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⌐ECONOMICAL USE OF HYDRO POWER, STEAM POWER AND SYSTEM INTERCONNECTIONS

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SUMMARY

ECONOMICAL USE OF HYDRO POWER, STEAM POWER, AND SYSTEM INTERCONNECTIONS

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The basic objective in the operation of an electric utility system is to provide reliable service to all customers in the most economical manner possible. Although many of the means for accomplishing this are common to all systems, others are intricately related to the specific power supply sources available. This is especially true when the system has hydro plants (with storage), steam plants, and adequate transmission interconnections, so that there is frequently some choice in the power supply sources to use.

This paper deals with those special considerations affecting operating economy that are peculiar to systems with the mixed type of supply sources. The subject matter is treated rather generally, since many of the operating procedures and requirements of a particular system are necessarily individualistic. The experiences of the Tennessee Valley Authority in operating a power system of this type form the basis for much of the paper.

The paper is divided into five sections which are discussed here, very briefly.

The Introduction presents the fundamental problem of choosing between hydro storage and steam power for the supply of system loads at any particular time. The variability and the unpredictability of streamflows are discussed. For systems with substantial hydro supply, this often results in the sale of interruptible power along with the more typical firm power. The different types of interruptible power that have been supplied by TVA are described.

The second section of the paper is Complementary Use of Stored Hydro Energy and Thermal Energy. The use of a basic rule curve to insure the delivery of firm power is explained. The choice between hydro and steam power for the supply of system energy requirements is made by comparing the probable future value of the top increment of storage, if retained, with its present steam replacement value, if used. The probable future value involves the determination of ideal operation for some future "governing period," with a recurrence of each streamflow year for a representative sample of years (obtained from the historical flow record). The final product, system economy guide curves, is illustrated.

The third section of the paper is Complementary Coordination of Hydro Capacity, Steam Capacity, and Interconnection Capacity. There is a discussion of the characteristics and use of each of these various power sources in supplying system peak demands as well as the hourly load variations over short-time intervals. The economics resulting from the complementary use of all sources is described and illustrated.

The fourth section is Economic Dispatch. There is an explanation of the general principles of economy loading, or economic dispatch, which permits the refined consideration of incremental transmission losses in the selection of generating sources. The application of these principles for all-steam systems is straightforward. For systems with hydro plants, however, the

application becomes much more complex. These problems of application are reviewed.

The last major section of the paper is Use of Interconnections for Economical Combination of Systems. The use of interconnections for the exchange of energy between a predominantly steam system and a predominantly hydro system is discussed. Also, there is a treatment of the use of interconnections to maximize the generation from the most economical steam sources of both systems. Capacity exchanges are very important in reducing the reserve requirements of separate systems. This is discussed along with the use of interconnections to take advantage of diversity in demands of connected power systems.

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INTRODUCTION

The basic objective in the operation of an electric utility system is to provide reliable service to all customers in the most economical manner possible. Some of the means for accomplishing this are common to all systems. Others are peculiar to the particular system, especially as affected by the specific power supply sources available. Many of the reliability and economic considerations in the operation of a system composed entirely of thermal plants are essentially different from those encountered in the operation of a system with only hydro projects. For systems with both hydro and thermal sources, the factors peculiar to both types plus many additional factors must be considered. Of course, the optimum use of transmission interconnections between systems is also a very essential requirement if the basic objective is to be obtained.

This paper is restricted primarily to a discussion of the economic integration of existing hydro and thermal sources in the supply of bulk power to the high voltage transmission system. The economical use of system interconnections for the exchange of power is also included in this discussion. The experiences of the Tennessee Valley Authority in operating a power system of this type form the basis for much of the paper.

TVA System

The present TVA generating plants, along with the major transmission lines and interconnections, are shown in Figure 1. The mixture of hydro and steam plants is not new, having been so throughout TVA's existence. However, the proportions and characteristics of these two generating sources have changed considerably over the years. In the 1940's and early 1950's the system was predominantly hydro, with steam plants of widely varying generating costs. In recent years the system has become predominantly steam, with a relatively narrow range in generating costs of the steam units normally being operated. As the system has changed, the importance of various factors in optimizing the operating economy has also changed. Some few factors require less detailed consideration, while others require considerably more refinement.

Fundamental Problem

Although the importance of various factors changes as a system changes, there is a fundamental problem for all mixed systems composed of hydro projects with considerable storage along with thermal plants. This problem is the choice between hydro and thermal power in serving the current load on the system. The problem is made particularly difficult because the future hydro supply is usually quite unpredictable, since it depends upon hydrological events associated with the vagaries of weather. Despite this handicap, the optimum operation of the system is for the one type of supply to complement the other in such a way that the average annual production costs are minimums.

Streamflow Regimens

Since future streamflows have such a significant effect on the operation of power systems of the type under discussion, it should be pointed out that the treatment here assumes that no prediction of actual streamflows can be made. Except for predictions of runoff from existing snow fields or other natural storage, it has been the universal experience that precipitation, though of seasonal and even daily patterns, is so variable in any time scale significant to this discussion that runoff predictions are no more than a guess. This is especially true since runoff is the marginal residual after water losses are met. So, while general patterns and average amounts are known, the system operator usually faces a widely variable and unpredictable basic source of supply. The only reliable clue is the past record of gaging stations over a sufficient period to form an adequate sample of the runoff resulting from the hydrology of the region.

Firm and Interruptible Loads

Loads supplied by power systems can usually be classified as either firm or interruptible loads. The former is typical of most utility system loads, but the latter is not an uncommon type where hydro energy is a substantial source of supply or where large industrial loads are served. There are many types of interruptible loads, since they usually reflect the peculiar conditions surrounding particular circumstances of power supply. Over the past 25 years or so, TVA has supplied interruptible power under several types of contracts. The earlier contracts were designed to minimize the supply of energy during years of severe droughts. The more recent interruptible contracts have been designed to permit interruptions during peak hours only for a maximum of 500 hours in a given year. Either or both firm and interruptible power can be supplied to other power systems over the transmission interconnections.

COMPLEMENTARY USE OF STORED HYDRO ENERGY AND THERMAL ENERGY

The larger part of the hydro generation on the TVA system comes from water storable at tributary multiple-purpose projects and therefore controllable over periods of many months under certain unique restrictions relating mainly to flood control. Because of these conditions the hydro generation can be treated as an entity and not as many unrelated, diverse pieces representing each plant. This seasonal type of integrated storage is considered in this section of the paper. It is further assumed that no transmission limitations of practical importance preclude the interchange of any bulk generation in supplying system load.

Basic Rule Curve

In this section of the paper, the reliability of service relates to the ability of the power system to supply customer requirements during critically dry periods. The basic rule curve has been the principal guide used by TVA to insure the availability of power during these periods. This curve, by various appelations, has been used for many years in the study and operation of systems with substantial hydro storage.

The basic rule curve indicates the minimum system storage levels throughout a year necessary to insure the delivery of firm power. The supply of interruptible loads is not so assured, since the ability to shed these loads during periods of adverse streamflow is one of the primary reasons for selling this type of power.

The determination of the basic rule curve can be divided into two parts. First, calculations are required of the average hydro generation needed for the supply of firm loads if all thermal sources are operated at capacity. These averages will normally be required for each week, or month, during the next year or so. Second, computations must be made of the system storage needed to "firm up" these hydro requirements if extremely adverse streamflows are experienced.

Normally, TVA has used the worst droughts of record as the criterion for the determination of basic rule curves.[1] It should be noted, however, that the basic rule curve can be determined by statistical methods and that TVA and other utilities have used such methods in varying degrees.[2]

Values of Incremental Storage

It is to be expected that full use of all thermal sources will be made whenever system storage falls below the basic rule curve. Also, at such times, interruptions of nonfirm load should be scheduled.

When system storage exceeds the basic rule curve, which is normally the case, surplus energy is available either for the replacement of the more costly thermal power or for the supply of interruptible load. Questions arise as to how much and what cost thermal power to replace and when to supply interruptible load. In TVA, this decision is made possible from a determination of the future value of the top increment of storage, if it is retained rather than used currently. This computed future value is then compared with the current worth of the increment, either for replacement of thermal power or for the sale of interruptible power.

It is obvious that the future value of an increment of storage will not be the same for the many streamflow conditions that are possible to occur. This being the case, such values must be determined for each year of a representative sample of streamflow years. The streamflow record is the best sample available and should be so used. Each streamflow year is assumed equally likely. Therefore, using the principle of group insurance, the value of the top increment in storage on the date in question is the average of the separate yearly values.

The determination of the yearly values of storage is rather complex, especially for large power systems. Some simplifications become necessary. One very helpful assumption is that each flow year is known in advance and that for each year the value of incremental storage will be an optimum under ideal operation--that is, operation with foresight.

In the following discussion of ideal operation and values of incremental storage, several other simplifying assumptions are made in order that the theoretical principles may be better understood. The market for interruptible power from week to week is assumed to be constant, as is the availability of each cost block of thermal power. Interruptible power is assumed to return a definite revenue per kilowatt-hour when being supplied but is not restricted as to curtailment rights. With this latter condition, if the sum of the firm and interruptible loads is thought of in terms of firm load, the periods of interruption of the curtailable load can be thought of as periods of thermal power supply, costing the same per kilowatt-hour as the loss in revenue from the interruptible power.

Two factors are probably most important in ideal operation. The use of the economical thermal power should be maximized and the uneconomical thermal power minimized. Somewhat contradictory, the hydro generation should be low during the first part of a flow period and higher later in order to maximize the heads at the storage projects.

With a given storage content on a given date, a first approximation of ideal operation is a constant level of thermal power for a future "governing period." This period ends when, for the particular streamflow year, the resulting hydro requirements cause the system storage to become tangent to either the minimum basic rule curve level or the maximum permissible storage level. If the point of tangency is the rule curve, any less use of thermal power during the governing period would result in system storage being drawn below the rule curve and thus endangering the supply of firm power. On the other hand, when the point of tangency is the maximum permissible storage level, any greater use of thermal power would result in water being spilled. The correct governing period is the longest period without causing spilling or violating the basic rule curve.

Other things being equal, this constant level of thermal power use will result in the least production cost during the governing period for the particular flow year. Any other operation in which a lower thermal output in one part of the period must be balanced by a higher thermal output in the other part of the period will result in greater production costs. Since the unit costs of thermal power increase with output, the total cost curve is concave upward; and only constant output will give minimum total cost.

The above unmodified ideal operation is illustrated in Figure 2 by the reservoir storage path OCG and the constant thermal power output C'G'. The first improvement to this operation would be to make full use of the 4-mills-per-kwh source in the first part of the governing period and no use in the last part, rather than partial use throughout. This would result in higher reservoir levels throughout the period and thus more efficient use of the available water supply. If the next-lower cost block of thermal power (the 3.5-mills-per-kwh block in the illustration) has a unit cost sufficiently close to the 4-mills-per-kwh cost originally justified, it may be profitable to replace some of this power at the end of the governing period by continuing the full use of the 4-mills-per-kwh source longer than otherwise indicated. This is so if and so long as, incrementally, the additional hydro energy resulting from the gain in head applied to the natural flow in the remainder of the period of lower cost generation has a greater value than the differential in the two thermal costs. There is a rapid convergence toward zero of this net saving because each succeeding gain in both head and flow is smaller than the preceding gain. This modified ideal operation is also illustrated in Figure 2 by the reservoir storage path ODKG and the thermal power use O'D'QK'G".

The next question that arises is whether it is economical to increase the head even further by the use of somewhat more costly thermal power. Consider one kwh of additional storage gained by the initial use of more expensive thermal power represented by the crosshatched area at P' so that the storage trace OPHDG results from the thermal power use P'H'RK'G". The additional storage plus the effect of the additional head results in the 4-mill energy reduction, H'D'QR, being equivalent in this illustration to 1.3 kwh. Consequently, a close approximation of the worth of the initial kwh of storage is 4 x 1.3 = 5.2 mills per kwh; and the 5-mill block of thermal power would be initially justified. The extent of use of the 5-mill power at the beginning of the governing period and replacement of the 4-mill power at the end of its period of use would have to be determined incrementally, as described above in the continued use of the 4-mill power for the later replacement of the 3.5-mill power.

The final evaluation of the top increment of initial storage, for a particular streamflow year, is determined in terms of its value in replacing the most expensive thermal power justified. The time of replacement is at the end of the period this thermal power is used. For the above example, this could be 5.0 x 1.02 = 5.1 mills per kwh.

As stated before, such determinations are required for each year of a representative sample of streamflow years. The following table illustrates how the values for two system storage levels on a given date might vary with streamflow conditions.

Value of Storage on June 1 (Mills per Kwh)

Sample of Streamflow Years	Storage @ 1,000,000 Mwh	Storage @ 2,000,000 Mwh
1910	3.3	2.1
1911	4.5	3.2
1912	2.2	0.0
1913	5.9	3.4
1914	4.7	3.3
1915	8.9	6.7
1916	11.5	9.1
1917	2.2	0.0
1918	4.9	2.3
1919	3.6	2.2
Average	5.2	3.2

It is the average values in the foregoing-type table that indicate the degree to which thermal power should be used to conserve the use of hydro storage. The same is true regarding the use of power available over the transmission interconnections. These averages also indicate when hydro storage should be used for the supply of interruptible power.

In order that the above average values be known for a range of storage levels on a given date, it is necessary to determine them for several discrete levels and then prepare a "value of storage" curve. Such a curve is shown in Figure 3.

Economy Guide Curves

Since such value of storage curves can be prepared for as many dates as desired, it is possible to draw a family of curves on a chart of system reservoir content versus time of year, in which points of equal value of incremental storage lie on the same curve. Such a family of curves for the TVA system is shown in Figure 4. These curves, which are given the name "economy guide curves," are useful over a period of time in the same manner as the previously described curve is useful for a given date.

Many hydro-thermal systems are so large and complex that it would be very difficult to determine economy guide curves in exactly the manner described above. This is especially true where the hydro system includes non-storage projects which are located downstream from the storage projects and which spill varying amounts of water in the different streamflow years. The procedure also becomes involved when there are many different cost blocks of thermal power, including power available from interconnections.

The TVA system is such a system. Especially troublesome is the occasional spilling of water at the downstream non-storage projects. This consideration reduces the value of the top increment of storage, but more significantly it adds a new dimension to the over-all problem. In Figure 5, a diagram of the TVA water control system shows both the storage and non-storage projects.

A graphical approach is used by TVA in obtaining a practical solution to the storage value problem. The details of this method are described in another paper.[1]

COMPLEMENTARY COORDINATION OF HYDRO CAPACITY, STEAM CAPACITY, AND INTERCONNECTION CAPACITY

The choice between thermal power and stored hydro power previously described is associated with the supply of the total energy needs of the system. Concomitant with that problem is the use of the various sources to supply the variations in load, particularly the peak demands. The various sources have different characteristics in this regard, and some discussion of this is pertinent.

Characteristics of Different Types of Capacity

Hydro--The dominant characteristic of hydro capacity is its flexibility. Since the fundamental force is one of transmission of fluid pressure to mechanical movement without the problems of heat transfer or high speeds, variations in output from a hydraulic turbine-generator set are comparatively simple to obtain. On the TVA system it is possible to have a large hydroelectric unit, which has been at rest, carrying load at full rated capacity within two to three minutes. The processes of opening the wicket gates, bringing the unit up to speed, synchronizing with the system, and shouldering load are distinct, orderly programs with little complex interrelationship to disturb their accomplishment. Once the hydroelectric set is on the line, the comparatively slow rotating speed with large WR^2 of the rotating elements give the hydro unit an inherently stable characteristic. Regulation characteristics are favorable for most electric system requirements. Hydraulic governor systems actuating the gates or valve to control the flow of water give quick, positive control over a wide range of power. In projects with long water conductors, however, the surge effects can become important.

The variation of efficiency with changes in load and head is dependent upon the type of prime mover. Francis turbines, impulse wheels, and fixed-blade propellers have sharper decreases from the optimum point than the adjustable types. In cases where multiple units are used, the effect is to provide a wide range in power output with relatively small changes in efficiency by the selection of the proper number of units to carry the load.

One of the advantages of hydro units is their adaptability for use as synchronous condensers in supplying reactive power to the system. With a small investment in tail-water suppression equipment, the units may be motored on the line quite conveniently and quickly as needed. On the TVA system this has been one of the common methods for voltage control.

The dependability of hydroelectric sets is high. Both the mechanical and electrical equipment of modern installations are capable of long periods of uninterrupted performance under most conditions with adequate maintenance. An availability factor of 96 to 97 percent is normally expected on the TVA system.

Steam--The steam-electric generating plant is a complex combination of several systems, which converts the latent energy in the bulk fuel by a controlled process to mechanical energy using the thermodynamic properties of steam, and then to electrical energy with conventional rotating machinery. There must be a system for the gathering, preparation, and delivery of the fuel to the boiler. The boiler, a combination of systems, must convert a tempest of high-temperature flame to a controlled flow of superheated high-pressure, high-temperature steam to the next system, the turbine and condenser. This precision machine efficiently transforms the steam to the useable rotating mechanical energy which drives the electrical generator, the final system. The complex problems of heat transfer and its control in the boiler-turbine systems are obvious. Moreover, it is apparent that any break in the chain of these rapid processes would stop power production from that unit.

It is clear that the time required to start up such a heat machine will be many times greater than for a hydroelectric plant. On the TVA system the period normally allowed for a start from a cold boiler is 4 to 6 hours. After the unit is delivering energy at the required rate, the problems of varying the rate of heat evolved and transferred are great. Depending upon provisions in the design, it is usually found impractical to reduce load below about one-fourth of the full-load rating. It is to the credit of equipment designers that variations within this range can be made within a matter of minutes, even though this cannot approach the rate for hydro units. For small variations in output, the regulation and response of a modern steam-electric set is satisfactory when associated with boiler tie-in controls.

Because of the great significance of the fuel cost, it is of utmost importance to realize that the most efficient operation of a steam-electric unit is for constant output at the point where design conditions are most nearly fulfilled. This will ordinarily be near the rated output of the set.

Because of the nature and number of critical elements involved, the dependability of steam-electric units is not as high as hydroelectric installations. The experience by TVA has shown an average availability of 87 percent.

Other Thermal Capacity--Diesel engines, gas turbines, and nuclear plants are not common generating units in TVA experience, and each has its peculiar characteristics--including advantages and disadvantages. The first two are closer to hydro in their flexibility for following load changes, while the characteristics of the latter are closely allied to the particular type of nuclear power employed.

Interconnection Capacity--The dependability of capacity from other systems over interconnecting transmission lines depends both upon the nature of the line, including its operation, and the type and kind of operation of capacity on the neighboring system. In TVA's experience the most favorable results have been obtained by parallel operation of the systems over the line with adequate telemetering and load control equipment on each system. System stability is usually improved with such multiple interconnections. Firm capacity will be contractually arranged and may have some particular agreements as to use.

Operation of Hydro and Steam Capacity

Load to be Supplied--One of the basic considerations is the characteristics of the system load. Daily, weekly, and monthly load factors vary among systems; there may be pronounced seasonal variations, and the ratio of minimum load to maximum demand varies considerably. These patterns will be directive in the use of available sources of capacity to meet the load variations. Daily load factors on the TVA system exceed 85 percent and at times 90 percent is reached; weekly load factors average 85 percent and usually exceed 83 percent. Monthly load factors are only slightly lower; however, there is a large seasonal variation due primarily to electric heating, which is at present over two million kw out of an annual demand of ten million kw.

As has been pointed out, TVA sells power to certain industrial customers which can be interrupted during peak hours. This is equivalent to short-term capacity available at a cost determined by the contract. It has an effect somewhat similar to that of gas turbine capacity for short periods. TVA has no gas turbines.

Complementary Use of Hydro and Steam Capacity--Whatever the daily and weekly variation, if steam capacity alone were available the load changes would necessarily be met by the complicated thermodynamic changes inherent in this type of capacity. While this is a common requirement on many steam systems, it is not as efficient as steady output at designed capacity and usually requires the daily starting and stopping of some units along with minimum loading on others. On the other hand, if hydro capacity alone is available the base load is carried by units which are otherwise well adapted to load variations. Moreover, during periods of low streamflow, inefficient loading points may become necessary in order to fit the available water to the load requirements. Also, there may be pondage limitations which operate in this unfavorable manner every pondage cycle.

When both types of capacity are available, there are opportunities for adapting each type to its most efficient use, as illustrated in Figure 6.

The most economical steam plants are best utilized by base load operation as indicated by Figure 6(A). All steam units that are economically justified under the current hydro-storage conditions should be operated at their full efficient loads as continuously as maintenance requirements permit.

The hydro plants with their favorable characteristics for starting and stopping and carrying variable loads are placed at the top of the load curve. This ordinarily does not mean operation at inefficient loading points. Because of the smaller average size of hydro units, they can be fitted into a schedule whereby each is operated at or near the point of best efficiency for the number of hours that the available water permits, moving up or down on the load curve as the water supply varies. When flows are high, some plants may need to operate continuously as shown in Figure 6(B).

The spinning reserve required by the system is most advantageously supplied by the hydro plants. Whereas a steam unit requires some minimum generation at inefficient coal use, the hydro set can operate as a synchronous condenser with no water use. Moreover, such a set can be shut down and yet be started and carrying system load within some 3 minutes. To even approach this, a steam unit would require the nonproductive use of fuel to keep the boiler hot and ready and extensive instrumentation on the turbine to enable it to pick up load quickly without dire consequences from steep temperature gradients.

Even in cases where peaking steam capacity must be used to supplement an insufficient availability of hydro capacity to meet the system peak demand, the variations on these more expensive steam plants can be kept to a minimum as shown in Figure 6(B). Where peak demands in such a case are seasonal or otherwise of short annual duration, gas turbines, or other sources which are quite flexible but burn relatively expensive fuel, may be employed to care for these relatively few hours economically. TVA's interruptible loads serve somewhat the same purpose.

Nuclear capacity, with its large fixed costs including fixed investment in fuel, is most likely to be used economically as a base loaded plant with relatively small incremental cost. The first such plant to be operated as a part of the TVA system is a relatively small unit of 25-mw capacity due to be commissioned by the Atomic Energy Commission in late 1962.

For regulating purposes, the coordination of the different types of capacity to take advantage of the characteristics of each is of economic advantage. In some cases the size of a single hydro plant may be such that its excellent regulating characteristics are large enough to provide economically the entire system regulation. In other cases it must be divided between the various plants, and it becomes a complex problem in which the good behavior of hydro units to relatively large load changes is coupled with the satisfactory response of the steam units to relatively small changes. On the TVA system, both have been used with the greater share taken by a few large hydro plants and "fringe" regulation by the steam units.

ECONOMIC DISPATCH

In recent years, with the advent of powerful electronic computers, there has been considerable development in the field of economy loading, or economic dispatch. Primarily, this field of work permits the refined consideration of incremental transmission losses in the selection of generating sources. It also enables interconnected utilities to determine more accurately the margins of profit in the sale or interchange of power at the interconnection points.

The principles and procedures have been developed to the point that both analogue and digital computers are being used by various utilities for hourly and even continuous economic power dispatch. TVA recently purchased an IBM 704 digital computer which is being used for economic dispatch, as well as for many other scientific and data processing purposes.

The fundamental principle of economy loading is to deliver power to the customers at the lowest over-all cost from the power supply sources in actual operation at the time. This is accomplished when the incremental cost of delivered power is the same from all projects not operating at maximum or minimum levels.

The general economy loading equation may be expressed mathematically as a nonlinear partial differential equation,

$$\frac{d f_n}{d P_n} + \lambda \frac{\partial L_T}{\partial P_n} = \lambda$$

where $\frac{d f_n}{d P_n}$ = the incremental generating cost at plant "n"

$\frac{\partial L_T}{\partial P_n}$ = the incremental transmission loss due to plant "n"

and λ = the incremental cost of delivered power.

Since the incremental transmission loss associated with the generation at a particular plant is interrelated with the generation at all plants, it is hardly necessary to say that the solution of this equation for a number of plants necessitates the use of an electronic computer.

In the foregoing equation, you will note that the incremental generating costs at all plants are required basic information. For thermal plants, the determination of these costs is straightforward, being a function of the incremental heat rates and fuel costs. For hydro plants, these costs must reflect the incremental turbine and generator efficiencies as well as the values of the water used. The incremental generating costs at nonstorage hydro projects are particularly difficult to obtain, since the use of water, even for a short period, is a dependent variable.

Apparently, no utility has determined the generating costs at hydro plants in a completely satisfactory manner for use in the economy loading equations. In TVA, the values of incremental system storage have been used at the various hydro plants as average generating costs. More recently, the principles discussed in this paper for the determination of these system storage values have been expanded so that values of incremental storage are now obtained at individual storage projects. (This has been possible through the use of the 704 computer.) These values have been used at the storage projects along with system values at the nonstorage projects.

The ultimate answer to the hourly economic scheduling of generation at hydro plants as part of the economy loading equations is not known at this time. In TVA, an attempt is being made to develop a computer program which will preschedule generation by plants for short periods, based on scheduled total discharges. The basic principles being used are those developed by The Hydro-Electric Power Commission of Ontario and the General Electric Company.[3] If this approach can be developed satisfactorily for the TVA system, perhaps the preschedules of generation at nonstorage projects can be used. This would leave the storage projects, thermal plants, and perhaps interconnections, for use in the hourly economy loading as determined concurrently by the 704 computer.

As previously stated, the principles of economy loading apply to power sources in actual operation at the time. The selection of thermal units or plants for on-line operation is largely a function of the relative operating costs as compared with storage values. Also, when peaking requirements cannot otherwise be met, the selection of the necessary additional thermal power is based on the relative operating costs. Through the use of the 704 computer, TVA is able to make the selections on the basis of delivered power costs, rather than generating costs. This, of course, further improves the economy of operation.

USE OF INTERCONNECTIONS FOR ECONOMICAL COMBINATION OF SYSTEMS

The previous discussions have pointed out the economies of coordinating the various types of energy and capacity sources on the same system. In a similar manner, operations of two or more systems can be economically combined by the use of interconnecting transmission lines over which the necessary exchange or sale of power can be made. These ties can be between systems using different "backbone" voltages by the use of autotransformers, usually placed at the system of lower voltage.

Energy Exchanges

Hydro-Steam Combinations--Despite the fact that two independent interconnected systems may have limited transmission capacity between them, it can be useful in effecting economies such as the conservation of stored hydro energy on one system by surplus steam energy from another system. A predominantly steam system will always have surplus capacity and energy during the offpeak hours. During these same offpeak hours, a predominantly hydro system with storage or pondage may often be able to reduce its use of stored or ponded energy by the import of the other system's surplus steam power. When the value of such stored water is greater than the cost of producing and transmitting the fuel-generated energy, economies between the two systems can result from such transfers. In some cases it may be largely a matter of substitution of more economical steam energy on the storage-hydro system; in others it may be a conversion of offpeak power to peak power through the reservoirs of the hydro system. The transactions of the TVA system with other interconnected systems have been mostly of the former kind in the past.

Steam-Steam Combinations--Because of the diversity between the fuel-energy costs of two interconnected systems, it is quite possible to use economically the interconnecting lines to transfer concurrently the most economical surplus energy from one system in substitution for the most costly fuel energy on the other system as long as the differences in cost are greater than the attendant transmission losses. The more recent transfers of power between TVA and neighboring systems have been of this character.

Capacity Exchanges

Reserve Capacity--One of the large problems of an isolated system is the provision of reserve capacity. At all times it is desirable to have at least enough spare capacity to take the place of the largest likely outage on the system. Two or more such systems by means of sufficient interconnections can share this task with smaller combined reserves than the sum of those necessary separately. This is due to the fact that the probability of simultaneous occurrence of large outages on both systems is considerably less, and this becomes increasingly true as the number of systems increases. With its many interconnections with other systems, TVA places great reliance on its interconnection reserves. With parallel operation of the many transmission ties and coordinated load control systems, a sudden failure on any one system is immediately met automatically by power flow from other systems.

Diversity--There are other diversities which can contribute to the economical operation of interconnected systems. One such system may have an afternoon or evening peak load, while the other may have a morning system demand. If this is true, there can be a daily exchange of capacity in which the total capacity necessary on both systems is less than that otherwise used when operating individually. In a similar manner, one system may have its greatest demand in one season of the year and another system in a different season. By combining their systems to meet these differing requirements, less capacity is needed on each system by drawing on the other during its critical period.

One of the large economies that attends these combined operations of systems through interconnections is the saving in fixed costs made possible by the reductions in production capacity that otherwise would be required under isolated operation.

CONCLUSIONS

Many opportunities for operating economy are available to power systems composed of hydro plants (with storage), steam plants, and interconnections with other systems. The means for obtaining some of these economies are fairly straightforward determinations. Others are so complex and individualistic as to challenge the combined efforts of the system operating group.

REFERENCES

1. Economic Complementary Operation of Hydro Storage and Steam Power in the Integrated TVA System, R. N. Brudenell and J. H. Gilbreath, AIEE Transactions, 1959, vol. 78, pt. III-A, pp. 136-156.

2. Utilization of Long Term Storage in Combined Hydro and Thermal Power System, S. Stage, Y. Larsson, World Power Conference, June, 1960, IIB/3.

3. Economic Operation of Variable-Head Hydroelectric Plants, A. F. Glimn, L. K, Kirchmayer, AIEE Transactions, 1958, vol. 77, pt. III, pp. 1070-1078.

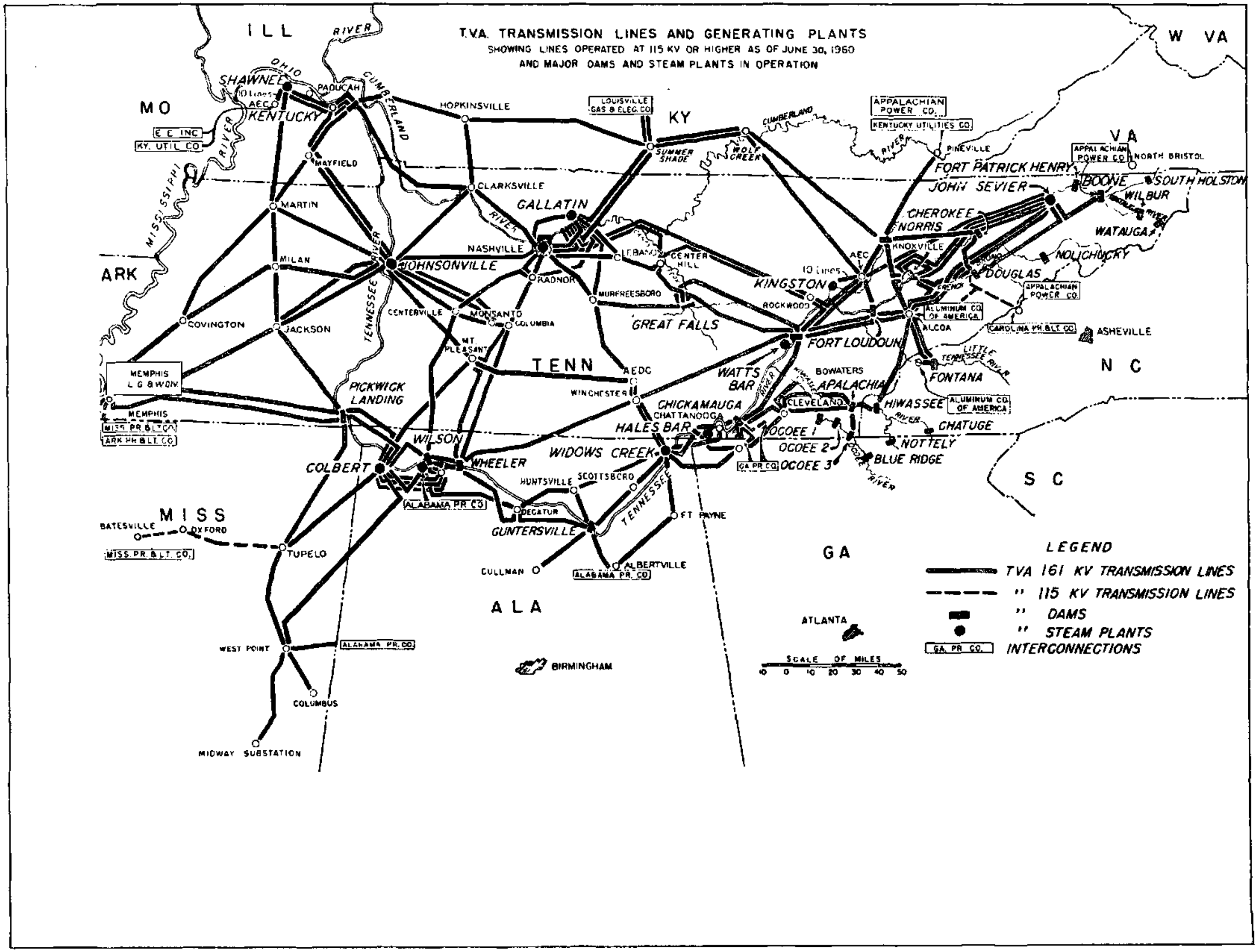

Fig. 1. TVA transmission lines and generating plants

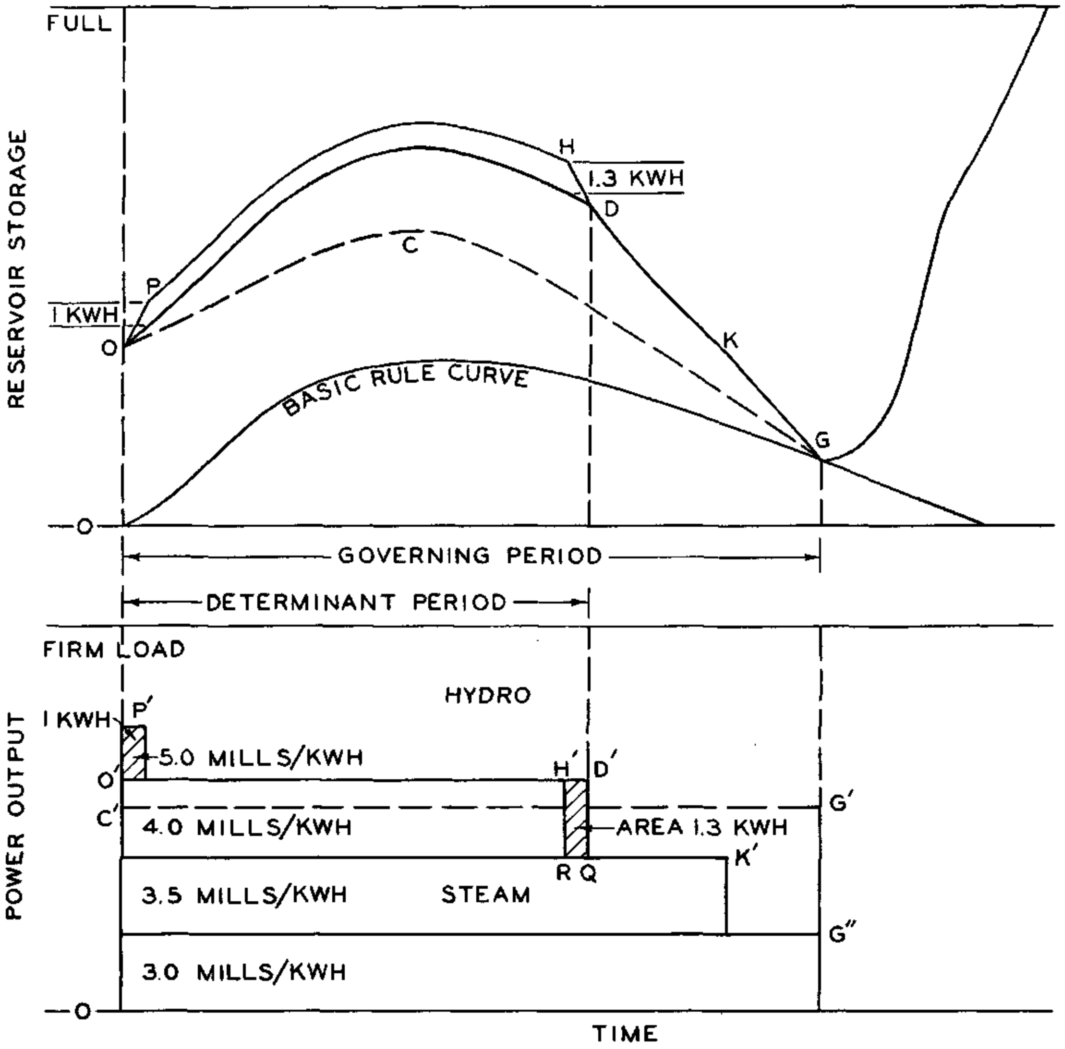

Fig. 2. Ideal operation and value of storage

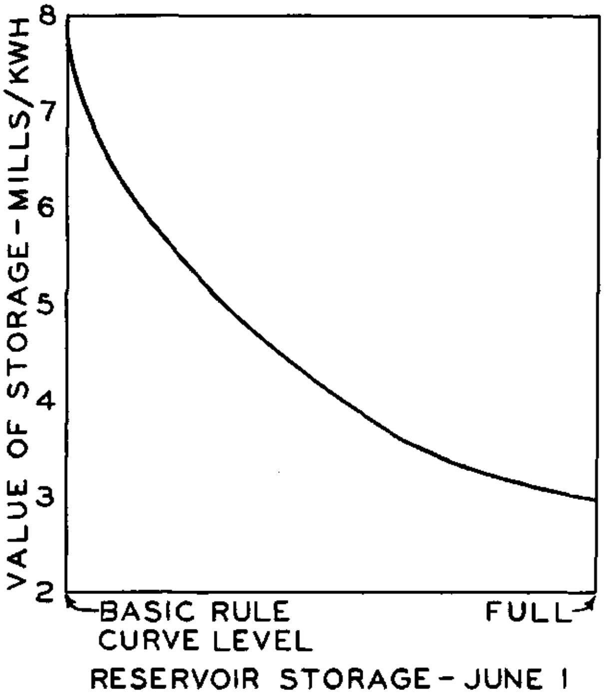

Fig. 3. Relationship of value of storage to reservoir content on a given date

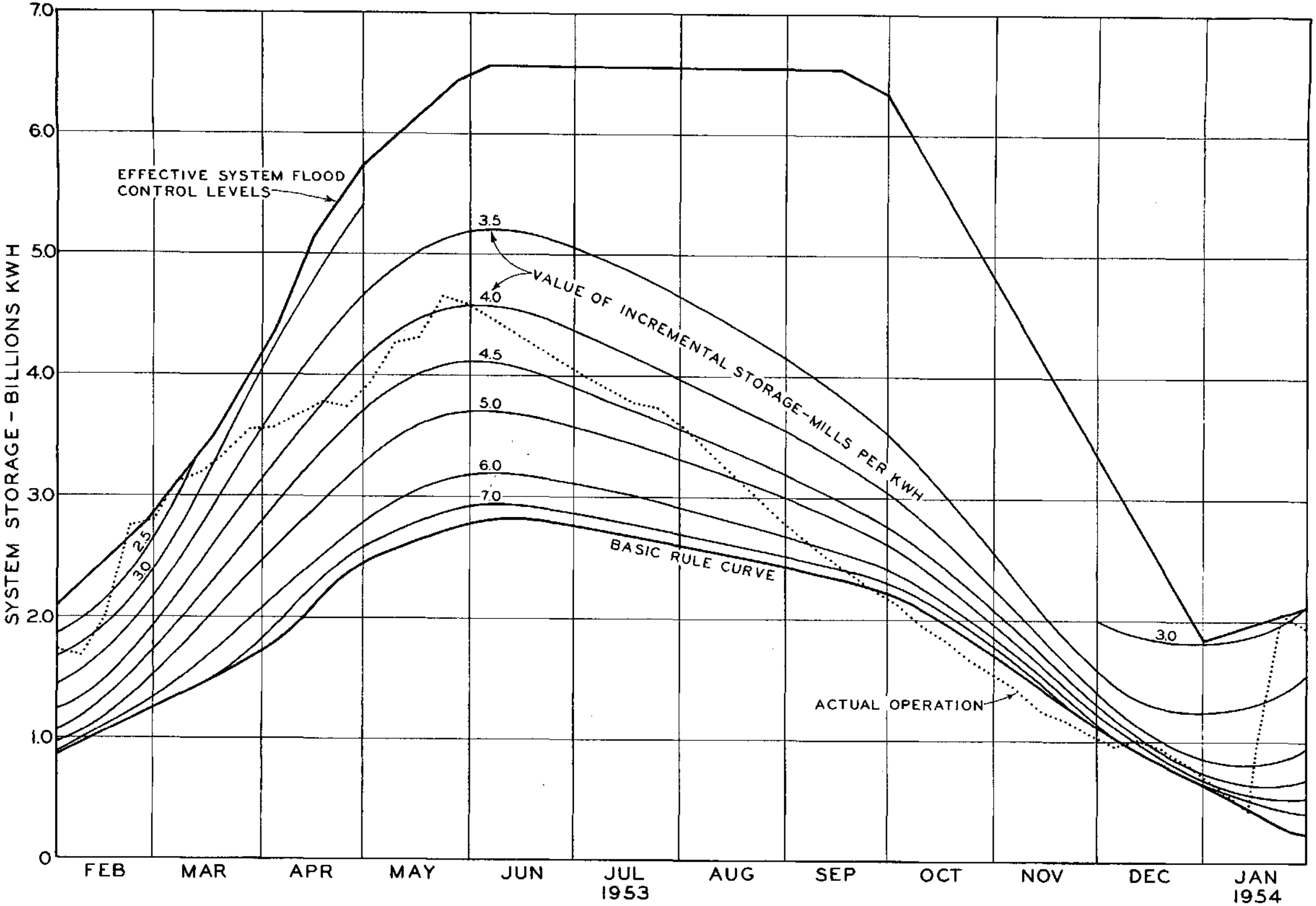

Fig. 4. TVA economy guide curves

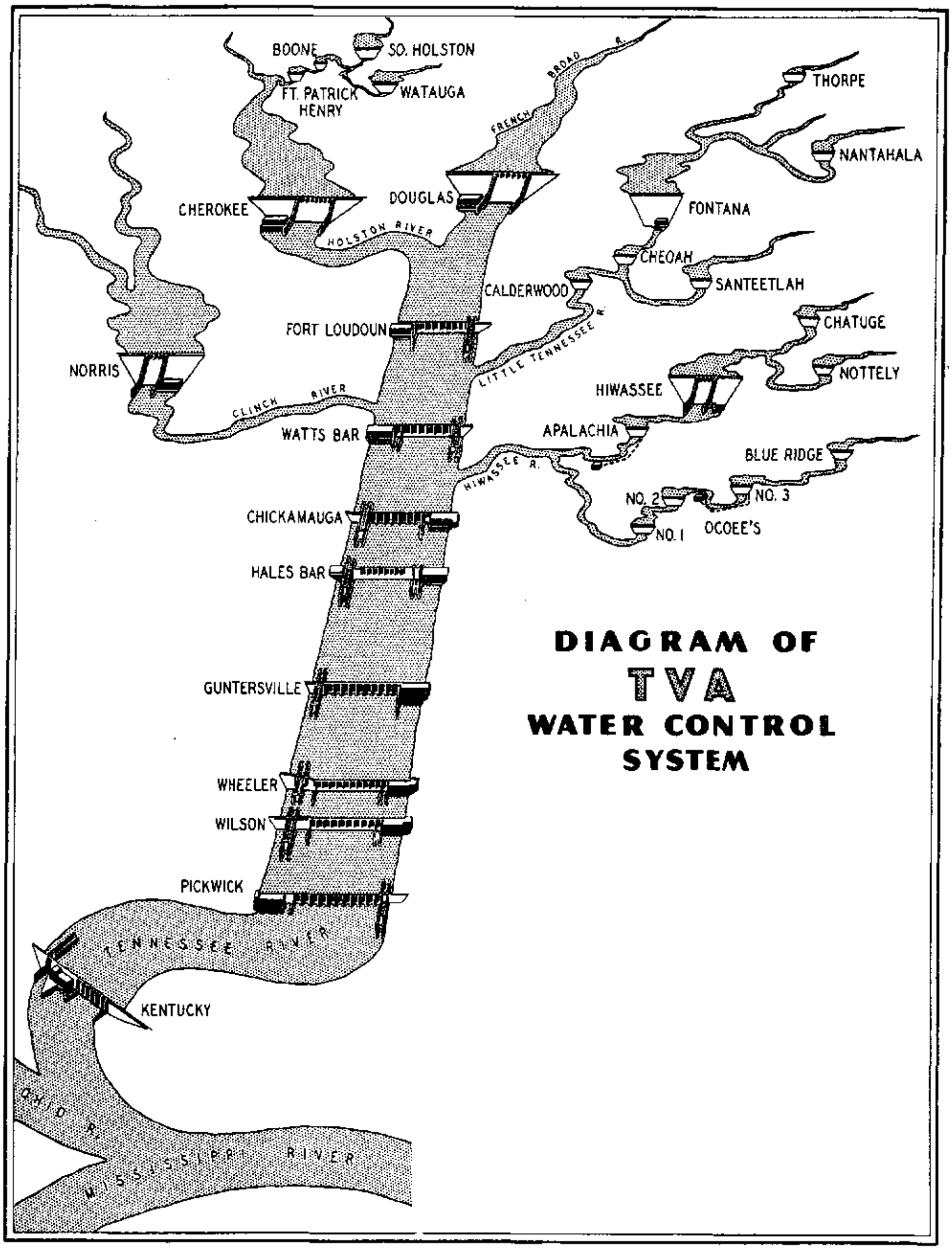

Fig. 5. Diagram of TVA water control system

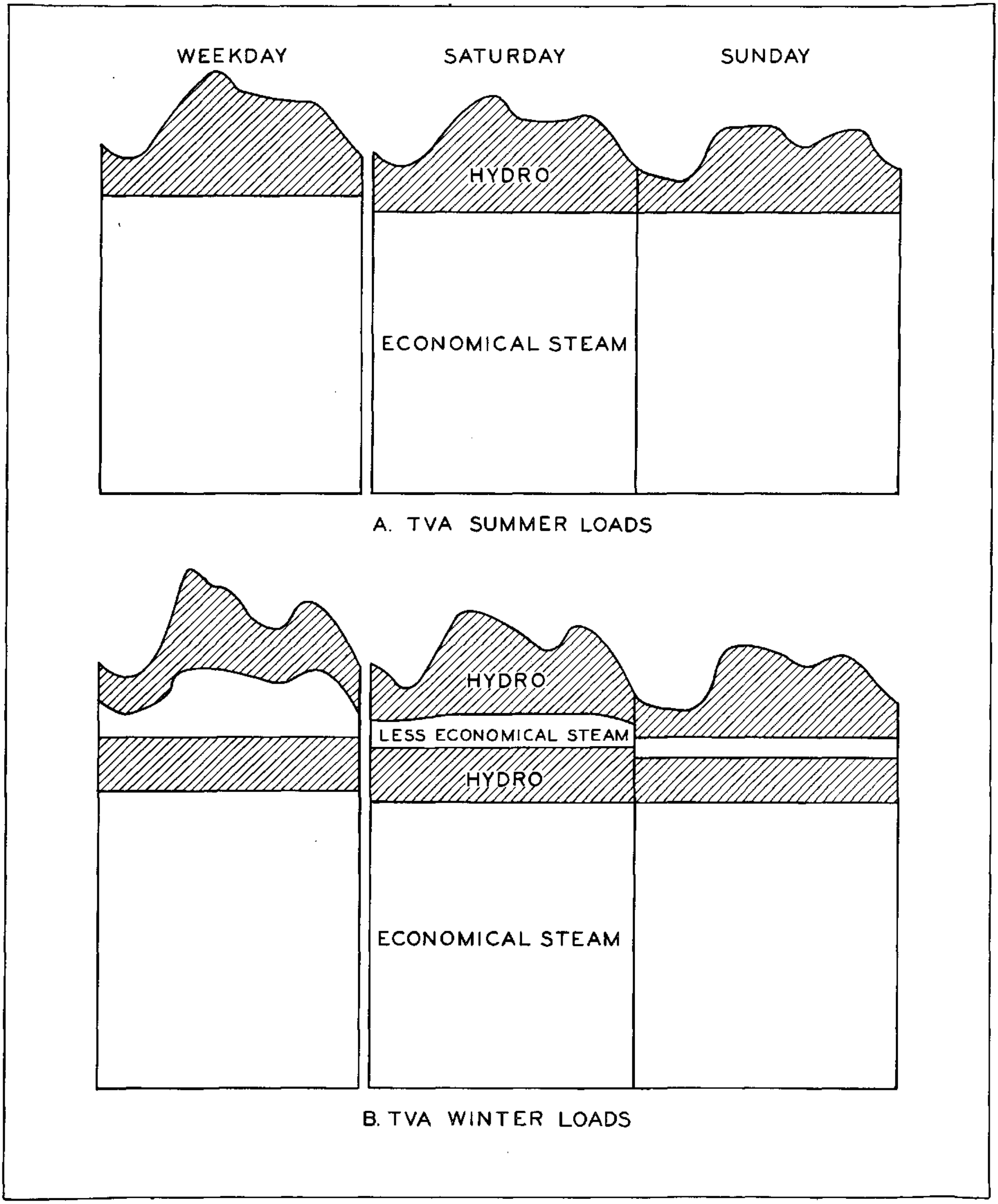

Fig. 6. Complementary use of hydro and steam capacity