	2050 EUR A3	2050 EURASIA A2	2050 EURASIA A3
Population, million	3645	5016	5016	1030	1030	6046	6046
GDP, billion US$(1990)	9597	27605	27605	30548	30548	58153	58153
Primary Energy Demand (Mtoe)	5007	8685	8505	6119	6104	14804	14608
Coal	1472	4001	1786	1226	137	5226	1923
Oil	1456	1189	796	1308	1088	2497	1884
Gas	936	898	1932	2088	2470	2986	4402
Nuclear	247	435	837	418	1207	853	2044
Renewables	895	2162	3153	1081	1202	3243	4355

Source: IIASA-WEC scenarios (Nakićenović *et al.*, 1998).

Energy demand projections assume that the next decades are characterized by successful reform and restructuring in Eurasia as a whole, leading to sustained investments in the energy sector and economic development that is reflected in the long-term improvement of energy intensities.

Total primary energy demand in Eurasia grows by a factor of between two to three between 1990 and 2050 in the scenarios of Cases A and B. This absolute growth corresponds to average annual growth rates of between 1.2 percent (Case B) and 1.7 percent (Case A). Overall growth in the ecologically-driven C scenarios in the same time period is approximately 60 percent or, on average, 0.8 percent per year. This means energy intensity reductions of between 0.9 (Case B) and 1.4 percent per year (Case C). Until at least 2050, Asia's demand growth will be the fastest in the world. Today Asia's primary energy demand is 1.8 Gtoe. In 2050 it is estimated to be between 5.5 and 8.7 Gtoe across the six scenarios in the absence of stringent environmental constraints.

The growth of regional energy use is illustrated by the energy map in *Figure 3*. There, the 11 regions of the IIASA-WEC study are drawn in proportion to their present levels of energy use for the middle course Case B scenario. In 1990, energy use in the rapidly developing countries of Asia was comparatively small relative to the industrialized countries in Western and Eastern Europe, the former Soviet Union and Japan. This imbalance changes dramatically in the long run and even accelerates in the high growth scenarios of Case A, the preferred scenarios from the perspective of the region's energy experts (see Nakićenović *et al.*, 1998).

Similar to the global perspective, primary energy resources are not a real constraint in Eurasia, but as at the global level, vast energy resources are concentrated in only a few areas. They include, in particular, the enormous oil and gas deposits in the Siberian and Caspian regions. The Russian Federation accounts for almost 40 percent of proven global natural gas reserves and for 27 percent of current global gas production. It also has large resources and production of coal and oil (e.g.,

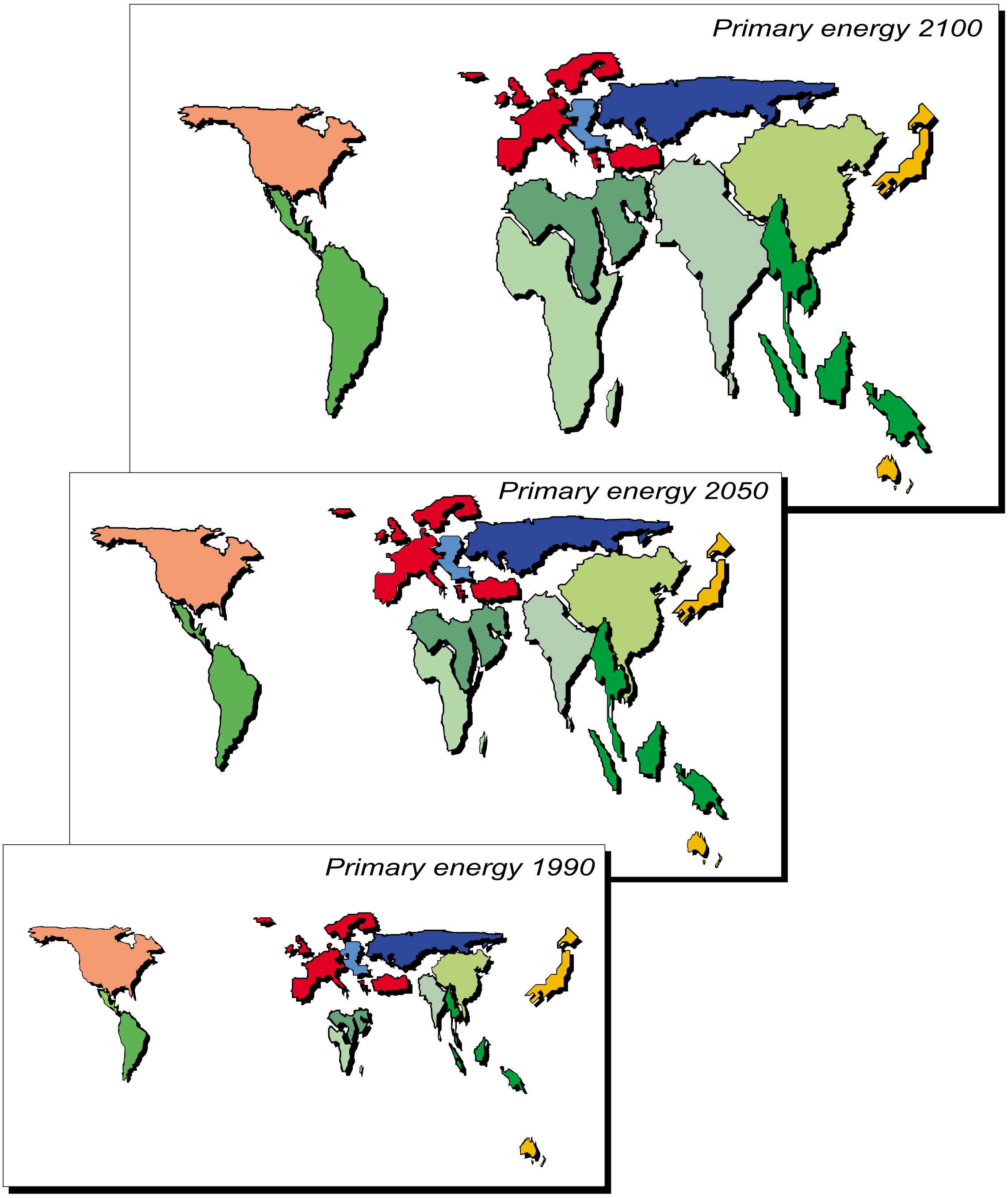

Figure 3. The changing geography of primary energy, “Middle Course” Case B scenario, 1990, 2050, 2100. Area of world regions is proportional to their respective 1990 levels of primary energy use. Source: Nakićenović *et al.* (1998).

Rogner, 1997; Ebel, 1997). This concentration of global and regional energy reserves and resources indicates the need for expanded energy trade and increasing energy interdependence in Eurasia. For Eurasia, the key future development issue for energy systems is how to bridge the increasing demand for clean and flexible energy forms (electricity and natural gas) with resources either available in the region, or being developed through increasing energy systems integration as well as through technological innovation.

By far the least attractive scenario is that of limited integration and limited energy supply diversification through new technology. By and large, this means a continuation of the coal-intensive development path for Asia, as illustrated by the A2 scenario of the IIASA-WEC study. Its negative environmental impacts are outlined in the next section.

An attractive alternative of progressive energy systems decarbonization is illustrated by Scenario A3. There, gas is the transitional clean fuel of choice enabling a technology-led transition to a post-fossil energy system in the second half of the 21st century. By the middle of the next century, the biggest relative and absolute natural gas use of all six IIASA-WEC scenarios is projected therefore for the A3 scenario: natural gas demand in Eurasia could exceed 5300 bcm (4400 Mtoe) in the year 2050. This is close to a factor three larger than current *global* gas use, and about 100 times larger than the capacity of the giant Yamal gas pipeline (approximately 60–80 bcm per year). Evidently, the infrastructure requirements of such a scenario are substantial. Assumptions on natural-gas conversion technologies are also reflected in the share of natural gas in total primary energy. The highest natural-gas share in Eurasia in 2050 is 30 percent (in the A3 scenario), a value lower than that of the Soviet Union in 1990. This means that even the most gas-intensive of the six IIASA-WEC scenarios has room for still higher gas shares. The prime candidate for still higher gas demand is the power sector but the transportation sector could also absorb substantial amounts of natural gas as illustrated by the example of Pakistan. There, a fleet of 100,000 CNG vehicles keeps growing further. The high share of natural gas in A3 is the result of the significant technological progress and cost reductions assumed in extracting, transporting and using natural gas.

Between 1990 and 2050 electricity demand in Eurasia is expected to increase by a factor of five in Asia and by nearly a factor of three in the European part (FSU, EEU and WEU). In 2100, electricity demand is expected to be even a factor 12 higher than 1990 in the A3 scenario in Asia, and nearly five times higher in Europe.

The challenge therefore is to match the rich energy resources of Eurasia to growing demands. Resources and demands must be matched geographically through trade, transportation networks and energy grids. They must be matched financially through investment flows and reforms designed to attract those investment flows. And they must be matched in terms of flexibility, convenience and cleanliness.

Eurasia has substantial energy resources, and substantial technological and financial expertise will be needed to match the rapidly expanding energy needs with the required energy supply. For instance, with rising incomes, high-quality fuels such as gas and electricity will need to expand faster than the energy sector as an average. Yet, with the exception of Western Europe (and LNG imports in Japan), grid connections and therefore trade possibilities for gas and electricity are largely undeveloped. The key question is therefore how best to apply available expertise and resources (technological, financial) to mobilize Eurasia's energy resources for economic and social development.

The IIASA-WEC study indicates that coal will remain largely a domestic or regional resource with its markets increasingly confined to the upstream conversion sector (electricity and, in the long-term, synfuels). Oil and natural gas with their associated versatility and, in the case of gas, cleanliness are both premium end-use fuels (for transport, services, and households) as well as premium industry feedstocks (for petrochemicals). With rapid developments in the economics and efficiency of gas turbines, natural gas is also becoming increasingly attractive in the power plant sector.

Thus, balancing supply and demand for oil and natural gas will constitute the main political, infrastructural, technological, and financial challenge in the decades to come. This problem is of particular importance for developing the vast hydrocarbon resources of the Caspian region and Siberia.

3 Environmental Impacts of These Developments

The IIASA-WEC study dealt with a number of environmental issues ranging from local and regional to global scales. The scenarios provide details on these environmental issues including for instance non-commercial energy use (as a potential source for local environmental degradation and deforestation) or sulfur emissions (potential source of acidification impacts, particularly pronounced in Asia). For each of the six scenarios, CO_2 emissions, as the dominant greenhouse gas, are determined by their level of energy consumption and the structure of energy supply. *Figure 4* shows the results and illustrates the environmental impacts of alternative primary energy roads of the three Case A scenarios.

CO_2 emissions vary substantially between the scenarios. In the coal-intensive Scenario A2 they reach 20 GtC (gigatons carbon emissions) in 2100, in Scenario A1, 14 GtC, but in Scenario A3 significant structural change in the energy system reduces the figure to 6 GtC. The latter is about the same level as current global energy-related carbon emissions, in spite of the fact that the energy consumption would have risen five-fold. Case B's emissions are comparable to those of Scenario A3 up to 2070, but are nearly double relative to 1990 by 2100. The two scenarios of Case C were constrained to stabilize emissions at current levels by 2050, in order to achieve an emission ceiling of 2 GtC (one-third their current level) by 2100.

The atmospheric CO_2 concentrations and surface temperature warming that might result from the scenario emissions were calculated using a carbon cycle and climate model developed by Wigley *et al.* (1994). The calculations also included non-energy sector greenhouse gases (GHG) emissions (taken from the IPCC IS92 scenario series, cf. Pepper *et al.*, 1992). By 2100 the two Case C scenarios achieve a stabilization of atmospheric CO_2 concentration below 450 ppmv (parts per million by volume). Scenario A3 is consistent with CO_2 concentration stabilization at 550 ppmv, assuming that the declining emission trends continue post 2100. Thus, it is the only high growth scenario that leads to stabilization of CO_2 concentrations, illustrating strategies of reconciling economic development aspirations with environ-

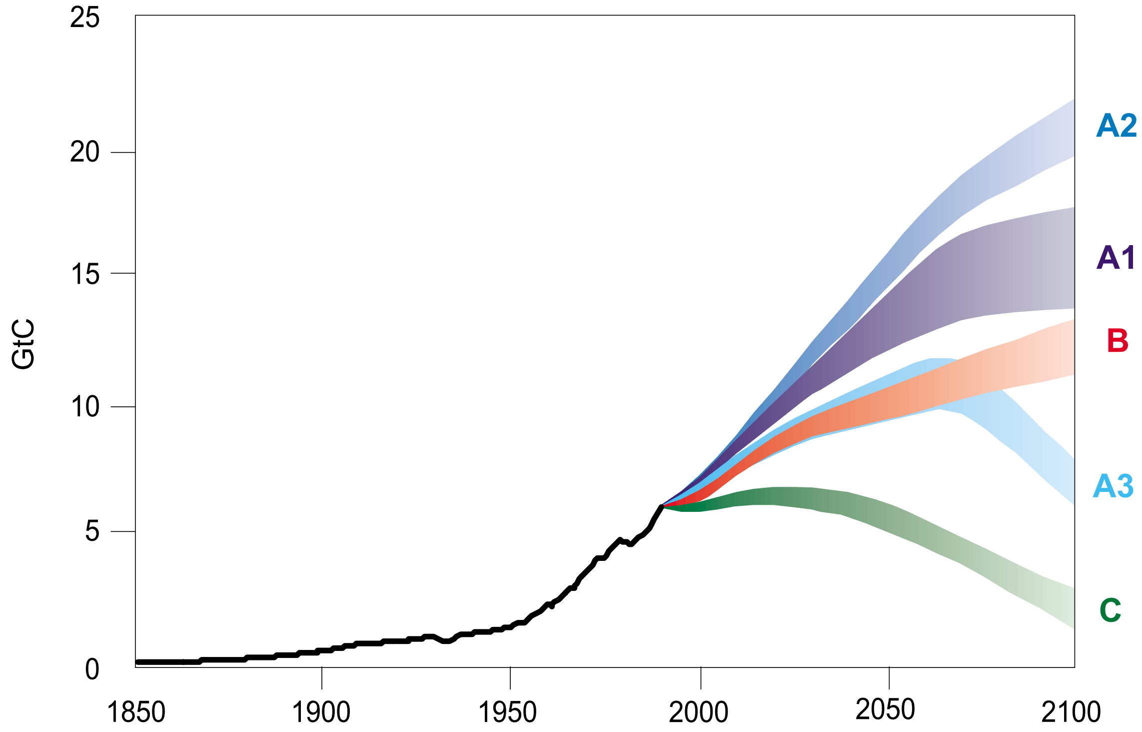

Figure 4. Global energy-related carbon emissions for three scenario families to 2100, in Gtc. Source: Nakićenović *et al.* (1998).

mental protection on all scales. All other scenarios result in continued growth of CO_2 concentrations. Case B reaches some 600 ppmv by 2100; Scenario A1 reaches 650 ppmv, and Scenario A2 reaches some 750 ppmv by 2100.

In terms of local and regional pollutants, the IIASA-WEC study concluded on the particular ecological importance of sulfur emissions. In view of the significant ecological impacts from acidification that would arise in the absence of dedicated sulfur mitigation efforts, particularly in the fast growing, coal rich regions of Asia, all IIASA-WEC scenarios assumed the progressive implementation of sulfur control policies. Therefore, even in the most "coal-intensive" fossil fuels scenario A2, global sulfur emissions in 2050 do not exceed 64 MtS, slightly higher than the 1990 level. Without the specified end-of-pipe controls, sulfur emissions in case A would be substantially higher.

But even with these pre-specified control measures, sulfur emissions in Asia are expected to be more than twice as high in the A3 scenario in 2050 as in 1990. Without specific sulfur controls Asian sulfur emissions could increase up to a factor five compared to 1990 levels. The environmental consequences (acid rain) of increased reliance on domestic fossil fuels without explicit controls are daunting. Sulfur deposition (see *Figure 5*) would surpass any known levels today, even when compared to the worst polluted areas of the so-called "black triangle" in Central-Eastern Europe. Excess depositions above critical loads (levels above which significant impacts on ecosystems are expected)calculated with the IIASA RAINS model (Downing *et al.,* 1997) would reach levels above 20 gS/m^2 and affect an area extending over

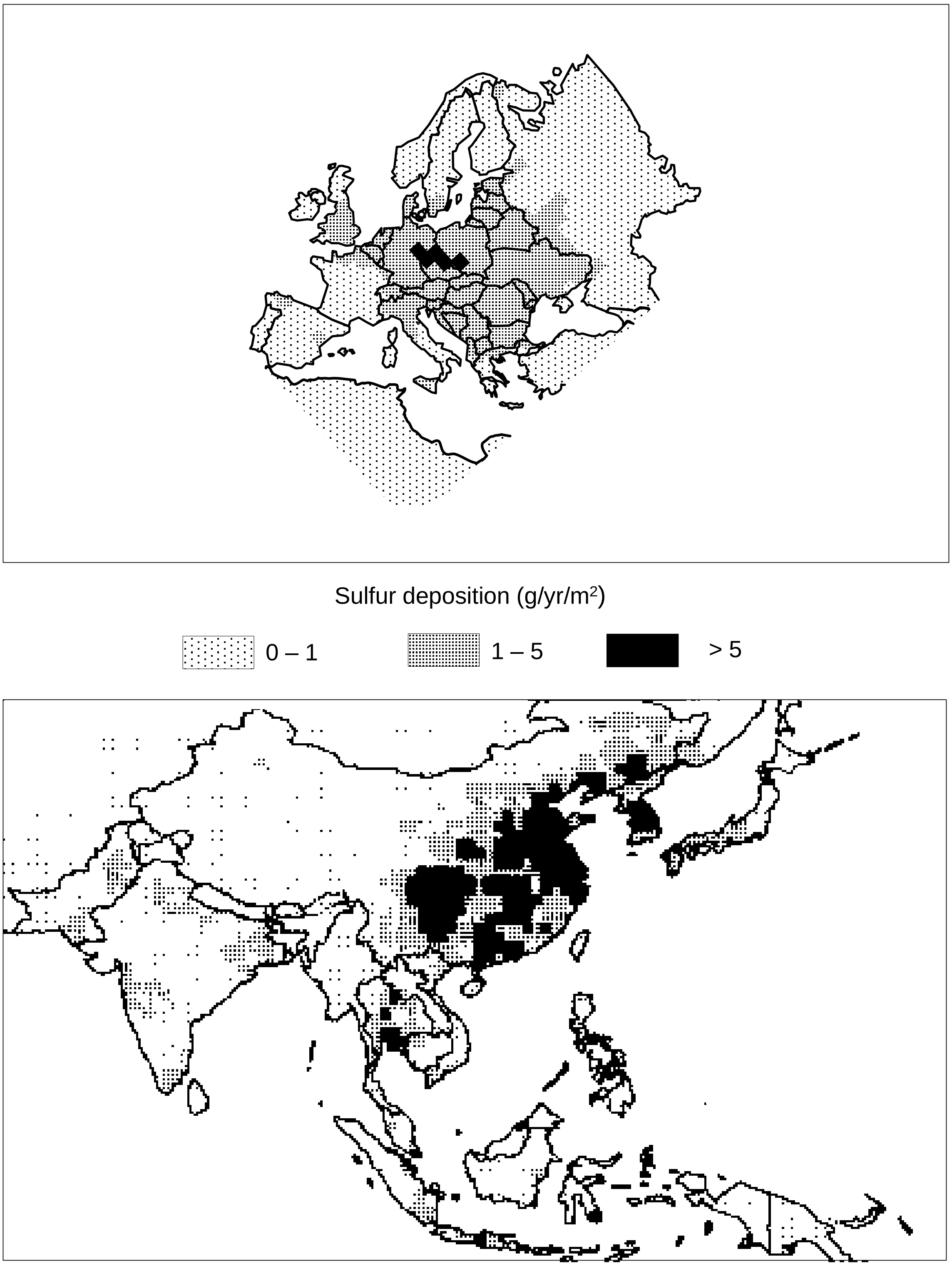

Figure 5. Sulfur deposition (grams per m^2) in Europe in 1990 (top) and in Asia in 2020 (bottom) for an unabated high growth, coal intensive scenario (A2). Source: Grübler *et al.* (1998) based on Amann *et al.* (1995).

200,000 km^2 in China alone. Critical loads would also be exceeded in Northeast India by more than 7 gS/m^2. Evidently, such high levels of acidic deposition imply ecological disaster for most natural ecosystems and also for economically important foodcrops. Analysis with an agricultural model (Fischer and Rosenzweig, 1996) for a similar scenario estimate that crop production in China would be reduced by up to one third over large parts of China threatening adequate food supply for a population reaching two billion people by the mid-21st century. On top of this, significant negative impacts for human health can be expected.

4 Illustrative Sketch of New Eurasian Energy Infrastructures

4.1 Energy integration

One of the important results of the IIASA-WEC study is the need for further energy integration in Eurasia to achieve the twin goals of supplying the energy services needed for economic development and reducing the adverse impacts on the environment at all scales. Clean fossil fuels would continue to be an important source of these energy services and would lead to further decarbonization of energy. This, however, requires the emergence of large-scale interconnected energy grids in Eurasia. Such developments could dramatically improve the match between demand and supply for cleaner hydrocarbons (oil and gas) and, in the long term, promote the further integration of Europe and Asia, e.g., through gas and electricity networks.

Historically, energy infrastructures have evolved radially through interconnections between a few large centers of energy demand and yet fewer centers of energy supply, as exemplified by the gas transport infrastructure between Urengoy and Western Europe, or the LNG route from Indonesia to Japan. At least from the demand side, a newly emerging "polycentric" structure could offer numerous advantages: enlarged resource availability, diversified supply, improved economics, and a cleaner environment.

The radial patterns of the evolution of energy infrastructures are primarily a result of differences in spatial energy demand densities. By and large, infrastructures "grow" from large spatial concentrations of supply (oil and gas fields) to large spatial concentrations of demand (e.g., urban agglomerations, city clusters). With low energy demand densities, the economics of building large, capital-intensive infrastructures simply do not exist. The mere existence of infrastructures can in turn stimulate energy demand growth.

Concepts and models of spatial energy demand densities have been developed at IIASA (Grübler and Nakićenović, 1990) and can be used to estimate future infrastructure needs in Eurasia. The basic problem is illustrated in *Figure 6*. Empirical investigations have shown that commercial energy use is almost perfectly correlated with night luminosity as gathered through satellite imagery (Elvidge *et al.,* 1997). The picture illustrates the high levels of night radiance and hence of commercial energy use in Japan and South Korea, and contrasts this with an indeed "dark" picture for North Korea. Japan's and South Korea's electricity use in 1994, for instance, were close to a factor of 30 and five larger, respectively, than that of North Korea.

With such low demand densities as those prevailing in North Korea, construction of a new dedicated infrastructure network to, or even passing through, the country will not be economically feasible. Construction of infrastructures would, in turn, become economically feasible if main trunk pipelines could be erected to high consumption density areas. In turn, these trunklines could provide the backbone for future network extensions, giving access to clean energy forms to other regions/countries also. The potential configuration of such future evolutionary infrastructure system development can be evaluated based on methods and data sets available at IIASA that have to date been applied to Europe and North America.

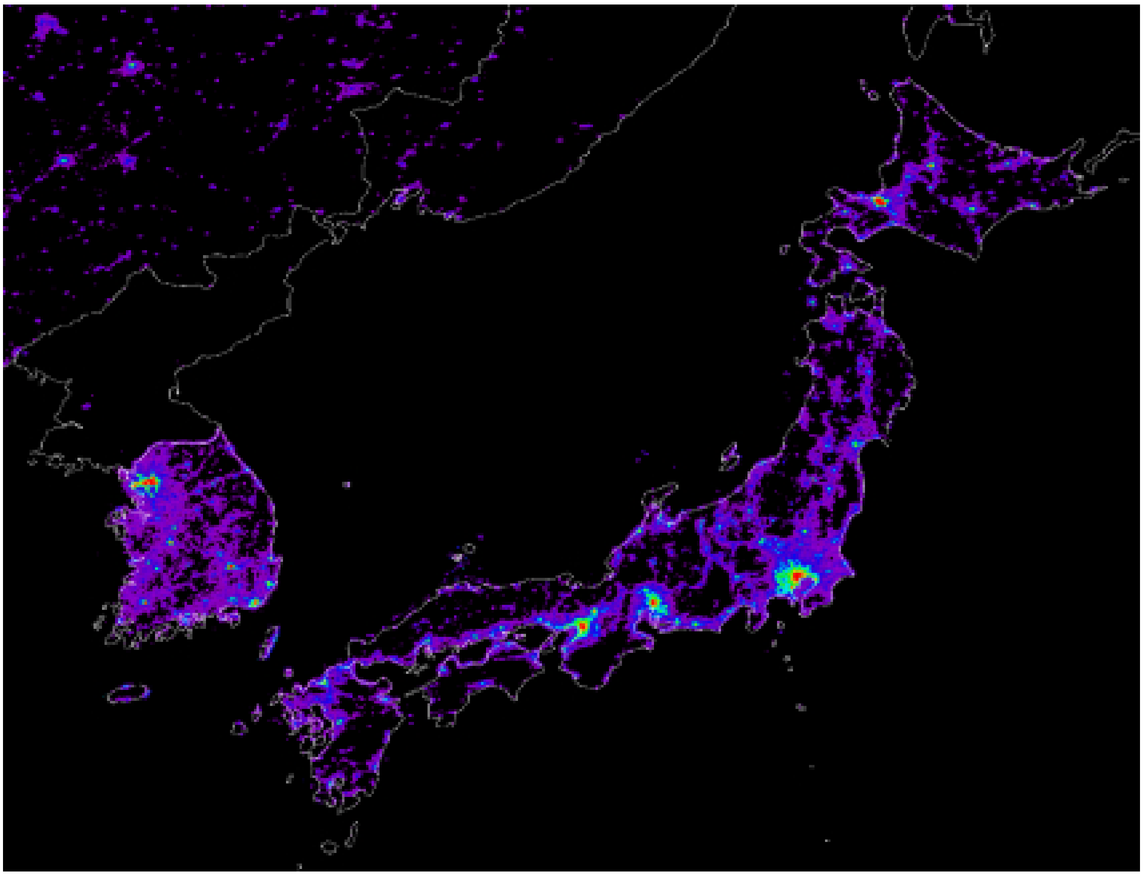

Figure 6. Night radiance intensities shown by a night satellite picture. Source: NOAA DMSP nocturnal visible near infrared emission data. Data courtesy of C.D. Elvidge, NOAA, Boulder, Colorado, USA.

The remainder of this section gives an overview of gas pipelines already planned in Eurasia and the possibilities to estimate associated investment outlays and costs. A similar approach is then made for electricity grids. This is followed by a discussion of the technical and economic requirements of such new infrastructure plans, and the relationship between the expected investments to overall investments in the energy sector over the coming decades.

4.2 Gas pipeline infrastructures planned

Currently, gas transit from the FSU to Europe totals nearly 210 bcm (in 1996) (Energy Charter, 1998). The majority of this (130 bcm) is transported from Russia to Western Europe. The total capacity available for transit through Ukraine, the Czech Republic and Slovakia amounts to around 260 bcm. Turkmenistan is the second largest supplier with 23 bcm in 1996 mainly towards other FSU countries. The remaining sources of gas for Western Europe are Algeria, Norway and the Netherlands.

At present, data suggest that worldwide the construction of nearly 12,400 miles of gas pipelines was foreseen to be finalized in 1998 (True, 1998). Of this amount 3,600 miles were under construction in the Asian-Pacific region (including the eastern part of the FSU) and 3,800 miles in Europe (including that part of the FSU west of the Ural). On the basis of average USA data a rough estimate indicates that the total investments involved in the Eurasian gas pipelines in 1998 was around 13 billion US$ (True, 1998). In 1999, gas pipeline construction to be finished will be a factor 2.5 higher than in 1998: a total of 29,000 miles is being constructed of which nearly 14,000 miles are in Eurasia. The associated investments in the Eurasian region are roughly estimated at around 35 billion US$ for 1999 only (True, 1998).

For the coming decades a large number of gas pipelines is being proposed or planned in the Eurasian regions (see *Table 2* for a preliminary overview). These new pipelines are intended to transport large volumes over long distances and consequently are expected to have high costs. Most of the potential pipelines will originate from the Caspian Sea region and the Middle East. The Yamal pipeline, for example, is foreseen to transport 60 to 80 bcm of gas each year from Siberia through Poland and Belarus over a distance of more than 4,000 km to meet West-European demands. The estimated costs are US$25–30 billion (Energy Charter, 1998). The Irkutsk-Japan gas pipeline is supposed to cross a stretch of over 2,300 miles from Kovykytinskoye in Russia, through Mongolia, China, South-Korea to Japan at a cost of $10 billion (Asian Energy News, 1997).

The nuclei of supplies are to be found in Siberia and the Middle East. In 1996, the FSU accounted for 30 percent of world gas production. The Middle East still takes the lead in supplying oil, and the construction of energy infrastructures in Eurasia presents an opportunity for oil importing Asian countries to import Middle East oil and to diversify this supply by additional gas imports. Centers of demand are especially to be found in WEU, CPA (Centrally Planned Asia and China), PAO (including Japan), and the Indian Subcontinent (SAS).

Data on natural gas reserves in relation to production make it clear that the long-term future of gas supply belongs to the FSU and MEA since they account for 35 and 30 percent, respectively, of proven recoverable and estimated additional reserves of conventional natural gas (Rogner, 1997; Skagen, 1997). The sum of conventional, as well as unconventional, natural gas reserves and resources are estimated to amount to 4,517 Gtoe in the FSU; more than 2,500 times world gas consumption in 1990 (Rogner, 1997).

At this stage it is not possible to give an accurate estimate of the expected investments in gas transit over the next century. More detailed information will be

Table 2. Proposed/planned interregional gas pipeline projects in Eurasia.

Source	Destination	Length (km)	Capacity (Bcm/year)	Capital Cost (billion US$ of 1995)	Source
Yamal-Russia	Europe	4,170	60-80	25-28	Energy Charter (1998), CEDIGAZ (1995)
Barentssea	Finland/Russia	3,450	25	10-12	CEDIGAZ (1995)
North Sea-UK	Niechorze-Poland	1,200	5-10	3	CEDIGAZ (1995)
Shatlyk-Turkmenistan	Erzerum-Turkey	2,700	31	3	OGJ (1999)
Libya	Italy	550	8-10	1	CEDIGAZ (1995)
Russia	Turkey	400	17	2	OGJ (1999)
Syria	Turkey	200	1.5		CEDIGAZ (1995)
Qatar	Europe	4,900	30	12	CEDIGAZ (1995)
Iran	Europe	4570	32	15	McMahon (1997) CEDIGAZ (1995)
Turkmenistan	China, Japan, S.Korea	6,000-8,000	28	11	McMahon (1997) WR (1999)
Yakutsk-Russia	China,Korea,Japan	3,900	20	24	CEDIGAZ (1995)
Irkutsk-Russia	China, Japan or South Korea	3700-China 1200-Japan	32	7	Sagers & Nicoud (1997) Paik & Choi (1997)
Sakhalin-Russia	Niigata-Japan	2,225	n.a.	2	CEDIGAZ (1995) Zhao (1999)
Dauletabad-Turkmenistan	Lultan-Pakistan	1,271	20	2	True (1998)
Dauletabad-Turkmenistan	Multan-Pakistan	1,500	n.a.	3	WR (1999)
Vietnam	Thailand	700	5.2-8.3	n.a.	Zhao (1999)
ASEAN countries	China, Taiwan, Japan, S.Korea	4,300	n.a.	5	AEN (1998)
Trans-ASEAN: Malaysia	Philippines, Singapore, Thailand	6,000	n.a.	10	CEDIGAZ (1995)
Oman	India	1,500	18	4	CEDIGAZ (1995)
Iran	Armenia	160	1-3	0.09	CEDIGAZ (1995)
Iran	Pakistan	1,600	8-10	4	CEDIGAZ (1995)
Iran	India	2,000	18-20	5-11	AEN (1997), CEDIGAZ (1995)
Qatar	Pakistan	1,600	25	3	CEDIGAZ (1995)
Total			>385-421	>151-162	

Notes: n.a.=not available; AEN=Asian Energy News; WR=World Reporter; OGJ=Oil & Gas Journal.
Interregional implies from one WEC region to another WEC world region.
Bcm=Billion cubic meters.

needed to account for the central factors that determine actual construction costs (IEA, 1994), for example:

- the length of the pipeline;
- the maximum flow required for a day of peak demand;
- pipeline diameter and the number of compressor stations;
- roughness of terrain, rights of way, etc.

Exact data can only be given using more detailed scenario projections on demand centers, transport routes, and location of potential supplies and more precise assumptions on the size, length and type (off-shore, onshore) of pipelines planned. For this purpose a large number of sources are available on costs (such as IEA, 1994; Kononov and Saneev, 1997; True, 1997; Berg *et al.*, 1998). Illustrative costs as a function of transport distance are shown in *Figure 7* based on IEA, 1994.

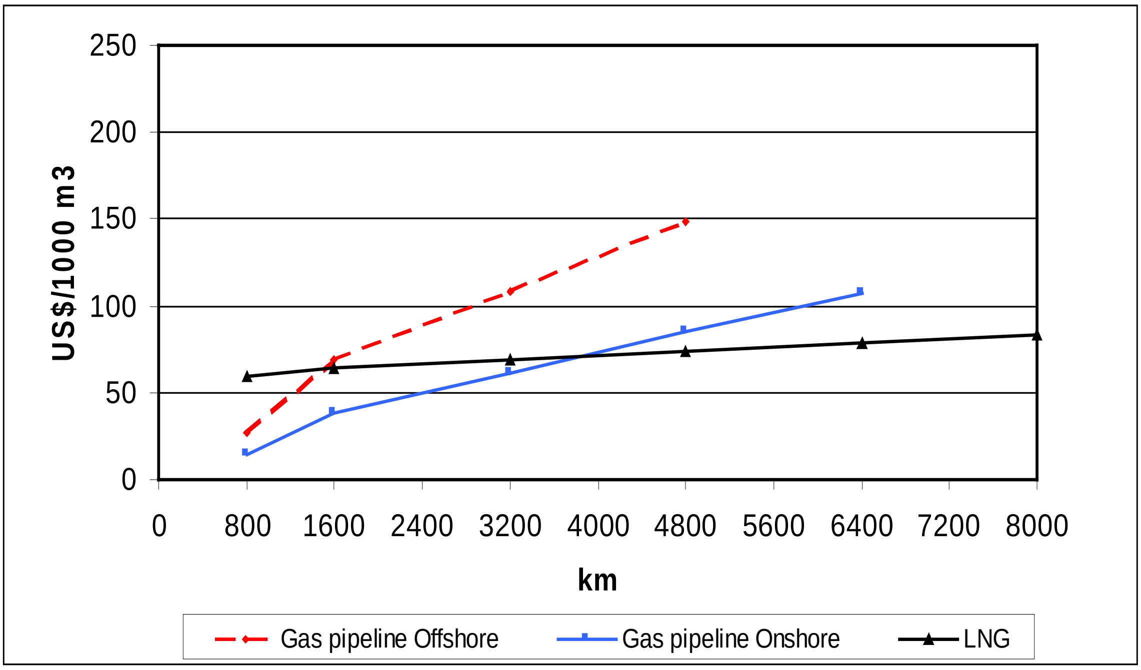

Figure 7. Gas delivery costs by alternative transport routes (onshore and offshore pipelines, LNG) as a function of transport distances, in US$ per 1000 m^3. Source: IEA (1994).

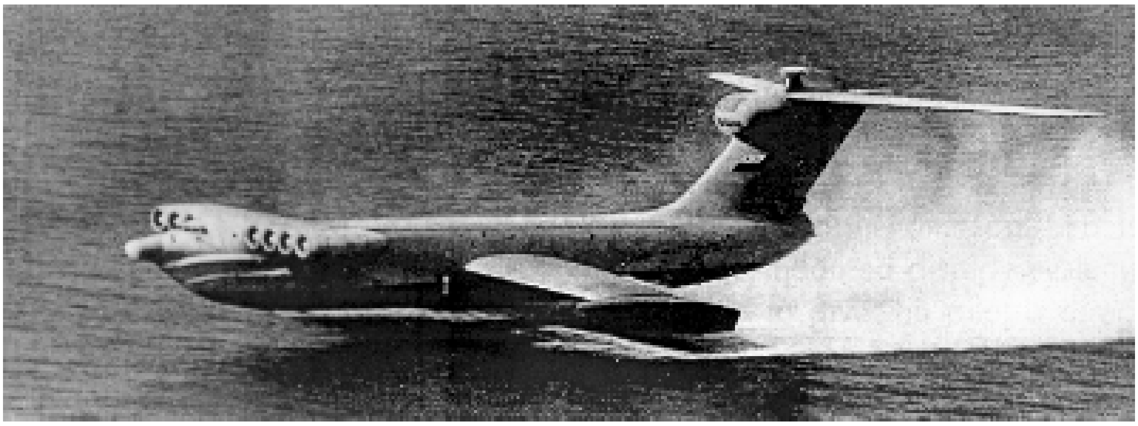

Figure 8. Giant wing-in-the-ground-effect transport aircraft flying over the Caspian Sea. Its use as alternative transport means for transporting natural gas in form of LNG has been proposed by Russian experts. Source: Lenovovitz (1993).

Pipeline lengths will obviously depend on the spatial distributions of both energy demand and supply. These can be determined using alternative methodologies and models of pipeline routings. In addition, innovative new technologies for gas transport, such as LNG transport via giant wing-in-the-ground effect aircraft developed in Russia, could have an impact on energy grid developments in as far as these technologies could be made competitive (see *Figure 8*).

Although the full details of possible infrastructure configurations and technologies for Eurasian energy grids of the 21st century are not available at this stage it is possible nonetheless to give an estimate of the order of magnitude of the expected investment associated with an expansion of natural gas use and pipeline systems in Eurasia.

The IIASA-WEC scenarios sketch widely diverging energy futures with different results for gas export and import flows. The next section elaborates on the associated gas trade flows in detail. Here, only a rough calculation of the investment outlays for gas pipeline infrastructure in Eurasia for two scenarios is given. The WEC A2 "conventional wisdom" (coal-intensive) scenario is contrasted with a scenario, termed here "bright gas future", that is a variant of the IIASA-WEC A3 scenario. In the latter, timely investments in gas transit routes from FSU to Asia are made. In the bright gas future scenario, piped gas exports from the FSU amount to over 1,025 bcm in the year 2050 and 3,700 bcm in 2100. The amount to be exported in 2050 would require nearly 20 pipelines of the capacity of the Yamal pipeline. In scenario A2 the exported volumes of gas would be more modest and amount to 480 bcm (in 2050) and 325 bcm (in 2100). On the basis of average data (see True, 1998; IEA, 1994, and *Table 2*), assuming an average length of 3,500 km, a size of 20–30 bcm per year per pipeline, and investments of 10–20 billion US$ per pipeline, overall investment outlays can be estimated. The result is an investment of 0.5 to 1.0 trillion US$ for the period up to 2050 and 1.8 to 3.6 trillion US$ up to the year 2100 for the FSU only. These tentative numbers indicate the gigantic size of the potential investments required. But they also indicate the size of the corresponding market opportunities for investors and equipment manufacturers (e.g., in Japan), and gas exporters, as they are indicative of the corresponding advantages to Asian energy consumers and the environment, once clean energy becomes available.

4.3 Electricity infrastructure

Currently, regional electricity exchanges resulting from optimizing grid operations are relatively small. In 1996, around 2.5 percent of total world electricity production was traded (Energy Charter, 1998). Of world gas production some 18.5 percent was traded internationally in 1996. The need for trade is smaller with electricity. Electricity is not a primary source of energy and the location of generation (with the exception of hydropower) is more flexible. Nowadays, electricity transit results more from the optimization of grid and capacity utilization than from deliberate trade patterns. In addition, self-sufficiency and supply security are the main reasons why many countries have relied on sufficient domestic production capacity while allowing for adequate spare capacity. The interconnected electricity grid of the FSU, the Unified Power System (UPS), is now confronted with a significant over-capacity. This over-capacity is a direct result of the fall in demand in the economies in transition. Transportation of electricity is expensive, and over long distances (over 1,000 km) is at present thought to be more costly than transporting the corresponding volume of energy as gas. International electricity trade statistics do not allow accurate statements on electricity transit (from one country though one or more other countries) since trade flows are only registered between neighboring countries. In addition, these flows are often reversed. Within the interconnected system in Europe, electricity exchanges accounted for 137 TWh in 1996 (around eight percent of net production). In the FSU, long-distance electricity transport is more

Table 3. Proposed and planned electricity interconnection projects in Eurasia.

Source	Transit Countries	Destination	Capacity GW	Length km	Investment billion US$96	Remarks
Russia[a]	Belarus, Lithuania, Poland	Germany	2	2000	1.1	500 kv DC
Baltic Ring[a]	3 Baltic States, Poland, Germany, Sweden, Finland, Russia, Belarus	Ring	n.a.	n.a.	n.a.	Ring
Russia[b]		Japan	10	3000	4.0	650 kv DC
Russia[b]	China	South Korea	3	1800	2.1	500 kv DC
Russia[c]	Mongolia	China	3	2200	2.3	600 kv DC

[a]Energy Charter (1998).
[b]Belyaev *et al.* (1996) Costs of transmission 0.65 million US$/100 km. Converter stations 100$/kw.
[c] Belyaev *et al.* (1998) for technical data. Costs calculated from Belyaev *et al.* (1996).
n.a. = data are not available.

important, although still mainly restricted to neighboring countries. In 1990, electricity exchanges equaled around 15 percent (or 227 TWh) of electricity generated in FSU. Due to financial problems and the general drop in electricity consumption this share dropped to 7 percent (or 85 TWh) in 1996 (Energy Charter, 1998). In Asia two weak 220 kV interstate connections exist between the Far East of Russia, North-East China and the electric power systems of Siberia and Mongolia. In 1995, Mongolia imported 12 percent of its electricity consumption from Russia (Belyaev *et al.*, 1998).

For the near future a number of interconnection projects between Europe and the FSU are under discussion (*Table 3*). The first project pertains to the establishment of connections and interface between the extended UCPTE network in Europe and the network of third countries in Europe (Belarus, Ukraine, Russia) including the relocation of conversion stations (European Commission, 1997). The second project is the Baltic ring which aims at strengthening and further developing the connections between the countries surrounding the Baltic Sea.

A number of projects have also been proposed that would link Russia with East-Asia. The first link (Russia-Japan) would transport electricity from the Uchursk hydropower plants in Russia to Japan in the summer to make use of differences in seasonal load curves to substitute conventional power plants. The second would link Russia, China and South Korea. Using seasonal load curve differences, electricity would flow in the winter from the Primorsk nuclear power plant and the South-Korean thermal plant to North-East China and Far-East Russia. In summer, South Korea would be receive electricity from Russia and North-East China. The third option would connect the Bratsk hydro power plant to the area of Beijing.

The expected investments in the electricity connections plus converter stations can only be roughly estimated at 8 to 9 billion US$ (1996). The total volume of transnational power flows that might be involved in Asia amounts to 115 Twh/year in the year 2010, half of which would be exported by Russia (Belyaev, *et al.*, 1998).

The overall investment picture is slightly different. For the Russia-Japan connection, overall investment might add up to 20–21 billion US$ if investments in new hydropower plants were included. On the positive side, investments in thermal power plants (and CO_2 emissions) in Japan and Russia could be avoided thus reducing investment outlays by 13 to 16 billion US$. This leads to a net investment increase of five to seven billion US$. For the second connection between Russia-China-South, total investments including those for a new nuclear power plant would add up to nearly five billion US$. The investment savings in spare capacities and thermal power plants cuts investments by nearly nine billion US$ so that on balance investments might decline by four billion US$. Over both projects, net investment outlays might add up to one to three billion US$. Although these might not be all possible connections, the investments in electricity grids would clearly be significantly lower than the possible investments (of 50 to 100 billion US$) in gas infrastructures discussed above. Over the long-term, however, the potential for large scale electricity exchanges via superconducting cables (electricity pipelines) should be kept in mind.

The financial viability of the electricity projects is difficult to judge at this stage. Preliminary estimates suggest that both projects (Russia-Japan, Russia-China-South-Korea) might lead to net cost savings because they reduce reserve capacity (Belyaev *et al.*, 1998). The extent of the cost savings will, however, depend on the rate of return (or the discount rate) required, the order of magnitude of the investments in transit and as well as in power plant capacity saved, as well as fuel prices. This requires further detailed analysis of the exact grid structure and underlying data as well as the extent to which (spare) capacities can really be saved taking into account the wish of governments to remain to a large degree self-sufficient in power supply. In the case of restricted financial resources the question also needs to addressed of whether alternative projects (such as combined cycle gas turbines) could earn higher rates of return also in view of electricity market liberalization that puts pressure on electricity prices. In addition, market liberalization leads to increased risk and higher discount rates, leading to a tendency away from capital intensive modes of production such as new nuclear power or hydro power.

From the environmental side, increased electricity interconnection is expected to have positive effects since it decreases the demand for fossil fuel. The Russia-Japan and the Russia-China-South-Korea connections substitute 8.1 million tce/year and would reduce carbon emissions by 5.2 million ton/year (compared with net carbon emissions in 1990 in CPA of around 690 million ton carbon). The impact of these electricity connections is, however, an order of magnitude lower, both in terms of financial requirements and environmental benefits, than the gas infrastructures sketched out above.

4.4 Capital requirements in relation to energy investments

A comparison of the energy infrastructure investment with total energy investments expected under the IIASA-WEC scenarios is useful to obtain an idea of their financial feasibility. Capital requirements for the energy sector are projected to be large, but not infeasible (growing less fast than GDP). Over the three decades up to 2020, global energy sector capital requirements across the IIASA-WEC scenarios are estimated to range between 10 to 15 trillion US$ (10^{12}) at 1990 prices (*Figure*

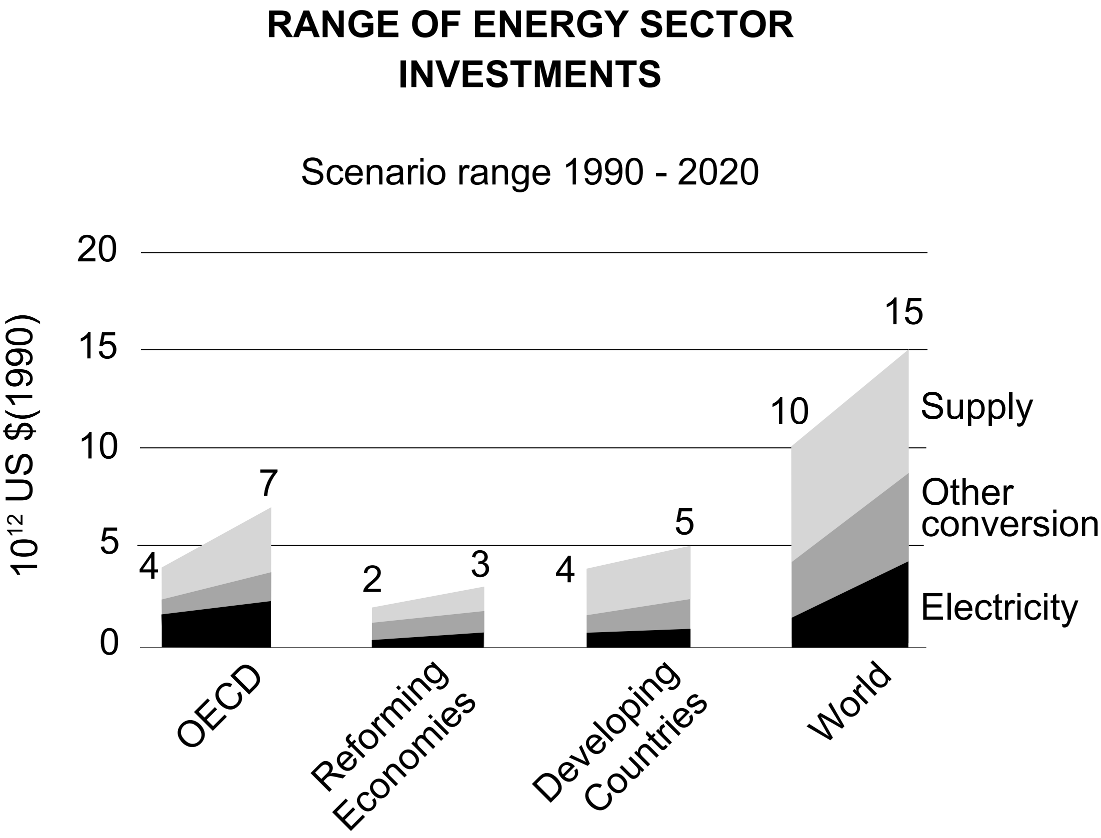

Figure 9. Range of cumulative energy sector investments for OECD, Reforming Economies, Developing Countries, and World, 1990 to 2020, in US$ trillion (10^{12}) at 1990 prices. Source: Nakićenović *et al.* (1998).

9). Overall, investment needs are dominated by the infrastructure-intensive oil and gas sectors (with investment needs of three trillion US$ (at 1990 prices) each from 1990 to 2020, followed by investment needs for nuclear and coal based electricity generation.

As a share of GDP, global energy investments range from 1.5 to 1.9 percent. They are highest in the reforming economies of Central and Eastern Europe and Central Asia where they could amount to seven to nine percent of GDP. For the FSU they could range from five to six percent up the year 2020. These high investment needs are a legacy of the high energy intensity of the former centrally planned economies and the recent declines in investments that accompanied economic recession. The result is a substantial need for reconstruction and upgrading of energy infrastructures.

How high are the expected investments in possible new gas transport infrastructures compared to the expected energy sector investments? For the FSU, cumulative energy investments up to 2050 vary from between four to six trillion US$ (in 1990 prices) (Scenarios A1 to A3). For Centrally Planned Asia and China (CPA), overall energy investments range from five to seven trillion US$ in the same period. This implies that for the FSU the rough estimation of possible investments (as estimated in the previous section) in gas infrastructures of 0.5 to one trillion US$ could, depending on the scenario, make up 10 to 25 percent of overall energy investments. If the investments would be covered by both CPA and FSU the share of gas transit infrastructures would be roughly five percent to ten percent of the overall energy investments in the two regions combined.

4.5 The challenge of financing

Financing gas infrastructure investments will be a challenging problem. The first challenge will be that an increasing fraction of the capital requirements will need to be raised from the private sector, where energy needs will face stiffer competition and return on investment criteria. Second, most of the investments that must be made are in the developing countries, where currently both international development capital and private investment capital are often scarce. The situation in the reforming economies of Europe and Central Asia are equally difficult. Third, as for all infrastructure investments, returns on investments (financially, socially and environmental) accrue in the long-term. Infrastructure investments are therefore currently often viewed as a too high a price to pay in markets where optimization of short-term share-holder value takes precedence over long-term sustainable development objectives. Below, private financial viability is examined, followed by an overall economic assessment (looking at impacts on other investments) and an broader socio-economic assessment that also includes environmental benefits.

When looking at private financial viability, the IIASA-WEC study concluded that the most important bottlenecks in energy sector investments in Eurasia are the perceived risks to investors both in the Caspian region and in the Russian Federation, as well as the long pay-back times required in building up a capital-intensive transcontinental gas transport infrastructure. Roberts (1996) mentions that bringing Caspian gas and oil to the market remains a controversial subject since decisions become entangled in political and security grounds rather than being taken on essentially economic grounds. Appraisal of gas and oil reserves, validation of their significance to the supply of gas, as well as assurance that supply commitments can be made are other aspects relevant for the feasibility of pipeline projects (Paik and Choi, 1997). Geographical isolation (e.g., of Kazakstan) implies that potential export routes depend on the political approval of the countries through which exports will take place. Ibrahim (1995) finds that the substantial capital investment involved demands long-term commitment between suppliers and consumers alike to overcome vast geographical, political and legal hurdles. Yet, it is also important to emphasize that historically, the interconnections between Russian gas fields and Western European gas demand could be achieved even in periods of political tensions. Sagers and Nicoud (1997) conclude that the economic feasibility of the export stage of the East Siberia-China gas pipeline is questionable because of the high costs involved, the uncertainty of the reserves and the need to meet regional (Irkutsk) demands as well. The International Energy Agency (IEA, 1998) adds that the routing options for most new pipelines are fraught with technical, financial, legal or political difficulties. Multiple export routes could increase energy security for both exporters and importers by making deliveries less vulnerable. Improved energy security will have to be balanced by economic feasibility, since a larger number of pipelines would mean smaller economies of scale. Bergmann (1996) notes that difficult climatic conditions and the great distances involved might require new and expensive infrastructures such as the Yamal-Europe project. These increased costs might not be matched by higher prices since increasing competition tends to push prices down making it more difficult to finance projects. In addition, regional domestic supply at the market might be sufficient for the medium term. A first rough estimate of the costs of the Russia-China pipeline suggest that this might involve a cost-price of exports of 110 to 120 US$ per 1,000 m^3, if based on a discount rate of seven percent (Merenkov *et al.*, 1997). This would be in between the gas price levels expected in the various IIASA-WEC scenarios. A close detailed examination of the underlying assumptions and the sensitivity of the associated costs of gas-pipelines and an assessment of alternative options, such as LNG, is therefore needed in order to be able to make sound statements on their financial viability.

From an overall economic perspective, the fact that energy investments as part of GDP are expected to decrease in the IIASA-WEC scenarios makes financing easier. In addition, several IIASA-WEC scenarios conclude that overall energy investments could be lowered through increased use of natural gas by perhaps up to 0.5 trillion US$. The stepped-up investments in gas production facilities, and especially transcontinental gas infrastructures (pipelines and LNG facilities), could then (partially or fully) be compensated by reduced investment in other parts of the energy chain (e.g., the lower capital investment needs of combined cycle gas turbines compared to their coal or nuclear alternatives). From a macro-economic perspective, cost savings are also possible in terms of reduced outlays on traditional end-of-pipe technologies such as flue-gas desulfurization. This is so in case these investments would otherwise be required under existing legislation or would have to be made to fulfill emission objectives. That is, the environmental externalities they address would have to be at least partially internalized. The next section shows that such cost savings might indeed be significant.

A possible, but speculative, initial financing arrangement might involve global carbon dioxide trading schemes. Should the Kyoto emissions reduction agreement or a similar scheme be ratified for the so-called Annex I countries that include OECD countries and the reforming economies in Europe, the Russian Federation is likely to acquire a large "emissions bubble" by 2010. Tentative estimates made at IIASA indicate that the "bubble" might be as large as 300 MtC in 2010 (Victor *et al.*, 1998). These excess emission rights could be sold to Europe and North America, as these regions will be severely limited by the agreed emissions reductions (of about five percent by 2010 for the whole Annex I region compared to the reference year 1990). Revenues from the Russian "bubble" could be invested to further sustainable development throughout Eurasia while reducing the long-term emissions. Shortly after 2010 this "bubble" is likely to disappear as energy consumption increases in the Russian Federation. In the meantime, it could provide a steady financing source for longer-term potential economic and environmental benefits from the Eurasian energy grids. For example, at about 50 US$ per tC (ton of carbon), a "bubble" of 300 MtC/year would generate annual financial flows of up to 15 billion US$ (Victor *et al.*, 1998).

In contrast to the short-term problems flagged above, long-term perspectives suggest a more sound and robust future. The IIASA-WEC scenarios indicate substantial economic and environmental returns from an extended Eurasian gas pipeline system that in the long-term may become interconnected and pave the way for similar developments for electricity. The economic robustness of pipeline construction is underpinned by continued short term growth in demand (McMahon, 1997; Bergmann, 1996) although the sectors that drive the demand for gas might differ from country-to-country. New pipeline infrastructure will give more and easier access to additional sources of gas. It also will open the way to diversification in power generation and the industrial and manufacturing sector and even in the domestic sector. In addition, the environmental benefits are not only significant but will also imply reductions in damage to food crops, human health and ecosystems, which can only partially be expressed in monetary terms.

In summary, in order to give a sound assessment, pure financial feasibility arguments need closer scrutiny taking into account the sensitivity for different assumptions. Such an analysis needs to be complemented by a more systemic macroeconomic evaluation which looks at the impacts in terms of reductions in other (energy) investments and in terms of environmental benefits as well.

Before turning to an assessment of the environmental impacts, estimates of the orders of magnitude of possible gas trade flows in Eurasia are given.

5 Provisional Quantification of Gas Trade Flows

Crude oil and oil products currently dominate international energy trade. Through 2050 they also remain the most traded energy commodities in the IIASA-WEC scenarios, although the spread across scenarios is quite large. However, trade in piped natural gas and LNG increases substantially, and by 2050 gas becomes the key traded energy commodity. In general, global energy trade patterns shift from primary energy to secondary energy, which improves trade flexibility and thereby lowers geopolitical concerns.

The most striking result from the IIASA-WEC study is the persistent growth in Eurasian import needs outside the Russian Federation and the Caspian region. This is due to comparatively low oil and gas resource endowments in Western Europe and Japan plus growing demand in the developing economies of Asia. Overall, annual imports of oil and gas into the region could increase to between 1.7 and 3 Gtoe, with gas trade accounting for more than 1 Gtoe.

These projected trade flows into Eurasia approximate or exceed the *global* trade in oil (1.9 Gtoe) and gas (0.4 Gtoe by pipeline and LNG) in 1996. The largest players in terms of export capabilities remain the Middle East for oil, and the Siberian and Caspian regions for gas.

Figure 10 shows gas export versus prices and resulting total export revenues for the former Soviet Union for the IIASA-WEC scenarios. The dashed lines in the figure are isoquants reflecting constant export revenues. A consistent finding is that through 2020 gas exports always increase to at least 300 billion cubic meters per year with export revenues increasing to at least 50 billion US$, i.e., five times 1996 values. After 2020 gas export prospects from the region could bifurcate. The most

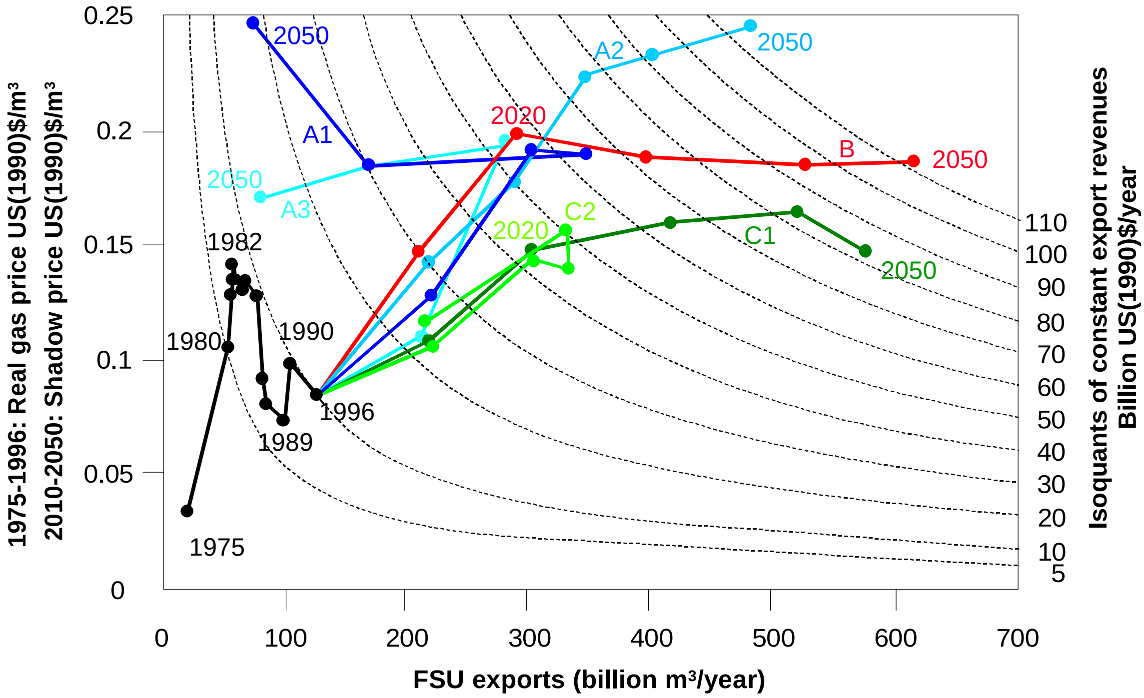

Figure 10. Natural gas export quantities and revenues of former Soviet Union, 1975 to 1996 and for export from the Siberian and Caspian regions in the six IIASA-WEC scenarios to 2050. Source: Nakićenović *et al.* (1998).

likely scenarios suggest growth will continue because alternatives are not developed quickly enough (Scenarios A2 and B) or because gas is favored by environmental policies (Scenario C1). In cases where more rapid technological progress makes it possible to tap unconventional gas resources outside the region, non-fossil energy technologies to massively penetrate energy markets, or domestic FSU demand increases significantly, long-term export potentials are reduced (Scenarios A1, and A3 in particular). However, revenues from gas export are unlikely to fall below 30 billion US$ per year.

Figure 11 shows natural gas flows for a scenario not part of the IIASA-WEC study. This global scenario labeled *bright gas future* is one with rapid economic development (similar to the Case A scenarios in the IIASA-WEC study) while assuming that timely investments are made in gas infrastructures leading to significant reductions in costs (Nakićenović, 1999). Even larger networks would be required for lowering the contribution of domestic coal in rapidly developing parts of China and Southeast Asia. A more ambitious gas trade within Eurasia could involve gas flows to Asia that would nearly match those going to Europe. Such ambitious Eurasian energy grids would bring large economic benefits to gas (and energy) exporting Regions. They would enable healthier economic development throughout Eurasia by the provision of cleaner and more flexible energy services but their economic feasibility and their environmental benefits require a more detailed assessment.

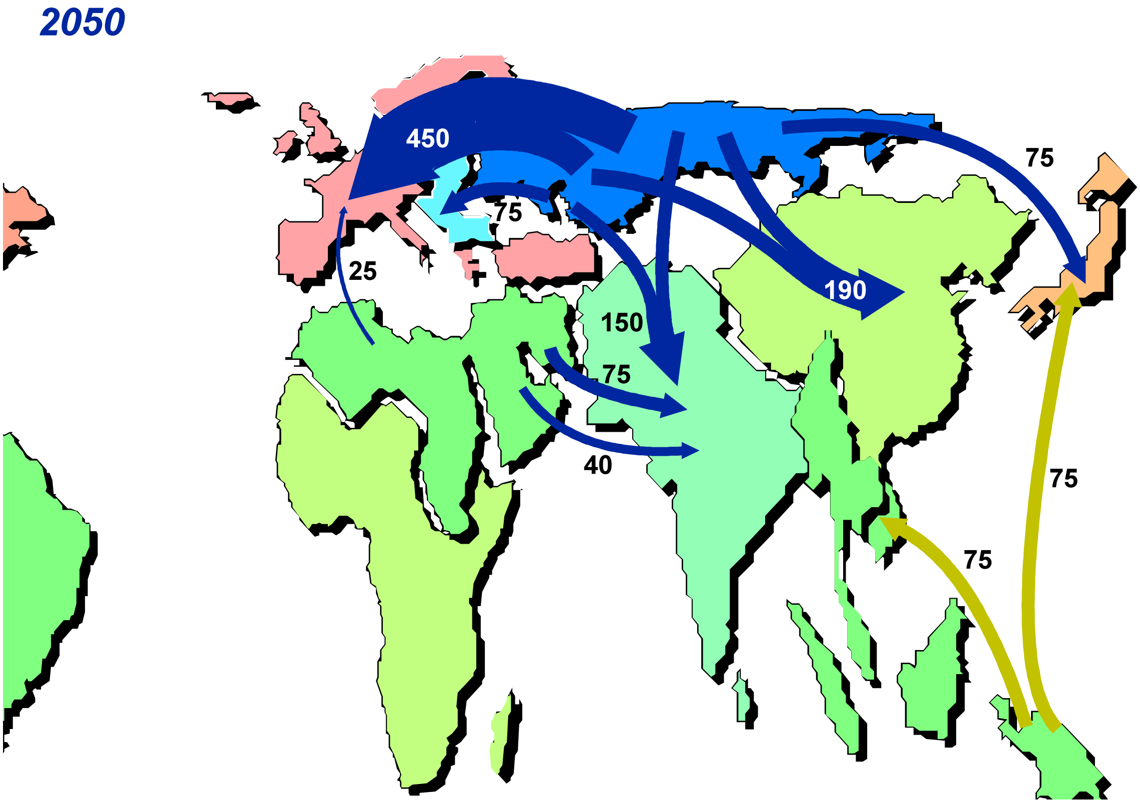

Figure 11. Natural gas trade within Eurasia in 2050 for a global scenario with rapid economic development and accelerated investments in gas production and transport infrastructures. Flows denote pipelines and LNG routes, width of trade "arrows" is proportional to gas flows, numbers are in Mtoe, areas of Eurasian regions are proportional to primary energy consumption in 2050. Source: Nakićenović (1999).

6 Illustrative Environmental Benefits

An urgent local environmental problem in densely populated metropolitan areas is the high concentration of particulate matter and sulfur dioxide. Regional air pollution could especially prove problematic in the rapidly growing, densely populated, coal-intensive economies of Asia. In the booming cities of China and Southeast Asia, high levels of air pollution must be addressed with both cleaner fuels and active abatement measures. A high dependence on coal with no abatement measures, would result in significant regional acidification and cause key agricultural crops in the region to suffer acid deposition that is ten times the sustainable level already before 2020 (see discussion above).

Figure 12 illustrates the possible benefits of a significant reduction in sulfur emissions such as might result from scenarios which expand natural gas use in Asia as a result of developing the appropriate gas infrastructure. The figure is only illustrative and the exact local benefits will depend on the volumes and spatial occurrence of gas use and the fuels that are being substituted. The figure shows that in comparison to an uncontrolled coal expansion case (*Figure 5* above) significant regional and local improvements can be expected in large parts of Asia. An expanded gas scenario could lower global sulfur emissions by 50 percent compared to 1990 levels

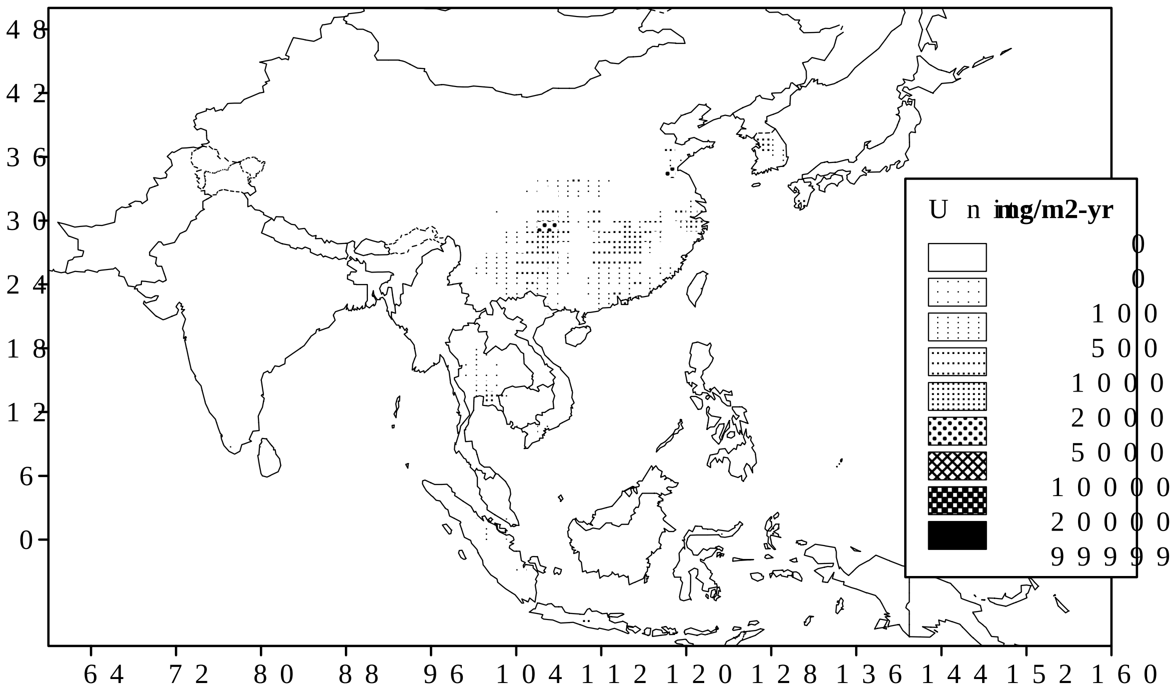

Figure 12. Excess sulfur deposition above critical loads in 2050 in a low sulfur case based on enhanced gas use in Eurasia.

(even without add-on technologies such as flue gas desulfurization). If legislation is in place that would require sulfur emission abatement, this would bring financial benefits since end-of-pipe measures (such as those required under Chinese legislation) can be (partially) avoided by cleaner energy use. Using the data in the RAINS-Asia model (Amann *et al.*, 1995) a rough estimate based on average costs per ton sulfur abated (of 400 to 500 US$/ton S, Olsthoorn *et al.*, 1997) and a reduction of around 30 Mton S ("bright gas future" scenario versus an unabated A2 scenario from the IIASA-WEC study) suggests that this might amount to financial savings of around 12 to 15 billion US$ annually. Over a (economic) lifetime of 20 to 30 years this would add up to a (undiscounted) sum of 0.2 to 0.45 trillion US$. This would cover a not insignificant part of the expected costs of an extended gas infrastructure in the region.

In addition, numerous studies show that reducing acidification has significant positive ancillary benefits for human health, mainly, but not only, because particle emissions tend to be reduced as well (Olsthoorn *et al.*, 1997). A study for the European Commission suggests that reducing sulfur emissions in major cities in Europe by 25 kton sulfur would reduce mortality in the short-term by 330–826 cases per year, reduce long-term mortality impacts (linked to small particles) by ten to 60 cases and would lead to lower effects on morbidity such as hospital admissions (Olsthoorn *et al.*, 1997). These results have been confirmed in recent updates under the leadership of IIASA (Holland *et al.*, 1999). Preliminary results from the bright-gas-future scenario suggest a reduction of around 30 Mtons sulfur compared to coal intensive futures. Clearly, reducing sulfur emissions by such an amount (a factor of 1,000 higher than in the European study) would tend to have vast positive implications for human health in Asia. Of course, the exact order of magnitude of these impacts will depend on the location of emission reductions, the atmospheric transport, close-response functions and the population at risk of excessive exposure. Nonetheless, the order of magnitude of these impacts is highly significant, especially in view of the fact that shifts to natural gas will also entail a reduction of particulate matter emissions. In contrast to the situation in Europe, no modeling tools seem to be available at the moment that are able to quantify these human-health impacts for Asia, but their significance can be derived from the above order of magnitude calculations.

In addition to conforming with local environmental and energy objectives, expanded gas use also lessens the possible global warming implications of increased fossil energy use. Of all fossil fuels, gas has the lowest CO_2 emissions per unit energy and thus the lowest global warming impact (provided methane leakages are controlled). In general, the shift to higher quality fuels results in the continued decarbonization of the energy system, and decarbonization means lower adverse environmental impacts (including reduced CO_2 emissions) per unit of energy consumed, independent of any active policies specifically designed to protect the environment.

Energy investments and energy strategies should be chosen in anticipation of uncertain environmental constraints. What can be concluded from the IIASA-WEC study and subsequent work at IIASA is that some constraints (e.g., on carbon emissions) are more uncertain than others (e.g., on sulfur emissions) and that in the face of uncertainty some strategies (e.g., accelerating technological progress, more emphasis on clean energy supplies such as natural gas, and enhanced cooperation in international energy technology R&D, nuclear safety, and energy infrastructures) are more robust than others. They constitute appropriate contingency strategies for the energy sector in the face of future uncertainties that are capable of generating progress across the diverse domains of energy demand, technology, and environmental policy.

7 Conclusions

The objective of this report was to explore the concept of new energy infrastructures (in particular gas pipelines) in Eurasia and to illustrate the order of magnitude of some impacts on future energy systems, on gas trade, and the improvement of local and regional as well as global environment.

The report, building on the IIASA-WEC study on global energy perspectives suggest the following conclusions:

- In all IIASA-WEC scenarios Eurasia becomes the largest energy consumer of the world.

- Resource availability is not expected to be a real constraint in meeting demand, but the concentration of resources in a limited number of areas is. The Siberian and Caspian regions are endowed with enormous gas resources. Natural gas could offer an ideal bridge to the post fossil era, but to achieve this, new Eurasian energy networks need to be planned and eventually developed.

- Expected increases in the use of domestic energy sources in Asia (coal) are associated with severe adverse environmental impacts at local, regional and global levels causing significant damage to human health and the natural environment.

- Up-front investment in gas transit pipelines may constitute a significant portion of the expected investment in the energy sector in Asia. The level of investments will depend on exact network design, but innovative financing schemes could become available under international agreements such as the Kyoto Protocol to the Framework Convention on Climate Change (FCCC).

- Financial risks are significant and will depend on intricate factors such as demand and supply development, technological progress, geographical and political environments and prevailing regulatory regimes (increase in competition in the gas market due to deregulation and transit price policies).

- Timely investments in the necessary infrastructure could imply that FSU gas exports could be ten-fold as high in 2050 as would be the case in business-as-usual type of scenarios.

- Building of the required infrastructure could have significant positive impacts on the global, regional and local environment and also imply significant positive economic impacts. In addition, supply diversification would be promoted.

Sufficient data and methodological resources appear to be available to conduct a more detailed study on the feasibility, costs and environmental benefits of new energy infrastructures in Eurasia. Such a study would be both timely and policy relevant in view of the above conclusions.

References

Amann, M., J. Cofala, P. Dörfner, F. Gyarfas and W. Schöpp (1995), *Impacts of Energy Scenarios on Regional Acidification*, report to the World Energy Council Project 4 on Environment, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Asian Energy News (1997), Asia's Oil and Gas Pipeline Projects, December 1997, p.9.

Asian Energy News (1998), News in Brief, November 1998, p. 1.

Belyaev, L., G. Kovalev and S. Podkovalnikov (1996), Efficiency assessment of "Russia-China-South Korea" electric ties with power export from Primoryer nuclear power plants, The first international World Energy Systems Conference, June 19–21, 1996, Toronto, Canada.

Belyaev, L., G. Kovalev and S. Podkovalnikov (1998), Interstate electricity ties in the Northern Pacific region, *International Journal of Global Energy Issues*, **11**(1/2):00–00.

Berg, E., P. Boug and S. Kverndokk (1998), Norwegian gas sales and the impacts on European CO_2 emissions, Working Paper 9.98, FEEM, Milan, Italy.

Bergmann, B. (1996), Russian Gas in western Europe, the potential for growth, *Petroleum Economist*, **63**(5):50–55.

Bos, E., M.T. Vu, A. Leven and R.A. Bulatao (1992), *World Population Projections 1992–1993*, Johns Hopkins University Press, Baltimore, MD, USA.

CEDIGAZ (1995), Planned gas pipelines around the world, CEDIGAZ, Paris, France.

Downing, R., R. Ramankutty and J. Shah (1997), RAINS-ASIA an Assessment Model for Acid Deposition in Asia. The World Bank, Washington DC.

Ebel, R. (1997), Energy choices and the near abroad: the haves and have-nots face the future, The Center for Strategic and International Studies, Washington, DC, USA.

Elvidge, C.D., K.E. Baugh, V.R. Hobson *et al.* (1997), Satellite inventory of human settlements using nocturnal radiation emissions: a contribution for the global toolchest, *Global Change Biology* **3**:387-395.

European Commission (1997), Trans-European Energy Networks, European Commission, DGXVII, Brussels, Belgium.

Energy Charter (1998), Energy transit, the multilateral challenge, Energy Charter secretariat, Brussels, Belgium.

Fischer, G. and C. Rosenzweig (1996), The Impacts of Climate Change, CO_2, and SO_2 on Agricultural Supply and Trade: An Integrated Assessment, WP-96-05, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A., and N. Nakićenović (1990), Economic Map of Europe: Transport, Communication and Energy Infrastructures in a Wider Europe, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A., and A. McDonald (1995), The drive to cleaner energy, *Options*, Fall/ Winter, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A., M. Jefferson, A. McDonald, S. Messner, N. Nakićenović, H.-H. Rogner and L. Schrattenholzer (1995), *Global Energy Perspectives to 2050 and Beyond*, International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), WEC, London, UK.

Grübler, A., M. Jefferson and N. Nakićenović (1996), Global energy perspectives: A summary of the joint study by the International Institute for Applied Systems Analysis and World Energy Council, *Technological Forecasting and Social Change: An International Journal*, **51**(3):237–264.

Grübler, A., S. Messner, N. Nakićenović, M. Strubegger, K. Riahi, and A. Röhrl (1998), Integrated Assessment Modeling of Global Environment Policies and Decisions Patterns, Final Report to CNRS, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Holland, M., D. Forster, K. King, H. Haworth and P. Watkiss (1999), Economic Evaluation of Proposals for Emission Ceilings for Atmospheric Pollutants, Interim report for DGXI of the European Commission, AEA Technology, Harwell, UK.

Ibrahim, H. (1995), Trans-continental transport of natural gas in Asia: project and prospects, *Revue de l'Energie*, **470**:557–562.

IEA (1994), Natural gas transportation; organisation and regulation, OECD, Paris, France.

IEA (1998), Caspian oil and gas: the supply potential of Central Asia and Transcaucasia, IEA, Paris, France.

Kononov, Y. and B. Saneev (1997), Role of Siberia in interstate gas-supply systems for the Asian-Pacific region, Proceedings of the 7th Economic Forum of the Asia-Pacific region, Ulan-Bator, Mongolia.

Lenovovitz, J.M., (1993), Russians completing new ground-effect vehicle. *Aviation week & Space Technology*, April 26, 62-63.

McMahon, B. (1997), Strong demand for gas set to drive construction boom, *Petroleum Economist*, **64**(5):18–22.

Merenkov, A, N. Ilkevich, Y. Kononov and B. Saneev (1997), Problems in creation of interstate gas-supplying systems for the Asian-Pacific region with attraction of gas resources from Siberia and Far-East, Proceedings of the 1996 World Energy Conference, Toronto, Canada, 1997.

Nakićenović, N., M. Amann and G. Fischer (1995), Integrated assessment, *Options*, Fall/Winter, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N. and H.-H. Rogner, (1996), Financing global energy perspectives to 2050, *OPEC Review*, **XX**(1):1–24.

Nakićenović, N. (1999), Energy Perspectives for Eurasia and the Kyoto Protocol, Section II Chapter 5 in The Sustainable Future of the Global System II, Fuchen Lo, K. Matsushita and H. Takagi (eds), *Proceedings of the International*

Conference on Sustainable Future of the Global System, 23-24 February, Tokyo, Japan, 71-92.

Nakićenović, N, A. Grübler and A. Mcdonald (eds.) (1998) Global Energy Perspectives, IIASA-WEC, Cambridge University Press, Cambridge, UK.

OJG (1999), Azeris must hurry to supply gas to Turkey, *Oil and Gas Journal*, October 18, p.26.

Olsthoorn, A., K. Dorland, H. Jansen, M. van Drunen, A, Bartanova, J. Clench-Aas, C. Guerreiro, J. Hendriksen, S. Larssen and M. Amann (1997), Economic Evaluation of air quality targets for sulphur dioxide, nitrogen dioxide, fine and suspended particulate matter and lead, European Commission, DGXI, Brussels, Belgium.

Paik, K.-W. and J.-Y. Choi (1997), Pipeline gas trade between Asian Russia, Northeast Asia gets fresh look, *Oil and Gas Journal*, **96**(6):41–44.

Pepper, W., J. Leggett, R. Swart, J. Wasson, J. Edmonds, and I. Mintzer (1992), Emission Scenarios for the IPCC. An Update: Assumptions, Methodology, and Results, Paper prepared for IPCC Working Group I, Geneva, Switzerland.

Roberts, J. (1996), Caspian pipelines, Royal Institute for International Affairs, London, UK.

Rogner, H.-H. (1997), As assessment of world hydrocarbon resources, *Annual Review of Energy and the Environment*, **22**:217–262.

Sagers, M. and J. Nicoud (1997), Development East Siberian gas field and pipeline to China: A research communication, *Post-Soviet Geography and Economics*, **38**(5):288–295.

Skagen, O. (1997), Caspian gas, reserves, markets and opportunities, Royal Institute for International Affairs, London, UK.

True, W. (1997) Construction Plans Jump: Operations Skid (Pipeline Economics OGJ Special) *Oil and Gas Journal*, **August 4**:37–44.

True, W. (1998), Robust pipeline construction plans threatened by spreading Asian Crisis, *Oil and Gas Journal*, **96**(6):37–44.

Victor, D., N. Nakićenović and N. Victor (1998), The Kyoto Protocol Carbon Bubble: Implications for Russia, Ukraine and Emission Trading, IR-98-094, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Wigley, T.M.L., M. Salmon and S.C.B. Raper (1994), *Model for the Assessment of Greenhouse-gas Induced Climate Change*, Version 1.2, Climate Research Unit, University of East Anglia, UK.

World reporter (1999), Dialog file data results, Laxenburg, Austria.

Zhao, J., (1999), The Diffusion and Costs of Natural Gas Infrastructures, Draft September, International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).