USSR ENERGY EFFICIENCY AND PROSPECTS

Yury Sinyak
International Institute for Applied Systems Analysis,
Laxenburg, Austria

RR-91-7
June 1991

Reprinted from *Energy*, Vol. 16,
No. 5, pp. 791–815, 1991.

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

Reprinted with permission from *Energy*, Vol. 16, No. 5, pp. 791–815, 1991.

Printed by Novographic, Vienna, Austria

Preface

The USSR and the countries of Eastern Europe now face many problems relating to the re-evaluation of economic and political concepts. This process will in turn influence energy systems (considered to be the basis for industrial development) which have become a heavy burden on their economies. However, political and economic changes are just beginning in Eastern Europe and it is too early to discuss *how the future shape* of economies will be, or *how far* the tranformation from planned to market oriented eocnomies will go, or *how soon* we can expect noticeable results. One thing is certain: the future economic structure of Eastern European countries, including the USSR, should and will be less energy intensive than they were in the past and are still at present. This means that practically all past energy projections should now be considered outdated (including the most recent ones). This is because they were developed on the basis of old economic concepts which, to a large degree, are now completely unreasonable, are publicly unacceptable, and are overburdened with heavy industries with rigid structures, low economic efficiency, and high energy consumption.

The study performed by Yury Sinyak within IIASA's Energy and the Environment Activity is aimed at analyzing enery efficiency in the USSR and at clarifying the main reasons why the energy intensity in this country is much higher than in many other industrialized countries. He shows the existence of a large energy saving potential in the Soviet economy, the utilization of which could substantially improve energy efficiency and reduce energy demand growth. An attempt is made to evaluate future energy developments with different assumptions for efficiency improvement rates and economic progress, as well as primary energy restructuring to achieve CO_2 reductions within the next decades.

BO R. DÖÖS
Leader
Environment Program

Energy Vol. 16, No. 5, pp. 791–815, 1991
Printed in Great Britain.

0360-5442/91 \$3.00 + 0.00

U.S.S.R.: ENERGY EFFICIENCY AND PROSPECTS†

YURY SINYAK‡
International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

(Received 17 May 1990)

Abstract—The U.S.S.R. is the largest energy producer and the second largest energy consumer in the world. Its share of global energy use reached above 17% in 1988. The Soviet energy system is characterized by low efficiency and high *per capita* energy consumption, although there are some reasons justifying the greater U.S.S.R. energy use per unit of product output than in other industrialized countries. The present energy-savings potential is approximately equal to one-half of the domestic energy consumption. Improvements in energy efficiency at all levels of the national economy are now considered to be the primary goal of national energy policy for the next couple of decades. Being endowed with abundant natural gas resources, the U.S.S.R. will count on this energy source in the future to improve its energy efficiency, reduce expenses and cope with air pollution. After 2005–2010, stabilized primary energy consumption may be reached or there may even be a decline of total energy use. The U.S.S.R. could reduce CO_2 emissions by 20% by 2030 but with substantial negative impacts on GNP growth. Required improvements in the Soviet energy system depend on changes in energy management, including reduction of the role of centralized planning, decentralization and privatization of energy-producing facilities, energy-price reforms, reshaping of investment patterns, reduction in military expenditures, etc.

U.S.S.R. ENERGY DEMAND AND SUPPLY (1960–1985)

The U.S.S.R. energy systems

In 1988, the U.S.S.R. production of all forms of energy reached more than 2.4×10^9 tce, including more than 624×10^6 tons of oil and natural gas liquids, about 750×10^9 m^3 of natural gas (NG), and 467×10^6 tce of coal. Electricity generation amounted to 1.705×10^{12} kWh. A considerable contribution of 216×10^9 kWh (corresponding to more than 65×10^6 tce) was provided by nuclear power plants. Exports of energy supplies reached 446×10^6 tce.

While producing around one-sixth of the world's gross national product, the U.S.S.R. is the second largest energy consumer in the world after the U.S.A. Its share of global energy demand exceeded 17% in 1988. Among Eastern European countries (CMEA), the U.S.S.R.'s share of the total energy demand equals 75% while its share of energy production is 85%. There is no reason to expect these proportions to change dramatically in the future.

The country's growing industrial requirements for fuel and energy are expected to be met primarily by energy conservation and by increasing NG production, as well as by the use of coal and nuclear energy, although to a lesser extent than was predicted in the past because of difficulties with coal production and acceptability of nuclear energy. As present, the Soviet Union has no energy program that is designed to respond to potential global warming. It is possible that Soviet energy policy will be reevaluated in the near future to make adjustments relating to CO_2 minimization.

The Soviet Union's energy system is summarized in Table 1. Vast amounts of available domestic energy resources (notably coal, NG, and hydropower) now determine the country's economic development and will continue to do so in the foreseeable future, while maintaining energy exports at high levels. This last statement may not apply over the long term and is strongly criticized within the Soviet Union. However, during the short and medium terms, the

†Report for Contract No. 89-17 between IIASA and the Central Research Institute of the Electric Power Industry, Otemachi Building, 1-6-1 Otemachie, Chyoda-ku, Tokyo 100, Japan, for a study on "Collection and Evaluation of Energy/CO_2 Data for the World with Major Emphasis on CMEA Countries".

‡Permanent address: Working Consultive Group of the President of the U.S.S.R. Academy of Sciences on Long-Term Energy Forecasting, Room 79–80, Vavilov Street 44/2, 117333 Moscow, U.S.S.R.

Table 1. Features of the U.S.S.R. energy system.

Vast domestic energy resources (coal, NG, hydro-power).
Long-distance energy transportation from East to West.
Limited possibilities for rapid structural changes.
Severe climatic conditions.
Mass urbanization with multi-story housing.
A centralized administrative system of management.

exports of crude oil and NG will provide the major sources of hard-currency income that is needed to sustain and provided *perestroijka* changes in the U.S.S.R.

The vast territory and uneven energy-resource distribution make the problem of long-distance energy transportation particularly important. The characteristics of two major parts of the U.S.S.R. (European and Asian) are described in Table 2. The primary cheap coal resource suitable for open cast mining, as well as the largest and most efficient hydropower and NG resources, are located in the eastern parts of the U.S.S.R. At the same time, 75–80% of the total current fuel and energy consumption is concentrated in the European U.S.S.R., including the Urals. In the future, this figure will drop but, even at the beginning of the next century, it is unlikely to be lower than 65–70%.

The eastern parts of the U.S.S.R. are extremely well endowed with bituminous coal (the Kuznetsk and Ekibastuz basins) and brown coal (the Kansk–Achinsk basin) located in favorable mining and ecological environments, which make these coals fairly cheap fuels at the points of production. These regions also contain the abundant hydropower sources of the Angara–Yenisey basin.

The world's largest NG fields have been discovered in Siberia and are currently being exploited. There are also considerable reserves, especially NG, in other parts of the country (the Pre-Caspian depression, Central Asia, the Far Eastern offshore region, Yakutiya).

Table 2. Comparative characteristics of the European part of the U.S.S.R. and the Eastern Regions (as of the early 1980s).

Characteristic or Feature	European USSR	Eastern Regions
Territory	25%	75%
Population	78%	22%
Population density per km^2	370	5
Raw material resources		
Iron ore	77%	23%
Phosphorite	65%	35%
Wood	21%	79%
Water	20%	80%
Agricaltural land	39%	61%
including arable land	68%	32%
Energy resources		
Potential	9%	91%
Developed	27%	73%
Specific costs relative to the USSR average:		
Fuel production	125-135%	50-80%
Electricity generation	105-115%	70-80%
Construction	100%	105-125%
Wages	100-110%	105-125%
Social infrastructure	85-95%	105-150%

Table 3. Heating seasons in different countries (Ref. 1).

Country	Minimum winter temperature, °C	Mean winter temperature, °C	Degree-days	Ratio to the USSR in %
USSR	-24	-3.2	4360	100
USA	-10	+4.9	2316	53
FRG (Bremen)	-11.8	+4.0	2530	65
France (Paris)	-9.4	+5.6	2456	56
UK (London)	-7.4	+8.1	2350	54

Despite the fact that over the past 10–20 yr virtually all new, highly energy-intensive industries have been developed in Siberia, the growing energy requirements of the European part and the scarcity of cheap Western energy resources (virtually all coal of the European U.S.S.R. is produced in deep mines from thin beds) make it necessary to move ever-increasing amounts of fuel and energy from the eastern part of the country to the European part. Bulk energy transportation increased substantially over the short period from 1970 to 1985: from 125 million tce to 975 million tce/yr. Over one-half of these resources are in the form of coal and of NG, the transportation of which over distances of 2500–4000 km is extremely costly. This is why the European U.S.S.R. has been and will remain a zone for expensive fossil fuels. This unique situation justifies the search for efficient ways of transporting large amounts of fuel and transmitting energy over large distances, which poses one of the most important scientific and technical problems for the U.S.S.R. energy-distribution network.

Available cheap fuel resources, as well as the internal political situation, allow the country to pursue a policy of self-sufficiency, which means developing energy-intensive industries such as metallurgy, bulk-product chemicals, etc. This emphasis has reduced the possibilities for rapid and efficient structural changes promoting a reduction in the energy/GDP ratio, as could be happening in countries where energy-intensive industries are being vigorously phased out.

The climatic conditions in most of the country differ considerably from those in most of Western Europe and the U.S.A. There are long, severe winters and moderate summer temperatures. This fact leads to a relatively large energy demand for low-temperature processes in space heating. There are almost twice as many space heating degree-days in the U.S.S.R. as in the majority of other developed countries (Table 3). Two-thirds of the Soviet population lives under harsh climatic conditions, compared with 16% in the U.S.A. (Table 4). This is a determining factor for the high level of energy consumption in the U.S.S.R. At the same time, it implies a large potential for energy savings based on energy-efficient technologies (e.g., cogeneration, heat pumps, etc.).

Mass urban housing construction, in the form of fairly compact housing complexes with multi-storied buildings, promotes large-scale centralized heating, which constitutes over 50% of the total low- and medium-temperature heat consumption for industry and the residential and commercial sectors (including 60% cogeneration for heat supply). A centralized heat-supply system helps to improve urban air quality drastically and offers good opportunities for the use of a multitude of fuels. Recently, the centralized heat suppliers in some big cities have had problems with reliable and efficient controls, which necessitates corrections and even changes

Table 4. Percentages of the population of the U.S.S.R. and the U.S.A. living in cold climates.

Temperatures	USSR	USA
-18° and below	66	16
-18° to -21°C	14	11
-21° to -25°C	32	4
-25° to -29°C	14	1
below -29°C	6	-

Table 5. Energy consumption in percent for various sectors during the early 1980s (from Ref. 1).

Sector	Sectors of the National Economy										
	Energy	Iron and Steel	Chemicals	Forestry	Machinery Construction	Construction	Consumer Goods	Agriculture and Fishery	Transportation	Other	Total
Coal	50.7	25.4	1.0	2.1	3.0	5.8	3.7	2.5	4.4	1.4	100.0
Crude-oil production	99.1	0.0	0.8	0.0	0.0	0.1	0.0	0.0	0.0	0.0	100.0
Crude-oil refining	15.9	3.7	5.2	3.4	5.2	13.3	3.4	23.8	24.2	1.9	100.0
Natural gas	36.4	18.8	8.6	1.4	10.4	13.8	5.1	0.0	0.2	5.3	100.0
Peat	64.4	0.2	0.2	1.3	0.4	5.0	3.8	23.1	0.2	1.4	100.0
Shale	43.9	4.8	8.4	6.4	2.7	24.1	7.3	1.1	0.2	1.2	100.0
Electricity and heat generation	10.9	14.9	13.7	4.2	16.5	13.6	8.9	3.7	8.4	5.2	100.0
Total	31.8	13.3	6.1	2.9	7.5	10.4	4.9	9.5	10.9	2.7	100.0

Table 6. Cost structure in percent of the Soviet energy system (from Ref. 1).

Sectors of the National Economy	Energy-System Sectors							
	Coal	Crude-Oil Production	Crude-Oil Refining	Natural Gas	Peat	Shale	Electricity and Heat Generation	Total
Energy	37.5	13.3	44.0	8.1	44.7	49.0	94.6	48.8
Iron and Steel	1.3	0.5	0.5	0.1	1.5	3.1	0.7	0.8
Chemicals	2.2	1.1	2.7	1.2	1.7	17.0	0.8	2.0
Forestry	9.0	0.2	0.3	0.2	1.9	4.7	0.1	2.9
Machinery construction	4.4	2.5	0.7	0.4	11.2	9.4	2.8	2.5
Construction	0.7	0.1	0.1	0.0	0.6	0.4	0.2	0.3
Consumer goods	1.5	0.6	0.5	0.2	2.9	2.5	0.5	0.8
Agriculture and fishery	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Transportation	38.0	64.3	36.0	89.7	34.4	13.3	-	33.8
Other	5.4	17.4	15.2	0.1	1.0	0.6	0.3	8.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

in the construction of large heating systems, especially for regions with future NG-based heat supplies. Almost one-half of the heat is produced at low efficiencies in small boiler plants and individual heating systems operating on solid fuels, especially coal.

The existing pattern of housing construction and centralized, largely electrically-driven public transport (suburban railway, the metro, trolley-busses, and trams) has reduced the need for extensive use of private cars for daily commuting to and from work. As a result, liquid-fuel consumption for transport is considerably lower than in other developed countries.

For a long time, the centralized administrative system of planning resulted in increased conflicts between long-range prospects, presumably based on assessments of cost-effective energy solutions (although careful analysis of the internal and external factors often showed that these assessments were seldom justified), and short-term management which demanded the fulfillment of production and management plans by whatever means, without taking into consideration the economic aspects of the problem. For energy sytems, this practice took place under a dual energy-pricing system: (i) state prices of fuel and energy based on cost calculations (in the Soviet case, without including the cost of return on capital), which are in use for everyday transactions and payments, and (ii) marginal energy prices, which were derived by optimization of the state/regional energy balances and included the full cost of energy production, processing, transportation, and distribution, plus differential rents reflecting the usefulness of different energy sources. The latter pricing system was recommended for assessments of new energy-related technologies. Because the two price systems differed by a factor of at least two, it became clear that the long-range solutions were contradicting the short-term needs. This policy of using dual-price systems has resulted in many ineffective solutions for the energy-supply and demand system. These solutions are based on short-term considerations prevailing over long-term interests.

Energy systems have close interconnections with other important sectors of the national economy. The links are not only determined by supply conditions for consumers using all types of fuels and energy sources and by ensuring energy development through investment but also by selections of feedstocks and materials and applications of the combined resources and facilities which involve appropriate technical solutions.

One can get some ideas of the structure and importance of the energy systems and their links to other sectors by analyzing the ties. Tables 5 and 6 show the product and material cost distributions for energy industries relating to a number of important sectors. Ties to the energy systems are seen to be dominant and amount to about one-third of the volume of distributed products and to about one-twelfth of all material costs. They are determined by fuel consumption for processing of other types of fuels, energy conversion and the sectorial energy needs. Of the external energy ties, those with the transport sector account for about 11% of all energy products in terms of cost. The transport share (Table 6) amounts to one-third of all energy expenditures and is relatively most important for oil and gas. Transport, agriculture and fisheries require nearly 50% of the oil-refining product costs. A large consumer of energy products, especially of coal (for coke production), gas and electricity, is metallurgy. The leading consumers also include chemicals, machinery and construction, the overall share of which equals one-quarter of the total energy costs. The share of the timber industry is mirrored in costs for the coal industry, which reflects the large need for timber in coal mining.

Primary energy supply and demand

Table 7 shows the primary energy supply and consumption in the U.S.S.R. from 1960 to 1988. During this period, the gross energy consumption increased three-fold, while the NMP (national material product) increased 4.2 times. The annual NMP growth rate declined systematically from 5.4%/yr in 1960–1970 to 2.6% in 1980–1988. This reduction did not result from an increase in energy efficiency but primarily from a downturn in economic activity in the 1980s. The share of fossil fuels during this 25-yr period decreased from 96 to 94%.

Export of energy resources reached more than 446 million tce, compared with 60 million tce in 1960, and constituted almost 18% of the total energy supply. About 90% of Soviet energy export in 1985 was in the form of crude oil, petroleum products, and NG. More than 30% of the crude oil produced is exported. For coal and NG, the shares of exported resources are only

Table 7. Primary energy supply and consumption in 10^6 tce (from Ref. 2).[a]

Supply or Consumption	1960	1970	1980	1985	1988
Supply, total	828.5	1402.5	2171.1	2439.2	2466.9
fossil-fuel production	692.8	1221.8	1895.6	2073.1	2277.2
hydroelectric power	23.8	45.5	60.1	69.1	81.8[b]
nuclear power	7.2	9.1	28.2	59.9	65.2
imports	10.7	14.1	17.8	30.8	42.7
Stock at the beginning of the year	94.0	112.0	169.4	206.3	
Consumption, total	828.5	1402.5	2171.1	2439.2	2466.9
Domestic consumption	670.0	1118.2	1673.3	1879.5	1985.6
secondary energy generation and processing (electricity, heat, compressed air, etc.)	238.6	487.2	788.9	908.2	n.a.
direct fuel consumption (including losses during transport and storage)	431.4	631.0	884.4	971.3	n.a.
Export	59.8	169.5	327.8	352.2	446.5
Stock at the end of the year	98.7	114.8	170.0	207.5	34.8

[a]The conversion factor for nuclear, hydroelectric, geothermal, and other renewable energies has been taken to be equal to the average specific fuel consumed in generating electricity in thermal power plants.
[b]Including other renewables and fossil fuels.

Table 8. Primary fossil-fuel production in 10^6 tce (from Ref. 2).

Fossil Fuel	1960	1970	1980	1985	1988
Coal	373.1	432.7	476.9	439.8	467.0
Crude oil	211.4	502.5	862.6	851.3	892.8
Natural gas	54.4	233.5	514.2	742.9	889.4
Other	53.9	53.1	41.9	39.1	28.0
Total	692.8	1221.8	1895.6	2073.1	2277.2

8 and 12%, respectively. The import of energy resources is much less than the export and constitutes around 1.3–1.7% of the energy supply for the entire period.

The growth of the share of secondary (processed) energy in domestic energy consumption is an indicator of progressive shifts in the national energy balance. For the last few years, this share has increased from 36% in 1960 to 48.3% in 1985. For the period under consideration, the electricity coefficient (share of electricity in the final energy consumption) grew from 7 to 13.1%.

Energy losses in the transportation and distribution systems continue to remain at a high level (76 million tce or more than 13% in 1985, of which two-thirds represent losses in the electricity and heat-supply grids: 43.6 and 7.7 million tce, respectively).

Major changes have occurred in the restructuring of domestic fossil fuel production (Table 8). The total level of fossil-fuel production increased from 690 million tce in 1960 to 2100 million tce in 1985. At the same time, the share of coal declined from 54 to 21%, the share of oil increased from 30.5 to 41.1% and NG from a mere 7.8 to 35%. Natural gas production is now almost equal that of crude oil; NG clearly exceeds all other sources in domestic energy consumption.

An overview of domestic primary energy consumption by sectors of the economy is shown in Table 9. The structure of energy consumption by sector reflects progressive changes in the

Table 9. Primary energy consumption by sectors in 10^6 tce (from Ref. 2).

Sector	1960	1970	1980	1985
Total domestic consumption	670.0	1118.2	1673.3	1879.5
Industry	390.6	661.6	900.3	957.4
Construction	12.3	27.8	41.9	53.4
Transportation	60.0	121.0	206.7	241.5
Agriculture	34.9	63.6	118.7	131.3
Residential and commercial	172.2	244.2	405.7	490.9

energy system. The share of the energy-intensive industrial sector declined from 58.3 to 51%, the transportation sector increased from 9 to 13% and the remaining three sectors (agriculture, construction, and the residential/commerical sectors) remained nearly constant. These moderate shifts in the distribution of energy have followed small improvements in the energy/NMP ratio during the last 25–30 yr. Achievements in reducing the energy intensity of the Soviet economy could have been far greater if the shifts in economic structure had been more pronounced.

Final energy consumption

The final energy consumption reflects the quality of the energy resources delivered to end-users. It follows from Table 10 that the share of processed energy (electricity and low temperature heat) rose from 30.8% in 1980 to almost 46% in 1985. At the same time, the growth rate of electricity use increased only from 9.2 to 13.0%, which suggests that modest technological changes in the economy did not increase productivity and efficiency significantly. Losses in energy processing were reduced from 42% in 1960 to 28% in 1985, demonstrating good progress in the energy-conversion sectors and contributing to the growth of overall efficiency.

Seventy-five percent of final energy consumption occurs for material production and the rest in the residential and commercial sectors. This proportion seems likely to stabilize in the near future. Table 11 shows the final energy consumption divided according to end-use processes. During the last 25 yr, large changes have taken place in the share of motive power (from 17% in 1960 to 23% in 1985) and there has been a reduction in the share of high-temperature heat (from 28 to 21%). These have contributed to an increase in overall energy efficiency, first because the use of electricity or petroleum products in motive processes takes place with higher efficiency than for steam drive and, secondly, because the high-temperature heat produced by fossil fuel burning shows very low energy efficiency. In the future, these trends are likely to continue. With further growth in the use of low and medium temperature heat, improvements will occur in the overall energy efficiency.

Table 10. Final energy consumption and applications in 10^6 tce.

Application	1960	1970	1980	1985
Total final energy	390.2	753.3	1144.5	1350.7
Direct fossil fuels, including motor fuel	269.9	457.0	630.2	736.7
Electricity	35.9	90.4	156.8	186.4
Low and medium heat[a]	84.4	205.9	357.5	427.6

[a]The heat-generation units are included in the category of energy-conversion equipment with their losses treated as energy losses in fuel processing and conversion.

Table 11. Final energy consumption for different processes in percent (from Ref. 4).

Process	1960	1970	1980	1985
Lighting	0.07	0.08	0.11	0.14
Electrochemical and electrophysical processes	0.45	0.60	0.90	0.90
Motive power	16.60	18.60	22.00	22.50
High-temperature heat	28.30	25.50	21.60	20.50
Low- and medium-temperature heat (steam and hot water)	54.40	55.20	55.40	56.00
Total final consumption	100.00	100.00	100.00	100.00

Electricity generation and heat supply

Since the beginning of Soviet history, electrification of the national economy has been considered to be a vital part of industrialization and the resolution of social problems. For many years, the growth rate of electricity consumption exceeded those of fossil-fuel consumption and of the NMP. For example, from 1960 to 1985, the average growth rate of electricity consumption was 6.9%/yr as compared with a NMP-growth rate of 5.5% and a total

Table 12. Electricity generation by power-plant type in 10^9 kWh (from Refs. 3–5).

Power Plant	1960	1970	1980	1985	1988
Thermal	241	612.9	1037.0	1154.1	1258.0
Nuclear	–	4.0	72.9	167.4	216.0
Hydro and other	51	124.0	184.0	222.7	231.0
Total	292	740.9	1293.9	1544.2	1705.0

primary energy-consumption growth rate of 4.2%. In spite of the importance of electricity in reconstruction and technological progress, the development of the electricity sector (especially in the 1970s and 1980s) has been associated with difficulties and tensions. As an example of the difficult situation in this sector, it should suffice to mention that since the 1960s, investments in the electricity sector have remained practically unchanged despite a manifold increase in installed capacity and the increasing length of the electricity-transportation grid. As a result, a number of obsolete installations are still in use. The Chernobyl accident further slowed the pace of reconstruction in the electricity sector. Not until the current 5-yr plan have investments been increased. It will take many years to improve the technical standard in the electricity sector.

Meanwhile, despite some difficulties, the Soviet electricity sector has achieved remarkable success over the last 30 yr (Table 12) during which time generation of electricity increased 5.3 times. The structure of electricity generation by primary energy changed slightly. While in 1960, 78% of electricity was produced in thermal power plants, in the mid-1980s, their share declined to 75%. Over the same period, the share of hydroelectricity also declined from 17 to 14%. The gap was filled with nuclear electricity the input of which in total electricity generation reached almost 11% in 1985.

More pronounced changes were seen in the mix of electricity generation from primary energy sources (Table 13). Over a period of 15 yr (1970–1985) the share of solid fuel in electricity generation dropped from more than 40% to less than 25%. The share of fuel oil, after some increase in the 1970s up to 28%, was reduced to 16%. The share of natural gas took off suddenly in the early 1980s from less than 20% to more than one-third. Nuclear electricity also grew steadily in the first part of the 1980s, reaching almost 11% in the mid-1980s. The share of hydroelectric power has been reduced from 20% to less than 15%.

The capacity factor for the whole electricity sector has improved steadily (Table 14), mainly due to the introduction of base-load nuclear energy with a higher level of capacity utilization. At the same time, a decline in the capacity factor for fossil fuel power plants and hydroelectric

Table 13. Electricity generation by primary energy sources in percent (from Refs. 6, 7).

Fuel Type	1970	1980	1985
Coal	41.4	32.1	24.7[a]
Fuel oil	17.8	28.0	16.1[a]
Natural gas	19.3	19.3	34.0[a]
Peat, wood, etc.	2.5	0.8	–
Nuclear	0.5	4.5	10.8
Hydro	18.5	15.3	14.4
Total	100.0	100.0	100.0

[a] 1987.

Table 14. Capacity factors and fuel efficiencies for electricity generation and heat supply (from Refs. 2, 3).

Capacity Factors and Fuel Efficiencies	1960	1970	1980	1985	1988
Capacity factors	0.54	0.54	0.57	0.58	0.58
Thermal	0.67	0.62	0.65	0.65	0.64
Hydro	0.44	0.47	0.42	0.41	0.42
Nuclear	n.a.	0.44	0.67	0.70	0.70
Specific-fuel consumption					
Electricity, g.c.e/kWh	468	367	328	326	325.0
Heat supply, kg. c.e./Gcal	181.2	175.7	173.0	172.9	172.9

Table 15. Electricity consumption by sectors in 10^9 kWh (from Refs. 2, 3).

Sector	1960	1970	1980	1985	1988
Industry	207.5	493.2	778.3	899.9	980.7
Transportation	17.6	49.6	97.4	113.7	132.7
Agriculture	10.0	38.6	110.9	145.7	166.8
Residential and Commercial	39.4	96.0	181.3	222.2	245.9
Grid losses	17.8	58.3	106.9	133.7	139.9
Export	0.03	5.2	19.1	28.9	39.0
Total	292.3	740.9	1293.9	1544.1	1705.0

stations was registered, due mainly to an increasingly uneven load curve. At the same time, a lower water supply resulted in a decline of hydroelectricity and less utilization of hydroelectric stations.

Shifts in fossil-fuel consumption for electricity generation toward heating oil and NG caused a reduction in specific fuel consumption of 30% during the period 1960–1985. The results would have been more impressive if there had not been the need to continue the use of out-of-date equipment with low energy efficiency.

The consumption of electricity almost equals generation, since the export of electricity, while increasing, has not yet exceeded 2% (Table 15). We note a decline in the industrial share from 71% in 1960 to 59% in 1985. During the same period, agricultural consumption increased from 3.4 to about 10%. The shares of the transportation and residential/commercial sectors changed little, although the absolute levels of electricity consumption increased substantially.

The penetration of electricity into all sectors of the Soviet economy largely accounts for the technological and social progress achieved during the last decades. Unfortunately, this success has not been adequately followed by organizational and institutional changes. It has been sufficient to prevent the economic difficulties the Soviet economy now faces.

In the U.S.S.R., over 35% of the primary energy resources are used for the generation of low-temperature heat, usually produced in boilers of various types, waste-heat installations, and small household heating devices (ranging from old Russian ovens used in rural areas for space heating and cooking to new electric devices such as heat pumps or radiative heaters). In spite of the fact that more than one-third of domestic energy is consumed in the heat-supply sector, the statistics for heat generation and utilization are incomplete and inconsistent. Sources often contain contradictory information. We have tried to put the information in order as far as possible. Nevertheless, we do not claim that the data on heat supply are now completely correct and consistent.

The heating demands of the Soviet economy increased from 910 million Gcal in 1960 to 3430 million Gcal in 1985 (Table 16). These demands have been covered by two different

Table 16. Low-temperature heat supplies as steam and hot water in 10^6 Gcal (from Ref. 8 and author's assessments).

Heat Supplies and Sources	1960	1970	1980	1985
Steam and hot water	590	1440	2500	2990
Direct fuel use (household devices and small boilers)[a]	320	460	450	440
Total heat supplies	910	1900	2950	3430
Sources of heat supplies				
Centralized systems	300	810	1580	2030
Cogeneration	270	700	1150	1480
Boiler houses[b]	30	110	430	550
Decentralized systems	610	1090	1370	1400
Small collective heating installations	275	590	810	810
Waste-heat boilers	15	40	110	150
Household devices	320	460	450	440

[a]Without cooking.
[b]Heat capacity >50 Gcal/h.

means: (i) steam and hot water (the share of which rose from 65 to 87% during the period under consideration) and (ii) radiative heat produced by the direct use of fuel in special installations of small dimensions, mainly in rural areas. This second form is decreasing steadily. At the same time, electric heating devices are becoming more important. While the contribution of these heating devices is not yet more than a couple of percent, the prospects are good as wider use is made of heat pumps for space heating, air conditioning, and hot water, both in centralized and decentralized systems. In the future, the share of direct fuel use will decline and the share of steam and hot water will also be reduced by increasing use of electricity.

A second pronounced trend in the Soviet heat-supply system is growth in the share of centralized systems from 33% in 1960 to 59% in 1985. At the present time, the concept of centralizing the heat supply further by using large heat-generating facilities (cogeneration power plants or large boiler stations) is being widely criticized because of the low reliability of these systems and associated high heat losses. A new concept of combined heat and electricity generation based on NG-fired gas turbines with waste-heat boilers appears attractive from economic, ecological, and energy-efficiency points of view.

Most of the heat produced in centralized systems comes from cogeneration plants, the output of which increased from 270 to 1480 million Gcal. In spite of the fact that the share of cogeneration heat production declined from 90% in 1960 to 73% in 1985, cogeneration remains a principal means of technological progress in this field. Cogeneration is energy-efficient (for example, in the early 1980s, the specific fossil-fuel consumption in condensed thermal power plants equalled 356 g/kWh as compared to only 265 g/kWh in cogeneration plants). The significant share of cogeneration electricity (almost one-third of all electricity generated in the U.S.S.R.) has made it possible to achieve progress in energy savings in electricity generation (see Table 14). Cogeneration facilities comprise almost 40% of the total installed capacity of thermal power plants. However, their contribution to electricity generation equals only 25%. This means that the utilization of cogeneration capacities needs to be improved through better adjustments of electricity and heat supply-and-demand (seasonal/weekly/daily) curves.

The structure of the centralized heat-generating facilities is given in Table 17. More than 50% of the heat produced is in the form of hot water and more than 70% is produced by small heat generators with a capacity less than 20 Gcal/h. Until recently, increased generating capacity was considered to be a means for improving the economic and energy efficiencies, but this concept is now being questioned by many scientists who recommend wider use of small and medium-sized devices equipped with NG-fired gas turbines and waste-heat boilers that provide higher reliability and improved efficiency for both costs and energy.

The growth of the centralized heat-supply systems has been followed by a steady increase in the lengths of the heat-supply mains, which now equal about 30,000 km. As the lengths of the heat-supply mains have been increased, so have their damage rates and this fact has lowered the reliability of heat supply and become a real problem in many cities of the Soviet Union.

Direct fuel use for low temperature heat supply continues in the residential and commercial sectors of rural areas, as well as in small agricultural enterprises. It is interesting to analyze the use of steam and hot water. Table 18 shows data on consumption in the form of steam and hot

Table 17. Heating values of centralized heat-generation facilities as of 1985 (from Ref. 9).

Facility	Total	< 20 Gcal/hr	20–50 Gcal/hr	> 50 Gcal/hr
Total number of boiler houses, 10^3	437.6	429.5	5.8	2.3
Number of steam boilers, 10^3	366.0	324.4	34.5	7.1
Total heat supply from steam boilers in 10^3 Gcal/hr	757.4	506.8	124.7	126.0
Number of water heaters, 10^3	617.1	605.3	7.6	3.9
Total heat supply from water boilers, in 10^3 Gcal/hr	826.0	606.5	57.5	162.0
Net heat supply, in 10^6 Gcal	1657.3	910.4	308.5	438.4
Fuel consumption, in 10^6 tce	290.7	165.1	52.3	73.3
Specific fuel consumption, kg ce/Gcal	175.4	181.4	169.7	167.1

Table 18. Steam and hot water heat supplies by sectors in 10^6 Gcal (from Ref. 8).

Sectors	1960	1970	1980	1985
Industry	350	711	1386	1533
Construction	5	25	41	44
Transportation	-	4	42	47
Agriculture	-	11	57	86
Commercial	35	189	286	313
Residential	80	233	335	584
Others	70	110	122	127
Grid losses	50	157	231	256
% cogeneration	46	49	46	46
Total district heating	590	1440	2500	2990

water. Industry remains the largest consumer of low-temperature heat of this kind, although its share declined from almost 60% in 1960 to 51% in 1985. The residential/commercial share increased from 19 to 30% during the same time period. There has been improvement in the living standards in the cities, where decentralized heat-supply systems based on direct fuel use were steadily replaced by centralize systems for space heating and hot-water preparation. Heat losses in the supply grid have remained constant at about 8.5%. The share of total grid losses is greater according to some.

Direct fuel use for low-temperature heat production is summarized in Table 19. The share of direct fuel use in total heat supply declined from 35% in 1960 to only 13% in 1985 and is still declining. In 1960, two-thirds of direct fuel use came from "other" sources, i.e., the self-supply by the population through wood gathering, refuse-burning, etc. By the end of the 1980s, the share of this source had been reduced to 9%. The remaining direct fuel use (mainly in rural areas and small settlements) was covered by the state fuel supply system and was divided almost equally between coal and NG or LPG. The share of coal is expected to decline in the future as the share of NG rises rapidly, especially in rural areas.

Table 19. Approximate structure of the direct fuel-use system in small heat-supply generators in percent.

Source	1960	1970	1980	1985
Coal	29.0	52.0	46.0	44.0
Petroleum products	-	-	14.0	12.0
Natural gas	4.5	13.5	25.0	35.0
Other	66.5	34.5	15.0	9.0
Total	100.0	100.0	100.0	100.0

Energy savings and overall energy efficiency

Primary energy saving reflects the efficiency of national efforts in energy conservation. There are direct savings as the result of improvements in efficiency, changes in fossil-fuel mix and shifts in industrial production. There are also indirect energy savings as a result of fossil-fuel replacement by nuclear and renewable energy sources. Table 20 shows that the fraction of indirect savings increased from 18% in 1960 to 38% in 1985. What we call direct energy-saving measures declined. Since energy conservation was not seriously pursued in the 1970s, direct

Table 20. Primary energy savings in 10^6 tce achieved for various time periods.

Energy Source	1970–1975	1975–1980	1980–1985
Fossil fuels	53.7	29.0	40.0
Electricity and heat	41.5	37.5	37.9
Motor fuels	15.0	14.2	14.7
Replaced by nuclear and hydroelectric energy	24.8	44.3	57.4
Total primary energy savings	135.0	125.0	150.0

Table 21. Direct energy savings by sector.

Sector	1960–65	1965–70	1970–75	1975–80	1980–85
Industry (%)[a]	49.7	61	63.8	71.3	67.6
Transportation (%)	47.7	36	28.9	18.5	21.0
Agriculture (%)	–	–	4	4	3
Residential and commercial (%)	3	3	3.3	6.2	8.4
Overall energy efficiency, in %	32	36	38	40	42
Total direct savings in 10^6 tce	167	130	90	81	93

[a]Including the energy supply sectors.

energy savings declined from 110 million tce in 1970–1975 to only 80 million tce in 1975–1980. The situation improved slightly in the 1980s and reached more than 90 million tce in the first 5-yr period of the 1980s.

Table 21 shows the direct energy savings by sector. In the 1950s, a large portion of the direct energy savings occurred in the transportation sector where low-efficiency stream drives in the railways were phased out and replaced with diesel or electric engines. This process was practically completed by the early 1980s. As a result the efficiency of energy-saving measures dropped. Major achievements in energy savings occurred in industrial processes, which have a large remaining potential for improvements and energy savings. A modest contribution to energy savings has been made in the residential and commercial sectors. Considerable savings potential remains.

According to some assessments, the overall energy efficiency of the Soviet energy system changed from 32% in 1960 to 42% in 1985. This means that in spite of many malfunctions in the system, the overall energy efficiency remains at a rather high level. Unfortunately, the overall energy efficiency reflects only one side of the national economy and has not been sufficient to reduce the energy intensity of the economy to desired levels. An inefficient productive system connected with an inadequate product-mix structure are the main potentials for improvements of the national economic situation, as well as the overall energy efficiency.

Rough assessments show that of 58% of the overall primary energy losses in the U.S.S.R., 22% occur in extraction, separation, transportation, and conversion of the primary energy resources, including approximately 12% of energy losses at the electric power plants. The remaining 38% of losses occur at the end-use locations.†

ENERGY/NATIONAL MATERIAL PRODUCT AND VALUE ADDED RATIOS

Energy supplies require considerable financial resources and both delivery rates and priorities must be properly selected.‡ A properly selected energy-development strategy is needed for accelerated economic development.

During the period 1960–1985, the U.S.S.R. national material product (NMP) or national income increased by a factor of 3.83 (Table 22) as compared to an increase in primary energy consumption by a factor of 2.8. If we consider the NMP growth rates over the 10-yr period from 1960 to 1970, we see that the Soviet economic system growth rate declined steadily: 6.74% for 1960–1970, 4.77% for 1971–1980, and 4.59% for 1981–1985. The NMP structure also changed during this period. The industrial share, which constituted almost 50% of the NMP in the early 1960s, decreased to 45% in the mid-1980s. In spite of efforts undertaken over the past years to improve the situation in the agricultural sector, its share dropped from 25 to 19% in 1985 (for the same period, agricultural production increased three-fold).

†Recalculated from Ref. 10.

‡From 1975 to 1988, the industrial output in the U.S.S.R. increased by 182% while energy production increased by only 155%. At the same time, capital investments in the energy sector increased from 12.7 to 45.1 billion rbl/yr, with the direct energy sector share in total investments increasing from 9.9 to almost 25%.

Table 22. Value added per sector in 10^9 rbl (1985[a] or 1988[b]) for the national material products (NMP) (from Refs. 2, 3).

Sector	1960[a]	1970[a]	1980[a]	1985[a]	1988[b]
Industry	73.3	135.0	198.0	217.7	269.5
Construction	14.3	30.9	54.7	63.2	80.6
Transportation	5.6	17.3	31.8	35.0	38.7
Agriculture	37.8	70.9	90.8	103.0	143.3
Others	20.0	45.9	112.7	147.1	98.7
Total	151.0	300.0	488.1	566.0	630.8

Table 23. Energy and electricity/value added ratios by sector.

Sector	1960	1970	1980	1985
Primary energy (tce/10^3 rbl)				
Industry	5.3	4.90	4.55	4.40
Construction	0.9	0.90	0.76	0.84
Transportation	10.7	7.00	6.50	6.90
Agriculture	0.7	0.90	1.31	1.27
Electricity (kWh/rbl)				
Industry	2.83	3.65	3.93	4.13
Transportation	3.14	2.87	3.06	3.25
Agriculture	0.26	0.54	1.22	1.41

The energy intensity of the different economic sectors also changed during this same time period (Table 23): energy/value added ratios in industry and transport decreased almost by a factor of 1.5 (from 5.2 to 3.6 and 10.7 to 7.0 tce/10^3 rbl, respectively). In the agricultural sector, the energy intensity increased at first to 1.8 tce/10^3 rbl until 1980 and then dropped back to 1.2 tce/10^3 in 1985. These improvements in energy intensities are responsible for the reduction in the total energy/NMP ratio from 4.44 to 3.24 tce/10^3 rbl (a 16% decrease compared to 1970), while the energy/NMP elasticity ratio decreased from 0.78 in the 1970s to 0.51 in the early 1980s.

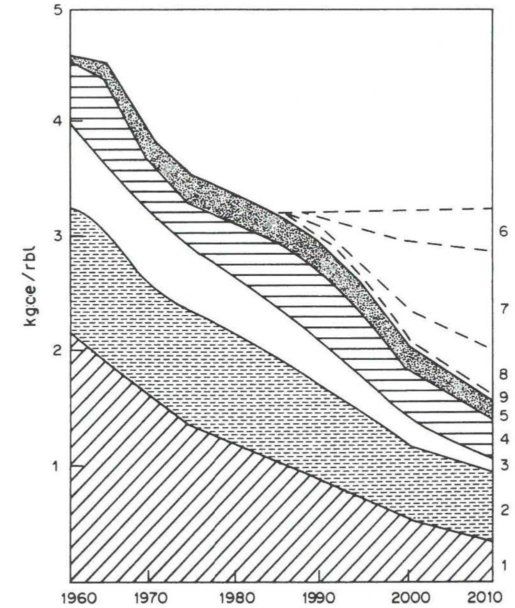

Fig. 1. The energy to value added ratio in kgce/rbl.[16] Ratio structure: 1—direct fuel use; 2—electricity; 3—motor fuel; 4—heat; 5—feedstocks and materials. Energy savings due to: 6—restructing the national economy; 7—improving energy efficiency; 8—technological progress; 9—waste energy use.

Table 24. Percentage changes in the energy/NMP ratio.

Energy-supply sources	1960	1985
Direct fuel user	56	35
Motor fuels	13	12
Electricity	25	25
Low temperature heat	11	19
Raw materials and feedstocks	5	9

Strong electricity-consumption growth is common to all developed nations. The U.S.S.R. electricity/NMP ratio grew in the 1980s from 1.94 to 2.76 kWh/rbl but then declined to 2.62 kWh/rbl by 1985. The 1985 electricity/NMP ratio was slightly above the 1970 level. Considering the ratio of electricity to value added by sector, we find that the electricity intensity in the industrial sector increased by 20% and almost five-fold in the agricultural sector. Figure 1 illustrates the different forms of final energy input compared to the reduction in national energy intensity. The structure of the energy/NMP ratio changed over the period 1960–1985 as is shown in Table 24. We note a reduction of direct fuel use per NMP unit by 50%, motor fuels by 38% and electricity by 27%. At the same time low temperature heat consumption increased by 20% and that of raw materials and feedstocks by 67%.

Table 25 shows the results of energy-conservation efforts in the U.S.S.R. and other industrialized countries in the 1970s and early 1980s. The absolute levels of the ratios energy/NMP depends strongly on the exchange rates. Nevertheless, it is clear that Soviet conservation policy was less effective than that of some Western countries. Since the early 1970s, energy/NMP in the U.S.S.R. decreased only by 16% to 1985, as compared to 21% on the average for the IEA countries, 31% for Japan, and 23% for the U.S. Such a modest success in the overall reduction of the U.S.S.R. energy/NMP ratio can be explained as follows: (i) abundance of domestic fossil-fuel resources and a secure energy supply have resulted in late awareness of the importance of energy conservation; (ii) over the years, the policy of economic independence from the West has resulted in slow structural changes, with continuously increasing shares of the energy-intensive sectors and industries; (iii) low energy prices did not stimulate energy conservation; (iv) the existing economic system, in which the energy ministries play a leading role in shaping the economy, concentrated on investments in the energy-production sectors instead of energy savings for end-users; (v) there is low energy efficiency for domestic energy generation and for consuming equipment.

In order to understand the changes in energy utilization better, it is of interest to analyze the energy/VA ratios in material production (Table 26). For the period under consideration, the energy intensity of material production decreased by 30% with decreases in the energy-intensive sectors: iron and steel by 38%, non-ferrous metals by 43%, and chemical products by 52%. Energy savings in the transportation sectors were even greater (by 68%). The energy intensity grew only in the agricultural sector (by 25%). This reduction is primarily explained by changes in the final energy structure, mainly increases in the share of electricity and

Table 25. Energy/GNP ratios for different countries.

Country	1985[b]	Percent Reduction[a] in 1985 compared to	
		1973	1979
USSR	3.32	14	3
USA	0.61	23	16
Japan	0.29	31	22
FRG	0.31	18	14
UK	0.35	20	13
Italy	0.33	20	13
Average of IEA countries	0.45	21	15

[a]For the U.S.S.R., the years 1970 and 1980.
[b]For the U.S.S.R. in tce/10^3 rbl; for other countries, in tce/10^3 U.S.$ (1980).

Table 26. Energy/value added ratios for material production in tce/10^3 rbl.

Industry	1960					1985				
	Electricity	Steam and Hot Water	Direct Fuel	Motor Fuel	Total Primary Energy	Electricity	Steam and Hot Water	Direct Fuel	Motor Fuel	Total Primary Energy
Iron and steel	3.33	2.17	20.05	0.86	26.41	3.57	1.75	11.04	0.19	16.56
Nonferrous metals	7.81	2.50	1.75	0.75	12.94	4.49	1.35	1.33	0.21	7.37
Fuel production	1.93	2.68	1.89	0.45	6.94	1.50	1.41	3.07	0.15	6.12
Electricity generation	10.94	1.00	[a]	–	11.94	9.42	1.12	[a]	–	10.54
Chemicals	4.56	6.72	0.28	0.39	15.72[b]	2.64	4.59	0.30	0.06	7.50
Machinery	0.66	0.77	0.24	0.11	1.74	0.46	0.61	0.17	0.02	1.26
Lumber and paper	0.35	0.58	–	0.30	1.23	0.75	1.53	0.17	0.36	2.83
Building materials	0.98	0.78	4.16	0.47	6.39	1.08	1.38	3.73	0.32	6.50
Textile	0.33	0.50	–	–	2.46[b]	0.32	0.42	0.03	–	0.78
Food	0.57	1.71	0.50	1.03	5.34[b]	0.51	1.76	0.29	0.42	2.98
Total industry	1.29	1.19	2.53	0.32	5.33	1.42	1.21	0.89	0.11	3.63
Construction	0.29	0.21	0.02	0.21	0.86	0.30	0.20	0.11	0.25	0.86
Transportation	1.36	0.32	9.61	11.11	22.40	1.25	1.22	1.77	3.00	7.24
Agriculture	0.09	–	0.11	0.71	0.92	0.35	0.06	0.24	0.50	1.15
Total Material Production	0.89	0.70	1.45	0.79	4.17	0.94	0.68	0.89	0.42	2.93

[a]Without fuel consumption for electricity generation.
[b]Including fuel consumption as raw material and for non-energy uses.

Table 27. Iron and steel losses in metal processing (from Ref. 9).

Processes	1970	1980	1985
Percent of waste in iron and steel production	29	28	28
Steel consumption in machinery (10^6 tons)	59.9	82.2	89.1
Percentage of losses during metal processing	22	22	21
Percentage of percentage losses in metal shaving	48	44	44
Total steel production (10^6 tons)	116	148	155

low-temperature heat which are characterized by greater utilization efficiency (for electricity) and production (for heat). The shares for both energy carriers increased: iron and steel production from 21% in 1960 to over 32% in 1985; chemical production from 72 to 92%, transportation from 6 to 17%, and agriculture from 10 to 30%, respectively. For total material production the fraction of processed energy sources increased from 38% in 1960 to 55% in 1985.

It is evident that all of these measures were not enough to achieve the level of energy conservation in the U.S.S.R. that was reached in the developed countries of the West. But this is only one part of the problem. We must analyze the major difficulties of the Soviet economy which led to small reductions of the energy intensity over the past years.

During the past few years, the Soviet economy had a very high level of material intensity, which decreased from 1975 to 1987 by only 5%, which is less than for the Western countries. For comparison, in the European Community, the iron and steel capacity (an energy-intensive sector) had the following reductions: cast iron, 13% (from 137 million tons in 1975 to 119 million tons in 1988); steel, 12% (from 190 to 167 million tons); hot-rolled stock, 14% (from 143 to 123 million tons). The share of the most progressive technology (continuous steel casting) rose from 15.3% of the total output in 1975 to 76% in 1986 (Ref. 11). During almost the same time period, the reduction of the oil-refinery output in Western Europe reached 30% (from 20.8 in 1976 to 14.4 million bbl/day in 1986).† Unfortunately, lessons of the oil crises have not been taken into account in the U.S.S.R. As a result, the Soviet economy remains technologically backward and material wasteful. An example of the Soviet industry's high material losses is provided by ferrous-metal utilization and is given in Table 27. The share of metal losses in steel production is very high (28%) and did not decline during the last few years. Very high losses (almost one-fifth) also occur in machinery production, nearly one-half of which is due to metal shaving. Both of the values indicate the low technological levels in both metal production and treatment, which reflect the high levels of lost energy indirectly.

The high energy intensity in the Soviet economy may also be explained by the low efficiency and quality of the machinery and processes in use. Only 16% of the total machinery stock (including energy conversion and end use) are on a par with world standards and one-quarter to one-third are far below national standards, which are often far behind world standards. Especially poor are the iron and steel and chemical-production industries, which are the most energy-intensive sectors. More than 40% of the machines and processes are 10 years or more old. Their utilization during the last 20 yr was 21% in the iron and steel industry and over 16% in the energy sector and chemical production. Even more serious is the situation of obsolete machinery and processes: over one-fifth of the machinery used in the iron and steel industry and in chemicals production are 100% obsolete. All of these factors play a decisive role in explaining the low energy efficiency of the Soviet energy system. The situation will hardly change over the next few years because a change requires high investments in modernization and restructure of the Soviet economy, which is presently lacking because of low past NMP growth and the priority given to resolution of social problems which have recently reached critical dimensions.

†Although the refinery load factor increased but the total refinery output for Western Europe was 24% lower than at the pre-1973 period (see Ref. 12).

Table 28. Equipment performance in percent as of 1 April 1986 (from Ref. 9).

Equipment	Best World Standard	National Standard	Out-of-date and Obsolete
Energy equipment			
Steam boilers	10.5	52.9	36.6
Waste-heat boilers	5.7	48.5	45.8
Steam turbines	2.6	36.6	60.8
Gas turbines	5.2	76.3	18.5
Hydro turbines	2.0	21.5	76.5
Compensating capacities	11.7	42.3	46.0
Diesel engines (w/o auto)	6.7	52.3	41.0
Electrothermal equipment			
Electric arc furnaces	4.9	38.6	56.5
Metal treating furnaces	7.8	47.4	44.8
Induction melting and heating equipment	9.8	51.1	39.1
High frequency industrial equipment	9.6	59.9	30.5
Electric welding equipment			
Open-arc welding machines	12.2	50.0	37.8
Contact welding machines	7.1	44.7	48.2
Special welding machines	9.8	50.7	39.5

Table 29. Useful energy/NMP ratio in Gcal/10^3 rbl (from Ref. 10).

	1960	1970	1980	1985
Material production	8.0	8.2	8.5	8.5
Non-productive sectors	3.7	3.2	2.9	2.9
Total	11.7	11.5	11.4	11.4

The situation is even worse with outdated and obsolete energy equipment (Table 28). In total, the share of modern equipment does not exceed 10%, while the share of outdated and obsolete equipment is 50%. This situation does not allow improvements in energy efficiency and is the reason for the high energy/NMP ratio in the U.S.S.R.

The lack of real progress in improving the energy efficiency and reducing the energy intensity is shown in Table 29. As can be seen, the useful energy consumption per NMP unit has remained practically unchanged over the last 25 yr. Moreover, the energy intensity in material production has even increased further. These facts indicate the critical state of the Soviet energy system, which is reflected in the low energy-efficiency improvements over the last decades.

USSR ENERGY-DEMAND AND SUPPLY PROSPECTS

1990–2005

The prospects for the Soviet energy-system development were defined in the *Energy Program,* adopted in 1982, in which the main directions for fuel and energy-complex development were stated up to the year 2000. This Program gave great importance to the production of NG, coal and nuclear energy and to energy conservation. Since then, the Program has been revised and, in the latest draft, the time frame was extended to include the period 2005–2010.† Due to the fact that the plans for nuclear-energy development between 1980 and 1985 were not fulfilled and the installation of nuclear power plants after the Chernobyl accident slowed down (1986–1990), provisions have been made to compensate for the drop in nuclear electricity production primarily through the accelerated growth of the natural gas industry. This Program requires increased production of NG to meet heat

†Economic and political uncertainties during the 1990s make it impossible to prepare a specified energy policy. The main trends of this policy are known and are being implemented in the current plans, although the economic crisis has affected the energy system, as well as other sectors of the national economy.

demands and cogeneration needs, while directing coal use to condensate-type power plants for electricity generation, which is dictated by ecological considerations.

Central to the Energy Program is *the policy of energy conservation.* The Program envisages that intensive work will be done to improve the efficiency of energy use. A serious drawback to the country's economic structure is the higher material intensity compared to that of other industrially-developed countries. Improving the structure of the national economy and implementing intensive energy savings will allow effective use of the vast potential for energy conservation.†

Electrification of the national economy will proceed rapidly and should promote the growth of labor productivity, thereby providing a basis for resolutions of many of the national social and economic problems. Conservation of primary energy resources is important, especially of premium hydrocarbon fuels. In the draft of the new program, special attention is devoted to the ecological aspects of energy-system developments. There is concern with the use of low-grade fossil fuels, in particular coal. Large investments are required to reduce negative impacts on the environment and human health. The ecological constraints are among the most important features of the new program.‡

The draft of the new Energy Program also stresses the importance of improving economic mechanisms for the energy sector itself with the goal of promoting the development of the energy industries on a self-supporting basis.

The Program assumes that the improvement of the fuel and energy complex will be achieved in two stages. The *first stage* (up to the year 2000) will be characterized by a continuous growth in hydrocarbon production with small absolute growth in oil and NG-liquid. Large increases in NG production were achieved in the early 1980s, mainly by the Tyumen gas production and transportation to the European U.S.S.R. During the next period, efforts will be focused on radical improvements in nuclear safety and reducing the costs of nuclear energy. Furthermore, stable coal production will be achieved, mainly by using the open cast methods in the eastern parts of the country.

In *the second stage* (first decade of the 21st century and perhaps beyond), efforts will be made toward achieving stable levels of hydrocarbon production to compensate for possible reductions in liquid fuel production by a further increase in NG production. Fossil fuel consumption growth at this stage will be reduced and met mainly by increased coal production. Energy conservation will possibly allow stabilization of nuclear energy growth. Options for economic developments without absolute energy-consumption growth are now being studied. But this transition to a new phase of energy development is likely to occur only beyond 2010.

The main goals of the Energy Program (draft) were as follows: (i) improvement in labor productivity by a factor of 2.2–2.3 by 2000 as compared to the 1985 level, due to further growth of electricity use and mechanical power use per labor unit sustained a stabilized productivity growth is sought beyond 2000. (ii) Reduction in the energy/NMP ratio by a factor of 1.3–1.4 by 2000 and thereafter by at least from 2.5 to 0.7%/yr, depending on the strategy, thereby achieving by 2010 a reduction of at least about 50% versus the 1985 level.§ (iii) Energy-production growth without further growth of the labor force in the energy sector. (iv) Freezing specific investments per unit of primary energy produced to 2000. (v) High-grade energy supplies to the population. (vi) Air-pollution reduction by factors of 1.2 and 2.0 to 2000 and 2010, respectively.

All of these goals are quite impossible to achieve by following current trends. There are persistent needs for finding new concepts and approaches in order to solve national energy problems.

†For comparison, during the past 25 yr (1960–1985), the GDP material intensity dropped by 20% in the U.S.A., 25% in Japan, 18% in the F.R.G., and only 3.9% in the U.S.S.R.

‡ Up to now, the problem of global warming and possible abatement measures have not been seriously studied in the U.S.S.R. The importance of this issue is presently under investigation and the Energy Program will most likely be revised with consideration of this subject from a long-range perspective.

§This goal now seems to be quite impossible to achieve because of the low activity in energy conservation and difficult economic situation in the U.S.S.R. in the late 1980s and early 1990s. Fulfillment of goals is pushed beyond 2010. The energy projections given below take this delay into account.

It may be most promising to follow a policy of *enhanced energy conservation*, which is the focus of the new Energy Program. According to some evaluations, structural changes in the productive system could provide only a 10–15% reduction in the energy/NMP ratio, which is equivalent to savings of 320 million tce in 2010 and 1.4–2.4 billion tce in 2020 compared to 1990. The remaining changes are to be achieved by improvements in energy efficiency. The technical limits for energy conservation correspond to about 1000 million tce/yr in the case of full utilization of all known technologies, i.e., not less than one-half of total current energy consumption.

Investments will be needed to implement energy savings measures. It is estimated that about 200 million tce/yr could be saved without additional investments. The savings potential for a 2- or 5-yr payback period (the latter is the highest permissible estimate for a payback period under free-market conditions) is equal to 450–650 million tce. With savings of up to 600 million tce, the required investments in energy savings are less than the direct average investments required for the primary energy-supply systems.

The level of primary energy demand is heavily dependent on the economic outlook over the projected period. This essential factor remains very fuzzy because of uncertainties associated with the Soviet economy. The best approach is to consider a broad spectrum of possible alternatives: from the pessimistic view on economic recovery with a 2%-growth rate in the 1990s to the optimistic concept based on a 3.5%-growth rate, compared to 4.5–5% in the official version of the Energy Program. In this study, it is assumed that the average annual growth in real terms will be about 2.5% and the energy/NMP ratio will decline by 1%/yr.†

Table 30 gives a description of the U.S.S.R. energy balance for the period 1990–2005. As a result of the energy-savings policy, primary energy consumption in the U.S.S.R. will increase only by a factor of 1.2 in 2005 as compared to 1990. Over the same time period, the real NMP will grow by a factor of 1.4–1.5. This means that the energy/NMP ratio will decline by almost 15% to 2005 as compared to the 1990 level; it was expected earlier to decline by 20–25%.

The NG industry will remain the most dynamic industry in the fuel and energy complex with its growth rate increasing by a factor of 1.35–1.38; the NG share in the production of all forms of energy will rise from 40% in 1990 to 47% in 2005. Natural gas production may reach 1.1–1.2 trillion m^3/yr in 2005. However, taking into account the permanent difficulties encountered in the coal industry and with nuclear energy, it is quite possible that this production level will be achieved even earlier. Until 2000–2010, NG will successfully compete with nuclear energy in the European part of the U.S.S.R. Beyond this time period, the situation remains quite uncertain. It is believed now that augmented use of NG in the country's energy balance will produce a "NG pause" for the next 10–15 or even 20 yr, which can be used to find ways of solving ecological problems arising from coal utilization and improving nuclear reactor designs to achieve improved safety and better economics. There will be many problems connected with NG production developments over the years to come, mainly of an ecological nature. It seems that these can be solved more effectively than problems associated with expanding production of other energy forms.

During the 1990s, *oil production* is expected to stabilize and then to decrease. For a short period of time, liquid-fuel production may continue to grow because of expanding NG-liquid production. The oil share in the country's energy balance will decline from 35% currently to 28–30% by 2005. An analysis of the situation shows that stabilization or even a slight growth of oil and NG-liquid production at a level of some 650 million tons annually after 2000 is technically feasible for the oil industry, although at a price. Instead, it appears expedient to have an absolute reduction in the oil-production levels beyond 1995–2000 by a few tens of million tons per year. This change will avoid the development of fields with very low productivity and to abandon the wide-scale use (at least for a couple of decades) of the most expensive new oil-production technologies.

†In a recent study made by the Commission on the Development of Alternative Energy Scenarios of the U.S.S.R. Academy of Sciences, the rate of energy-intensity improvement is assumed to be 1.8–2.7%/yr to 2005, which seems to be too optimistic. During the last 15 yr this rate was 0.9%/yr on average (Ref. 13).

Table 30. U.S.S.R. energy supply and demand for 1990 and 2005 in millions of tce (from Refs. 13–15).

Activity	Solids	Liquids	Gaseous	Renewables	Nuclear	Electricity	Heat	TOTAL
Primary energy production 1990	468	880	1025	76	75			2524
2005	540	830	1390	135	120			2935
Balance of trade 1990	-30	-255	-145					-430
2005	-45	-225	-180					-450
Domestic consumption 1990	438	625	880	76	75	-5		2089
2005	495	605	1210	135	120	-20		2545
Electricity generation 1990	-168	-120	-315	-76	-75	212	211	-331
2005	-250	-75	-445	-115	-120	310	260	-435
Other energy sectors 1990	-15	-35	-102			-58	-33	-243
2005	-15	-40	-140			-80	-40	-315
Materials production 1990	155	168	287			101	134	845
2005	170	100	330			135	160	845
Transportation 1990		172	11			13	2	198
2005		215	15			20		250
Residential/commercial 1990	90	40	115			35	42	322
2005	50	30	185	20		55	60	400
Non-energy use 1990	10	90	50					150
2005	10	145	95					250
Final energy 1990	255	470	463			149	178	1515
2005	230	490	605	20		210	220	1795

For the anticipated stabilization and even some reduction in oil production beyond 2000, top priority should be given to the rational use of petroleum products and to search for ways of decreasing crude-oil demand. In the early 1980s, motor-fuel yields in oil refining amounted to over 40% and nearly the same amount of fuel oil was produced. In the future, these ratios will change radically: motor-fuel yields will be up to 60–65% while fuel-oil yields decline to 15–17%. There will also be a substantial increase in the share of feedstock for petrochemistry and non-fuel products.

Changes will also occur in the pattern of petroleum-product consumption. Present crude-oil consumption for mobile units accounts for only 40%; in the future, it will rise to 65%. It will decline from 35 to 12% for heat and electricity production. Petroleum-product consumption will be strongly influenced by a shift to more economical vehicles, electrically-powered railways, public urban transport, and the use of compressed methane for a part of the intracity freight traffic.

The country's oil-refining industry will enhance its productivity by using thermocatalytic refining processes and fuel-oil hydrogenization with methane-based hydrogen. Great importance is attached to the production of lead-free gasoline and low-sulfur diesel fuel to reduce ecological problems in the big cities. It is expected that by 2010, the total capacity for fuel-oil processing will have been increased three-fold compared to 1985 and the extent of oil refining by a factor of 1.5 to reach 87–90%. This is a substantial change in the pattern of petroleum-product utilization and implies a 30–35% reduction in crude-oil consumption due to fuel-oil processing.

Coal production will slowly grow to 540–550 million tce in 2005, as the result of the development of coal deposits located in the eastern part of the U.S.S.R. (Kuznetsk, Kansk–Achinsk, and Ekibastuz basins). Coal production in the European part will reach a stable level before 2000 and will decline thereafter. The large-scale users in eastern Siberia and Kazakhstan (power plants, iron and steel factories, cement works, etc.) consume local solid fuels, which are cheaper than nuclear energy. For environmental reasons, the use of coal will be limited in these regions and, where possible, it will be replaced by NG. In western Siberia and central Asia, because of the local unstable seismology and high capital costs for nuclear power plants, Siberian coal will remain competitive with nuclear energy but probably not with NG during the period up to 2010–2020. Coal production will increase very slowly during the next few decades because of ecological and social constraints. In order to limit CO_2 production, coal use could decline after 2005–2010.

Because of serious difficulties encountered by *the nuclear industry,* only moderate growth rates are expected during the next decade. The nuclear share in primary energy production will increase from 3% in 1990 to 4–4.2 by 2005, which is much lower than was previously predicted. Nevertheless, electricity generation by nuclear power plants will almost double by 2005 and increase steadily thereafter.

The hydroelectricity potential of the European part will be fully utilized by 2010 and that of the Eastern part by 2040. *Unconventional renewable energy* sources are likely to play a noticeable role only well after 2000. We expect to see 10–20 million tce/yr of renewable energies to meet thermal energy needs in the residential and commercial sectors by 2005–2010. The total contributions from nuclear, hydroelectric and renewable sources will amount to 250–260 million tce annually in 2005; thus, their total fractional share to primary energy production will not exceed 8–9%.

The final energy consumption will increase by 18–20% by 2005, whereas the increases in material production will be only 6–8%, in transportation 26–30%, and in the residential and commercial sectors 25%. As a result of these differences in growth rates, the fractional share of energy use for material production will decrease from 56 to 50% while those for the other activities will remain practically the same. This slow restructuring will have the positive effect of industry maintaining the lead role. By contrast, in more energy-effective economies, such as U.S., industry, agriculture and construction accounts for less than one-third of total energy use; in Western Europe, they account for less than 40% while the residential and commercial sectors account for 60%.

With the initiation in the early 1920s of the GOERLO Plan (the first Soviet plan for electrification of the national economy), electrification† has increased and will continue in an upward trend, rising from 10 to 12% by 2005.

Soviet energy policy envisions continuing *energy-export growth* especially for NG and coal, with nearly stable export of oil and oil products. During the past decades, energy export has played an important role in the U.S.S.R. economy. The need to pay for foreign trade expenditures has required large energy exports, especially of hydrocarbons. In 1986, the net exports were 396 million tce of the total available energy resources of 2536 million tce and thus accounted for more than 15%. During the past 25 yr, exports of hydrocarbon fuels have increased as follows: in 1986, oil exports amounted to 21.1% of the oil produced vs 12.1% in 1960; the corresponding gas exports were 11.5 and 0.5%, respectively. In 1986, oil exports to capitalist and socialist countries were 130 million tons, oil products 60 million tons and gas almost 80 billion m^3. These sales brought 65% of the total hard-currency income, which is urgently required to strengthen the U.S.S.R. economy. The present Program requires *improving the ecological situation* in big industrial cities of the country by reducing the amounts of hazardous pollutants emitted by power-generating units by a factor of 1.5 by 2000 and more than two-fold over the succeeding decade.

†Measured as the share of final energy consumption for electrification.

2005–2030

The energy sector is one of the main sources of anthropogenic CO_2 emission and also of CH_4. In order to mitigate possible global warming, it is essential to reduce fossil-fuel use. The greenhouse effect is a global problem and must be treated at the international level. Recommendations for U.S.S.R. energy policy should be based on global projections. This position is reflected in the documents on the State Program concerning sustainable long-term economic development in view of global climate change. The following issues are expected to be analyzed: (i) social and economic assessments of the efficiency of conservation measures; (ii) prospects for the replacement of fossil fuels with high CO_2 emission (coal, oil) by NG; (iii) improved safety for nuclear energy use; (iv) prospects for effective utilization of renewables; (v) technologies for CO_2 disposal.

The first projections for Soviet energy development to 2030 have recently been issued.[13,14] Several scenarios for social and economic developments are considered in this study with different rates for economic restructuring and efficiency improvements. According to these scenarios, energy demand in the U.S.S.R. may reach 2500–3600 million tce in 2030, depending on the extent of economic activity. The following three scenarios are chosen: (i) *a*

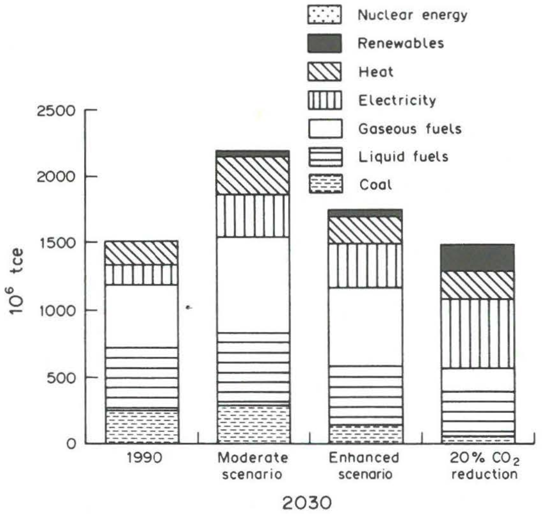

Fig. 2. U.S.S.R. final energy demand in 1990 and 2030 for various scenarios.

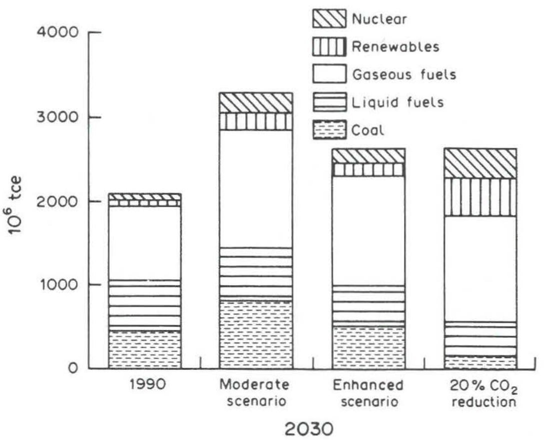

Fig. 3. U.S.S.R. primary energy demand in 1990 and 2030 by scenario and primary energy type.

Table 31. Estimated percentage distribution for energy use in 1990, 2005 and 2030.

Sector	1990	2005	2030		
			Moderate scenario	Enhanced scenario	20%-CO_2 reduction scenario
material production	55	50	48	45	35
transportation	13	14	15	17	20
residential and commercial use	21	22	23	24	28
other uses	11	14	14	14	17

Table 32. Energy supplies for the domestic sector in percent.

Energy Sources	1990	2005	2030		
			Moderate scenario	Enhanced scenario	20%-CO_2 reduction scenario
solids	21	19	24	18	6
liquids	30	24	19	20	15
gaseous	42	47	43	50	49
renewables	3.6	5	6	6	18
nuclear	3.4	5	8	6	12

moderate scenairo with some improvements in economic restructuring and energy conservation; (ii) *an enhanced scenairo* with large improvements and the aim of stabilizing primary energy consumption after 2005–2010; (iii) *a 20% CO_2 reduction scenario* compared to 1990.

These scenarios deal with three important cases, namely, business-as-usual with moderate dynamics of improvements in the economic and energy systems, an energy-stabilization scenario, and a CO_2-reduction scenario after 2005–2010. The last two scenarios are expected to have a profound impact on the national economic system and could lower economic growth rates to 2005–2010. However, less energy-intensive systems may ultimately result in an improved economy.

Scenario elaboration requires careful attention to energy requirements for different energy-consuming sectors. Also account must be taken of social and economic goals. Estimates of energy reserves and resources, as well as of state-of-the-art production systems, must be used.

Figures 2 and 3 show the final and primary energy demands for 2030. As it could be seen, the scenarios differ substantially in the levels of energy consumption and energy-system structure. For the *moderate scenario,* the primary energy consumption is expected to grow by a factor of 1.2 compared to 2005 and by more than 1.5 compared to 1990. For the other two scenarios, stabilization of energy consumption is reached after 2005–2010.†

Due to increased electrification and large improvements in the efficiency of electricity generation, the final to primary energy ratio will steadily decline: from 72% in 1990 to 70% in 2005 and further to 67% for the *moderate* and *enhanced* scenarios and to 57% for the *20% CO_2 reduction scenario*. The final structure for energy use is summarized in Table 31.

The changes in domestic primary energy consumption are summarized in Table 32.

The three scenarios are closely related to the capital investments made for the energy sector during the period 1990–2030. Table 33 contains estimates of the required capital investments. For *the moderate scenario,* required investments during 1990–2030 are almost 6.5% of the total national income produced within this time period. For *the enhanced scenario,* 6.9% are needed. For *the 20% CO_2 reduction scenario*, required additional expenses are 9–10% of the total

†Soon after 2005, weak growth of primary energy consumption is assumed, which diminishes and becomes negative after 2010–2015. Around 2020, the same level of energy consumption is projected as for 2005.

Table 33. Approximate capital investments in the energy sector (1990–2030) in billions of roubles.

Energy Sector	Moderate scenario	Enhanced scenario	20% CO_2 Reduction scenario
coal	125	95	65
oil production	650	590	540
oil refining	75	70	60
gas production	280	280	275
gas transport	700	700	685
electricity, total	875	1065	2330
fossil	145	160	150
renewables	275	410	1190
nuclear	165	135	215
electr.transport	290	350	775
energy conservation	595	1150	925
Total	3300	3940	4880
% of the national income	6.3	6.9	9.3

Assumed fuel costs: coal = 100 rbl/tce, oil = 210 rbl/tce (300 rbl/t), oil refining = 25 rbl/tce (30 rbl/t), natural gas = 60 rbl/tce (70 rbl/1000 m^3), natural gas transportation and distribution = 250% of natural gas production, thermal power plants = 250 rbl/kWe (lifetime = 20 yr), renewables = 1000 rbl/kWe (lifetime = 10 yr), nuclear = 1000 rbl/kWe (lifetime = 20 yr), electricity lines = 50% of electricity generation, energy conservation: moderate scenario = 150 rbl/tce; enhanced and 20% CO_2 reduction scenarios = 200 rbl/tce.

national income, which is hardly possible. The capital investments for developed countries are typically 5–6%. Consequently, energy-system development in the U.S.S.R. may lead to large financial difficulties.

A summary of energy projections is given in Table 34. During the next 40 yr, the energy intensity will decline by a factor of 2–3 compared to the 1990 level. This energy efficiency improvement will occur in two stages: 1990–2005 when the rate of decline will be only about

Table 34. Features of U.S.S.R. energy scenarios.

Features	1990	2005	2030		
			Moderate scenario	Enhanced scenario	20% CO_2 reduction scenario
Population, millions	289	320	355	355	355
National income, 10^9 rbl.(1990)	655	950	2300	2650	2300
% growth		2.5	3	3.5	3.5
Primary energy, 10^6 tce	2089	2545	3260	2600	2600
tce/cap.	7.2	7.7	9.3	7.4	7.4
Electricity production, TWh	1725	2500	3700	3500	5000
Energy intensity, tce/10^3 rbl	3.14	2.68	1.42	0.98	1.13
Electricity intensity, kWh/rbl	2.65	2.63	1.61	1.32	2.17
Energy savings to 1990, 10^6 tce	-	440	3960	5720	4620
CO_2, 10^6 t/yr	4070	4690	5890	4585	3265
% change from 1990		115	145	113	80

1%/yr according to our projections because of system inertia and economic problems. After 2005, the energy intensity decline could be 3–4%/yr. *Per capita* energy consumption will continue to increase from 7.2 to 7.4 to 9.3 tce. The energy savings by 2030 are impressive: 55% for *the moderate scenario* and more than 65–70% for the other two scenarios.

Implementation of the scenarios requires the following: (i) decentralization and privatization of the large energy-supply systems and introduction of a market economy concept in the energy sector; (ii) changes in the energy-pricing system with allowance for social costs; (iii) introduction of competition into the energy-supply and demand systems; (iv) changes in investment policy with greater emphasis on energy savings and conservation rather than on energy production; (v) conversion of the military industries; (vi) conditions for the expansion of western capital investments in the U.S.S.R.; (vii) R&D collaboration with Western partners in high priority areas such as energy savings, power-plant modernizations, research and development on joint European electricity and NG supply grids, access to research, student and specialist exchanges; (viii) time to assess and improve the new energy policy.

REFERENCES

1. *Optimization of Fuel-Energy Development* (in Russian), A. S. Nekrasov ed., Energoizdat, Moscow (1981).
2. *Soviet Economy for 70 Years. Statistical Manual* (in Russian), Finance and Statistics, Moscow (1987).
3. *USSR Economy in 1988. Statistical Yearbook* (in Russian), Finance and Statistics, Moscow (1989).
4. *USSR Energy Complex* (in Russian), L. A. Melentiev and A. A. Makarov eds., Economica, Moscow (1983).
5. *USSR Energy Systems in 1986–1990* (in Russian), A. A. Troitsky ed., Energoatomizdat, Moscow (1987).
6. *USSR Electricity Sector in 1976–1980* (in Russian), Informenergo, Moscow (1981).
7. R. Akhmedov and Yu. Slyusarev, *Power Engineering,* Novosti Press Agency, Moscow (1989).
8. L. A. Melentiev, *Historic Review of Soviet Energy Systems* (in Russian), Nauka, Moscow (1987).
9. *Material and Technology Supplies in the Soviet Economy* (in Russian), Finance and Statistics, Moscow (1988).
10. A. A. Beschinsky and Yu. M. Kogan, *Economic Problems of Electrification* (in Russian), 2nd edn, Energoatomizdat, Moscow (1983).
11. E. A. Karpova, *Bulletin of Foreign Commercial Information* (in Russian), No. 74 (28 June 1988).
12. European Refinery Industry, *Petroleum Times Report* (13 May 1988).
13. *Soviet Energy Scenarios* (in Russian), USSR Academy of Sciences, Commission on Alternative Energy Scenarios, Moscow (1990).
14. A. Makarov and I. Bashmakov, *The Soviet Union: a Strategy for Energy Development with Minimum Emission of Greenhouse Gases,* Institute of Energy Research of the USSR Academy of Sciences and State Committee for Science and Technology, Moscow (1989).
15. D. Volfberg, K. Dimerchan, T. Klokova, A. Makarov, and M. Styrikovich, *Energetika i Transport* (in Russian) No. 1 (1989).
16. A. Makarov, *New Concept of Energy Development in the USSR,* IIASA Meeting on Global and Regional Energy Prospects, Laxenburg, Austria (14–16 November 1988).