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Science, Technology,
Engineering, and Economics:
Capital as a Cost

Introduction

IT IS A universally recognized truism that science and technology in the two decades since the end of World War II have become interwoven with daily living on a scale far exceeding anything that prevailed previously. Throughout the world, science and technology have provided us a new primary source of energy, more rapid and reliable methods of transportation and communication, new methods of data processing, and a promise of new sources of food and new methods of, and mechanisms for, education.

Since the middle of 1966, for example, there have been placed on order in the United States some 51 nuclear power reactors, totaling approximately 40 million kw. These will be installed some time between 1968 and 1975 and will represent an investment cost of approximately \$5.8 billion. In their active lifetime these reactors will generate about 8.5 trillion kwh, and displace over 3 billion tons of coal.

This is a technological-economic development of major significance. It already has had, and will continue to have for many years, an influence on coal mining, transportation, defense, and on international political relations. It is making it possible to look at the future with hope and confidence, and without fear for the possible exhaustion of our inanimate energy resources. While this fabulous aggregation of energy conversion equipment is not yet here, it is in the making and will continue to grow to still more vast proportions.

The foundation of this development is a scientific discovery — atomic fission. It all rests on one basic reaction — the splitting or fissioning of uranium-235, one of the lighter isotopes of the heavy element uranium. In that fissioning process, uranium-235 captures a neutron and for a brief period becomes uranium-236. It then splits into two nearly

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equal parts. These are lighter elements in the middle of the periodic table, but are not always the same. Altogether some 40 to 45 different fission products have been identified. The important fact is that the combined weight of the two atoms into which the uranium atom splits is less than that of the original. The lost mass of the annihilated matter, in accordance with Einstein's famous formula, has been converted into energy that appears as heat.

Einstein proposed his theoretical formulation some 60 years ago, and the phenomenon of fission was discovered by Hahn and Meitner some 30 years ago. The demonstration of a controlled fission reaction was provided in the famous experiment at Stagg Field in 1942 — 25 years ago — and at this point the main work of the scientists ended. The practical harnessing of that discovery has taken 25 to 30 years spent upon a great deal of developmental work on the part of engineers — and the engineers have just begun. Thus, technology and engineering based on scientific discovery have brought society a new source of energy — energy that is so essential for the continued development of an industrial society.

It is clear that science and technology together have played a major role in bringing this nation the highest standards of material welfare more broadly disseminated throughout its population than have ever been achieved by any society in the history of the world. Despite the troubled consciences on the part of a good many well-intentioned of our citizens, this scientific and technological progress has failed to bring about any revolutionary changes in our society, and the benefits it has brought have outweighed the problems and dislocations. And for the continuing welfare of our society science and technology need to be vigorously carried forward, perhaps even at a slightly accelerated pace,

to enable us to solve the many economic and social problems confronting our world.

We need to continue to provide more goods and services, to raise living standards still further, and to disseminate these standards still more widely. We need greater productivity to give people more leisure and to provide many of our social-economic needs — housing, transportation, pollution control, continuing education, and beautification — all with a view of creating a better life and a better society. We need to help the underdeveloped world to lift itself from the slough of poverty to heights comparable with those our own society has managed to reach.¹

To achieve these objectives, it is imperative that we understand better than we do the dual mechanism that is the principal tool — technology and engineering and the science on which they are frequently based, and particularly their interacting relationship with economics if these promising tools are to be properly developed for society's benefit, and if they are to be properly taught at such a great institution as M.I.T.

I shall attempt this task in the course of the four lectures I have undertaken to deliver at weekly intervals starting this afternoon — an undertaking I agreed to gladly even while entertaining some inner doubts as to my ability to carry it out with reasonable adequacy.

*Science, Applied Science, Technology,
Engineering, and Economics*

In connection with our Apollo program there is a well-worn witticism that if any particular operation goes off well

¹ National Commission on Technology, Automation, and Economic Progress, *Technology and the American Economy*, United States Government Printing Office, Washington, D.C., 1966.

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it is reported as a scientific triumph, but if it fails it is an engineering failure. There is no question that since the end of World War II we have had an absolute rise in the enrollment of science students and an absolute drop in engineering students. For a country as technologically oriented as is the United States, this is a bad development and, because it is vitally related to the main theme of these lectures, I would like to clarify our coming discussions with a few brief explanatory definitions of the terms science, applied science, technology, and engineering, with a particular emphasis on their relationship to economics.

SCIENCE Science and technology are both vitally important to our society. Science may be said to represent a body of systematic, experimentally verifiable knowledge regarding the relationships among the complex phenomena of the physical world. Scientists are concerned with improving man's understanding of his physical environment and with the expansion of the range of physical phenomena embraced by man's understanding. Science bears no direct relation to economics. In fact the attitude of many a scientist is that if what he is doing has any practical significance or application he is not interested in it.

APPLIED SCIENCE AND TECHNOLOGY Applied science is science applied to the solution of a practical problem. Although in recent years many schools of engineering have changed their names to schools of applied science, the definition of the term remains vague. Too often it is simply poor technology because of the failure to consider economics adequately. Unfortunately, also, too frequently the general development of applied science is confined to areas of social technology — defense or space, for example, where the

need for careful economic analysis is believed to be less urgent. The economics that enters into applied science, therefore, is frequently almost negligible. This may account for the high mortality rate among applied science organizations once they make an effort to transfer their activity to an atmosphere of civilian economics.

Technology is a better term for what is often referred to as applied science. It is a newly developed or an accumulated body of knowledge related to a specific area of economic activity, such as making steel or producing nylon or polyethylene or generating electric energy from fossil fuels. It is based upon scientific discovery or experimentation or merely successful practice over many years that makes possible the practicable production of a specific economic good or service.

Although I have specified practicable, I have not said economic. Essentially a technology can be developed in the sense that it provides a mechanism for achieving a stated purpose but still be economically infeasible. Thus, the technology is available for cleaning the SO_2 from the effluent of a power plant burning high-sulfur coal, but it cannot be done without imposing an extremely high-cost burden on energy production. Small nuclear reactors can be built to give every municipality, large or small, a supply of electric energy ash and sulfur-free, but the cost of a unit of energy so generated would be prohibitive. All transmission and distribution can be placed underground but at a cost in the case of 345,000-volt transmission of six to eight times the cost overhead. Technology recognizes economic limitations and is not satisfied with technical feasibility alone. It seeks to achieve — even though it sometimes does not find — economic feasibility as well.

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ENGINEERING In a lecture he delivered some five years ago,² Dean Gordon Brown of the M.I.T. School of Engineering stated, "engineering is practicing the art of the organized forcing of technological change," and ". . . when an engineer works at the frontier of his field his main function is to couple science . . . with his particular problem in order to build something and make it work."

This description, I believe, needs to be supplemented. The engineer must often go beyond the limits of science and question judgment based on alleged existing science. He must frequently exert his own overriding judgment and stake his reputation by going into areas beyond those which have been fully explored scientifically. After all, many advanced engineering structures were brought into being in the ancient world centuries before the existence of a scientific understanding of the interrelationship of the forces that made them work.

The engineer is the key figure in the material progress of the world. It is his engineering that makes a reality of the potential value of science by translating scientific knowledge to the extent it is available, filling in the scientific gaps with the help of experiment, past experience, and judgment — to marshal tools, resources, energy, and labor, and bring them into the service of man.

This need of the engineer to bring his work effectively into the service of society, involving as it does the need for society to judge his product good, i.e., serviceable, obviously recognizes the fact that the product must have economic validity.

Some six years ago a committee of the School of En-

² Brown, Gordon S., "The Engineer: Today's Pacesetter of Change," The Mendenhall Lecture, Harvey Mudd College, Claremont, California, May 7, 1962.

gineering at M.I.T. wrestling with this problem issued a statement³ from which I quote:

Science . . . is a search for knowledge. The science of mathematics extends abstract knowledge. The science of physics extends organized knowledge of the physical world. In each of these consideration can be limited to a carefully isolated aspect of reality.

The engineer must deal with reality in all its aspects, he must not only be competent to use the most classical and the most modern parts of science, but he must be able to devise and make a product which will be used by people.

Thus, engineering goes well beyond technology — beyond putting together technical parts of systems that will work. Engineering must encompass the broad principle of economy of all resources — material, capital, labor — and their optimization at a given time in terms of the society of which they are a part. The principle of excellence is indispensable for engineering, but not in a limited sense of excellence, not merely in technical relationships. Excellence in engineering must include economic aspects — costs and values — and if it fails to include them it is not engineering.^{4,5}

One would think this would be so patent as to be axiomatic. Yet only a few years ago the entire system of production in the USSR gave almost no recognition to the existence of economics as a part of engineering. A deputy

³ Committee of the School of Engineering, M.I.T., Statement by Committee, Engineering and Education, March 1961.

⁴ Chapters by I. I. Rabi, and Harvey Brooks in *The Impact of Science on Technology*, Edited by A. W. Warner, D. Morse, and A. S. Eichnar, Columbia University Press, New York, 1965.

⁵ Sporn, Philip, *Foundations of Engineering*, Pergamon Press, Oxford, 1964.

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premier of the USSR at a public luncheon given in his honor by the Secretary of the Interior of the United States, chided me for mixing, so he claimed, politics with engineering. When I replied that he was mistaken, that what he probably meant was that I was mixing economics with engineering, his reply was that it did not make any difference, economics too ought to be kept out of engineering. Surprised as I was at his statement, I was not too surprised to make the rejoinder that in our country we believed that engineering without economics is impossible and is no engineering. Indeed, the USSR itself is coming around to this view.

Science, Technology, and Engineering as Agents for Advancing Human Welfare

Although science, technology, and engineering are commonly linked as the architects of the world of today and tomorrow, the mechanism by which they make their individual contributions is quite different and it stems from the differences between scientists and engineers in their training and basic approach to problems. They are, as Dr. Arthur M. Bueche pointed out at Cornell a little over a year ago, quite separate and distinct professions.⁶

There are, it is true, a number of common ties between them — the number who innovate, for example, in either group is relatively small and for most effective results they need to work together. But essentially science by itself and the work of the scientist is ineffective in advancing human welfare. For that technology and engineering are required. It is the engineer's function to bring together resources,

⁶ Bueche, Arthur M., "A Look into the Future of Scientific Research in Industry," *Cornell Engineering Quarterly*, Vol. 1, Fall 1966.

tools (in the broadest sense), energy, and labor and to combine them in a productive entity to achieve or produce something wholly new or previously impossible, to achieve an improvement that yields a better product at the same cost or the same product at a lower cost, or even a better product at lower cost. Unless and until these factors are brought together in a productive combination, no social or economic benefit results.

The nature of the components of a productive entity is not new. They have always been the three elements: resources, tools, and labor. The big change that technology and engineering have brought about in our society today is to modify the relative contributions of resources, tools, and labor. Economics is particularly important in engineering because it provides the analytical mechanism for determining the relative participation of these three factors and the value of a new technology to society.

Thus, in its report "Technological Innovation: Its Environment and Management," the Panel on Invention and Innovation⁷ set about to determine the costs in successful product innovation and particularly to examine the role of research and development in the total process of bringing a new product to market. Surprisingly it found that the step commonly called research and advanced development or basic invention accounts typically for less than 10% of the total innovative effort cost. The cost of engineering and designing the product, tooling, and manufacturing engineering amounts to more than eight times the cost of research and development, the approximate distribution being as shown in Table 1.

⁷ Panel on Invention and Innovation, *Technological Innovation: Its Environment and Management*, United States Department of Commerce, January 1967.

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Typical Approximate Distribution in Successful Product Innovations

Operation	Approximate Percentage of Total Innovation Cost
Research-Advanced Development	8
Engineering and Designing the Product	15
Tooling-Manufacturing Engineering	50
Manufacturing Start-Up Expenses	10
Marketing and Start-Up Expenses	17
	100

The dominant item obviously is engineering in the several stages of bringing the product to market — engineering concerned with the design and organization of the tools of production. These tools, acquired by the investment capital, are a dominant item in bringing about innovation. If the economics of this important segment of the total cost is mishandled, the viability of the whole product is placed in jeopardy and scarce resources are wasted. And it is this segment of the total cost that is most frequently mishandled.

The Seminal Effect of the Introduction of Economics into Technology

Proper economic analysis is indispensable to the design of productive technology and is independent of the particular form of social-economic organization. This sometimes takes a little while to find out by experience. Thus, the USSR discovered to its dismay that the lengthy construction time of some of its major hydroelectric projects involved costs and these costs, which in our economy are recorded as forthright interest during construction, but which they choose to label frozen costs — these costs were sufficient

seriously to affect adversely the attractiveness of hydrogenation. This discovery, interestingly enough, resulted in a change of policy and a shift of emphasis in their electric power program in favor of thermal generation.⁸ And the dismay of the managers of Soviet manufacturing enterprises at having to give an account of the capital burdens of their plant in determining cost and profitability — a dismay that has only recently come to the foreground — is entirely understandable when many of them grew up in a society where the philosophic approach toward capital plant and equipment, even where the state was the capitalist, was heavily muddled by their ideological, anathematic view of a capitalistic society. In having all these years yielded to capitalistic society the exclusive utilization of economic evaluation, the USSR had, in fact, surrendered economics as a capitalistic monopoly.⁹

Economic forces not only provide a rational approach to the choice among many alternative routes in any complex technological development but serve to stimulate technological advance and the inventive process on which so much of our new technology is dependent.

It is interesting to examine a few examples that reflect the interplay of economic forces and the development and exploitation of technology. Agricultural employment in the United States declined between 1947 and 1964 from 14% to 6.3% of the total civilian employment, and the total employed in agriculture declined from 7.67 million to 4.4 million. Yet in that same period, with the total acreage in

⁸ Sporn, Philip, and Abraham Gerber, "Soviets Find Capital Costs Make Hydro Less Economical," *Electrical World*, Vol. 158, No. 8, pp. 56-59, August 20, 1962.

⁹ Schwartz, Harry, *Russia's Soviet Economy*, Prentice-Hall, Inc., New York, 1951.

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the United States remaining practically unchanged at roughly 1.15 billion acres, output of wheat went up 17%, soya beans 264%, rye 41%, barley 51%, maize and corn 412%, and productivity rose some 161%.

The mechanization of American farms, shown by the increase of some 75% in available horsepower, the rapid increase in the use of fertilizer of 102% in the period, and the consolidation of farms into larger sizes, brought about the amazing improvement in farm productivity that made it possible for American agriculture to feed a growing population with a strikingly declining labor force. It represented a technological response to the changing relationships between supply and demand for the factors of production throughout the economy, especially the rapid growth in the demand for labor in the manufacturing and service industries. In turn this made it possible for our society to meet that demand with only relatively mild dislocation. Indeed it demonstrated the ability of a free economy in a free society to optimize the allocation of its resources. In contrast the failure of Soviet agriculture to respond similarly has limited the availability of labor and other resources for more intensive industrial development.

Next year will mark the second centenary of the patenting by Watt of his famous separate condenser steam engine, which is commonly accepted as marking the birthday of the industrial revolution, which in turn is the foundation on which the great industrial society that was England in the nineteenth century was built, and which served as the foundation of all other industrial societies, including ours.

Watt, with all his great genius, built on Newcomen and Newcomen built on Savery, and Savery, an inspired mechanic, was interested in solving the economic problem of keeping the mine pits in Cornwall free of water without in-

curing prohibitive costs. Neither science nor applied science entered into it, but economics did.

The story of the origin of the electric light and the electric power industry which came along to exploit the electric light is another example of economic motivation. Edison, having watched the development of the gas lighting industry to one of the leading industries in the United States (and this was matched in other industrially advanced countries) was prompted to start his work that was to lead to the electric light and the electric power industry of today by economic motivations. He recorded it in his notebook as follows:

Electricity versus gas as general illuminant. Object: Electricity to effect exact imitation of all done by gas, to replace lighting by gas by lighting by electricity, to improve the illumination to such an extent as to meet all requirements of natural, artificial and commercial conditions.

Economic incentives, or perhaps lack of economic incentives, are not always on the side of the angels — they do not always exert an influence to advance and improve technology, but frequently act as disincentives to technological progress. Here the examples are many. Let me cite a few.

The development of the great railroad systems in the United States left them at the turn of the century in the position of enjoying almost a complete monopoly on long distance passenger and freight traffic. The lack of an immediate economic incentive to improve facilities and service: road bed, locomotives, cars, speed, schedules, comfort, and tariffs, left them in the poorest sort of spirit to anticipate competition or to meet it, and so they eventually lost a good deal of their freight traffic to trucking and practically all

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their passenger traffic to the automobile, the bus, and airplane. They were able for far too many years to live and live well without doing anything constructive or innovative. Today the railroad systems of the country are, with some exceptions here and there, completely decadent. As Alfred E. Perlman, then president, New York Central System, pointed out in *The Wall Street Journal* of July 14, 1967, "it is ironic that the United States, the most economically powerful nation in the world, has allowed its basic transportation facilities to nearly dry up."

The great coal industry and the energy base it provided the United States for many years made possible the industrial development of the United States to the most productive nation of the world. The coal industry participated in that growth and experienced a period of 50 to 60 years of great prosperity. The most important single area of coal use was railroad transportation and it was also the most profitable. For many decades any coal mine locating on or near a railroad could be certain of having its share of that railroad's coal requirements for motive power at prices that were generous, if not too high. But the consequence of that was that the coal companies almost completely eliminated themselves as parties at interest or critics in and of the cost of transportation. No incentive existed in the coal industry to develop any ideas to invent or conceive arrangements to cut transportation costs, even though these costs in many cases were equal to or greatly exceeded cost at the mine and even though in many cases it was the cost of transportation of coal which determined the economics of coal as a primary energy source to the user.

In the case of the electric utility industry we have the spectacle of the combination companies rendering impartially electric and gas service with full regulatory and stock-

holder approval, supremely unconscious of the deadening effect this has on management and operating personnel in their inability to exert effort to improve the condition of either service because of the economic loss this might lead to in the operations of the other.

Capital as a Cost in Economic Analysis

A little while ago in discussing the differences between science, applied science, technology, and engineering, I pointed out that until the engineer brings together resources, tools, energy, and labor and combines them in a productive entity to achieve or produce something wholly new or previously impossible no social benefit can result from either the science or technology. The largest of these components in our modern advanced technological societies is tools. Tools cost money. It is the tools — the complex plants and their equipment — that represent the capital cost of our modern capitalistic societies. There are few if any individuals who are in the least bit confused about the cost of smaller tools that they themselves have acquired. They found out the first time they tried to assemble an even modest and small group of such tools consisting of say a plane, a cross-cut saw, a soldering iron, two pliers, a set of screw drivers, a hammer or two, a few wrenches, and a few miscellaneous small tools that they had spent most of a \$50 bill. But somehow, when confronted with the larger tools — the kind that cost \$250 million, as is the case in an assembly to produce atomically 200 mw of electric capacity and 100 million gallons per day of desalinated sea water — doubts creep in as to whether these are costs of the same nature and need to be considered in determining the cost of the product they make possible.

In our times the leaders of Russian society throughout

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the 50 years following the 1917 revolution have been the most remarkable followers of that folly. Of course, they had an excuse. They were Marxists — of a kind — and they were started on the wrong track by Marx himself in his theory of surplus value. But Russia has been taking a second look at costs. This started almost ten years ago. As early as 1959, Premier Khrushchev indicated that in Russia capital has a price. He justified a cutback in hydroelectric power construction on the grounds that such projects tie up great amounts of capital for long periods before making any return. Thus he admitted the cost of capital funds — in Soviet parlance a social cost, but in more pragmatic terminology a return on capital (interest, dividends, taxes and — once operation has started — depreciation).

It is so convenient to be able to utilize a flexible cost of capital, particularly when trying to promote a project or program that has a difficult time finding justification under a more rigid economic analysis. Thus, at the recent International Conference on Water for Peace, Mr. Gus Norwood in his paper, "Public Objectives in Water Resource Development," commends "the United States government policy of using low cost money to achieve optimum development of water resources."

There are, however, lower costs than those obtained by using low-cost money — at least they have been conceived and proposed. Some 17 years ago, the principal manager of the nationally owned water supply system in Israel expressed his judgment that the capital facilities of that system ought not to be burdened with any interest charges whatsoever in view of the great social importance of water to that society. Interestingly and not surprisingly the Minister of Finance disagreed completely with that view.

Another very low form of capital cost is what for want of

a better term I would call eleemosynary economics. In discussing with the secular managing head of a great United States church-supported university the relative economics of self-generation versus purchased electric energy, he rejected as an item of cost the carrying charges on the investment on the ground that the self-generating plant was a gift, rejected depreciation as a charge on the ground that when this plant was worn out some other donor would furnish a new plant, rejected cost of labor on the ground that the religious order administering the university had no difficulty in enrolling qualified members to its midst, and thus cost of energy to the university came down to fuel and some maintenance materials.

In the United States there is a pervasive body of opinion that costs vary with the form of social organization. The influential Federal Power Commission periodically prepares appraisal reports for licensing various potential hydroelectric projects. In one such report,¹⁰ the Commission, using the exact same capital cost for the exact same project, arrives at the following annual costs:

By Private Financing	\$4,442,000
Financing by the Federal Government	1,507,000
Financing by the Rural Electrification Administration	1,370,000

We note here three annual costs in descending order from private financing to federal financing to Rural Electrification Administration financing. The Rural Electrification Administration obtains its funds from the federal government at a fixed interest rate of 2%, irrespective of the cost to the

¹⁰ Federal Power Commission, Bureau of Power: Appraisal Report, Chippewa River Basin, 1965.

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federal government of borrowing such funds. In this particular case, to determine the cost to the federal government an interest rate of 3.125% was used. For private financing an interest rate of 6.25% was used. In the case of the federal government, no additional cost resulting from taxes forgone was included. In the case of the Rural Electrification Administration 0.5% was allowed for taxes or payments in lieu of taxes. For private financing 5.72% was included for federal and all other taxes. In all cases the annual benefits, based on the cost of an alternative privately financed thermal power plant, were exactly the same — \$2,648,000. This yielded the following benefit cost ratios: for REA financing 1.93; for federal financing 1.76; and in the case of private financing 0.60 or less than 1.00.

This, therefore, allegedly demonstrated that on the basis of private financing the project was economically infeasible, while economically feasible under either of the other two alternatives. Thus, with exactly the same installation, the same use of real resources, and the same benefits, the economic desirability of the project varies not only in the degree of desirability or viability, but even to the extent of changing it to undesirable or nonviable, depending on what choice of ownership one selects. Furthermore, one is confronted with the absurd "logical" conclusion that an agency which, in the economic sense, is a ward of the federal government borrowing money from the federal government at what constitutes, in effect, negative interest, can do the job at a lower cost than the federal government itself. This obviously irrational conclusion, stemming from an Alice-in-Wonderland system of economics, did not in the least daunt the Commission. One can only conclude that this is another illustration of the failure to fully comprehend the real cost of a project to the economy.

*Sound Economic Evaluation Is Independent
of the Particular Economic System on
Which a Society Is Organized*

As you can see, taxes have a great deal to do with affecting the relative costs. Taxes are sometimes looked upon as an unfortunate economic necessity. But this is obviously short-sighted. In a modern socially advanced society government must carry out many activities that it alone can carry out on behalf of society as a whole. This covers such activities as defense, education, health, and many other broad scientific, technological, and social activities. None of these is possible without income to government. Since as a general rule these activities are carried out for the benefit of society as a whole, every branch of the national economy must contribute its share of what it costs to carry out these indispensable social activities. Taxes are the basic mechanism for making every member of that society contribute his share. When special groups are given special privileges and exempted from making their contribution, they create special burdens on the rest of the society which will have to be taxed for the benefit of the special or privileged group.

Taxes not paid or forgone represent a cost to the economy. It is part of the total return on investment. The fact that part of the return is distributed to the investor and part to the tax collector merely represents the allocation of the return on the investment between the investor and the government. Therefore, the return, including income taxes, represents the true investment opportunity cost to the economy. To put it another way, you cannot wash out the tax component, that part of the productive return on the investment that is allocated to support government functions, from consideration of alternative investment opportunities.

The Soviet economist, Z. F. Chukhanov, mentioned in

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an earlier reference,⁸ arrived at the same conclusion, although he expressed it slightly differently in a paper that he prepared a few years ago for *Teploenergetika*.¹¹ Of course, it was necessary for him to contrive an artificial substitute for a market rate of interest. However, he also allowed a rate equivalent to taxes, which he described as that income from investment necessary to meet the nation's "quite large nonproduction expenses for pensions, scientific research, defense, etc. . . . Since power generation, as most other branches of the national economy, must contribute its share to the national income, it is necessary to add another term to the (social cost) equation." Mr. Chukhanov, in his paper, by taking into account capital cost including the equivalent of taxes for support of the government, concludes that hydroelectric development in the Soviet Union has been wasteful when compared with the alternative of thermal power stations. Further, he concludes that in the period 1952 to 1958 no hydroelectric power capacity should have been built in the Soviet Union. The strong shift in emphasis in Soviet power development in recent years from hydroelectric to thermal indicates that this basic argument has had some effect on Soviet thinking regarding water resource development.

The elements of capital cost are rather simple and for any society are universal regardless of its social form of organization. They are the following:

1. Return on investment

This is the annual amount earned by an investment in any project or enterprise over and above its operating costs.

2. Depreciation

This is the annual charge against revenues used to repay

¹¹ Chukhanov, Z. F., "The Economic Effectiveness of Thermal and Hydroelectric Power Stations," *Teploenergetika*, No. 12, 1961.

the original cost of the investment over its productive life. The total depreciation charges over the life of the plant should add up to the total expended to provide the plant.

3. Taxes

Taxes are considered separately, although as was just pointed out they are really part of the return on investment. They are that part of the total return that by law must be allocated to the support of government services.

It is argued sometimes that capital costs would be lower if they were handled on a governmental basis. Loans for many classes of facilities could be obtained at lower interest charges, and taxes could be excluded from consideration.

This is, of course, true from the point of view of the money cost. This may or may not represent the true cost of capital in terms of the alternative opportunities available for capital expenditures for purposes of evaluating the desirability of a given project. For this purpose the total return on the investment must be considered, and this includes taxes and the full return available on alternative investment opportunities.

We also have the case of Great Britain, with a mixed economy, but one in which the national government owns all the electric power resources. A white paper published in 1961¹² pointed out:

If the profitability of capital development is assessed on different (and easier) financial criteria from those adopted in industry generally, there is a risk that too much of the nation's savings will be diverted into the nationalized industries. Again, if the prices of the goods and services which the nationalized industries provide are uneconomically low, demand for them (and for in-

¹² Her Majesty's Stationery Office, *The Financial and Economic Obligations of the Nationalized Industries*, April 1961.

vestment to produce more of them) may be artificially stimulated. Thus the operation of the nationalized industries with an unduly low rate of return on capital is sooner or later damaging to the economy as a whole.

This white paper further pointed out that British industry as a whole is earning a gross rate of return, including taxes, of about 15%. However, it stated that because utility service involves somewhat less risk than other industry, the nationalized utilities can earn a somewhat lower rate, and a figure of about 12.5% for the return on Central Electricity Generating Board facilities was established.

Recently the Electricity Council was confronted with a decline in the rate of growth of demand on the nationalized power system. As a result it faced the prospect of an unexpectedly large reserve in generating capacity and therefore greater capital charges per unit of energy sold than anticipated. This would have reduced the net available for return on capital below 12.5%. When the appropriate ministry was asked what to do about this, the reply was a directive for an across-the-board rate increase of approximately 10%. This caused some dismay throughout the country, particularly since the entire British economy is operating under very rigid guidelines; so far, however, there has been no indication that the order will not be placed into effect.

From the point of view of optimum development and use of resources, the comparison of the costs of several alternatives needs to be based on true representations of the various alternative costs in terms of real resources rather than on distortions based on artificially contrived monetary arrangements.

Return includes an allowance to provide for risk. It is sometimes argued that where the full credit and faith of the government stands behind a loan, the rate of return can be lower because risk is eliminated. However, this refers

only to the financial risk to the lender. The fact that the credit of the government stands behind an investment does not diminish the risk to the economy from such an investment. The same risks stemming from a variety of developments — technologic, economic, and social — will continue to influence every area of economic activity whether owned and operated by private capital enterprise or by government. Thus, in the case of the coal industry in Great Britain, which is nationalized, the fact of nationalization has in no way reduced the economic impact of a decline in coal production that has been taking place. The rate of obsolescence of many of the old mines has, if anything, been accelerated since nationalization, but only because of the competition of oil and, most recently, nuclear power and natural gas. The economic pressure of nuclear power is as great or greater than in the United States. And the social pressure on coal, owing to its greater proclivity to contribute to pollution, will be only slightly less, but may be more, as a result of coal's being a nationalized industry.

By and large, technological change is a factor that too often is underestimated or even ignored. Economic evaluations of water resource projects, for example, frequently are based on estimates of anticipated physical durability of the project rather than on its economic life, and the value of the output is projected without regard to the outlook for technological change that could affect this value. Economic obsolescence needs to be considered especially in the particular area of power generation, where technological progress has for some years now been proceeding at a very rapid rate. Thus, for example, regional shifts in growth and development can affect the demand for the output from a particular water project, or changes in technology can affect the competitive value of the output. For example, in connection with one proposal for a continent-wide multipurpose water

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development project in North America, it has been suggested that a large part of the cost of the project could be reimbursed by the sale of power from the project at 4.5 mills per kwh. Apart from many other considerations that might shed doubt on the economic feasibility of the project, this one basic assumption is open to grave doubt. Certainly the development of nuclear power technology over the next 20 to 25 years to the point where 3.5-mill or lower costs per kwh will be feasible, a more than fair probability, would make 4.5-mill power from a hydro project unmarketable.

In short, a sound economic evaluation of any major capital project is independent of the social, political, or other motivations, and is independent of the particular economic system on which a society is organized. If a given society is not to be led astray and if it is not to make a mess of the indispensable business in the proper allocation of its limited total resources, it is important that the proper — and this means total — costs be used in the evaluation. Having done this, the society is then in an excellent position to assign priorities. This does not prevent it from upgrading the priority of any socially desirable project at the expense of another less costly. But the intelligence and sound judgment with which this will finally be done will always be materially enhanced by having properly determined values and costs. Subsidies, desirable and granted, do not change cost.¹³

For economic studies and economic evaluations to make a contribution to the development of any complex technological project, it will be necessary to go beyond the critically important immediately relevant capital cost. It will always be necessary to make similar studies on and of operating and maintenance costs involving materials, transportation — of both the raw and finished product — operating labor cost,

¹³ Engineers' Joint Council, "1957 Restatement of Principles of a Sound National Water Policy," *EJC Report No. 105*, May 1957.

cost of energy, water — including the obtaining and disposal — and the cost of maintenance and ecological measures. These need to be optimized not only vis-à-vis themselves but against variants in the main system plan, including its siting, the availability of labor, the effect of the labor and tax climates on the operation coming in, and finally the effect of such changes in the social-economic environment as inflation or deflation, in income tax structures, and likely changes in ecological regulations.

This involves in many cases side studies, looking far into the future, of the likely economic developments that will influence the availability and price at which raw materials entering importantly into the product will be available. Thus, in the case of an important thermal electric plant, the kind of plant, the terminal conditions of its thermodynamic cycle of conversion, the degree to which the efficiency of turbines, alternators, main transformers is pursued are all dependent in most cases on the present cost and the projected cost of fuel to be converted. It is the trend line of cost of the primary fuel that plays a dominant role in decision-making as to what is justifiable in capital expenditure in these areas. What is good economics for a given amount of dollars necessary to save 10 Btu per kilowatthour at 35¢ per million Btu may be wholly unjustified at 25¢ or 20¢ per million Btu.

If labor saving opportunities present themselves, the expenditure one can afford with good economic result is totally different if an inflationary trend — slow, medium, or rapid — is anticipated than if stability is to be anticipated.¹⁴

These so obvious observations would be wholly unjustified if industrial records were not replete with scores of

¹⁴ Sporn, Philip, and Abraham Gerber, "The Social-Economic Evaluation of Water Resource Projects," International Conference on Water for Peace, Washington, D.C., May 1967.

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examples where poor engineering and poor economics — or more precisely, poor economics and, therefore, poor engineering — overlooked these main bases for decision but concentrated fully and, almost microscopically, on technological details.

Many a brilliant project — brilliant technologically — has been wrecked on the shoals of unsound economic evaluation. To the extent these shoals were not charted it represented bad economics and bad engineering. And this in large measure distinguishes engineering from science and technology. It requires a broad understanding of the technological and economic environment and the ability to organize resources to achieve economically and socially desirable objectives.

The application of these ideas to the problem of primary fuels for electric energy generation will be the subject of my next lecture.