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BASIC PROBLEMS IN ELECTRIC POWER DEVELOPMENT

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NOTE: This text is subject to editorial revision.

CONTENTS

Introduction

It may be of value to begin by stating some basic concepts.

The cost of achieving a given economic objective will normally be made up of several components. For instance, one method may necessitate large capital expenditure but may have low operational costs. Another may not be so capital intensive but require a large operational labour force.

In these examples the choice of method could be influenced by the relative abundance (and hence the cost) of capital and labour.

Electricity is a processed and refined form of energy. Most sources of primary energy could be converted into electricity and the cost of the conversion process largely determines whether it is worthwhile to do so. One other factor which can materially affect the cost of electricity to the user is the distance of the source of primary energy from the point of use.

It is expensive to convert primary energy into electricity. It is also costly to transport most forms of energy (including electricity) over long distances.

The production and distribution of electricity therefore is a capital intensive process. The capital investment required to provide an electricity supply system is usually at least four times the value of the annual revenue derived from the sale of electricity supplied from that system.

On the other hand, in modern systems the direct labour content in the cost of production and supply of electricity can be quite small, and as the tendency is to increase the use of automatic devices for operation and control, future systems may be even less labour intensive.

The decision to begin to supply electricity will be influenced by the estimate of its profitability. In the domestic field this will be assessed by an estimate of whether or not the disposable income of a sufficiently large proportion of the community is sufficient to satisfy their essential requirements of food, clothing and shelter, and have enough left over to pay the price demanded for a service of light, power and perhaps heat. Electricity will be in competition with all the other desirable things for a share of the disposable income of the people whom it is proposed to serve.

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Similarly, the rate of growth of the demand for electricity for domestic purposes will depend upon how high the value of this service stands in the instinctive list of domestic priorities. Experience shows that the use of electricity increases as the general standard of living improves. The basic human needs always have first priority but when the disposable income is materially above this subsistence level electricity, because it can do so much to alleviate toil and provide comfortable living conditions, has a high claim upon a share of the surplus income.

As stated earlier, the equipment employed in producing and transmitting electricity is costly. New heat is the lowest form of energy. It is the form into which all other forms are dissipated in doing work. Tyre friction, which enables an automobile to move, is dissipated as heat, so is the work done in a lathe in cutting metal. Heat, and especially low-temperature heat, is an energy sump of lowest usefulness. Hence, it will usually be found that electricity cannot be sold competitively to the poorer people simply to be dissipated directly and immediately for space heating. A people of modest means will usually find a less expensive way of providing comfort heating.

Consequently an organization proposing to introduce an electricity supply system for a low-income community should consider first whether it can be made to pay when providing the requirements of that community for light and power only.

The use, and the rate of increase in use, of electricity for industrial purposes stands on a somewhat different footing. If a country is to improve its standard of living it must increase the value (that is the usefulness) of its natural resources. The possibility of doing this on a sufficient scale depends first upon the natural resources being available in sufficient quantity. In this connection the important natural resources are water, fuel (or equivalent hydro power), minerals of all kinds, a fertile soil and timber. Strictly speaking it is not necessary to have an abundant reserve or supply of all these things, for if some are plentiful and they, or their products, are transportable they may be sold abroad and the proceeds used to buy those things that are not available locally.

/But the

But the country is specially fortunate that is well endowed with them all.

Assuming that some natural resources exist, the normal way to increase their value is to do work on them intelligently. All natural resources are a free gift; we give water added value by impounding it for domestic or power or irrigation purposes; fuel and minerals acquire value by extracting them from the earth and transporting them to the points of use. Their value may be increased further by refining and processing.

All this can be done on a small scale by manual labour but, if it is to be done on a large scale, we require the assistance of power-driven equipment. We require to harness natural energy.

The prime difficulty in getting such a development started is that to purchase the materials or equipment for extracting and processing fuel and minerals, and for water supply, hydro power and irrigation, usually requires the use of capital on a scale which cannot be matched by the savings of a low-income community however hard they work and self-denying they are.

Apart, therefore, from the availability of raw materials and fuel, the rate of development in the early stages will depend upon the ability to attract foreign capital either as money or as equipment. Capital will flow towards projects where the yield and the security are most satisfactory, so the rate of development could depend upon the stability of national governments and institutions, the guaranteed national policy on the security of foreign investment and the economic viability of the projects in which the investment is to be made.

One further matter which could influence the rate of industrial development is the availability of trained personnel to manage, operate and maintain the expensive equipment, and design and direct the processes whereby value is given to raw materials. These valuable products must then be used profitably at home or sold abroad.

Finally, the rate of progress can be influenced by the willingness of a sufficient number of people to exchange the simple life of farming and fishing for the more complex relationships of an industrial community

/which offer

which offer the possibility of a higher standard of living but perhaps less personal freedom. Climate will play a part in this decision, the more agreeable the climate the smaller the urge to forsake the easy ways.

1. Methods for predetermining electrical demand and load growth

From the foregoing generalisation it will be apparent that there is no simple formula which can be applied to predetermine the rate of electric power development in its early stages. It will depend upon a large number of conditions, some of which have been mentioned. The existence and the importance of the individual conditions will vary from case to case.

The practical solution in new and isolated supply systems is a step-by-step process. Nowadays it takes at least three to four years to build a power station and at least two years to add more plant to an existing station. Consequently those who initiate an electric power system should provide enough capacity to supply the estimated demand for three to four years from the date that the first generating plant is placed in service. The estimation of this demand will be done by canvassing prospective users, perhaps by entering into firm contracts with prospective industrial users, by shrewd guessing and so on. This provision will enable at least one year's actual experience of supply to be gained before it is necessary to order plant for the first extension. An acceleration in the rate of growth of demand, if that is what is desired, can be stimulated by propaganda; the actual rate of growth of load will be conditoned by the ability to supply and this in turn may be determined by the availability of capital. In the early years the total quantum will be fairly small unless there is some very special circumstance, such as spectacular exploitation of a local natural resource. In that case, capital will, no doubt, have been made available for this commercial exploitation and will be more readily forthcoming to finance a power system to service it.

/Early development

Early development therefore will be on an empirical basis. As experience grows it will be possible to use the previous rate of growth corrected for known local developments as a guide in estimating what is likely to be required in, say, five years time. Guidance may be obtained from the experience of other underdeveloped countries, from an examination of the correlation of electricity growth with national income, supplemented by an analysis of the potential use by the main consuming sectors.

The experience of industrially-developed countries is that after an electric power system has been firmly established the rate of growth of demand is exponential. However, the early experience of industrialised countries may be somewhat misleading. These countries were considerably advanced when the use of electricity began to develop and their rate of electricity growth is in part the result of electrification of existing industry. Also, the levels of income permitted the development of domestic electrification at a rate that may not be practicable in less industrialised countries.

In the United Kingdom the demand has more than doubled every ten years since 1920, and there is little sign of approaching saturation. Fig. 1 shows the actual growth. It is true that the general supply of electricity began about 1880, and from Fig. 1 may be deduced the slowness of the development in the forty years up to 1920 compared with that in the subsequent forty years. Part of the reason is the multiplying effect of exponential growth, and part of it is that in the earlier period the steam engine (in the development of which Britain had done pioneering work) was in general use to provide power for many individual factories and there was no economic justification for changing to the newer method until existing engines were due for replacement.

The importance of accurate forecasting increases as the demand increases and as the possibility of saturation being reached becomes a reality. General plans should be made for, say, fifteen/twenty years ahead and more detailed plans for five/seven years, whilst contractual commitments are usually entered into for execution within four years for

/generating facilities,

generating facilities, and two years for distribution facilities. When the demand is increasing steadily, intelligent estimating of growth should secure that the corresponding plant capacity will match the demand within narrow limits. If the estimate is slightly optimistic plant may be available one year ahead of requirements; if pessimistic the supply organisation will be hard-put-to-it to meet the demand without load shedding. The object is to have the facility available neither too early nor too late. When the rate of growth is tending to diminish the problems of the estimator become acute. He has to try to visualise what changes in the current trends will affect the demand and what the result will be quantitatively.

The importance of accurate estimating may be illustrated by the fact that in the United Kingdom the direct annual capital expenditure on the electricity supply service is about £330 million. This is some 9 per cent of the country's home capital investment. Unnecessary capital expenditure on electricity supply could curtail some other desirable development; insufficient expenditure on the electricity service could cramp the nation's economic expansion.

In a supply system that is integrated on a national basis it is necessary to employ a small expert staff continuously on the estimation of future requirements of both kilowatts and kilowatt-hours. In this way, there is built up a fund of knowledge of past events and an appreciation of the other national trends which influence growth.

The simplest form of estimating is to extrapolate the recent exponential trend. In periods of steady exponential growth this gives a result which may be sufficiently accurate for four years ahead. The exercise is repeated each year, so that if there is any change in the actual rate of growth it will be given due weight in the extrapolation. Here it is necessary to distinguish between a fundamental change in the rate of growth and an accidental change caused by, say, abnormal weather or a temporary boom or recession in trade. This is where the skill and experience of the estimators, in using the statistics at their command, play a part.

/A second

A second and more refined method of estimating is to relate the growth of demand to the various national economic indices. The Gross National Product and the Index of Industrial Production are two of which there are long-term statistical records. The estimators know the history of these indices and endeavour to assess from national and international information available to them their forward trends. Various other bodies attempt to project these indices for several years ahead and their results form a cross check. The past relationship of electrical load growth can be applied to the most probable trends.

An estimate of this kind is always adjusted in the light of what is known about projected developments assessed separately for each industry. The trends in domestic and commercial usage are also given due weight. Thus there is built up piece-by-piece an assessment of total load growth based on national and international information. This exercise is repeated annually and each time this is done the result is projected one year further into the future.

A third method is to collate the estimates made by the regional electricity supply organizations based upon knowledge of developments in their region. These organizations have smaller management units who have detailed knowledge of the major developments in housing and industry in their district. Thus, there can be assembled a detailed picture of what the known developments will entail in terms of kilowatt and kilowatt-hour requirements.

This is corrected in two ways; one, by the elimination of duplicate estimates where enquiries have been made by industrialists in more than one district for what will ultimately emerge as only one project, and two, by the application of appropriate factors for general developments about which specific enquiries have not yet been made.

An advantage of these regional estimates is that they indicate the geographical pattern of the increase in demand, a point of importance to the central body responsible for the national generation and transmission programme.

/From these

From these three sets of information a final estimate of demand and output is prepared and submitted, with the supporting evidence, for a policy decision by the governing Board. The estimates so approved become the basis of the plant and fuel purchasing programmes for the years in respect of which it is necessary to enter into contractual commitments. They are considered to be "firm" for the first five years ahead, "provisional" for the sixth year and "tentative" for the seventh year and beyond. The consequent plant programmes form the main basis of the capital investment programme of the industry in each year for which commitments have been, or are being, made and in respect of years beyond this period for which information on general forward planning is required.

2. The economic evaluation of indigenous primary resources

The economic evaluation of indigenous primary energy sources could be considered under two broad heads:

(1) Valuation of the several indigenous resources in relation to one another.

(2) Valuation in relation to external primary resources that could be imported.

Before completing an economic assessment under (1) it would be necessary to know the quantum of energy in and the rate at which it could be extracted from each competing source and the cost of power (energy) delivered to the customers from each competing source.

Thus, for hydro sources a hydrodynamical and a hydrometeorological survey should have been made over many years to obtain reliable data of maximum, minimum and average flow, the cycle of maximum and minimum flows and an estimate of the proportion of the flow that will be available for power generation. Similarly, if an artificial reservoir is to be created to impound the surface water of a given catchment area long-term measurements of rainfall evaporation and absorption are essential.

In most developing countries such statistical evidence will not have been collected over a sufficient period to provide a reliable guide.

/If, however,

If, however, it is proposed to utilise only a fraction of the flow or catchment it is possible to make calculations of costs based upon this limited development without waiting for very long-term statistical evidence.

If the fuel to be used is coal, it is essential to know from geological surveys and development guarantees the extent and tonnage of each coalfield, the quality of the coal, the minimum rate of output that will be made available for power purposes and the estimated pit-head price per ton for a period at least equal to the economic life of the proposed power plant.

Similar relevant information is required in the case of indigenous oil.

In each case the evaluation will include the cost of conversion and the cost of transport to the point of use. With coal and oil there is a choice between transporting the primary material or the electricity. For coal in United Kingdom conditions it is cheaper to transmit electricity by overhead line at 275 kV than to transport coal if the distance is more than 60 miles and the average loading of the line is not less than 70 per cent of its rated carrying capacity. This is true for transport by railroad under United Kingdom conditions. For sea transport, which is cheaper, the minimum economic distance would be greater.

One of the greatest difficulties in making these economic comparisons is that of estimating the delivered price of the fuel throughout the economic life of the power plant. There is no short answer to this problem; it depends upon the differential effect of wage rates and general inflation on the cost of fuel from the alternative sources. The best that can be done is to make a number of estimates, each based upon a postulated cost of fuel and exercise judgment when making the comparisons. The alternative estimates should cover the probable range of costs over the period.

In many cases the decision to proceed with a development may have to be made upon considerations other than those of pure economics. For

/example, the

example, the overall economic comparison may be in favour of a hydro-electric project but if the capital cost of that scheme is higher than that of a thermal scheme of the same output, the less economic scheme may have first priority because of a shortage of capital.

As mentioned in (2) above, the cost of utilization of indigenous resources may have to be compared with that of imported resources.

The foregoing discussion is relevant in this case also and, in addition, questions of the national balance of payments may have to be taken into account when making a policy decision.

3. Problems of plant and system development

The economic criteria for the development of power systems depend upon the size of the system and upon the result of the evaluations mentioned in the previous section.

In an isolated system the spare generating capacity should be not less than the capacity of the largest generating set. This is to ensure that the largest set can be out of service without prejudice to the ability to meet the full demand. The satisfying of this requirement in the most economical manner sometimes restricts the size of the largest set that can be used to a capacity well below that of the largest set that can be manufactured. For example, on a system with a demand of 90 megawatts the largest set would probably have an output of not more than 30 MW and the safe spare capacity would therefore be 33 per cent of the system demand.

On an interconnected system of 2000 MW demand, the spare capacity can be pooled over a number of power stations and would probably be 15 per cent of the demand, or, say, 300 MW, which under modern technology could be constructed as one 300 MW set, but probably on a system of this size would be provided as two 150 MW sets, or even as three 100 MW sets.

For a system demand of 20,000 MW the spare capacity would probably be 10 per cent, or 2000 MW. This is greater than the capacity of any one set that it is possible to manufacture in the present state of knowledge. Hence a system of this size permits the use of the largest and most economical sets that it is practicable to design and construct.

/The economies

The economies of size in thermal generating sets and stations is illustrated in the following table, which is based upon actual experience.

Table 1

Unit size	Index of thermal efficiency	Index of capital cost of complete station
MW (installed)		
30	100	100
60	112	85
100	123	87
120	131	79
200	138	75
275	138	61
550	140	58

In fact the economies of size are a little greater than that shown in the table because the cost of the stations with the largest sets is based upon 1959 prices and that of the other stations based upon the lower price levels obtaining some years earlier.

These economies are not confined to capital cost. Fundamentally, efficiency of conversion from raw fuel to electricity depends upon the difference between the initial and final pressure and temperature of the operating fluid. It is therefore a happy coincidence that high-pressure, high-temperature steam can be used most effectively in large turbines. Although expensive materials have to be used to contain this very hot steam safely there is an overall economic gain both in capital and operating costs by using large thermal generating sets suitable for these conditions provided the idea is not carried too far. In the present state of knowledge there is an upper economic limit of temperature (mainly due to the diminishing return on the investment beyond this limit but also to the lack of materials capable of withstanding higher temperatures for long periods). This limit, which at present is about 1050°F., should be raised when metals with superior temperature characteristics become available at reasonable cost.

/The interconnection

The interconnection and unified operation of isolated systems renders possible these economies of size. In a very large heavily interconnected system not only is it possible to use large generating sets but it is also possible to locate power stations near the fuel sources and thus take advantage of the economies of electrical transmission as compared with the physical transport of fuel to power stations located near to the points of use.

Furthermore, in a heavily interconnected system it is possible to operate the most economical generating sets at full output all the time that they are available irrespective of the location of the electrical demand.

Finally, such a system is well suited to the integration of conventional thermal, nuclear and hydro plants. At present there is a tendency to build nuclear power stations away from centres of population. On the other hand, the cost of electricity from nuclear sources is lowest if these power stations are operated at the highest practicable plant load factor. These requirements tend to conflict unless there is a strong transmission system between power stations and points of use. Similarly, hydro power - whether direct or as pumped storage - can usually be integrated most economically on a heavily interconnected supply system.

Each country will relate these general principles to their own circumstances and test them in the light of local conditions.

4. Investment requirements and means of finance

Three of the most testing circumstances are climate, topography and finance.

Climate and topography will determine the availability of water and the priorities of irrigation, flood control and hydro-electric power development. Availability, in this sense, is something that the planners cannot alter and the development priorities will depend upon the natural fertility of the soil without irrigation, the need for flood control and the relativity of the real costs of power from hydro and from other available sources. However, all developments will be conditioned by

/the will

the will and urge of the people, through the various organizations, to proceed with the necessary tasks, and the amount that can be accomplished will depend upon the availability of the means of financing it. As stated earlier, initial developments could be financed by foreign investment, but in the long run it is the will and ability of local people to make the investment remunerative and the project prosper that influences the availability of further foreign capital or the generation of local capital. Climate has much to do with the energy level of the people.

Descending into detail it is impossible to give relative capital costs of generation, transmission and distribution equipment that would be applicable to every country and every source of energy.

The cost of hydro-electric schemes depends very much upon local conditions. Sometimes these are more suitable for base-load power, sometimes only a peak-load scheme is practicable. In these two extremes the cost per kilowatt or per kilowatt-hour may differ widely and yet if wisely chosen each in its right setting may be the most economical development taking the supply system as a whole.

Again, the annual capital charges are the main revenue cost of a hydro project and since a large proportion of the capital is usually spent on civil engineering works, which have a long life, the depreciation or redemption charge can be spread over this long period.

The relative capital cost of conventional thermal power stations related to the size of the generating sets for United Kingdom conditions is shown in table 1.

The average cost relationship per kilometer of overhead transmission line for 11 kV, 33 kV, 132 kV and 275 kV lines in Great Britain is shown in table 2.

/Table 2

Table 2

RELATIVE COST OF OVERHEAD LINES IN THE UNITED KINGDOM

Description of line	Voltage kV	Relative cost per kilometer	Rated capacity (of each circuit) M.V.A.
Single circuit three phase (with aluminium alloy conductors, 0.15 sq.in. copper equivalent on single wood poles and pin type insulators)	11	100	7.5
Double circuit three phase (with aluminium alloy conductors, 0.15 sq.in. copper equivalent on H type wood poles and pin type insulators)	11	190	7.5
Single circuit three phase (with aluminium alloy conductors, 0.15 sq.in copper equivalent on single wood poles and pin type insulators)	33	110	22.5
Double circuit three phase (with aluminium alloy conductors, 0.15 sq.in. copper equivalent on H type wood poles and pin type insulators)	33	200	22.5
Double circuit three phase (with steel cored aluminium conductors, 0.175 sq. in. copper equivalent on steel towers and suspension insulators)	132	370	100
Double circuit three phase (with steel cored aluminium conductors, twin 0.4 sq.in. copper equivalent each phase consisting of two such conductors, on steel towers and suspension insulators)	275	950	620

The rated carrying capacity of each circuit is indicated for British conditions where the transmission distances are fairly short.

In any complete analysis the cost of transmission will include the cost of the lines plus the cost of terminal equipment. Where the

/transmission distances

transmission distances are short, the cost of terminal equipment expressed as a proportion of the total is larger than where the transmission distances are long.

The cost and the efficiency of a distribution system is influenced by the voltage of supply to ordinary consumers. The difference in this cost for supplies at 120 volts. and 250 volts., single phase, is very much in favour of the higher voltage. Experience has shown that in practice there is little difference in the safety factor between two such systems. Apart from the difference in cost of supply at any stage of development, the higher voltage system has a much larger capacity and is capable of further development at less cost than the lower voltage system.

In all distribution systems it is economically important to bring the high voltage (say 33 - 15 or 11 kV) supply as near as is practicable to the consumers' terminals - in other words, to minimise the length of medium voltage distribution.

Finally, it is perhaps worth stating that if individual supply systems are to gain the maximum benefit from interconnection they should all operate at the same frequency. Where the frequencies of supply systems differ, one objective of national planning should be the standardisation of frequency.

The financing of the electric power service presents problems in every country. First, it is a capital intensive service and, second, it is a quasi monopolistic service. In most countries it is felt that a basic service that is vital to most industrial activity and which enjoys monopoly rights, in the sense that no one else is permitted to provide this service in the same area of supply, should be under some degree of control as to the prices charged for the product and the profits distributed by the supply authority. In practice the reward offered to the investor must be sufficient to attract capital and, where the industry is capital intensive, the reward must attract a large capital investment. A figure of £80 to £100 per kilowatt of maximum demand may be of the right order.

/The assets