entered history twice: it knew both I V Kurchatov and Anna Akhmatova.

Back to Lev Andreevich, though. After I had visited A P Aleksandrov (in 1963) and received his support for founding the Institute for Theoretical Physics (ITF), he charged L A with the ensuing activities in the USSR Academy of Sciences needed to create a 'gypsy camp' of theoreticians. L A was a very influential figure in the Academy – he occupied the lofty position of the Academician-Secretary of the Division of General Physics and Astronomy. Correspondingly, the creation of a new institute within the Division was part of his responsibilities, and thus we were in close contact at the time. Lev Andreevich was a benevolent person: his entire appearance advertised solid aristocratic upbringing. We had met before at family reunions at the country house of Petr Leonidovich Kapitza in Nikolina Gora.

By 1971, ITF was safely standing on its own feet and we were conducting the Second Soviet–American Symposium in Leningrad, where the local authorities closely watched over us. The Soviet participants in the symposium were contacting the foreigners far too freely and without restraint. I had to discuss the summary of the symposium with Lev Andreevich in a rather unpleasant context: he phoned me and began to reprimand me nervously for the 'wild' behavior of our physicists in Leningrad, where one of them ended up in either the hospital or the drunk tank. In complete deviation from the academic style of discussion, L A demanded that I provide a written so-called 'explanation'. We had never had anything like this complication before, and it seemed that the Leningrad authorities had placed us under a microscope and had written a heavy-handed shadowing report. I will not go into the details of how the crude reply was composed or of the suffering of our colleague who had worked so hard during the symposium that he ended up in the hospital. I had never deigned to send explanations to bosses and did not wish to create a precedent. As luck would have it, Arkadii Migdal lived in the same house, in an apartment on the same floor as Lev Andreevich, and they were friends. I decided not to mail the explanation but to pass it on by hand through A B Migdal. It appears that, having received the explanation on the stairs, L A felt a certain uncomfortableness and tore it up immediately. That was the end of the sensitive story with the explanations. We were able not to slip to the level of the explanations informing others on the behavior of respected young scientists. It cannot be ruled out, though, that L A recalled that when his sharp 'politically incorrect' remarks made in 1950 about the Korean War were reported to Lavrentiy Beria, the story ending with a 'hello' passed on to L A through I V Kurchatov, warning L A to be more prudent in his remarks.

And something about the Korean War, by the way. When it ended at the same time as Stalin's death, every organization was ordered to send gifts to North Korea, which by that time had almost been wiped off the face of the Earth. The Academy of Sciences had a list of possible gifts drafted and sent it for a second opinion to the Institute for Physical Problems. The list reached me and Abrikosov. I still remember that the first two items on this 'list of gifts' were a pedestal of a candelabrum from Nakhichevan and a list of courses served at the table of Patriarch Job. It is possible that this list continues to be 'relevant' in some way to North Koreans.

L A could not stomach moral corruption. One example comes to mind. A good theoretician, Boris Davydov, worked for many years at IAE. He was a modest man but the circumstances of his family life were far from trivial. It so happened that he married the former wife of the accompanist of the famous singer Alexander Vertinsky. Vertinsky, together with his accompanist Brokhes, often gave concerts at foreign embassies in Moscow. Big Brother did not rule out the possibility that Brokhes' wife may have visited these embassies, too (this was absolutely off-limits for ordinary citizens). Only Davydov's closest friends knew about the marriage, but one of them did alert 'those who needed to know'. The end was disastrous: Davydov lost access to classified work and was fired from the Kurchatov Institute. Many of us had a good idea who the fink was.

Once there was a sort of party at L A's division at IAE on the occasion of an 'event' (this could be a revolution-related festivity or an informal gathering to summarize a successfully completed job). The party was in full swing when the door opened and a person from Davydov's circle of 'friends' entered. L A looked the new arrival straight in the eye, then addressed the rest of the company in a well-modulated voice: "What is this fink doing here?". The man burst into tears, covered his face with both hands, and hastily retreated. Very soon he found employment in another organization where colleagues did not know that much about him.

By tradition, everyone present at Petr Leonidovich Kapitza's birthday parties in his country house in Nikolina Gora (where the cream of the Moscow intelligentsia would get together) delivered a toast, one after the other. This wave of toasts was conducted by the well-known sculptor Nokogosyan, who spoke with a recognizable Armenian accent. I still remember his loud invitation: "Ai, Artsimovich, we wish to hear you!" L A would obediently rise from his seat and deliver a brilliant toast — as he always did.

Lev Andreevich died early. I will never forget his smiling face, on which you would invariably read that he was very happy in his personal life.

PACS numbers: 89.20.Bb, **89.30.–g**, **89.60.–k**
DOI: 10.3367/UFNe.0179.200912l.1337

Avenues for the innovative development of energetics in the world and in Russia

V E Fortov, A A Makarov

1. Introduction

In this paper, we consider the expected avenues of scientific and technological progress (STP) in energetics, as well as the possible effects of innovative development of energy production in the coming decades, with an outlook to 2050. Accelerated social development and economic globalization urgently require the study of the potential, possibilities, and strategic priorities of the innovative development of anthropogenic energy production — a set of means of energy conversion (covering all populated areas of our planet) into forms useful for human activity. Nowadays, the anthropogenic energy production that exceeds the cumulative energy of people living on Earth by 15 times and their power by 60 times, is already discernible in the Earth's biosphere, reaching 5% of the energy released in photosynthesis processes supporting life on Earth, but yet indiscernible at the level of space, making up less than

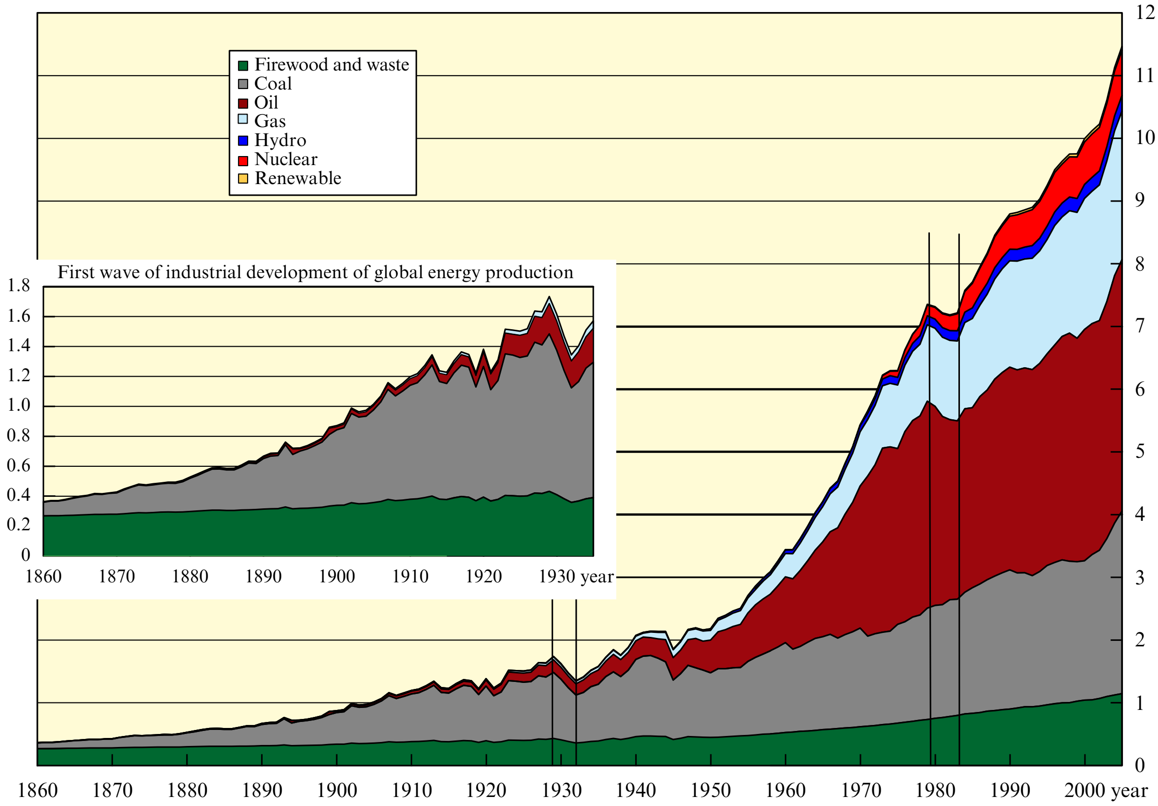

Figure 1. Dynamics of global energy resource production (in billion tons of oil equivalent).

two ten-thousandths of the solar energy falling upon the Earth.

Energetics represents a foundation of modern and future civilizations, and it influences the directions and rates of economic and social development in the world, its security, and international relations. Almost all aspects of human life are to some extent related to energy conversion and use. Food and clothing supply, housing construction and maintaining comfortable conditions in homes, cargo transport and the movement of people, communication and information exchange — all these examples of human activity require the consumption of energy.

2. Development stages of energetics

In prehistoric times, a human being could count only on muscular energy, disposing an average power of about 150 W. Nowadays, according to our calculations, there is 3 kW of electric motor power per person on average across the world, and the available electric power approaches 20 kW per person in developed countries and continues to grow. Taking into account fuel-powered engines, the general availability of power more than doubles for every human.

After mastering fire, humans used dead plants which accumulated solar energy in the chemical photosynthesis reaction

$$6CO_2 + 6H_2O + h\nu \Rightarrow C_6H_{12}O_6 + 6O_2 \,. \tag{1}$$

However, that was only a 'collection', and anthropogenic energy production appeared with the addition of mechanical power to thermal biomass energy. At first, it was the muscular force of domesticated animals kept alive by those same green plants, and then the energy of flowing water and wind. This opened a second channel (in addition to biological — through photosynthesis to animals) of conversion of solar radiation energy into mechanical energy. From the Copper Age (third millennium BC) to the time of decline of the Roman Empire (4th century AD), such energy production stably provided up to 6 GJ per person in a year in agricultural civilizations, and up to 4.5 GJ for other populations which increased during this period by 30 times [1].

The industrial revolution, which happened about three hundred years ago, was caused by the discovery of methods of conversion of thermal energy into mechanical work. It opened a third channel of conversion of solar radiation energy into thermal and mechanical energy — through the chemical energy of combustible fossils (coal, oil, and natural gas) that accumulated energy through photosynthesis millions of years ago. This expensive but huge source of highly concentrated energy strikingly changed the world's current look, having caused rapid population growth and unprecedented rapid development of civilization.

But it was only after a century and a half, in the last quarter of the 19th century, that the chemical reaction of burning fossil fuel, accompanied by the energy release, namely

$$C + O_2 = CO_2 + 94 \text{ kcal mol}^{-1} \,, \tag{2}$$

turned into the main energy source of the industrial world (Fig. 1). Additionally, energy statistics reworked since 1860 revealed 'long waves' of development of the world's energy production [1].

The first wave lasted for 70 years, until the peak of great depression (1929–1933), and increased the world's energy

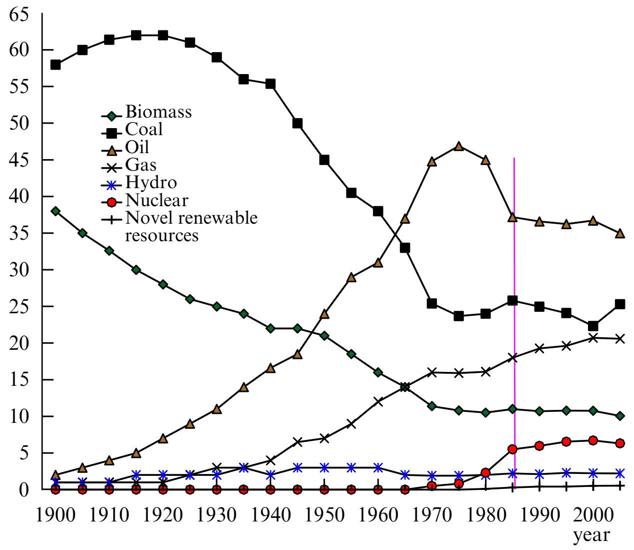

Figure 2. Structure of the global production of energy resources (in %).

production by 4.5 times (see Fig. 1) — from 0.36 to 1.6 million tons of oil equivalent (t.o.e.)[1], almost tripling the average production of the world's energy per capita — from 0.29 t.o.e. to 0.7–0.8 t.o.e. (correspondingly, from 13 to 31–36 GJ) per year. Firewood and the motive power of animals were substituted by coal and coal-fuelled steam engines, then the use of internal-combustion engines expanded in the last third of this wave and undermined the domination of coal in the world production of energy resources (62% in 2015–2020) because of the accelerated growth in the use of oil (Fig. 2). An even more important event in the first wave was a technological breakthrough in the conversion of not only chemical (galvanic cells) but also mechanical energy into electric power and its transmission across large distances. That provided the energy foundation not only for industrial, but also for post-industrial society.

The second wave, lasting 50 years, increased the production of energy resources by further 4.5 times [from 1.6 to 7.3 million t.o.e. (see Fig. 1)], with the next doubling of the average energy production per capita to 1.65 t.o.e. (75 GJ); it attenuated around 1980 due to the oil crisis. That was indeed the 'century of motors' and oil domination in the general production of energy resources — its share increased from 11% to 47% in 1975, but after the termination of the oil crisis it started to decrease, with an increasing share of coal and atomic energy (see Fig. 2). Industrial employment of the first 'extrasolar' energy source — nuclear fission — became the main technological breakthrough of this period. At that time, experiments began for military and then peaceful applications of controlled thermonuclear fusion.

Thermonuclear reaction is the almost inexhaustible energy source of stars (and our Sun) appearing in the exothermic nuclear fusion of light elements (lighter than iron). On the Sun (according to H Bethe), this is the helium cycle in which four protons are transformed into the He^4 nucleus releasing 26.7 MeV of energy. In the conditions on Earth, investigations aim at the practical realization of lower-threshold fusion reactions between deuterium and tritium:

$$D_1^2 + T_1^3 \rightarrow He_2^4 + n + 17.6\ \text{MeV}\,. \qquad (3)$$

The third wave is identified with the coming of post-industrial society and qualitatively differs from the previous ones. First, for its longest period (until 2002) and for the first time in the industrial age, the average energy production per capita in the world has almost not changed (1.56–1.68 t.o.e., or 70–75 GJ per year), and for the wave's end around 2010, because of the economic crisis, the growth in global energy production will be almost three times smaller than in each of the previous waves. Second, with the origination of this wave, a prompt cyclic reorganization of the industrial structure of the world's energy production was replaced by its smooth evolution, with a reduction in the share of oil in favor of more environmentally favorable energy resources such as natural gas and novel renewable energy sources (see Fig. 2).

Figures 1 and 2 demonstrated the dynamics and structure of primary energy production, but the true purpose of anthropogenic energy production is to satisfy social needs in the energy directly used in the production processes and human vital activity. On the way to this final energy, the primary energy resources are undergoing a number of transformation stages, inevitably accompanied by losses. Figure 3 [2] presents the ultimately aggregated view of the main energy fluxes — from main primary energy resources via their transformation to the principal energy carriers (electric energy, steam and hot water, and various sorts of household, technological, and motor fuels) and to the generation of final energy in the processes of its direct use (medium-, low-, and high-temperature processes, stationary and mobile power processes, etc.); actually, the energy fluxes are much more diverse and are rapidly becoming more complicated with time.

From the mid-20th century, in most industrial countries and in the whole world final energy has constituted only 37–39% of the primary energy, which is even less than the energy utilization factor of the primitive bonfire in a cave. This paradox can be explained by the action of opposing tendencies: the constant increase in the efficiency of particular energy conversion technologies was offset by higher and higher requirements regarding the quality of energy used, which are satisfied by larger energy losses (smaller process efficiency η). Indeed, 1 MJ of indoor heat can be obtained by burning fuel with $\eta = 0.9-0.95$, we obtain the same energy for melting metals with $\eta = 0.45-0.5$, for electric power production with $\eta = 0.35-0.42$, and for a car with only $\eta = 0.25-0.3$. At the same time, from the middle of the last century, the heating share in global final energy consumption has decreased three times with a doubling of mobile processes and almost an order of magnitude growth in electrophysical and electrochemical processes. To break the established balance and to transfer to stable growth of the general energy utilization factor as the main indicator of scientific and technical progress (STP) in energy production is one of the major tasks of its innovative development in the forthcoming period.

Another problem consists in lessening the large inequality in energy supply to populations of different countries and regions. P L Kapitza was, apparently, the first to note the relation between the level of economic development of a country and its available per capita power: for most of the 20th century (prior to the beginning of the 1970s), the gross

[1] 1 ton of oil equivalent equals 44.76 GJ or 10^7 kcal.

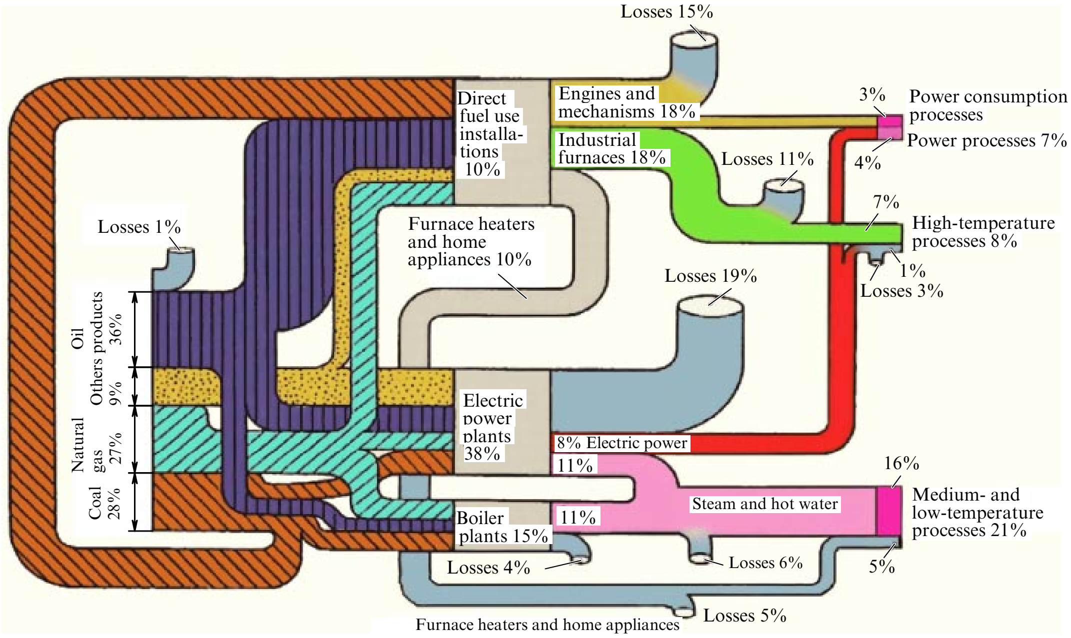

Figure 3. Aggregated diagram of energy conversion fluxes (according to Ref. [5]).

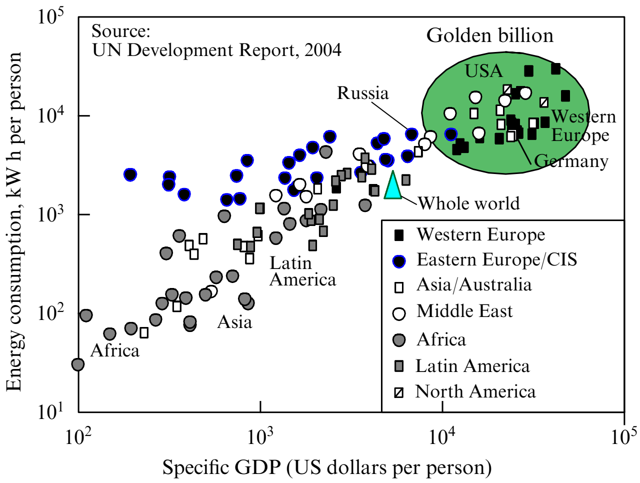

Figure 4. Relation between gross domestic product and per capita energy consumption. Until the 1970s, a 1% growth in gross domestic product corresponded to a 1% growth in energy consumption; now it is 0.3–0.5%.

domestic product (GDP) and primary energy consumption increased with almost identical rates in many countries, and in the world as a whole. However, with the coming of post-industrial society this synchronization was more disturbed because of the increased role of quality (and not just quantity) of energy used. Nevertheless, Fig. 4 [3] shows a good correlation between the human development index (including life expectancy, education, and specific GDP) and per capita power available in different countries. It can be seen that higher results were achieved only by the countries (included in the so-called golden billion) capable of creating powerful and modern energy production. At the same time, nearly 2 billion people on Earth now have no access to electric power, and 3 billion are short of it. The elimination of such outrageous inequalities must become a task for the future.

3. Prospects for global energetics

It is impossible to predict the future in particular details, and even a prediction regarding the main tendencies is a risky but necessary business in order to make a wide range of critical decisions, especially such long-term ones as the creation of new technologies, the development of fuel sources (for example, sea shelves, including those of the Arctic), the development of power systems and other infrastructure, etc. In today's setting, the uncertainty of the future is aggravated by the next bifurcation of global energy production: the first global economic crisis (with the main symptom being the bursting of the oil price bubble) interrupted the beginning of the successive period of accelerated growth in global energy consumption. Therefore, not tending to total generalizations here, we restrict ourselves to an analysis of the main factors determining the development of power engineering — the possible dynamics of the social requirements for energy and restrictions raised by them (first of all environmental), the energy resources available to humankind (with an acceptable price), and progress in energy technologies — by carrying out systematic agreement of these three components in scenarios of energy production development that are reasonable and feasible for society.

3.1 Demand for energy resources

The dynamics of the demand for energy resources determines first of all the growth in the population's well-being. In the last decade, on the wave of economic liberalism, international organizations gave more and more optimistic forecasts for GDP growth and, following that, a rise in energy consumption was also forecast (Fig. 5). Thus, in the last base scenario of the International Energy Agency (IEA) [4, 5], energy demand will increase from 2005 by more than one and a half times by 2030, and will almost double by 2050. And though the world economic crisis will correct these forecasts downwards, such growth in energy consumption seems to be a dead end.

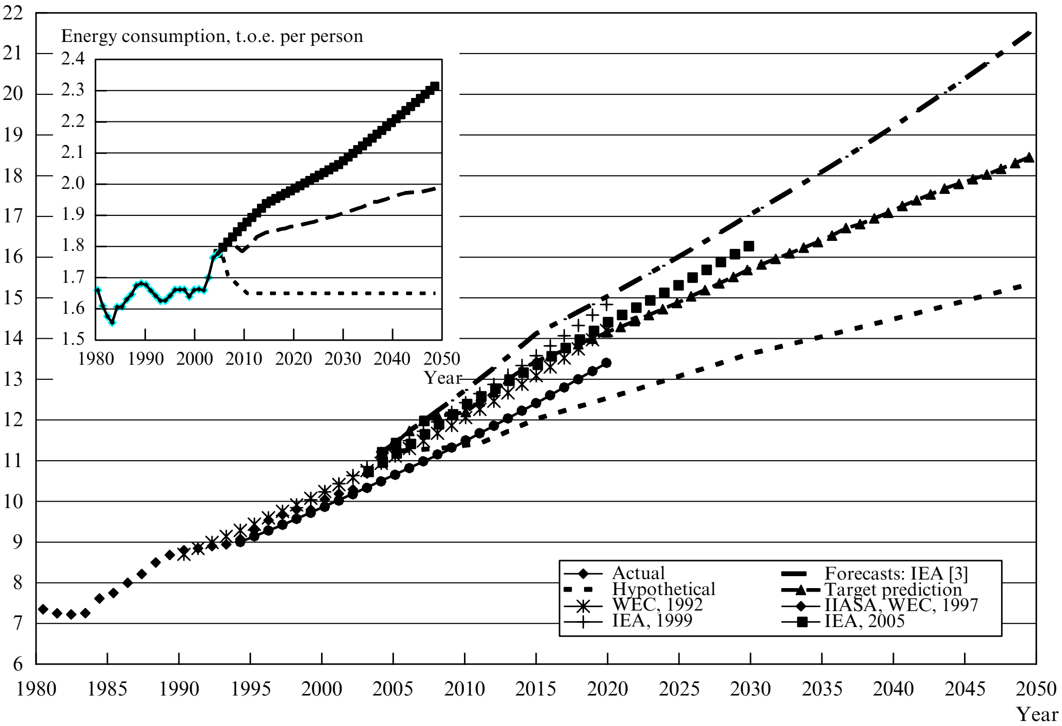

Figure 5. Forecasts of energy consumption in units of billion t.o.e. (WEC — World Energy Council, IEA — International Energy Agency, and IIASA — International Institute for Applied Systems Analysis).

Indeed, with a passage to post-industrial development in the 1980s, it appeared that there was an encouraging tendency of stabilization in average world energy consumption per capita, but recently it again rapidly increased and the rising tendency is continued in the IEA's *base* scenario (see inset to Fig. 5). Preserving the per capita consumption at the average level of the end of the 20th century (see the *hypothetical* scenario in Fig. 5) would reduce the energy demand growth by three times, which is, probably, utopian. However, it seems that (taking into account the necessary growth in the population's well-being and energy supply in developing countries) the *target* scenario shown in Fig. 5 with its almost twofold decrease in per capita energy consumption growth is realistic enough. This is impossible without a decrease in the consumer aspirations of the so-called golden billion in developed countries and a decrease of their growth in developing countries. We hope that the experienced world crisis will force the elaboration of economic and social arrangements to leave the consumer paradigm of social development, but without essential loss of the intensity and efficiency of human activity, which are in every possible way encouraged now in developed countries by the availability of consumer credit and penalized by strict measures for failures to repay them. That would slow down energy consumption growth by almost one and a half times, easing the burden on energy production and the environment.

Refusing to impose restrictions on its own energy consumption, society, at the same time, puts forward more and more severe environmental requirements for energy production. In response, with the passage to post-industrial development, energy technologies were created that allow a reduction (to admissible levels) in the negative *local* impact that energy production has on the environment without an essential price rise. Up-to-date technologies have almost eliminated the once acute problem of acid rain and atmospheric pollution from solid particulates. And though they have not yet been ubiquitously applied, from the scientific and technological point of view the problem of local pollution can be considered as having been taken under control. In return, however, the large-scale problem of *global* environmental impact of anthropogenic energy production has appeared.

This problem has a number of aspects. The direct thermal influence of anthropogenic energy production on Earth's thermal balance is still indistinguishably small compared with the influence of solar radiation energy falling upon the Earth's surface. According to Ref. [3], it constitutes 3% of insolation changes caused by periodic alterations of Earth's orbit, and on the order of 0.1% of the solar radiation variation during an 11-year cycle. However, the effect of energy production on the atmosphere's chemical composition through the changes in the carbon cycle and the global thermal balance due to the greenhouse effect [3] may already show itself to be serious. This effect, predicted by S Arrhenius more than 100 years ago, directly interferes with one of the fundamental cycles for life on Earth and consequently is a subject of great interest for specialists in energy production, climatologists, politicians, and businesspeople (trading emission quotas for greenhouse gases, etc.).

According to Ref. [3], green plants absorb approximately 100 Gt of carbon from the atmosphere during the photosynthesis process and release a similar amount back upon decomposition. Ocean plankton gives approximately as much carbon (90 Gt). The total amount of carbon in Earth's biomass is estimated at 220 Gt; there is almost 200 times more carbon in the ocean, and it annually takes away about 2 Gt of carbon from the atmosphere. Geological sources of carbon (for example, volcanoes) are cumulatively insignificant (about 0.1 Gt per year), but provide dangerous volley emissions.

Anthropogenic energy production emits about 5.5 Gt of carbon per year, 2 Gt of which the ocean absorbs and about 0.2 Gt of which forests and other vegetation absorb. The natural capabilities of the biosphere possibly compensate for only about 40% of anthropogenic emissions of carbon, and its concentration is increasing in the atmosphere, creating serious barriers to the development of energy production. If energy consumption doubles by 2050 (see Fig. 5), energy production will emit 400 Gt of carbon into the atmosphere and will increase its content from 750 Gt to 1000 Gt. It is doubtful that Earth's ecosystem can sustain such a load.

As a matter of fact, energy production over the course of a few centuries is returning the carbon of organic origin accumulated in sedimentary rocks over several million years [2] to the atmosphere and oceans. This is a hazardous experiment with a result difficult to predict. Thus, the global problem for the innovative development of energy production is to limit organic fuel emissions or, in general, to try to abandon carbon energy production.

The requirement of global environmental security determines the dynamics [through an energy conserving way of life (see the target scenario in Fig. 5)] and structure of anthropogenic energy production, and finally its cost to society. Indeed, according to the IEA's base scenario, from 2005 to 2050 emissions of greenhouse gases produced by energy production will increase from 28 to 62 billion tons of CO_2 (which will raise Earth's temperature from today's level by 6 °C), and such development of world energy production to 2050 requires $65 trillion. To reduce emissions of greenhouse gases by more than two times in 2050 (returning to the level of 2005), an additional $17 trillions of capital investments is required, and for a further cut in half (to 14 billion tons of CO_2, which, according to existing estimates, will provide stabilization of the planet climate) almost twofold larger capital investments are necessary [5]. The major interdisciplinary scientific problem is not only to be aware of the reality of the climate hazard by greenhouse gas emissions, but also to develop the most effective counteraction measures, including scientific foundations and geoengineering methods. Otherwise, sustaining climate by decreasing greenhouse gas emissions would almost double capital investments in energy production — from $65 to $115 trillion.

3.2 Provision with energy resources

The unprecedented rise in fuel prices just before the global economic crisis once again actualized the hundred-year-old discussion on whether Earth's natural resources are able to meet the increasing demands for energy. Visually, the positive answer, displayed in Fig. 6, gives a comparison of the current annual global energy consumption with Earth's accessible reserves of various sorts of energy resources; the quantitative data are given in Table 1. It follows from them that for the last 150 years, 8% of conventional (accessible by current technologies) resources of organic fuel and only 2% of its general reserves on Earth have been used if we take into account nonconventional resources requiring, however, the application of new technologies. Hence, even if energy consumption doubles in each of the next half-centuries, over the course of two centuries humanity will not burn even half of all organic fuel resources. This especially relates to Russia, which is rich in energy resources, with 10–11 times more per capita value than an average over the planet [7].

Wide application of new technologies using solar, nuclear (with breeder type reactors and secondary fuel cycles), and, in the longer term, fusion energy will provide the ultimate solution to humankind's energy problem for the 'over-the-horizon' outlook over many centuries. Undoubtedly, this is the historical mission of physics with regard to humankind — to release it from the 'energy death' predicted by many. And then the existence of our civilization and generally of life on Earth (if we move away from gloomy scenarios like nuclear

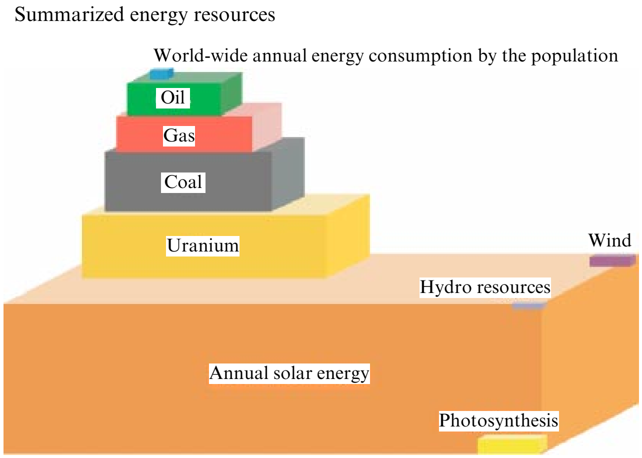

Figure 6. Proportion of potentially accessible energy resources on Earth (Source: National Petroleum Council, 2007; after Craig, Cunningham, and Saigo).

Table 1. Accessible resources of organic fuels and nuclear fuel* (in million t.o.e.).

Energy resources	Oil and condensate	Natural gas	Gas hydrates	Coal	Fuel altogether	Uranium and others	Breeders	Total
Extracted	146	66		159	371	27		398
Proved	150	141		606	897	57	3390	4344
Possible	145	279		2800	3224	203	12,150	15,577
Altogether traditional**	441	486	0	3565	4494	287	1540	20,319
Used, %	33	14		4	8	9		2
Nontraditional***	525	850	18,650		20,025	150	8900	29,075
Total resources	966	1336	18,650	3565	24,519	437	4440	49,396
Used, %	15	5		4	2	6		1

* According to Energy Information Administration US 2007 data, *British Petroleum* (2007).
** Resources accessible for an acceptable price by using modern technologies.
*** Resources whose development will only be financially viable with the use of new technologies.

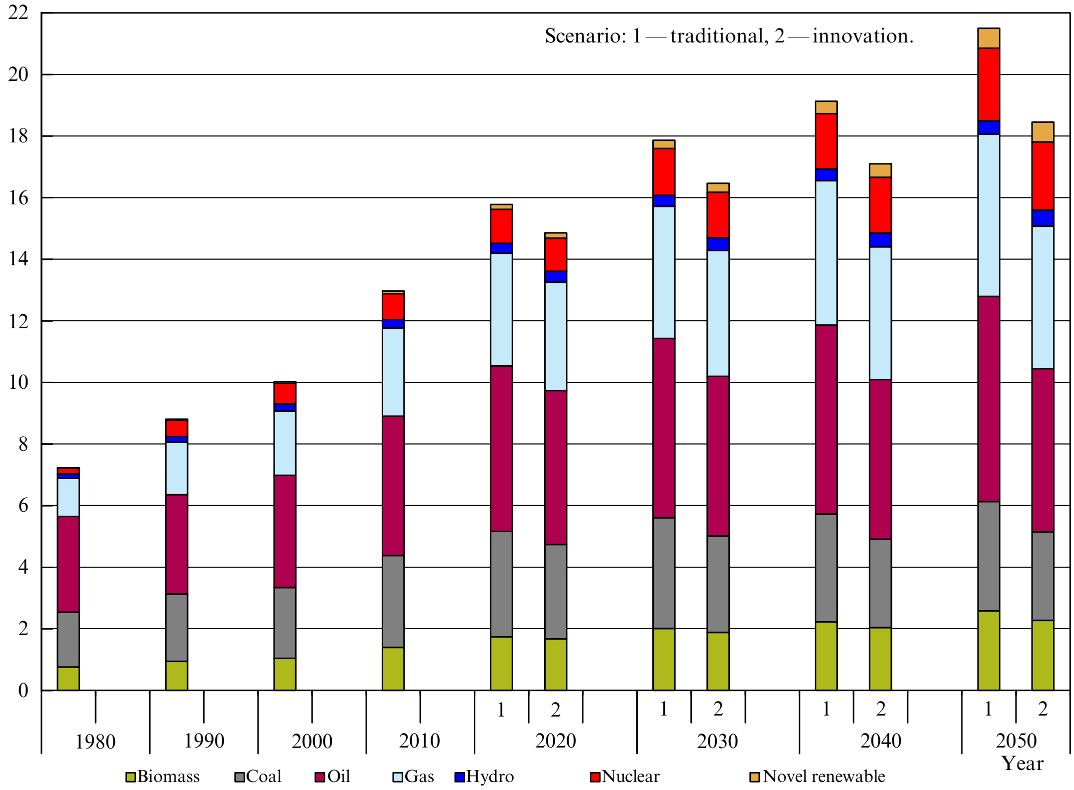

Figure 7. Forecasts for global energy resource production (in billion t.o.e.).

wars and large-scale epidemics) will be determined not by depletion of Earth's energy resources but by global processes of the cosmic evolution of the Sun — our major energy source. According to the current view [8], the Sun is an ordinary star of the yellow dwarf class, where the basic energy release is due to helium and carbon–nitrogen thermonuclear cycles. The period of stable solar thermonuclear burning will take around 5 billion years, after which the Sun will expand and its surface will reach Earth's orbit, killing all that lives.

Thus, there is no threat of a general shortage of energy resources on Earth, but there is a real problem of the exhaustion of cheap oil reserves. As shown in Table 1, for the past one and a half centuries, the third of traditional oil resources that has been used was the cheapest oil. In the last decade, an increasing gap has emerged between preparation of oil reserves and production volumes, together with strong underfinancing of the whole branch. Unfortunately, the natural gas branch is the next in line, with 14% of its traditional resources having been currently used up (see Table 1).

Despite the high percent of extraction, continuation of the developed trend of oil production is expected, and in the presence of a wide variation of former estimates, the IEA's recent base forecasts predict its increase by 50% by 2050 (Fig. 7). Additionally, an almost twofold acceleration in natural gas production growth is expected by 2050. Although oil and gas production forecasts are periodically corrected towards a decrease, organic fuel remains the basis of world energy production, providing, according to the base scenario, the current 55–56% of general primary energy production until the middle of the century (see inset to Fig. 7).

An increase of oil production cannot be based on reserves that are currently being developed — they will bring the production down threefold already by 2020. Involvement in the exploitation of already explored reserves will allow supporting today's production until 2015–2020. Hence, almost all predicted increases should be based upon traditional and then nontraditional oil resources. This requires new methods of finding and developing hydrocarbon fields on land and shelves (including underice production), which would allow increasing economically acceptable hydrocarbon reserves by 1.7 times before 2030 and to triple them leading up to 2050. Without that, oil production growth will stop and turn into a decline in 10–15 years, and gas in 20–25 years, which will sharply raise requirements for a technological reorganization of energy production and, possibly, will slow down the world's economic development.

Major production of oil will be still concentrated in the Middle East (with an increase from 1.7 billion tons in 2005 to 5–6 billion tons by 2050), and its remaining share will be proportioned approximately evenly among countries of the former USSR, Africa, and South America. The unequal distribution of energy resources makes it necessary to create international, transcontinental, and global energy production networks. In the next decades, the operating oil network will be complemented by a global gas network (Fig. 8).

3.3 Scientific and technological progress in energetics

Here, we briefly discuss a number of innovative areas in energetics.

Scientific and technological progress in energy production is accumulating advances and is one of the main channels of practical realization of the results of practically all sciences that create ideological and scientific and technological basic

Figure 8. The Eurasian gas network.

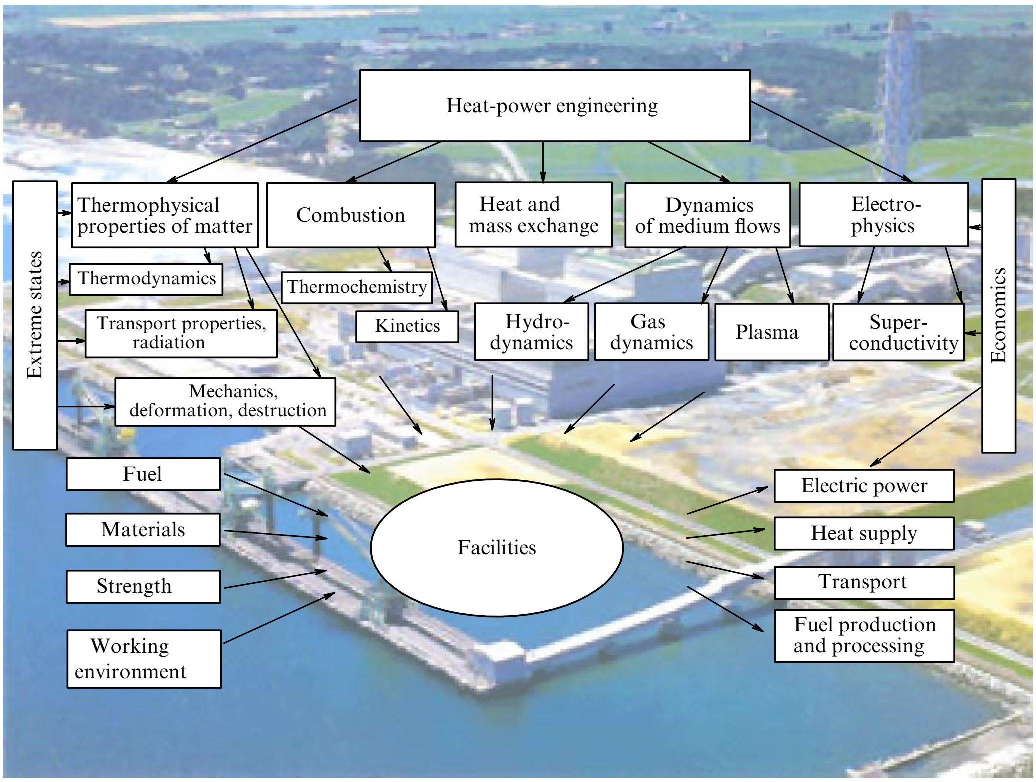

Figure 9. Scientific and technological aspects of heat and power engineering.

conditions for the innovative development of humankind's energy base. Figure 9 illustrates this for the example of thermal power production. The results of some sciences (first of all, economic and environmental sciences) influence the requirements of society concerning the development of energy production, others (geology, biology, physics) determine available energy resources, a third group (physics, chemistry, mechanics) creates concrete preconditions for innovations in energy production, and a fourth group (mathematics, information technologies, control processes)

Table 2. Research and development expenses for key technologies in energy production (in trillion US dollars, 2007) [1, Table 3.1].

Key technologies in energy production	Research and development	
	GGE1*	GGE2**
Electric-power production	3.2 – 3.8	3.9 – 4.5
Nuclear power stations	0.6 – 0.75	0.6 – 0.75
Wind power stations	0.6 – 0.7	0.6 – 0.7
Coal-fired plants with hypercritical steam parameters	0.35 – 0.4	0.35 – 0.4
Coal gasification power plants	0.35 – 0.4	0.35 – 0.4
Biomass gasification power plants	0.1 – 0.13	0.1 – 0.13
Solar energy/electric energy converters	0.2 – 0.24	0.2 – 0.24
Solar energy concentrators	0.3 – 0.35	0.3 – 0.35
CO_2 catching and disposal in thermal power plants	0.7 – 0.8	1.3 – 1.5
Structures, buildings	0.32 – 0.42	0.32 – 0.42
Energy-efficient buildings and home appliances	No data	No data
Heat pumps	0.07 – 0.12	0.07 – 0.12
Solar heating and water heating	0.25 – 0.3	0.25 – 0.3
Transport	0.26 – 0.3	7.6 – 9.2
Energy-efficient transport vehicles	No data	No data
Second generation biofuel	0.09 – 0.12	0.09 – 0.12
Electrical transport and power network-connected transport	0.17 – 0.2	4 – 4.6
Transport using hydrogen fuel cells	No data	3.5 – 4.5
Industry	0.7 – 0.9	1.4 – 1.7
CO_2 catching and disposal in industry, hydrogen production, synthetic fuel production	0.7 – 0.9	1.4 – 1.7
Energy-efficient industrial engines	No data	No data
Total	4.5 – 5.4	13.2 – 15.8

* Cuts in greenhouse gas emissions (GGE) by 2050 to 2005 levels (28 million tons of CO_2 equivalent).
** GGE cuts by 2050 to nondangerous levels (14 million tons of CO_2 equivalent).

ensures the controllability and stability of created energy technologies and networks.

Innovations in power engineering clearly demonstrate a pronounced international character and global trends. Consider them on the basis of the last IEA technological forecast [5] prepared according to the results of two-year studies made by almost 2000 researchers from Organization of Economic Cooperation and Development (OECD) countries.[2] Eight classes of key energy technologies (Table 2) as a part of more than 120 new technologies, and nine classes (almost 170 new technologies) of energy use were recognized as priority ones. Sufficiently detailed 'roadmaps' of their inclusion in innovative energy production were developed for each class of technology with terms and volumes of research and development work (R&D), utilization scales and required capital investments. In particular, a roadmap of actions was developed for electrical power engineering to maintain CO_2 emissions at the level of 2005 for average annual growth in electric-power production of approximately 5% (approximately 110 GW per year) by the annual commissioning of:

- 30 coal-fired power stations at 500 MW with CO_2 catchers — 15 GW per year;
- 24 nuclear power stations at 1000 MW — 24 GW per year;
- 30 hydro power stations at 500 MW — 15 GW per year;
- 5000 wind turbines at 4 MW — 20 GW per year;
- 45 CSP stations (Concentrated Solar Power) at 250 MW — 12 GW per year;
- Solar panels totaling 115×10^6 m^2 in area — 17 GW per year.

Table 2 presents classes of key technologies singled out by the IEA and the R&D expenses necessary for their realization. To return by 2050 to the greenhouse gas emissions levels of 2005, from \$4.5 to \$5.5 trillion are required, and mostly for technologies of electricity production. Cutting emissions twofold in order to stabilize Earth's climate will triple these expenses, mainly in relation to transport technologies.

Thus, the 'greenhouse threat' promises the world scientific community \$15 trillion, almost twice the expenses for military R&D if current annual volumes are maintained. It is not surprising that such prospects are encountering heated responses in certain circles.

In the IEA's forecast, the conclusion is drawn that the technologies already brought to the stage of industrial trial are capable of solving the problems faced by power engineering, at a minimum, until 2030. It would seem that the issue of the innovative development of power production at the given stage is solved.

However, it is necessary to emphasize that the IEA's technological package is entirely oriented on a conjuncture of Western energy markets, and two thirds of these technol-

[2] By their goals, scale, and methodology they are close to the energy item of a program that was developed in the 1980s under the supervision initially of V A Kotel'nikov and then of A I Anchishkin: "Complex program of scientific and technological progress in the USSR." These studies should certainly be renewed in Russia under new socio-economic conditions and at a new level of knowledge and methodology.

ogies (according to costs) are guided towards aggressive greenhouse gas emission cuts. As we shall show below, the priorities and, most importantly, the technical and economic characteristics of these technologies are not appreciably rational for Russia's energetics.

The ascending stream of possible energy technologies is based on the fundamental achievements in physics, chemistry, and, recently, biology, which are used by such physical and engineering disciplines as electrical physics and electrical engineering, thermal physics and heat engineering, hydraulics and hydraulic engineering, atomic and nuclear physics and nuclear engineering. This is the essence of corresponding studies and the foundation of technological progress in energy production, and according to rough estimates, up to 70% of scientific efforts in the field are devoted to them.

An overwhelming part of electric power in the 21st century will still be produced by the burning of organic fuel in thermal power plants. Apparently, in foreseeable decades, the steam–gas (or combined) cycle based on the successive applications of gas-turbine installations and steam–gas installations remains the most promising. The current efficiency of 58–62% can be increased to 75–80% by introducing high-temperature fuel cells into the cycle, improving blade cooling by air and water steam, applying high-strength high-temperature materials and barrier coatings, improving the gas dynamics of blade and flowing channel parts, and applying physicochemical and electrophysical control methods of combustion, i.e., by using all the scientific arsenal of modern high-temperature thermal physics. Coal-steam plants are being created by applying various methods of coal gasification — in close cycle or in a fluidized bed. This is especially important for Russia, in the European part of which natural gas accounts for 70% of power plant fuel — currently burnt in an inefficient steam-power cycle with an efficiency of only 38–40%. Coal can also be an efficient fuel in the conventional Rankine cycles working at supercritical steam parameters ($T \approx 600-650\,^{\circ}$C, $P \approx 300-350$ atm) with an efficiency of 47% [6].

Undoubtedly, fuel cells and 'electrotechnological' installations will be developed to obtain coal-derived liquid fuel, high-energy gas, etc.

The main alternative energy sources are hydroelectricity, solar energy, bioenergetics, and exothermic nuclear reactions. Other sources (wind power, ocean tides, and geomagnetic sources), though of certain local value, can hardly become significant on a global scale, the more so because the world's energy consumption structure demands that about 50% of energy be delivered to the user in a continuous (base) regime. For many alternative sources this means energy recuperation and, accordingly, the necessary doubling or tripling of power during their active operation.

Thus, a solar plant with 1 GW mean power should have a 3–4 GW peak power and a hydroelectric plant with the power on the order of 1 GW and a water basin area of approximately 30–40 km^2. As an alternative, the use of solar power for hydrogen production is possible. As a whole, solar power engineering is now actively developing since use began of semiconductor photoelectric converters and heat machines. In the first of these areas, impressive results have been reached — the efficiency of third-generation cascade heterostructures utilizing most of the solar spectrum is at the level of 40–50%.

As an interesting but not a close prospect, large-scale projects of space-based photoelectric converters in heliosynchronous orbits, and the transmission of produced energy through microwave (MW) power channels to Earth are being considered. Such a project assumes the application of advanced energy and space technologies, as well as large-scale international cooperation.

Hydraulic energy amounts to 21% of global electric energy. Its development is determined by available water resources and, as the majority of the most attractive hydro resources have already been developed, the power of hydroelectric plants will be at the level of 1.5–1.7 TW. Here, the outlook is related to realization of new large-scale projects (for Russia — in Siberia and in the Far East), as well as the development of modern hydrogenerators with gigawatt power and a variable rotation speed. Large-scale hydro power engineering has good prospects in combination with developed power transmission lines to transfer the produced energy to the European part of Russia during peaks of daily power consumption.

The prospects of using biomass in power engineering, as the most ancient method of producing energy, depends in many respects on advances in bioengineering associated with developing highly productive green plants and methods for processing them into fuel. It is also necessary to make sure that the fuel energy produced from biomass exceed the energy spent for plant cultivation. At present, to grow agriculture produce with the energy equivalent to 1 GJ it is necessary, for its cultivation, to spend not less than 3 GJ of fuel [3]. Advances in biology and chemistry provide the scientific basis for conversion of biomass of various sorts into high-quality liquid fuel and gas fuel with the use of fermentation, for developing new species of cellulose-containing cultures with enhanced productivity, which do not compete with food-destined cultures, and for developing other bioenergetic technologies. It is important that this way of producing energy not disturb the carbon balance, while changing, however, the nitric and phosphoric cycles. According to Ref. [3], by the middle of 21st century bioenergetics can produce up to 3.5 Gt of carbon (3.5% of carbon fixed by Earth's plants), processing 18–22 Gt of biomass and providing about 12% of total demands for energy. However, the development of bioenergetics can be restricted by competitive demand for land and fertilizer from agricultural producers.

On the basis of advances in chemistry and materials science, technologies are being developed to obtain liquid fuel from gas, coal, slate, and especially biomass, as well as methods and means of direct conversion of chemical energy into electric energy. It is known that the use of electric power began with galvanic cells. Nowadays, the power of chemical batteries exceeds the power of all power stations on Earth, and ahead is the development of fuel cells for the transport and distributed energy production. Of particular interest are supercapacitors of enhanced capacity and small accumulation times and time to release electric energy.

As highly attractive candidates for basic power engineering, atomic power stations (APSs) using the energy of the chain fission of heavy nuclei are again being considered. APSs deliver energy production of approximately 6% of the total energy produced (15% of the electric power; in Russia — 16%, in France — up to 70%) in the world. Recently, considerable progress has been achieved in increasing APS safety by developing active and passive safety measures. Today, nuclear power technologies are considered as highly safe and nonpolluting. The IEA scenario assumes an increase in power from nuclear reactors from the present 370 GW to 433 GW by 2030 [4].

In the nearest 20–30 years, most developments should demonstrate tank water-cooled reactors, fast-neutron liquid metal-cooled reactors, and high-temperature helium-cooled reactors. There is parallel work to create new-generation oxide and nitride fuels, designed for higher burn-off levels and improved safety characteristics.

Known caution in the development of nuclear power engineering is related to the problem of nonproliferation of nuclear materials suitable for nuclear weapons and of long-life radioactive waste. Here, the future outlook is related to reactors with increased (interior) safety and fast-neutron reactors with extended nuclear fuel recovery and a closed nuclear cycle involving uranium-238, and then thorium-232, reserves. We note good prospects for fission reactors with external neutron illumination, which demonstrate full internal safety.

The use of nuclear reactors for hydrogen recovery, which is used afterwards as a nonpolluting energy carrier in the electric-power engineering and in transport, has interesting prospects.

The more than 50-year period of intensive research on controlled nuclear fusion (CNF) has resulted in the beginning of practical implementation of this carbon-free and, in essence, inexhaustible energy source. The goal is to reproduce the CNF reactions of light elements, which give energy to stars and our Sun, on Earth. For this purpose, it is necessary to heat plasma in the conditions found on Earth to huge temperatures and to confine it for a certain time. Two approaches compete here: the use of fusion installations with magnetic or with inertial plasma confinement. There was recently impressive progress in both areas, allowing proceeding to practical applications of fusion energy in power engineering.

In CNF schemes with magnetic hot plasma confinement in closed toroidal tokamak systems, three machines — JET (Joint European Torus) (Europe), JT60-U (Japan), and PLT (Princeton Large Torus) (USA) — have already attained conditions where the energy input into the plasma is close to the energy release from thermonuclear reactions [3]. That has allowed proceeding to the construction of the International Thermonuclear Experimental Reactor (ITER), costing $13 billion (commissioning in 2017, with an operational life of approximately 25 years) and which is expected to reach a thermonuclear power of 500 MW and the energy release from the fusion reaction exceeding the power input for plasma heating and confinement by 10 times. The major scientific and technological results are planned to be obtained within 8 years from the beginning of ITER's operation.

Success of the ITER project will then allow proceeding with the construction (approximately in the 2030s) of the $10–$20 billion DEMO thermonuclear reactor (DEMOnstration/prototype fusion power plant) which will become a prototype of an industrial thermonuclear power station. As a prospective combined 'fusion-fission' scheme, a variant of a nuclear reactor is being considered in which the CNF reactor is used as a source of thermonuclear neutrons for an external-shell fissile fuel (which resides in an undercritical regime).

In parallel with the development of magnetic CNF power plants, an alternative scheme is being successfully developed based on inertial confinement of thermonuclear plasma that is heated up to temperatures of 10^8 K and compressed to huge densities (on the order of 1000 g cm^{-3}) with soft X-rays generated by powerful laser-heated plasma or by high-current Z-pinch plasma. Towards that end, a powerful laser system, NIF (National Ignition Facility), was constructed at Lawrence Livermore National Laboratory, consisting of 192 laser beams with a total energy of 1.8 MJ and a pulse length of about 10^{-9} s. A similar installation — LMJ (Laser Mégajoule) — is being constructed in France. According to estimates from their developers, both these facilities should provide positive thermonuclear energy release in the form of microexplosions.

With some delay, work in the area of pulsed power inertial CNF is being carried out rather vigorously, as well. In this case, soft X-rays compressing and heating a thermonuclear microtarget are generated by the collision of high-velocity (up to 500 km s^{-1}) plasma fluxes, which are accelerated by a huge pulse current (to approximately 40 MA).

In recent years, significant progress has been achieved in understanding the physical processes in hot plasmas of extreme states, occurring when compressing a target by laser and X-ray radiation. It is important that modern thermonuclear microtargets have already been tested in underground nuclear explosions, which provide the required radiation parameters [8]. The conditions for the ignition of fusion reactions have already been attained and consequently there are no doubts that CNF with inertial confinement can lead to success. The main technical problem faced by researchers working in this field is to make an effective pulse driver to accelerate thermonuclear microtarget shells. Along with the use of lasers and high-current pinches, intensive relativistic heavy-ion beams and various sophisticated combined schemes like 'fast ignition' are being considered here [8].

Speaking about thermonuclear research, we especially stress that the generation of extremely high temperatures and pressures is necessary to ignite thermonuclear reactions; that requires detailed studies of the physical properties of hot plasmas in extreme states occurring in astrophysical objects, but is difficult to attain in laboratory conditions [8].

Thermonuclear energy production is especially attractive because of its virtually unlimited fuel resources and ecological cleanness. The widespread deuterium isotope can easily be extracted from sea water. Tritium is sufficiently recovered in the reactor from lithium whose reserves (like those of deuterium) will be available for many thousands of years. The fusion reaction product — helium — is not radioactive. While there is an induced radioactivity in reactor materials, this problem already has satisfactory solutions.

Currently, it is difficult to say which CNF scheme — magnetic or inertial — will be the basis of future industrial thermonuclear reactors, but, considering the significant difficulties of this project, practical implementation of thermonuclear energy production is predicted [7] not to take place earlier than in the second half of the 21st century.

Development of thermonuclear and space power engineering in the future will require, according to the forecast of the International Council on Large Electric Systems (CIGRE), the creation of a global electrical power system (Fig. 10).

Along with power generation, a considerable and crucial part of the present-day electrical power engineering is represented by electrical transmission and distribution networks. Over the previous decades, one of the world's largest united power grids was built in Russia; however, it now requires reconstruction and development based on new power technologies. Recent progress is related here to the

Figure 10. The global electrical power system — a project of the International Council on Large Electric Systems (Conseil International des Grands Réseaux Electriques, CIGRE).

Figure 11. Mobile explosive simulator of lightning strokes based on a magnetic explosion generator.

creation of so-called controlled (or 'intellectual') electrical systems, practical use of high-temperature superconductivity, development of new composite conductors with improved strength and low resistance, as well as development of modern semiconductor schemes of control and monitoring of power networks, and many other solutions which physics is now offering to energetics [9]. Implementation of FACTS (Flexible Alternating Current Transmission System) technologies for creating controlled power networks allows radically increasing their reliability and decreasing losses (to 5%, instead of Russia's average 10–15%) owing, in particular, to the application of power semiconductor electronics and modern information systems of diagnostics, control, and monitoring. This enables optimizing and controling the transmitted active and reactive power, changing as required the electric power fluxes and effectively control voltage levels in the basic and emergency regimes. To create such intellectual systems requires perfect high-current semiconductor devices. Today, up to approximately 40% of all electric power produced in the world passes through various high-current semiconductor devices which are quite reliable and effective for the control of considerable outputs in power transmitting, distribution, limiting, and conjugating devices. Here, especially attractive prospects are related to the application of silicon carbide, as well as large-scale implementation of semiconductor devices for controling electrical power, and improving its quality and reliability.

To transfer the power supply network sector to a new technological level, it is necessary to apply large-scale efforts and expenses to create an elemental basis of high-current semiconductor electronics [9] with the subsequent development of controllable reactors, synchronous compensators, devices of transverse and longitudinal compensation, phase rotation systems, static compensators (statcoms), and semiconductor rectifiers for conjugation inserts. Other methods can potentially increase the reliability of electrical systems, in particular, the employment of highly reliable and fast explosive circuit breakers and commutators, and mobile simulators of lightning strokes based on powerful magnetic explosion generators, as suggested by Andrei D Sakharov (Fig. 11).

Superconductivity and especially high-temperature superconductivity remain the most promising fields of work in electrical power engineering. Recently, there was a serious breakthrough related to an increase in the critical temperature of superconducting transition, which exceeded the boiling temperature of liquid nitrogen. There is widely active work to make superconducting inductive storage systems, short-circuit current limiters, synchronous compensators, superconducting cables and solenoids, magnetic systems, electric motors, transformers, etc. [9].

In 2006, the USA commissioned the longest (350 m) semi-industrial superconducting cable made of a second generation superconducting wire, rated at a current of 0.8 kA, a voltage of 34.5 kV, and a power of 35 MW. In our country, work has started to make a superconducting cable 200 m in length with a current of 1.5 kA, a voltage of 20 kV, and a power of 50–60 MW. These developments, which are already solving the complicated problems of energy delivery into densely built-up historical parts of megacities, provide a technological basis for the construction of more extended superconducting industrial lines and other electrotechnical units without electric power losses [9, 10].

Radical change in the electric power engineering is expected, of course, with the discovery of 'room'-temperature superconductivity — one of the central issues of modern physics [11] and on which large teams of skilled physicists of various specialties are persistently working.

3.4 System studies of the development prospects of energetics

Energy science selects effective energy technologies from a large number of possible technologies following M A Styrikovich's paradoxical principle: "Energetics is physics+economics." Such a selection is made according to the criteria of *economic efficiency and environmental sustainability*, taking into account all aspects of *reliability and controllability* of technologies. Ten to fifteen percent of energy studies are devoted to that and, apparently, they define the STP priorities in energetics.

First, however, the above selection criteria of effective technologies are quite ambiguous and very inconsistent: it is clear that the more reliable and 'environmental-friendly' the technologies are, the more expensive they end up being. Second, energy technologies do not usually work in isolation, but in complexes or systems where the sum of local

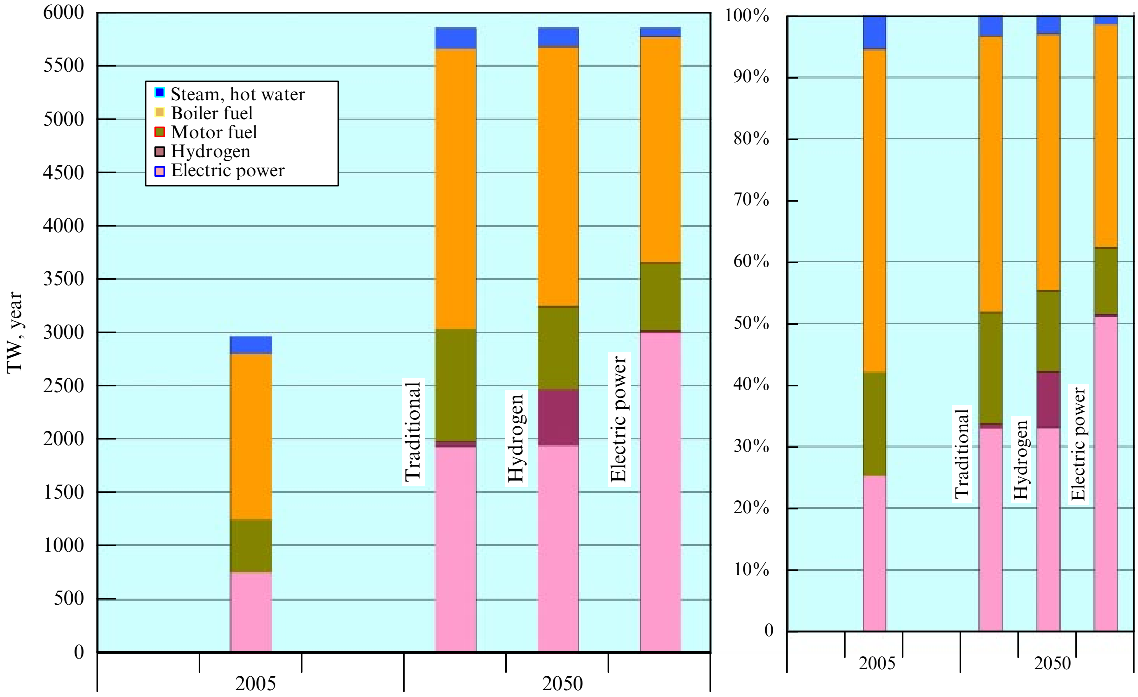

Figure 12. End-use energy supplied to customers.

optima by definition does not correspond to the global optimum.

Therefore, an important field of energy science covers research and development of energy systems, which consumes another 10–15% of efforts. System studies in energetics on the basis of mathematical modeling using computers have been widely expanded since the 1960s, and the Soviet school of L A Melent'ev [2] ranked among the leading positions in the world. However, because of large uncertainties regarding the future and the ambiguity of scientific and technological process, this methodology does not also provide sufficiently robust predictions of innovations.

Thus, to determine effective avenues and priorities of scientific and technological progress, in addition to what was said above, it is necessary to involve studies of evolving trends of spatial and industrial development of energetics, i.e., the quintessence of 'as it actually was' in the past [1, 12]. Up to 5% is focused on this in energy research.

Spatial development of energetics follows the trend of creating interstate, transcontinental, and global systems. Such systems have a powerful *physical and technological basis* in the form of pipelines and electrical networks and simultaneously act as more and more *complex industrial systems* and, nowadays, as *energy markets*. The global oil system, formed during the 1980s–1990s, in the next 10–15 years will be complemented by (and integrated with) the global system of gas supply (see Fig. 8) that is being formed by the wide use of liquefied natural gas in combination with the development of the Eurasian gas supply system [13]. Later on, probably after 2050, a global integration of regional electric-power systems will be required for wide use of space and thermonuclear energy (see Fig. 10).

The *technological development* of energy production, as was already stated, follows the path of a quick increase in the variety of consumed energy forms and increasing energy quality. At the same time, the avenues of scientific and technological progress discussed in Section 3.3 promise at last to overcome the 'imprecation' of efficiency reduction when producing higher-quality energy. Understanding these trends allows aiming to achieve an efficiency of more than 50% by the middle of the 21st century for the basic indicator of energy production innovation — the general available energy factor — and accordingly formulating the technological policies and searching for means to achieve this goal. But for this purpose it is necessary to see the possible directions of the changes in end-use energy consumption structure.

Figure 12 shows that for the IEA's predicted doubling of global energy production from 2005 to 2050, the share of electric energy in the gross end-use energy will increase *according to established trends* from 25% to 33% with a reduction of the share of direct burning of fuel (boiler and motor in total) from 69% to 63%, and the share of heat (steam, hot water) from about 6% to 4%.

The USA, the European Union, and Japan plan to proceed from this traditional trajectory to the *hydrogen energetics* scenario according to the 'Bush hydrogen initiative'. Even by optimistic estimates, hydrogen will provide no more than 10% of end-use energy consumption, which will demand the development of infrastructure to produce, transmit, store, and distribute (to car refueling stations) up to 3 billion cubic meters of this highly volatile, very fluid, and dangerously explosive gas. (For comparison, the world is currently producing an approximately similar amount of natural gas, and significantly simpler issues of its safe use are already expensive enough.)

The hydrogen scenario will barely change the share of electric energy in end-use energy consumption, and the share of fuel (basically, liquid) will be reduced to 55%, and the share of heat to 3%. But even with wide replacement of present water electrolysis by thermochemical technologies of hydrogen production, its use will require large electric power consumption. Meanwhile, hydrogen will replace oil fuel in fuel cells, again with producing electric power: a hydrogen car is, as a matter of fact, an electric vehicle. As a result, we shall obtain a sort of special electric energy storage, but with a cycle efficiency of less than 20%.

As an alternative, there is an *electrical global* scenario where more than half of the end-use consumption is provided by electric energy. With qualitatively new accumulators, it will reduce the direct burning of fuel to 47%, first and foremost, in transport and in distributed energy production, and with mastering superconductivity will facilitate the use of renewable energy, especially solar and tidal.

This is one of the major bifurcations of innovations in power engineering. The demand for other areas of STP and the general configuration of future power engineering strongly depend on who wins the race of ideas and technologies in the field of effective storage of electric power. Yet, in the IEA's forecasts, there is no clarity with respect to this issue.

The system estimate of possible scenarios for global energy consumption growth (see Fig. 5) taking into account expansion of accessible reserves of primary energy resources (see Table 1 and Fig. 6) and STP possibilities in energetics (see Section 3.3) allows one to make the two following conclusions on the development prospects for global energetics in the first half of 21st century:

(1) Realization of the IEA's traditional scenario [4, 5] is unlikely because of the global crisis, as well as of internal inconsistency of the scenario: on established trends of technological progress in energetics this scenario would give us intolerably high emissions of greenhouse gases with a high risk of planetary climate change, and its modification suggested in Ref. [5] of the forced development of 'less carbon' technologies will only reduce emissions to a 'safe' level (nearly 14 billion tons of CO_2) by doubling the expenses for the development of energetics, which will hardly be acceptable for the global economy.

(2) It is necessary to apply the best efforts of the public, politicians, and business (otherwise it will be initiated by the course of events through economic crises and natural cataclysms) for the conscious transition to an energy-effective way of life with deceleration and then termination of the growth of the world average energy consumption per person (see target scenario 2 in Figs 5 and 7). Then, the 'safe' scale of greenhouse gas emissions will be almost twice as cheap as in the traditional scenario, or even cheaper if the methods of geoengineering to reduce overheating of the atmosphere will also be used.

4. Prospects of the Russian fuel and energy complex

Russian energetics has important features leading to specifics of the country's energy policy and its scientific and technological component.

The main feature is the wealth of comparatively cheap energy resources: Russia possesses more than 15% of the global explored fuel reserves for less than 3% of the world's population and 6% of the global energy consumption. That objectively predetermines a large export component of our energetics.

Furthermore, Russia is the coldest (two thirds of the territory is a permafrost) and the most extended (11 time zones) country, with a very low density of population and energy infrastructure — four and seven times smaller than in the USA, respectively,. It is partly for these reasons that the energy efficiency of the Russian economy is five times

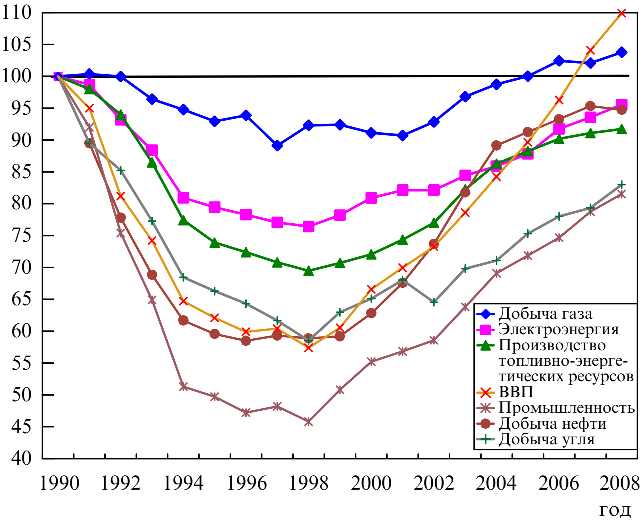

Figure 13. Dynamics of Russia's gross domestic product, industry, and FEC branches (in %).

worse, and the load of energetics on the economy is four times larger, than the world average: capital investments in our energy production are reaching 5% of the gross national product, while they are 1.5% in the world as a whole.

It is important that Russia is relatively neutral to the climate warming and, possibly, can even benefit from it, and therefore this topic concerns us (objectively) to a lesser degree.

As an inheritance from the USSR, Russia obtained a powerful (second in the world by production) fuel and energy complex (FEC) which experienced a heavy recession together with all of the nation's economy. Recently, its basic branches had almost recovered to the pre-reform level (Fig. 13), but the world crisis brought new losses.

Despite an acute shortage of investments, in last 15 years Russia's FEC supported the reconstructed national economy; that caused crisis phenomena in its important sectors. Commissioning new facilities in the electrical power engineering was reduced by 10 times, and the depreciation of equipment reached a threatening magnitude. Half of the electric power capacities and up to 60% of heat networks in the country have used up the base resource and require replacement, and 10–20% of them are in emergency state. The share of our most perfect combined-cycle plants is depressively small — only 1.5%. Losses in heat networks reach 30%, and in electric networks reach 15%, with an average European level of approximately 5%. To replace discontinued facilities, it is necessary to commission 7–8 GW of new installations annually, whereas the actual input is nearly 1 GW.

The current Energy Strategy of Russia for the period to 2020 (ES-20) aims to overcome these deficiencies [12, 13], and in 2007 work began to amend and extend it to 2030 (ES-30). The global economic crisis brought essential corrective amendments not only to global prospects, but also to Russia's, having delayed by 5–7 years the achievement of planned (in the middle of 2008) development levels for the expected national economics (Fig. 14) and energy production (Fig. 15). But with reduced expectations for the growth in the country's gross national product by 2030, the amended forecasts for the period to 2020 remain within the range of ES-20 values.

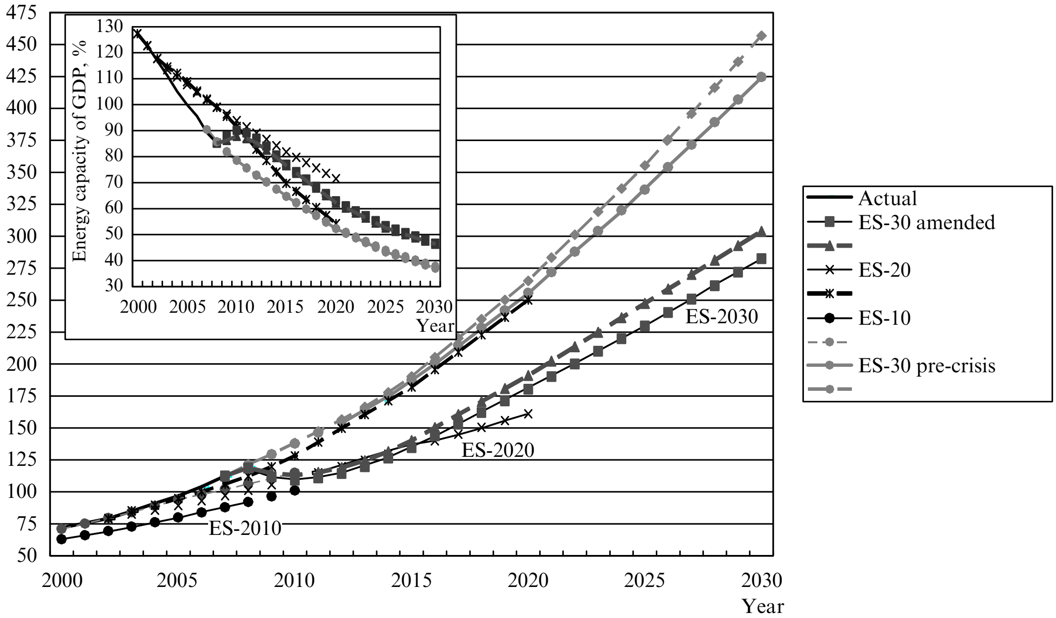

Figure 14. Actual and forecast Russia's GDP (in % of 1990).

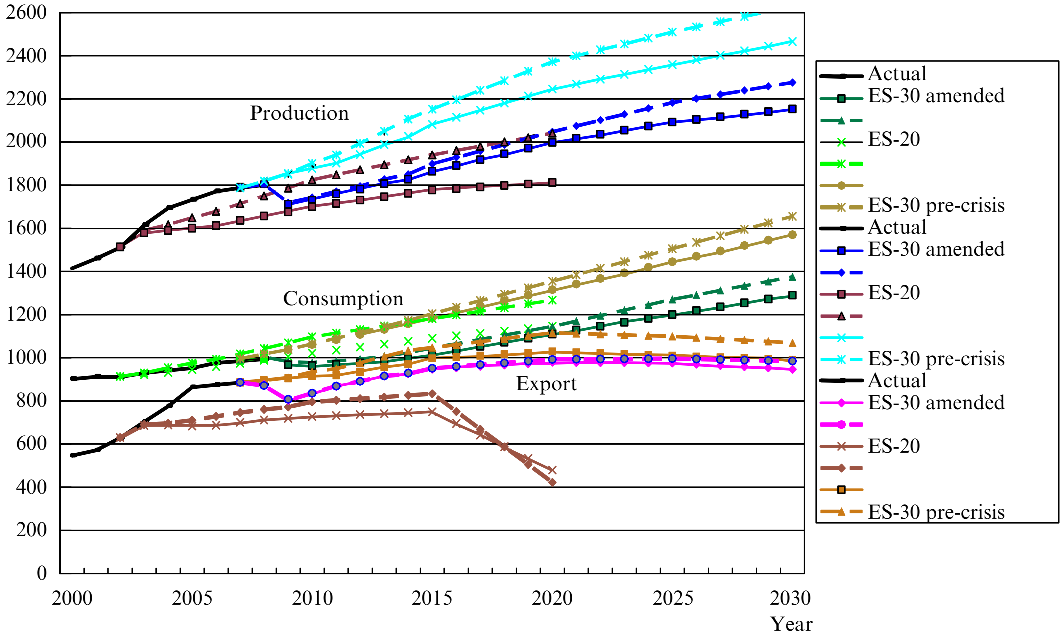

Figure 15. Primary energy resources (in millions of tons of hydrocarbon fuel).

The above specific features of Russia's energetics essentially distinguishes its innovative development priorities from those developed by the IEA [5]. The highest priority for us is power efficiency in organizational–administrative, and also in technological, aspects. Innovations in long-distance power transmission and in distributed (decentralized) energy production, as well as in deep fuel (especially hydrocarbons) processing and in heat-power engineering are also very important for Russia. But the means and technologies for realizing these priorities are seriously restrained in Russia by an acute shortage of investments. Therefore, with relatively cheap fuel and energy in Russia, it is more rational to use moderately capital-intensive technologies, even with slightly worse efficiency compared to the highest achieved efficiencies in countries with expensive energy.

In addition, Russia's technological policy should be oriented towards moderate costs of measures to restrict greenhouse gas emissions.

Taking the above into account, adjusted scenarios for Russia's FEC development suggest renewal from 2014–2015 of sufficiently high rates of economic development (with a growth in gross domestic product by 2030 of 2.9–3.1 times (see Fig. 14) compared to GDP in 2005). However, the crisis has not just slowed down, but also for 2–3 years has turned back the decrease in energy capacity of GDP (in 2000–2008, the energy capacity decreased by one third), having returned its subsequent dynamics in the mid-range of the ES-20 forecasts (see inset to Fig. 14). Thus, the economics will show a rise in demand for energy resources, in which their consumption to 2030 will increase, with respect to 2005, by

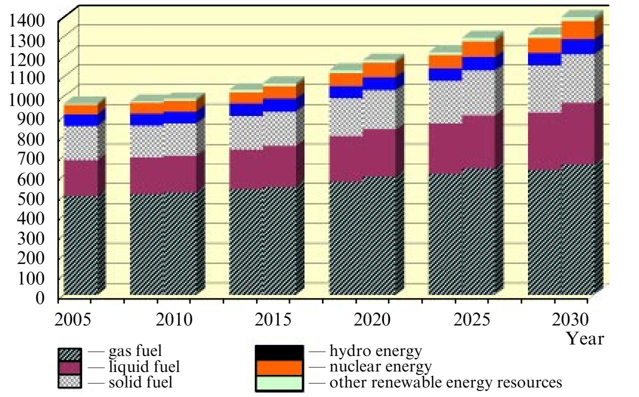

Figure 16. Consumption of primary energy resources in Russia (in millions of tons of hydrocarbon fuel).

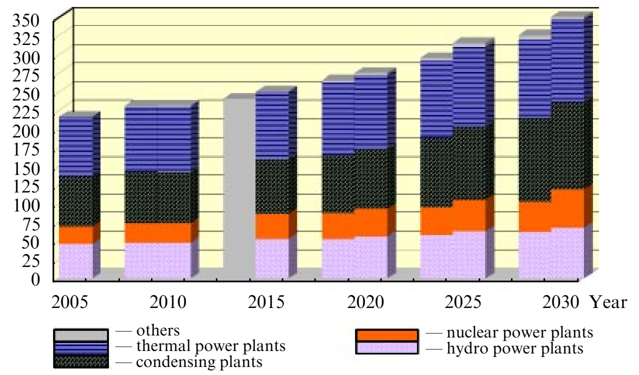

Figure 17. Power of Russian electric power plants (in 10^6 kW).

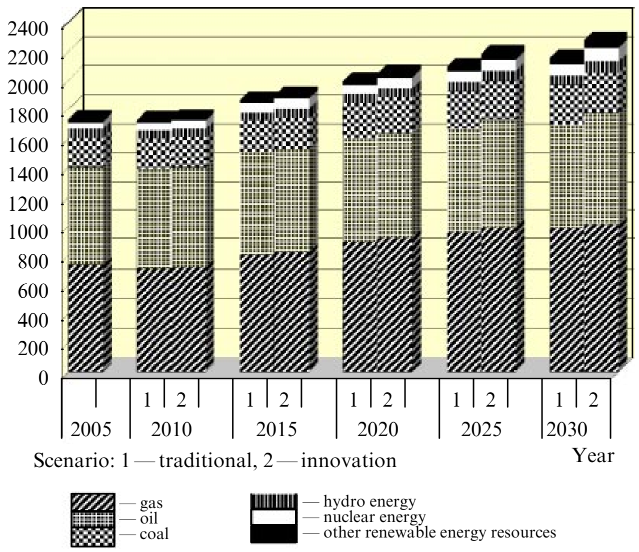

Figure 18. Production of energy resources in Russia (in millions of tons of hydrocarbon fuel).

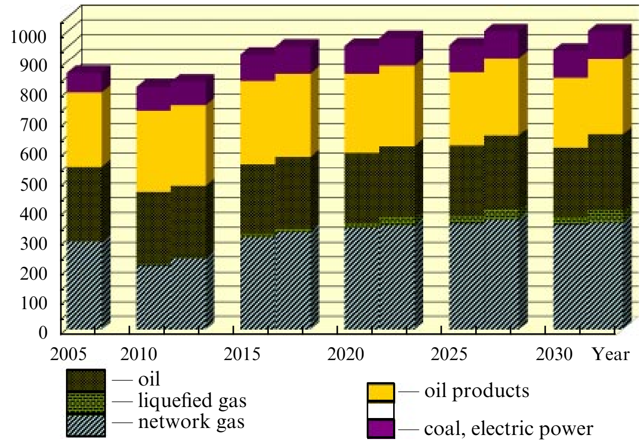

Figure 19. Export of energy resources (in millions of tons of hydrocarbon fuel).

35–45%. At the same time, reorganization of the internal demand structure — transition from gas to other energy resources — will be slowed down essentially, as long as gas still remains the cheapest fuel (at least to 2011–2012). Only then will the share of natural gas in the country's energy consumption begin to decrease to 48–49% by 2030 (Fig. 16). Electric-power stations whose power production will increase with respect to their figures in 2005 by 34–42% in 2020, and in 1.7–1.9 times by 2030 will still be the major consumer (41–42%) of energy resources in our country, with an increase of the cumulative share of hydroelectric plants, nuclear power plants, and renewable sources from 32.3% in 2005 to 33–36% (Fig. 17) and a reduction in the share of gas in fuel consumption from 67.9% in 2005 to 64–65% in 2030 (Fig. 18). Overall, production of energy resources in the country from 2005 to 2030 will increase by 25–30% with the essential replacement of oil (from 38.5% to 33–33.5%) by nuclear energy (increase from 2.8% to 3.5–4.2%), renewable sources (from 1.2% to 1.7–2.4%), and coal (from 11.7% to 13%) (see Fig. 18). Oil production will increase from today's 480 million tons to 500–535 million tons by 2030, mostly because of Eastern Siberia and the Far East, but the major increase in energy resource production will be provided by natural gas production to 855–885 billion m^3 in 2030, mostly in Yamal and the Shtokman field, as well as in Eastern Siberia and in the Far East. Also, an advanced growth in coal mining to 420–425 million tons in 2030, mostly in the Kuznetsk and Kansko-Achinsk basins, is expected.

All this will allow fuel export (relative to the crisis' lowered level of 2010) to increase by 16–17% by 2020, with subsequent stabilization or even a decrease (Fig. 19) and replacement of oil exports (from 61.5% to 49–50%) by natural gas exports through pipelines (growth from 34% to 37–39.5%) and in a liquefied state (to 3–4%).

Such development in Russian energetics will allow keeping greenhouse gas emissions below 1990 levels up to 2030 (Fig. 20). Capital investments in energetics' development for this period as a whole will be 3.5–3.7% of the country's GDP, reducing from the current 4–5 % to 3% by 2026–2030. Thus, the main social and economic parameters of energy production can be significantly improved compared to analogous parameters in pre-crisis forecasts.

To achieve the above results, our energy science should concretize Russian STP priorities, while taking into account global trends, and creating technologies with parameters corresponding to Russian conditions. It is also important to secure, using documents from the Energy Strategy, the composition, parameters, terms, and scale of application of priority energy technologies with their necessary financing.

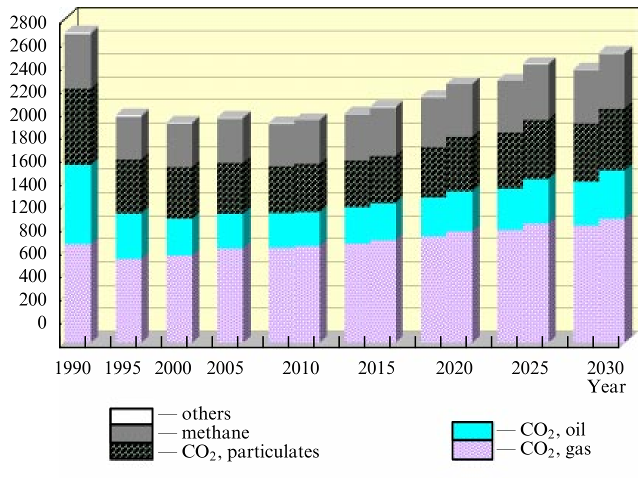

Figure 20. Greenhouse gas emissions by fuel types.

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PACS numbers: **01.65.+g**, **52.35.–g**, **52.55.–s**
DOI: 10.3367/UFNe.0179.200912m.1353

Lev Andreevich Artsimovich and extremely strong hydrodynamic instabilities

A M Fridman

A brief background account is perhaps in order to explain how it was that Lev Andreevich presented my graduate thesis to *Sov. Phys. Dokl.* journal.

The story starts with the 1962 *Phys. Rev. Lett.* paper [1] by R Geller, a prominent American experimentalist, who demonstrated for weakly ionized plasma in a magnetic field that its diffusion across the field builds up as the field is monotonically increased from a certain value.

This finding seemed to be at odds with well-known earlier experiments indicating that both the classical and the Bohm diffusion coefficients decrease with increasing magnetic field H.

I was then an undergraduate at NGU*, and here is what Roald Sagdeev, my teacher, told me that same year when leaving for summer vacation: "I'll tell you what. I will be back in a month and if I find your paper on my desk explaining the Geller effect, you will be a postgraduate at IYaF upon your graduation. If not, at NGU."

Roald did find the paper on his desk on his return, and he then arranged with Lev Andreevich for the paper to be presented at the T seminar (on thermonuclear fusion) at what was then LIPAN (Russian acronym for Laboratory of Measuring Instruments of the USSR Academy of Sciences, currently the RRC 'Kurchatov Institute'). Two days after my talk there, Sagdeev told me that Lev Andreevich suggested presenting my graduate thesis to *Sov. Phys. Dokl.* (see Ref. [2]), but that he would like to speak to me first.

The conversation with Artsimovich is a memory I will never forget. What I saw and heard struck me. It had never occurred to me that what I did could be looked at in that simple back-of-the-envelope way. With one exception (coefficient $k \ll 1$), all aspects of my work were explained by Lev Andreevich at a totally elementary level.

As an illustration of what our conversation was about, a few pages of my thesis follow below.

The analysis in Ref. [2] leans upon the following equations to describe the dynamics of weakly ionized plasma with electrons magnetized and ions not magnetized:

$$\frac{\mathrm{d}}{\mathrm{d}x}(T\,\delta n) - en_0\,\frac{\mathrm{d}}{\mathrm{d}x}\,\delta\varphi + \frac{e}{c}\,n_0\,\delta v_{\mathrm{e}y}B + \frac{\mathrm{d}\ln n(x)}{\mathrm{d}x}\,T\,\delta n = 0\,, \tag{1}$$

$$\mathrm{i}k_y T\,\delta n - \mathrm{i}k_y e n_0\,\delta\varphi - \frac{e}{c}\,n_0\,\delta v_{\mathrm{e}x}\,B = 0\,, \tag{2}$$

$$\mathrm{i}k_z T\,\delta n - \mathrm{i}k_z e n_0\,\delta\varphi = -n_0 m_{\mathrm{e}}(\nu_{\mathrm{ei}} + \nu_{\mathrm{en}})\,\delta v_{\mathrm{e}_z} - n_0 m_{\mathrm{e}}\nu_{\mathrm{ei}}\,\delta v_{\mathrm{i}z}\,, \tag{3}$$

$$\mathrm{i}\omega\,\delta n + \mathrm{div}\,(\mathbf{v}_{\mathrm{e}0}\,\delta n) + \mathrm{div}\,(\delta\mathbf{v}_{\mathrm{e}} n_0) = 0\,, \tag{4}$$

$$\mathrm{i}\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}x} + e\,\frac{\mathrm{d}}{\mathrm{d}x}\,\delta\varphi = 0\,, \tag{5}$$

$$\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}y} + ek_y\,\delta\varphi = 0\,, \tag{6}$$

$$\omega m_{\mathrm{i}}\,\delta v_{\mathrm{i}z} + ek_z\,\delta\varphi = 0\,, \tag{7}$$

$$\mathrm{i}\omega\,\delta n + \mathrm{div}\,(n_0\,\delta\mathbf{v}_{\mathrm{i}}) + \mathrm{div}\,(\mathbf{v}_{\mathrm{i}0}\,\delta n) = 0\,, \tag{8}$$

where T is the electron temperature (it being assumed that $T_{\mathrm{e}} \gg T_{\mathrm{i}}$); e is the electron charge; c is the speed of light in a vacuum; m_{e} and m_{i} are the electron and the ion mass, respectively; ν_{ei} and ν_{en} are the electron–ion and electron–neutral collision frequencies, respectively, and $\mathbf{v}_{\mathrm{e}}$ and $\mathbf{v}_{\mathrm{i}}$ are the directed velocities of the electrons and ions, respectively.

* NGU, Novosibirsk State University; IYaF, Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences.