ENERGY CONSUMPTION AND TECHNOLOGICAL DEVELOPMENTS

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Foreword

Throughout mankind's history, energy consumption has changed substantially due to the growth of the world's population and the great changes in human activities. The world's population continues to increase, having nearly doubled during the past third of this century. World energy consumption has increased even more rapidly, having more than quadrupled over the same period. The observation of historical consumption data over a significant time period, made by the author of this article, clearly indicates that there are no reasons to expect an interruption of this growth in the future which is considered to be the most important stage in the history of energy consumption. Each level of energy consumption has been accompanied by the corresponding primary energy sources and by the energy-related technological development.

According to the author's conclusions, the development of energy systems will be determined in the near future (the next 30–40 years) by contemporary energy technologies based on the exploitation of traditional energy resources, but in the more distant future technologies based on the exploitation of thermonuclear and solar energy will play the decisive role. Future energy development will be determined to a great extent by social and ecological factors and by the public's acceptance of new energy technologies. The Technology, Economy, and Society Program at IIASA has been involved for several years in assessing the socioeconomic and ecological determinants of global energy development and will continue to study this activity in more depth.

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ENERGY CONSUMPTION AND TECHNOLOGICAL DEVELOPMENTS

Vasilij Romanovič O k o r o k o v

The paper determines an outline of the world energy prospects based on principal trends of the development of energy consumption analysed over the long past period.

According to the author's conclusion the development of energy systems will be determined in the nearest future (30 - 40 years) by contemporary energy technologies based on the exploitation of traditional energy resources but in the far future technologies based on the exploitation of thermonuclear and solar energy will play the decisive role.

INTRODUCTION

One of the characteristic features of our time is the fact that a common viewpoint is shared by the energy community that our society is in a transient state towards new sustainable energy systems. Such new sustainable energy systems should be more efficient, reliable and safer, invironmentally cleaner and flexible to future energy demand. Many opinions exist as to what these new energy systems should look like and the possible paths of transition to this future. The first Energy Program, carried out at IIASA under the leadership of Prof. W. Häfele, showed that possible bases for sustainable energy systems are nuclear fission and fusion and hard solar power /1/. And with hydrogen as a possible energy carrier nuclear and solar systems seem to be very reasonable and promising as a sustainable energy option /8/. Novel horizontally integrated energy systems /2/ were considered the most favorable transition to this energy future along with the use of methanol /11/. The past years have brought about a change. First, estimates for oil and gas reserves and resources have changed substantially. Second, the price for oil decreased despite of many forecasts and third, Three

Mile Island and Chernobyl caused serious debates about the future of nuclear energy. In spite of these new circumstances and considering old uncertainties about the future energy demand, it will be interesting to observe the historical human energy consumption and energy technology development. As the proverb states, the future exists in the past, this exercise will help in assessing future energy development.

HISTORICAL ENERGY CONSUMPTION AND FUTURE PROSPECTS

Human societies use energy for many purposes. The level of energy consumption varies from country to country and region to region, depending on resource availability, technological development, economics and other factors such as lifestyle, culture, climatic conditions, etc. At present, total consumption of all forms of energy is very high (Fig. 1).

During the next half hour you spend reading this article about 250,000 tons of coal will be mined worldwide. During the same half hour, over 1.0 million barrels of crude oil, or about 150,000 tons, will be extracted worldwide and nearly 100 million cubic meter of natural gas will be pumped from wells or separated from crude oil. Further, 0.5 billion kilowatt-hours of electricity will be transmitted from power plants - energy which could light up five billion 100 W light bulbs during that half hour (Tab. 1). Valued in per capita terms, these energy flows amount to nearly 70 GJ annually, equivalent to about 2.5 tons of hard coal or 1.6 tons of crude oil for every inhabitant of this planet.

Throughout the history energy consumption has changed substantially (Tab. 2). There are at least seven stages of the energy consumption level which reflect human development (Fig. 2). The primitive man, about one million years ago, had only the energy content in the food he ate. The hunting man, who lived about 100,000 years ago, produced more food and used wood for heating and cooking. For these reasons his energy consumption increased. The primitive agricultural man, who lived about 5000 B.C., produced crops and used animal power for cultivation, and his energy consumption level was much higher than that for the hunting man. By 1400 A.D., the advanced agricultural man used already coal for heating and also water and wind power. This enabled him to produce more food and to trade his products. The industrial man of the

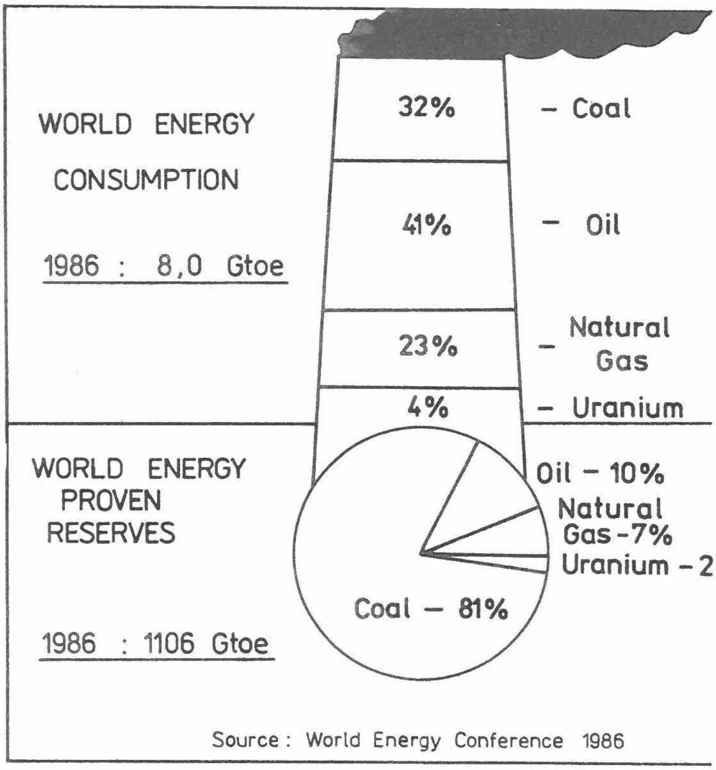
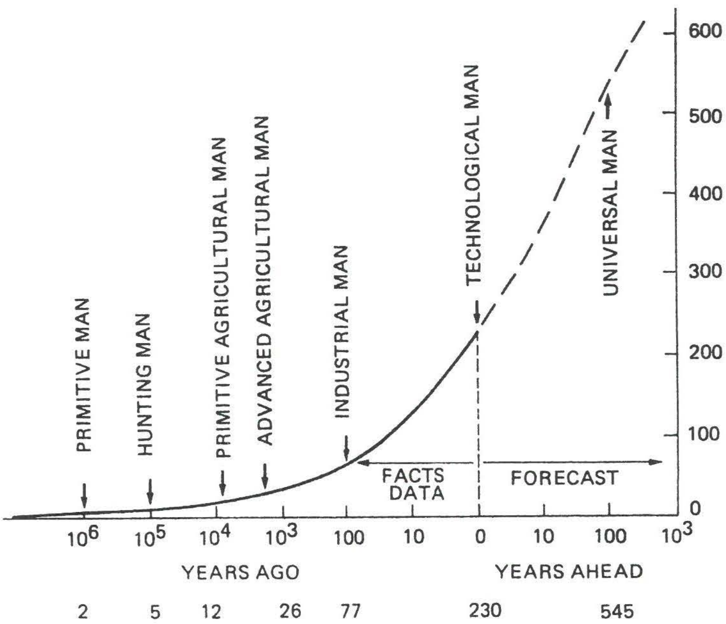


Fig. 1 World Energy Proven Reserves of Non-renewable Energy Sources and Structure of World Energy Consumption

Energy Sources	Energy Flows, Worldwide, in		
	Half an Hour	One Hour	One Year
Coal (t)	250,000	500,000	4.4×10^9
Crude oil (t)	150,000	300,000	2.63×10^9
Natural gas (million m^3)	100,000	200,000	1.85×10^{12}
Electricity (kWh)	0.5×10^9	1.0×10^9	8.8×10^{12}

Table 1 Global Energy Flows in 1987



V. Okorokov, IIASA, 1988

Fig. 2 Human Energy Consumption Throughout History - Daily per Capita Consumption (1000 kcal)

	Daily Per Capita Consumption (1000 kcal)				
	Food	Residential and Commercial	Industry and Agriculture	Transportation	Total
Primitive man	2	-	-	-	2
Hunting man	3	2	-	-	5
Primitive agricultural man	4	4	4	-	12
Advanced agricultural man	6	12	7	1	26
Industrial man	7	32	24	14	77
Technological man	10	66	91	63	230
Universal man*)	35	100	220	190	545

*) Source: E. Cook, Scientific American, September 1971
Estimates by V. Okorokov, IIASA, 1988

Table 2 Energy Consumption Throughout History late 19th century introduced the steam engine as a source for mechanical energy and added electricity as a new source for industrial development. Therefore, total energy consumption increased many times in comparison with the advanced agricultural man. The modern technological man utilizes advanced steam and gas turbines, electrical engines and nuclear reactors as well as rockets as tools for technological development, improving his physical comfort and quality of life. As can be seen from the historical energy consumption data for the whole period of human existence, there was a continuous growth in energy demand (Fig. 2). During the last two centuries this growth was substantial, which is the most revealing sign of mankind´s rising civilization. And there are no reason to interrupt this growth in the future, which we consider the seventh stage in the history of energy consumption.

For many reason, the future energy consumption must be considered the most important stage in the history of mankind. First of all, alterations to the natural resources will continue in order to use their energy more effectively, which will increase the future energy growth. Second, technological progress will continue in all directions of human activity - in agriculture, transportation, and industrial and residential areas. Great progress will be made also in space. The universal man will not only travel through the universe, but also do everything in order to use nature´s forces in the most universal way. The universal man will consume much more energy than the technological man. As can be seen from Fig. 2, the daily per capita energy consumption in 100 years will be not less than 545,000 kcal, i.e., 2.37 times more than the daily energy consumption of the technological man. He will consume more energy for food production and its storage, for housing and transportation and for his innovative-technological activity, which will include agriculture, industry and commerce in their current meaning. More energy consumption will allow mankind many other activities, hard to envisage now. For example, using other planets and oceans as raw mineral basins and new energy sources and using deserts for agriculture and for growing energy production, etc. Energy is the blood of human activity and growing human activity provides new possibilities for increased energy production.

ENERGY CONSUMPTION AND SUBSTITUTION

Each level of energy consumption was accompanied by the corresponding primary energy sources. The primitive man used only wild food in order to have energy for his physical activities. The hunting man used wood as the main energy source. The primitive agricultural man used farm waste and the advanced agricultural man used animal, water and wind power. The industrial man fulfilled his energy needs with coal and the technological man uses natural gas and oil as the main energy sources (Fig. 3). Following this way of thinking it is possible to conclude that the universal man will use nuclear fusion and solar energy as the source with the highest energy content. From this observation one can conclude that growing energy consumption is also accompanied by the corresponding primary energy sources with higher energy content (Fig. 4). This observation also shows that at the early stages of energy consumption man used mostly local energy sources which were more accessible and only at later stages man used more complicated energy sources like water power, coal and, of course, oil, gas, and nuclear.

The process of energy substitution does not have a consistent pattern. Consumption of previous energy sources continues although with a declining share. This is the result of related energy technology development, which will be discussed in the next section.

BRIEF HISTORY OF ENERGY TECHNOLOGY DEVELOPMENT

Throughout the history, the growth of energy consumption was accompanied by the energy-related technology development. On one side this growth was a result of the progress in energy technology development but on the other side it stimulated inventions. Energy-related technology development has a very long history. It started over more than one million years B.C., when the hunting man made use of fire. During this period many discoveries were made and many inventions were carried out (Tab. 3). The most important discoveries in energy development were made during the past two centuries (invention of the steam engine, discovery of electricity and nuclear power, etc.), which encouraged a dramatic increase in industrial and technological developments and their related energy consumption increases (Fig. 2). Energy technology develop-

Year	Event
2 million	First use of stones as tools
1 million	First use of fire by hunter-gatherer societies
15000	Beginning of pottery
3500	Rise of cities, first use of metal, invention of wheel
1500	Invention of lever
1300	First tools made from smelted iron
1000	Chinese produced natural gas from 3000-ft wells and transported the gas in bamboo pipelines;gas was used for space heating and light
700	First use of pulley
400	First drilling for oil
B.C. 27	Invention of waterwheel
A.D. 250	Chinese first to use water mills and gunpowder
600	Windmills development by Arabs
1118	First use of cannons in Europe
1200	Coal mining begun in Europe
1230	Rockets and hot-air balloons development in China
1600	Firewood and timber scarcity in England
1688	First distillation of coal gas
1694	Shale oil produced in England
1712	Invention of steam engine by Thomas Newcomen
1743	Water turbine development
1747	Discovery of atmospheric electricity by Benjamin Franklin
1769	First automobile (three-wheeled steam-powered vehicle by Cugnot in France)
1800	Electric battery built by Volta
1802	First steam locomotive
1831	Electric generator developed by Faraday in England
1834	Electric motor developed by Thomas Davenport
1837	First electric automobile
1860	First internal combustion engine (two cycle)
1876	Bell invented telephone; Otto built first four-cycle internal combustion engine
1879	Edison invented incandescent light bulb
1881	First hydroelectric power plant. Godalming, England
1883	Steam turbine developed
1894	Diesel engine developed
1895	Discovery of X-rays
1903	Wright brothers flew first airplane
1904	Invention of radio communication
1905	Einstein discovered the relationship between energy and mass: $E = mc^2$
1927	First nonstop transatlantic flight from New York to Paris (Lindbergh)
1937	First regular television broadcast (Great Britain)
1942	First atomic fission reactor (Chicago)
1945	Atomic bomb used for the first time on human populations (Hiroshima and Nagasaki, Japan)
1951	First electronic computer built for commercial applications
1952	Hydrogen bomb exploded by the United States (first fusion bomb)
1954	First commercial nuclear power plant in the USSR
1957	First satellite launched in the USSR
1961	First J.Gagarin space flight
1969	First lunar landing
1986	Discovery of high temperature superconductor
1987	Nuclear fusion ITER project signed in Vienna
Near future	Many inventions are at the doorstep (superconductivity etc.)
Distant future	Many scientific and technological inventions to come

Table 3 Brief History of Energy-Related Development

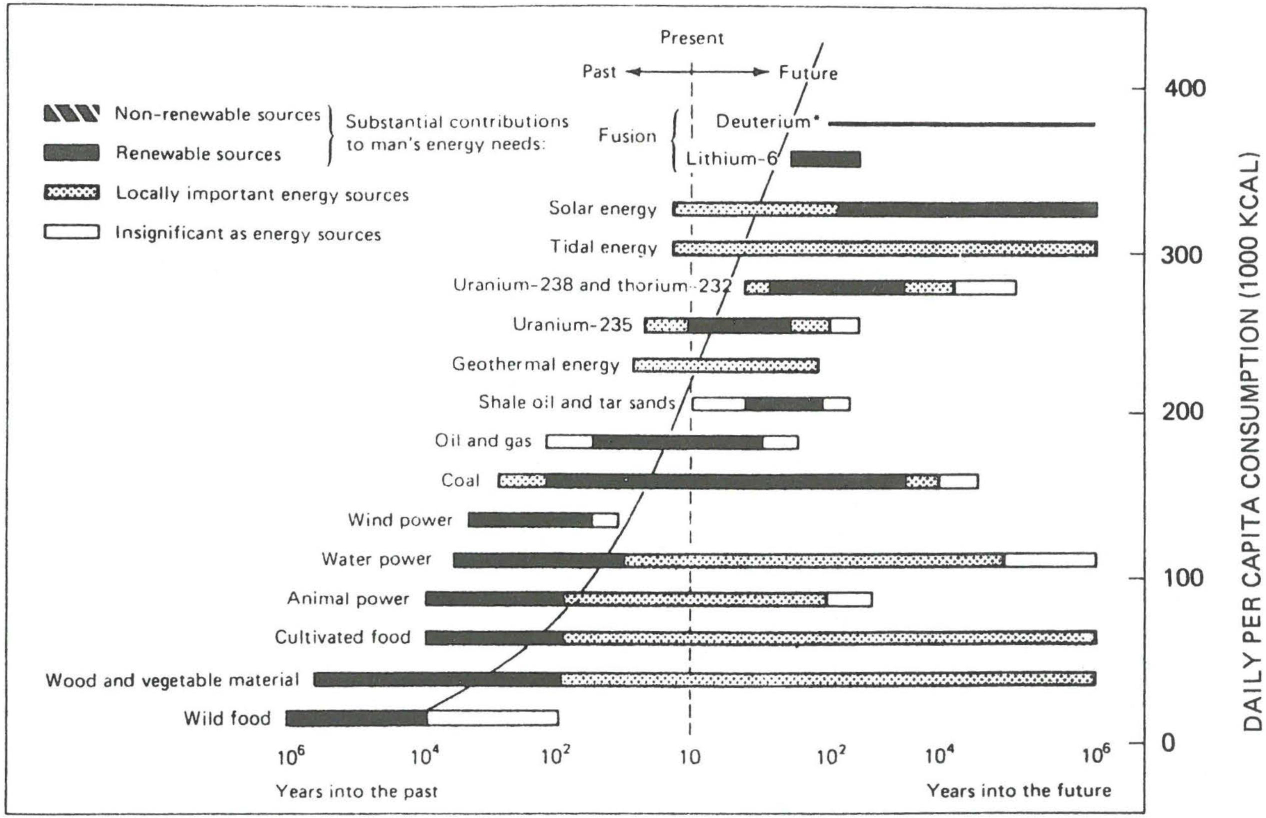


Fig. 4 History of Energy Sources Substitution and Prognoses for the Future (Source: Earl Cook, Technology Review, MIT, December 1972. V. Okorokov, IIASA, 1988)

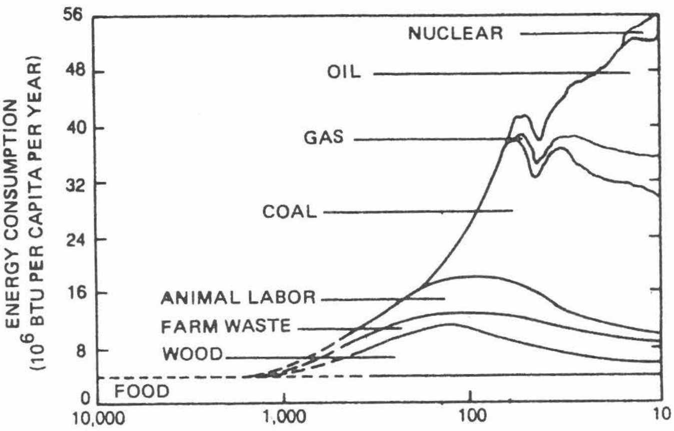


Fig. 3 Consumption of the world´s Energy Resources through the Ages
(Source: Energy Perspectives, Edison Electric Institute, February 1976. V.Okorokov, IIASA, 1988)

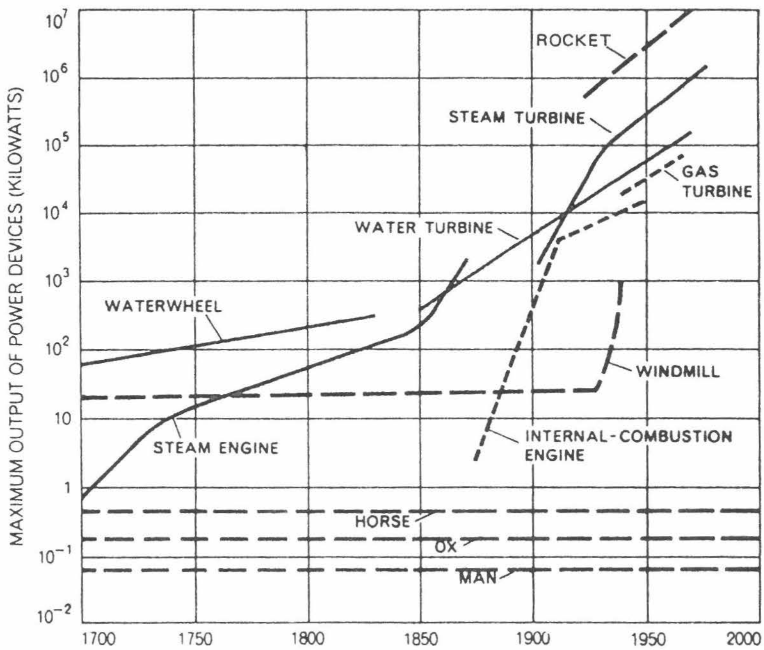


Fig. 5 Power output of Basic Machines
(Source: Ch.Starr, Scientific American, September 1971. V. Okorokov, IIASA, 1988)

ments came about in two ways. The first resulted in an increase in the number of machines and the second in an increase of the power output of a certain machine (Fig. 5). For example, for the steam engine and its successor, the steam turbine, the total increase in power output has been more than six orders - from less than a kilowatt to more than a million. This process of energy technology development will continue. Many inventions are now at the doorstep (superconductivity etc.) and many scientific and technological inventions are to come.

SOCIOECONOMIC FEATURES OF ENERGY DEVELOPMENT

The specific features of today´s energy development are of economic, social and ecological nature. The most characteristic property is the continuous growth of energy consumption and, as was mentioned, there are no reasons to stop this growth. But this continuous growth in energy consumption is accompanied by a declining energy intensity, due to technological progress on one hand to energy conservation policies on the other. Growing energy consumption is also accompanied by an increasing share of high quality, final energy carriers. Electricity, oil and oil products, natural gas and gaseous products are energy carriers which all tend to increase their share in the final energy balance. And this tendency will continue because high quality energy carriers are needed in order to ensure a continuous social and technological progress. Another reason for this is the need for harmony between energy development and environment. There are many ways to achieve such harmony which will not be discussed here in detail. One way in this direction are the low-waste (emission free) energy production systems based on the integration of different forms of energy production /2, 10/ and on low-waste energy technologies. We believe that such future integrated energy systems will dominate not only from an environmental point of view but also because of the increased need for an efficient use of primary energy sources. The consumption of clean, renewable energy sources like wind, hydro and others, will increase also due to the mentioned reasons, but they will only cover local needs. The use of these renewable energy sources on a global scale is unlikely in the foreseeable future.

One of the most important features of future energy development will be, technologically, the rationalization of energy consumption, possible with the implementation of computers in energy systems operation and control. Socially, the integration of different energy production systems will also assist in the rationalization of energy consumption.

FUTURE ENERGY FORECASTS

It is obvious now that energy forecasts are very unreliable because future energy development depends on many economic and social factors which are unknown at present. Many forecasts are of limited value /4, 7/. Despite this fact we would like to give some highlights concerning the future energy developments, keeping in mind the proverb, which says that the future exists in the past. As mentioned, energy consumption will continue. The present world energy consumption exceeds 8.26 Gtoe per year. The total world proven energy reserves are 1106 Gtoe /13/. Assuming an increasing energy consumption with annual rates of 1-2 %, then the world proven energy reserves will be exhausted in one hundred years (Fig. 6). Of course, this estimate is relative due to the possible technological progress, which will increase the reserves, and the discoveries of new energy resources. But it does not matter at what period the world proven energy reserves will be exhausted, during the next 80 or 120 years. It is obvious that in the foreseeable future all traditionally exploited proven energy reserves will be exhausted and we will have to use alternative energy sources. As can be seen from Fig. 6, in the long-term future there are only two primary energy sources, which are able to meet the demand of the growing energy consumption, namely, nuclear fusion and solar. The energy potential of these sources is high enough to maintain the continuity of energy services during the next one million years or so. But what primary energy sources will maintain the continuity of the service in the short- and medium-term, let's say, during the next 25--30 and 50-70 years? The answer to this question depends on the availability of traditionally used energy sources and their technological, economical, ecological and social conditions of exploitation. In order to answer this question it is necessary to consider the above mentioned factors. Let us try to do this.

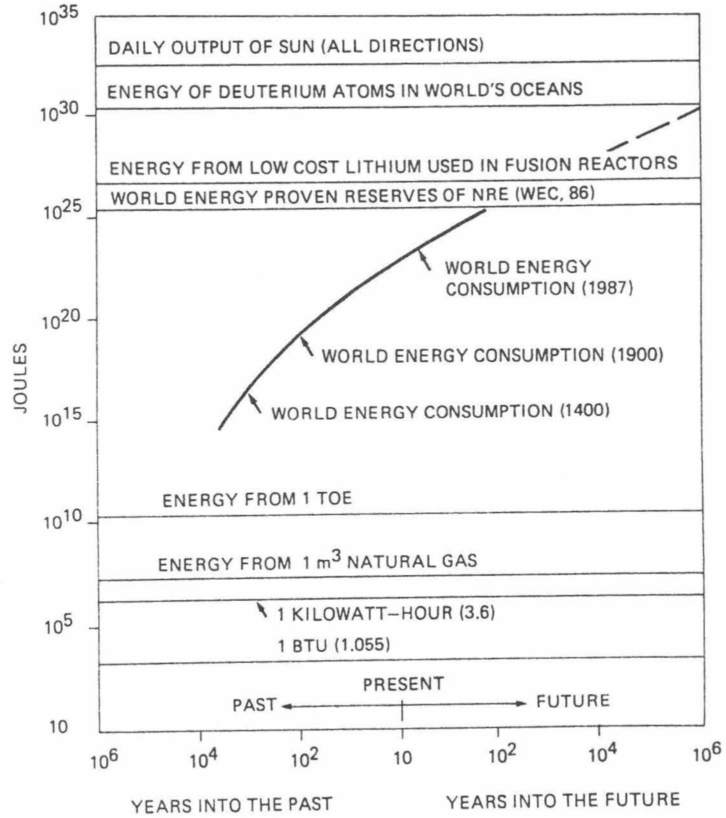


Fig. 6 History of World Energy Consumption and Prospects for the Future

AVAILABILITY OF FOSSIL ENERGY SOURCES

The energy potential of the proven fossil energy sources is high enough to meet the growing energy consumption of mankind during the next century. It is very possible also that during this period the current proven world energy sources will increase. Additional utilization of renewable energy sources, e.g., hydro and wind, will also extend the time horizon of the traditionally used energy sources. Therefore, from the availability point of view no great changes are expected in the world energy consumption pattern.

TECHNOLOGICAL PROSPECTS

There are many technologies on the world energy market, the traditional ones and the new ones. Among the traditional technologies, the oil, natural gas, coal and hydro based utilization of these technologies have good prospects. Nuclear technologies have not the experience as the traditional ones, and their technological potential is not fully expanded yet. There are many indicators that the next generation of nuclear technologies will have much more advanced technical and economic properties than the today's have /4, 5/. There are many new energy technologies like MHD generation, photovoltaic power generation, fuel cell power generation, etc., which are on the world energy market, but their technical properties cannot compete with the traditional technologies. There are also many well-known technologies based on alternative energy sources, e.g., wind, solar, geothermal, but today's level of their technological development is not sufficient to provide the continuity of the growing energy demand. Hence, for the near-and medium-term, there is no evidence that the traditionally used energy technologies will be replaced by the new ones. Only one new energy technology, nuclear, has promising future prospects.

ECONOMICS OF ENERGY SUBSTITUTION

Production costs for one unit of traditionally used primary energy sources are now less than those for one unit of the new energy sources. With one exception, and this is nuclear energy. Nuclear energy competitiveness has suffered because of increased standards for reliability and safety. The renewables, e.g., wind, solar, geothermal, due to their low economic potential, can only be considered additional energy sources. Therefore, it is unlikely that the situation will change in the near- or medium-term.

ECOLOGICAL PROSPECTS

Ecological requirements for future energy development will increase to a great extent. The anthropogenic energy flow is equal to or more than that of the natural energies,e.g., thermal gradients of oceans and surface, tides, etc., and in the next century it will exceed the level of natural energies (Tab. 4). The ecological impact

	Energy (TW)	
	At Present	Middle of Next Century
Anthropogenic Energy	6.0 - 7.0	55.0 - 100.0
Capacity of Power Plants	2.5	25.0 - 40.0
Thermal gradients of oceans and surface	2.0 - 2.5	
Tides and low tides	5.0 - 6.0	
Hurricanes (tornadoes)	20.0 -30.0	
Earthquakes	25.0 -40.0 (and more)	

Table 4 Comparison of natural and Anthropogenic Energy Flows

of current energy systems is very high and will increase in the future, if energy production will continue to be based on existing technologies and traditional primary energy sources. Future energy development will take at least three different directions. First, under equal conditions, preference will be given to the clean energy sources, e.g., natural gas, nuclear and others. Second, current technologies will be improved in quick response to the increasing ecological requirements. Third, no waste or low waste technologies will enter the energy market, many of them are at the pilot stage today /4/. It is very likely that for the near-term the first two directions will be taken, but for the medium term the third option will determine the energy development.

SOCIAL ASPECTS

Energy development has both positive and negative social effects. First of all, energy development is a pre-condition for economic and social development thereby improving the living standard. Throughout the history, increasing energy consumption has dramatically changed the structure of human activities: man´s leisure time and formal education has increased but time spent for his working activities has decreased substantially (Fig. 7). Also the life expectancy of mankind has greatly increased: from 18 years for the primitive man to more than 75 years for the technological man. Along with this, also the quality and variety of food and goods

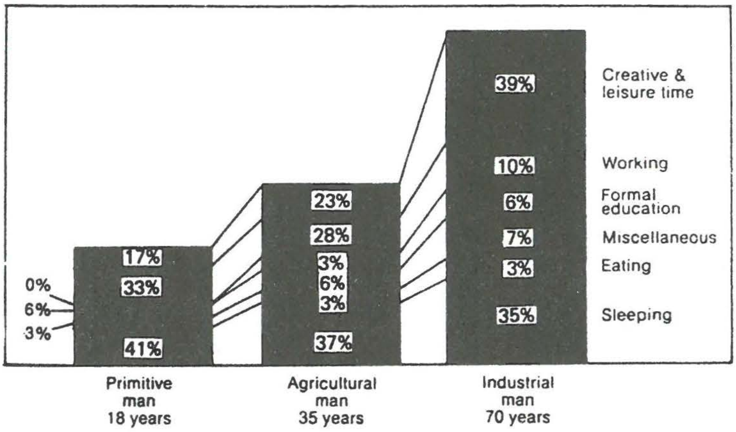


Fig. 7 How Man has spent his Time (Source: Energy Perspectives, Edison Electric Institute, February 1976

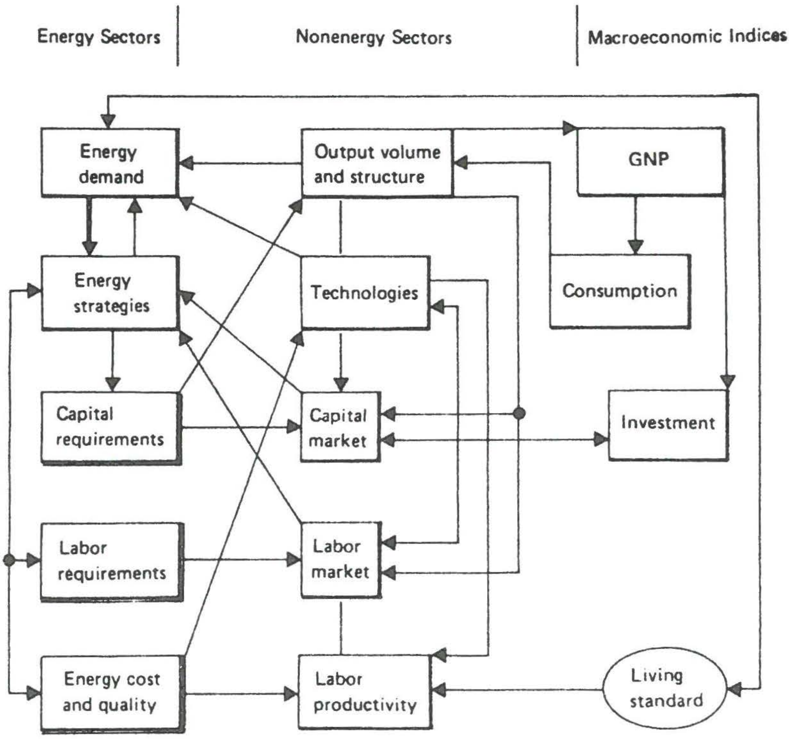


Fig. 8 Energy-Economy Interrelationship

used have increased: from natural products to a variety of complicated products with many useful properties. Living space, environment, and travel distances also have changed - the primitive man only knew his cave and immediate surrounding whereas today's man knows the whole world, due to modern transport and communications systems. And the universal man will know the universe. First steps in this direction have been made by space flights, landing on the moon, etc. These positive social changes will continue to have influence on future energy development thereby still increasing energy consumption, particularly the consumption of energy sources with high energy content and quality, e.g., nuclear energy, natural gas and oil products, electricity, etc.

But energy development also has negative social impacts. The infrastructure of the current energy systems consists of many components requiring different processes - from the extraction of raw materials and fossil fuels to the energy production in its different forms. Development of an energy complex infrastructure requires big amounts of capital, material, and labor resources, due to the complicated energy-economy interrelationships (Fig. 8). Assessments made in the USSR for the energy complex requirements of a national economy show that over 30 % of all capital investments in industry and more than 19 % of the aggregate capital investments of the whole economy are allocated to the development of fuel and power production systems /6, 10, 12/. To this should be added considerable investments allocated to supply energy to branches which are not part of the energy sector, e.g., boiler stations, small-size power plants, etc. For the operation and future development of the energy systems, 6-8 % of the gross output for machinery production and 11-12 % for construction materials are used directly; but if we take into account all material inputs of the related economic sectors, the share of the energy complex in the consuming industrial products can grow two to six times /12/. The continuous capital- and material-intensive growth of the energy complex and the related increasing share of national resources consumption can result in an decrease of the national income growth rates and particularly in decreasing consumption funds. Calculations have shown that a growth of this share from 14-20 % can result in slower annual average increment rates for the national income by 0,1 % and that for the consumption fund by 0.2 %, under a more intensive economic development, and by 0.25 and 0.7, respectively, under a more extensive development. If the share in national resources consumption of the energy complex exceeds 25 %, then it will be likely to cause some disproportions in the development of the national economy /9/. Considering this social effect, it will be preferable to have a less capital- and material-intensive energy development.

But there is still another negative effect, the so-called social instability /10/. Each component of an energy system is subject to social instability but their relative importance depends on the energy system and the type of fuel used. Social instability is caused by two factors: direct and indirect damage due to emissions at all stages of energy production, and the potential damage due to possible failures, accidents, explosion, etc. Direct and indirect damages are of stable character and exist as long as energy systems are operating; potential damage has a probability character: it may or may not be. The accident probability for a single power plant is very small but increases with the number of power plants. The amounts of raw materials and fossil fuels used for energy production today are enormous. The annual global fuel consumption amounts to about 10 billion tons of coal equivalent. Potential damage due to possible accidents along the energy chain (tanker accidents, gas and oil pipeline explosions, power plant failures, etc.) is probably equal or higher when compared to wars, natural catastrophes, and others (tornadoes, etc.). Accidents which occurred during the last years (Three Mile Island, Chernobyl) witness that damage caused by such events is very high and must be considered in the decision making process.

The direct and indirects costs of power generation can be calculated, but it is very difficult to estimate social instability costs for each component of the energy system: direct and indirect damage due to emissions and potential damage due to possible accidents. There are many reasons for the ineffective assessment of social instability costs. First, the information basis for such assessments in general is inadequate due to uncertainty, complexity, and the lack of systematic management of this problem. Second, the importance of such an assessment became evident only in the last years, when the consequences of social instability turned into social hazards.

Today´s decision makers do not have reliable methods of estimating social costs for electricity production. The public, from a social point of view, estimates the costs of electricity produc-

Type of Energy	Energy Significance	Renewable yes/no	Air Poll.	Water Poll.	Land Impact	Visual Poll.	Thermal Poll.	Wilderness Impact	Noise Poll.
Oil	4	N	3	2	4	3	2	3	2
Natural gas	3	N	1	1	1	1	2	1	1
Coal	4	N	4	3	3	2	3	3	1
Synfuels	Exp.	N	1	3	3	2	2	2	2
Nuclear fission (normal)	2	N	1	1	1	1	2	1	1
Nuclear fission (accident)	1	N	4	4	4	?	3	4	?
Nuclear fusion	Exp.	?	?	?	?	?	?	?	?
Geothermal	1	?	1	1	1	2	1	2	1
Solar	2	Y	0	0	1	1	0	1	0
Hydro	2	Y	0	1	3	1	0	2	0
Wood	2	Y	4	1	1	2	1	1	1
Wind	1	Y	0	0	1	2	0	1	2
Biomass	1	Y	1	1	2	1	1	1	0
Tidal	1	?	0	1	0	1	0	1	0
OTEC	Exp.	Y	0	1	0	1	1	?	0
Wave power	Exp.	Y	0	1	0	2	0	2	1
Conservation	3	Y	1 (indoor)	0	0	1	0	0	0

Table 5 Environmental Analysis of Various Energy Resources

(Exp., experimental; 0, negligible; 1, some; 2, considerable; 3, very much; 4, extreme; ?, unknown.
Source: Based on a chart developed by Jane Albee, Vermont Technical College, Randolph Center, VT.)

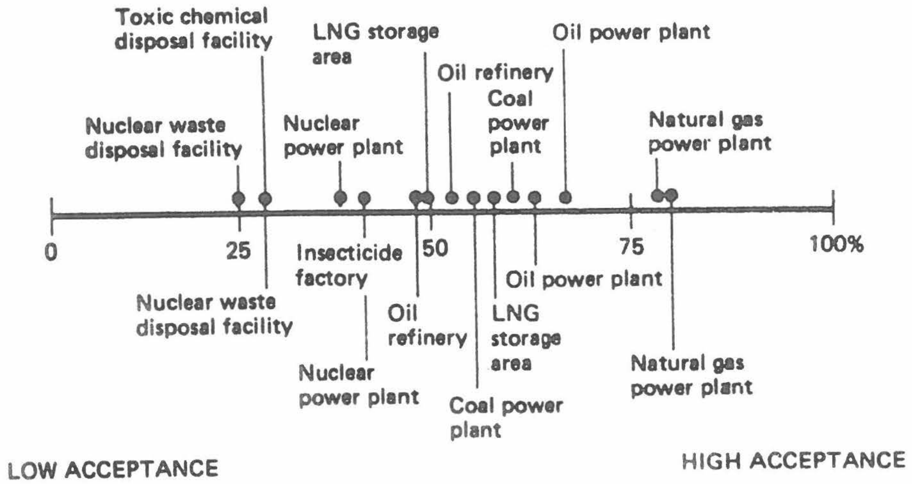


Fig. 9 Acceptance Scale for Eight Different Facilities in Two Surveys (Source: Upper data, Lindell and Earle, 1983, p. 249, Lower data, Lindell et al., 1978)

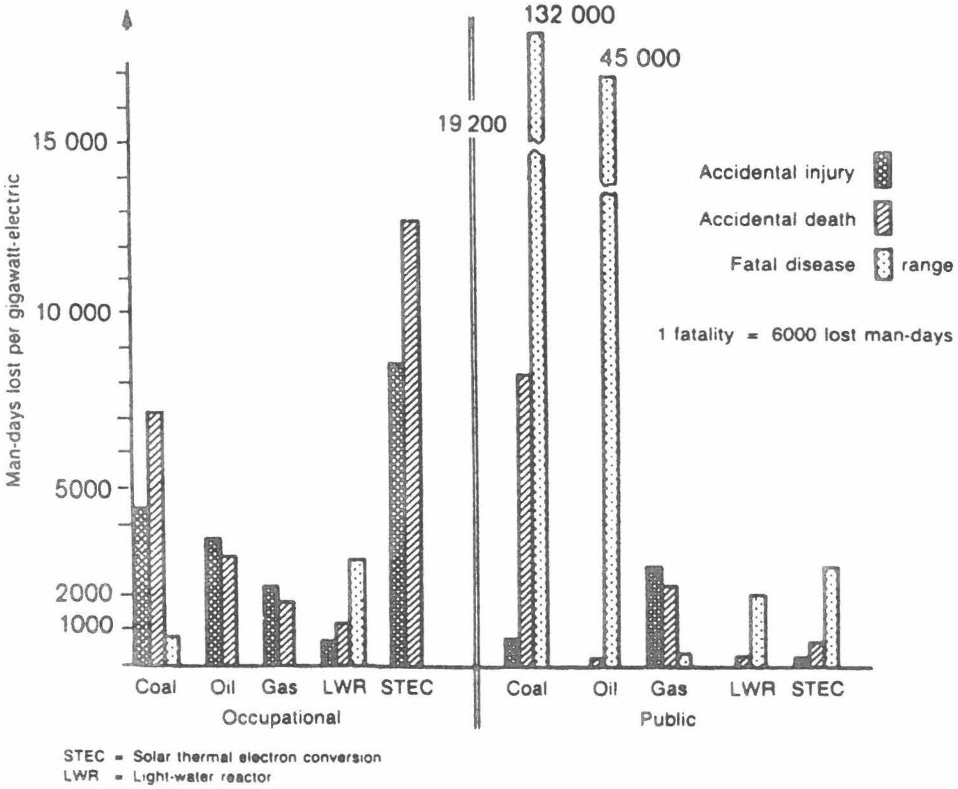


Fig. 10 Risk Comparison of Energy Technologies

tion measured by the level acceptance. Figure 9 and Table 5 give a comparison of the level of public acceptance for different facilities. It can be seen that the level of acceptance for nuclear power plants is much lower than that for coal power plants, despite the occupational health hazards associated with electricity production for those two plants (Fig. 10). It seems that in the future social costs and social acceptance will play a much bigger role than in the past. The development of nuclear energy (e.g., in Austria, Sweden, the USA, etc.) and coal-fired power stations (e.g., Poland, the GDR, etc.) show that these social factors must be taken into consideration already in the near-term.

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