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ECONOMIC ASPECTS OF COMBINING THERMAL AND
HYDROELECTRIC PLANTS

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NOTE: This text is subject to editorial revision.

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The purpose of this report is to analyse the combined operation of hydro and thermal power plants and to stress the substantial benefits deriving from such a combination, the scope of which will naturally depend upon the physical and economic characteristics of the particular country, or section thereof, concerned.

This study should make it possible to determine the best size for the hydro plants and to estimate their income potential so that the plants may be listed, in logical order, in an electric power production development plan.

1. Operation of interconnected plants

An area cannot be supplied with hydro power alone unless enough water is stored every year to ensure uninterrupted service at all times. If dam sites are scarce, if construction costs are high or, again, if silting up is expected to occur too rapidly, the utilizable feed flow of the plant may have to be sharply reduced and, in some cases, little more than the low-water flow can be used. This constitutes inadequate use of natural sites, particularly if there is no prospect whatsoever of expansion. In such cases, the grounds on which large dam projects have been opposed in the past remain valid.

On the other hand, if the hydro power plant is combined with thermal power, the former will be able to give a much greater output. The output thus installed is still considered to be the specified output.

We proposed to analyse the combined operation of hydro and thermal power plant, taking first the simpler case of a single hydro plant connected to a network also supplied by thermal plants.

P will indicate the heaviest demand of customers of the interconnected network at a given period. P_H and P_T will indicate the maximum output of the hydro and thermal plants, determined at the points where the power is actually consumed, i.e. after deducting losses sustained in transport; installed output at power production sites is shown as P_{iH} and P_{iT} .

The hydro plant cannot itself provide year-round service to a network the daily peak load of which is P_H because the volume of water available is governed by the irregular flow of the river, compensated to some

/extent by

extent by the annual or inter-annual reserve.

In spite of this factor, thanks to interconnection the P_H output is still a specified output within a very wide range, thus allowing for broad discretion in the choice of the output to be installed, which could be much greater than the minimum flow discharge compensated by the reserves.

If P_{iH} is installed capacity corresponding to the minimum head, taking into account variations in the upstream and storage levels, and P_H is the power at the terminal point of the transmission lines, related to this definition of P_{iH} , the sum of P_H and P_T may be absolutely equal to P , no additional power being needed at any time except for the reserve power that has to be available while the machinery is being repaired or when an emergency arises.

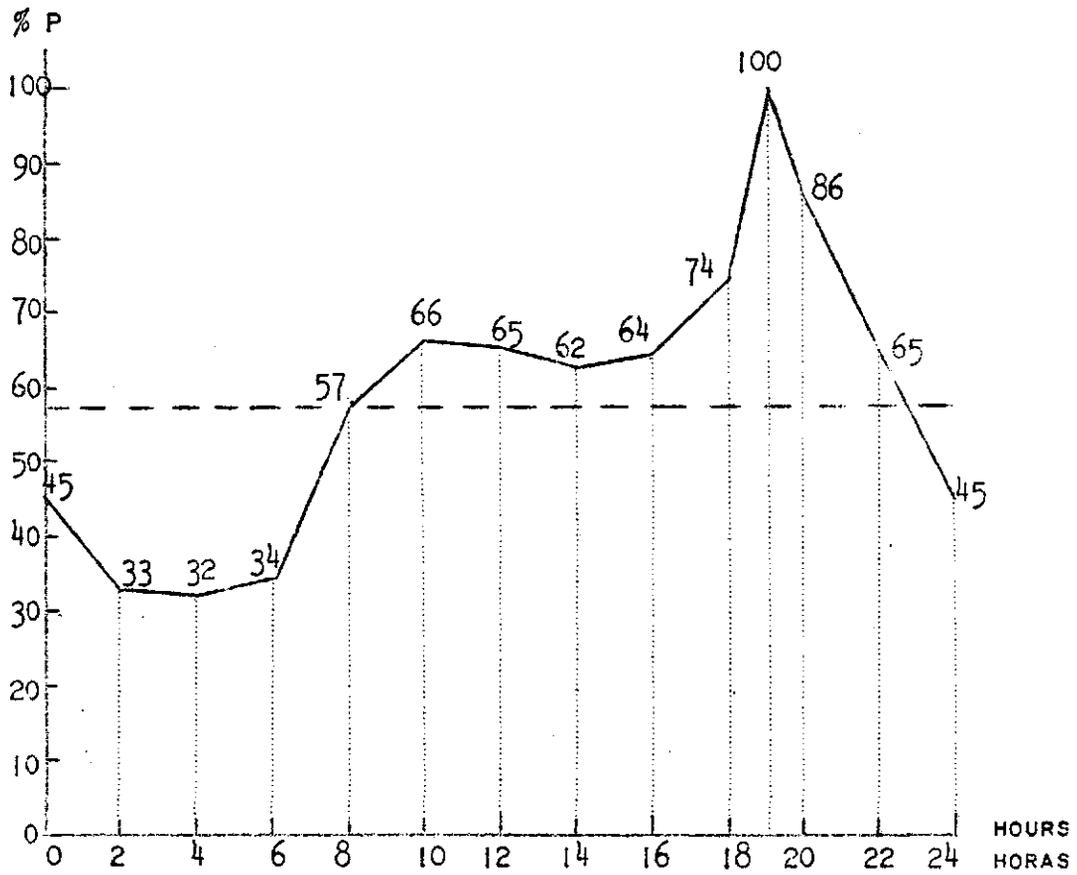
The daily load curve may, for instance, be represented by figure I, corresponding to an annual peak load utilization of 5,000 hours. Any other type of curve may be considered in the same way without affecting the general conclusions reached in the present study.

All the interconnected plants operate at full capacity during peak load periods. The demand for power is reduced at other hours and the output of either the hydro or the thermal plants, or both, may be curtailed. During periods of water shortage the hydro plant will only supply power at peak load periods, i.e. the installed capacity will not be used except for a few hours a day. As the volume of river water increases, hydro power will be used during more hours so as to be geared to the hydraulic potential; conversely, the output of the thermal plants will be curtailed as far as conditions will allow, thus saving fuel. Thus, the hydro plant might be the base of the load diagram and the thermal plants its apex.

This mechanism is shown, for purposes of illustration, by the designs in figure II drawn on the assumption that thermal and hydro installed capacities are equal. The designs give the breakdown of power use (a) during dry periods, (c) when water is plentiful and (b) during an average period. The transition from (a) to (c) may be affected constantly by proceeding through all the various stages. The shaded area proportional to the daily consumption of water or fuel, as the case may be. As a

/simplification, it

FIGURE 1
GRAFICO 1



DAILY LOAD CURVE
CURVA DE CARGA DIARIA

simplification, it has been assumed that the peak load of the network remains constant throughout the year.

Thus, water consumption may vary substantially from one day to the next or from one season to another and may be adapted easily to the flow of the rivers, with the hydro power P_H available for a sufficient number of hours to be considered a specified output within a very wide range.

In order to set out this simple mechanism in more specific terms, Diagram III shows three curves based on the load curve.

E_H , E_T and E will be the daily amount of energy supplied, within the network under study, by the hydro plant, the thermal plants and a combination of the two respectively.

Curve $Y_1(x)$ represents the relationship between the shaded area of the design at the top of figure II (a) and that of the daily total E when $\frac{P_H}{P} = x$ varies from 0 to 1. This curve thus represents, in terms of total energy, the fraction of hydro energy at the apex régime.

Curve $Y_2(x)$ represents the relationship between the shaded area of the design at the top of figure II (c) and that of the daily total E when $\frac{P_H}{P} = x$ varies from 0 to 1. This curve thus represents, in terms of total power, the fraction of hydro power at the base régime.

The amounts of thermal energy would thus be respectively:

$E_{y2}(1-x)$ when the hydro plant operates at peak.

$E_{y1}(1-x)$ when the hydro plant operates at base.

It can thus be easily seen that:

$$y_1(x) + y_2(1-x) = 1 \quad \text{and that}$$

$$y_2(x) + y_1(1-x) = 1$$

The dotted curve $\frac{y_2}{y_1}$ thus represents the relationship of water consumption between the base and peak régimes.

Therefore, subject to the hydro energy being combined with a suitable thermal energy, any hydro energy, however irregular the flow of the river, is a specified output since in theory the relationship between the two

extremes of water consumption may be made to vary at will between one and the infinite.

In practice, without developing this argument further, the diagram shows that if the combined thermal and hydro outputs are equal, the relationship between the two extremes of water consumption is established at the value of 3.55. The plant can thus be equipped to produce much more power than if it depended upon hydro power alone.

It is also clear that such co-ordination is valuable in the case of a plant at the foot of a dam regulated annually since the water that can thus be saved during dry periods can substantially reduce the level of water used and thus increase the specified output of the plant.

The plant operator, therefore, need not estimate the rate of flow well in advance because he can change his method of operation from one day to the next and virtually eliminate the risk of having to interrupt the power supply. The output of the hydro plant can thus be calculated on the basis of the yearly average. There is simply an annual variation in the fuel consumption of the thermal plants, only the average value being defined.

2. Method of determining the most desirable features of a hydro system operating in conjunction with a thermal plant

Figure III provides the basic data contributing to the speedy solution of an essential problem - that of determining the height of the dam and the output of the plant by giving the normal flow of a section of the river the harnessing of which the prospective operator considers economically feasible.

(a) First case

Let us first take the simplest case - that of a single hydro system in which the head is higher than the dam and may therefore be considered constant.

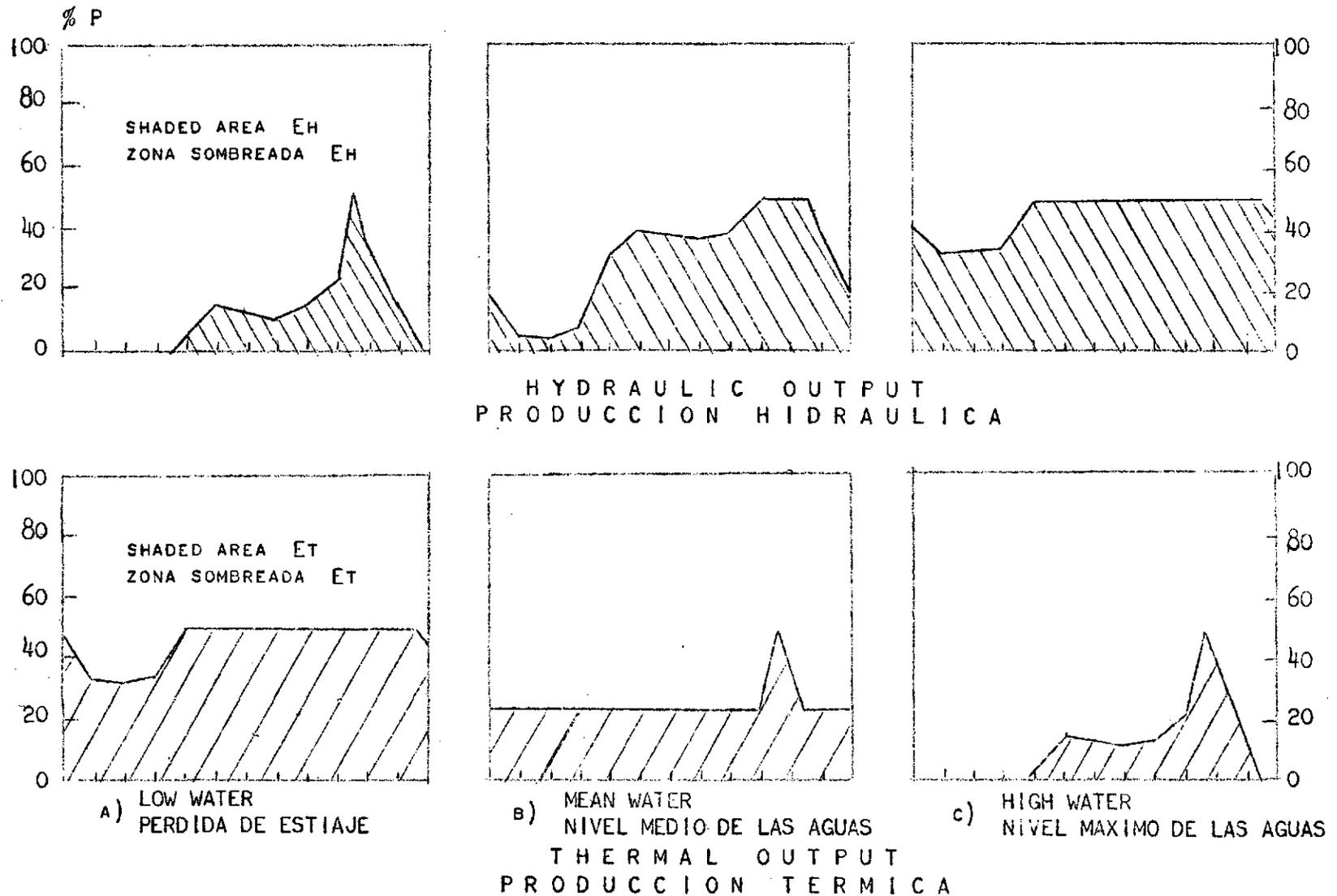
It will further be assumed that the height of the dam will at all times be adequate to accumulate a daily water reserve so that the discharge may be limited to a fraction of the day.

Several variations of the project will be considered and compared.

/We propose

FIGURE II
GRAFICO II

DISTRIBUTION OF HYDRAULIC AND THERMAL OUTPUT CALCULATED ON THE BASIS OF $P_H = P_T$
DISTRIBUCION DE LAS PRODUCCIONES ENTRE HIDRAULICA Y TERMICA CALCULADA EN EL CASO EN QUE $P_H = P_T$



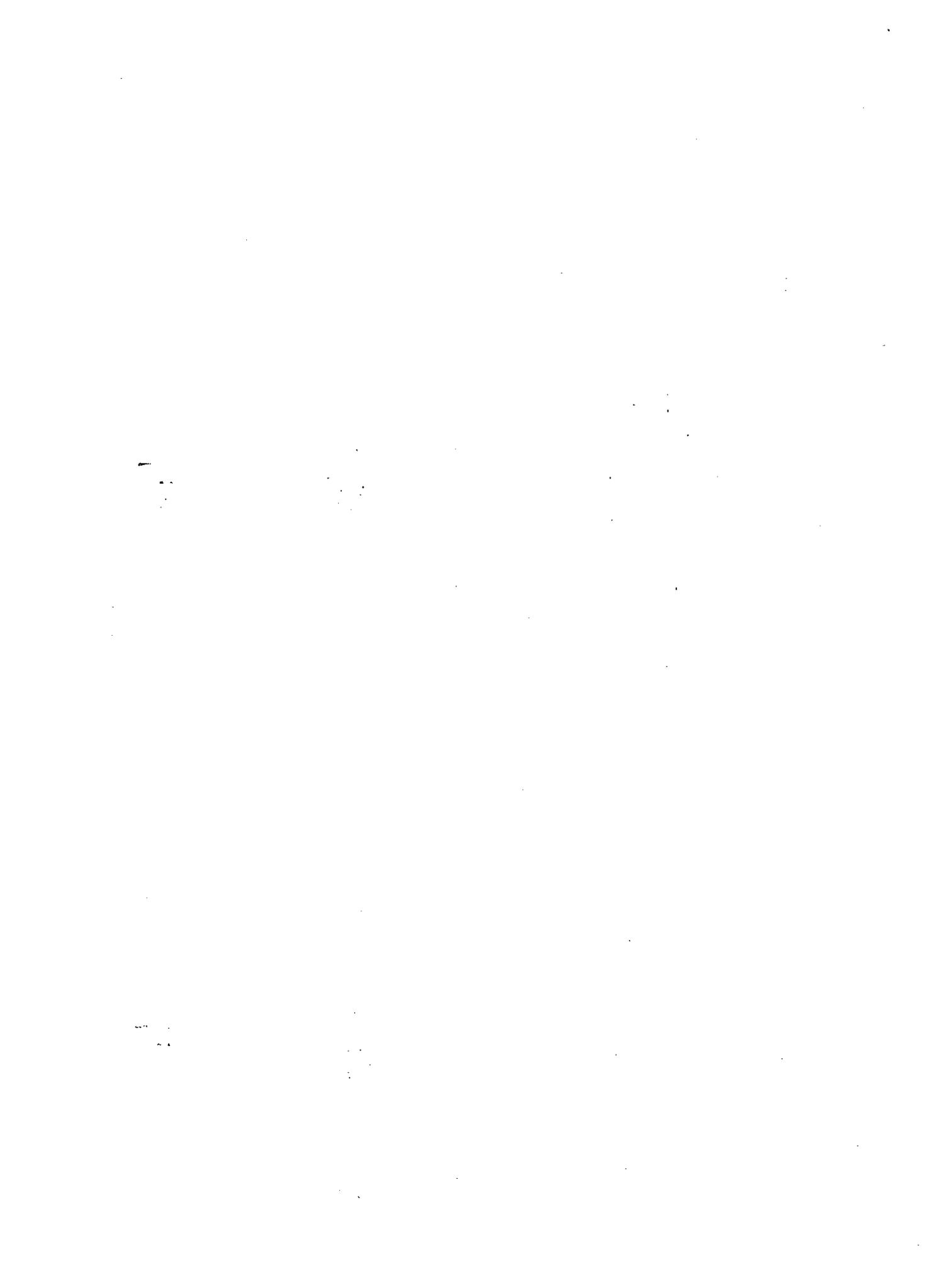


FIGURE III ST/ECLA/CONF.7/L.2.6
 GRAFICO III

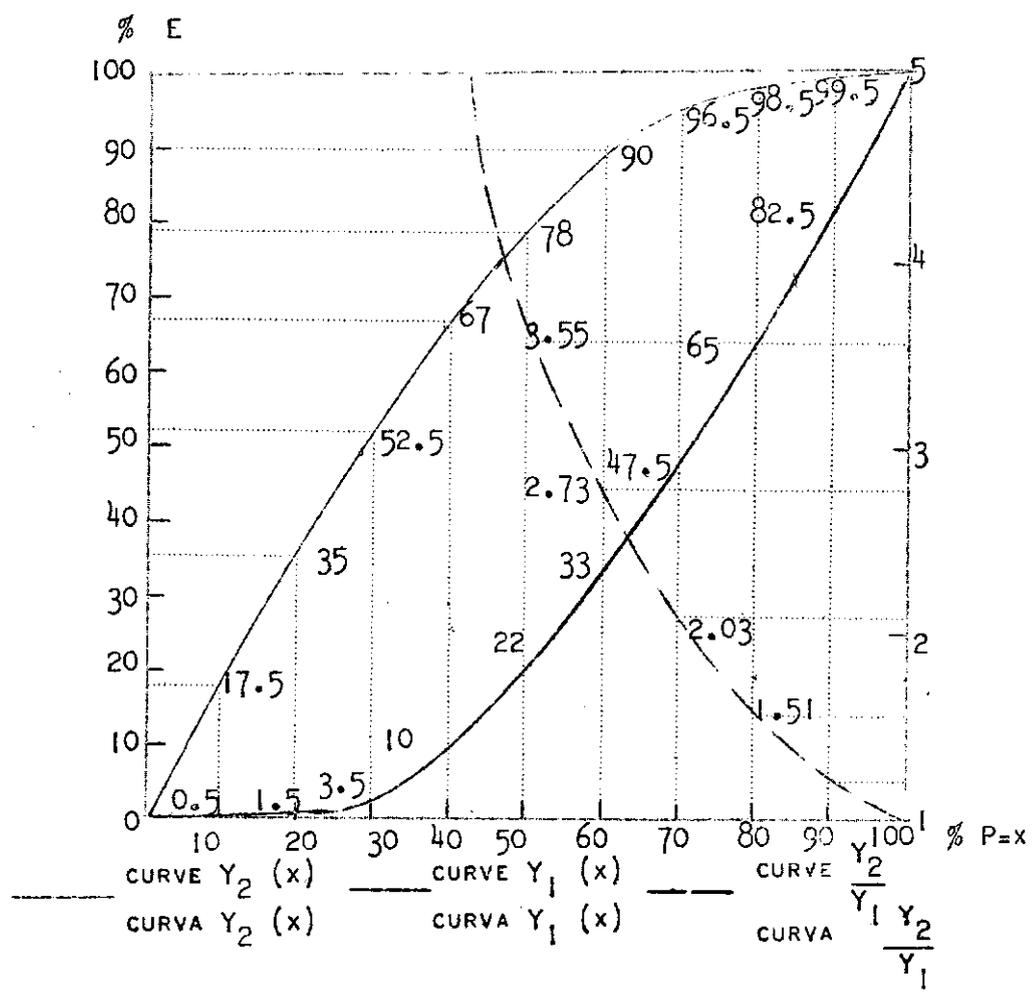
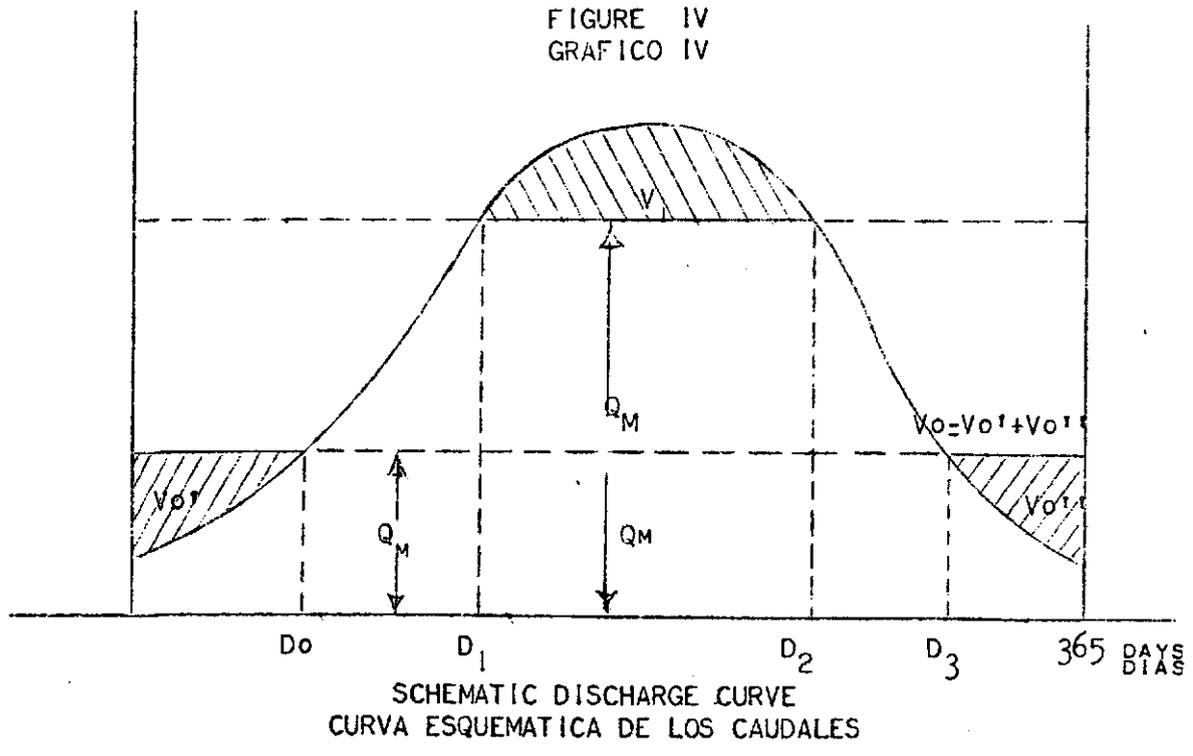


FIGURE IV
 GRAFICO IV



We propose to show that they depend upon not more than two parameters.

(a) the daily average discharge - Q_m - which may be ensured during the minimum flow period by natural discharge supplemented by water drawn from the reservoir. By means of simple hydraulic study, based on the lowest flow known or expected, Q_m can be calculated in terms of the capacity of the dam. The parameter Q_m is thus directly related to the height of the dam.

(b) The relationship $\frac{P_H}{P} = x$, proportion of the hydro output of the entire system under consideration, or $\frac{P_T}{P_H} = \frac{1-x}{x}$, proportion of the thermal output combined with the hydro output.

The maximum specified output of the hydro plant is determined for each value of these two parameters.

Thus, let Q be the utilizable discharge corresponding to this maximum specified output. It must adequately meet the requirement that the plant should have enough water to ensure peak load by the network during low water periods.

The relationships are $\frac{P_H}{P} = x$ $\frac{E_H}{E} = y_1(x)$

$$E = 24P \frac{5000}{8760} = \frac{24P}{1.75}$$

$$\text{thus } E_H = \frac{24}{1.75} P_H \frac{y_1(x)}{x}$$

But the P_H power is proportional to the utilizable discharge

$$P_H = KQ$$

And E_H is equal to the energy produced during 24 hours of the day if the average daily discharge Q_m is used

$$E_H = 24 KQ_m$$

Therefore:

$$\frac{Q}{Q_m} = 1.75 \frac{x}{y_1(x)}$$

It is thus obvious that for each Q_m value the utilizable discharge - Q - depends only on $\frac{P_H}{P}$

/For $\frac{P_H}{P}$

For $\frac{P_H}{P} =$	50%	60%	70%	80%	90%	100%
$\frac{Q}{Q_M} =$	4.00	3.18	2.58	2.15	1.91	1.75

Thus, when the related thermal power varies from 0 to 100 per cent of P_H , the calculated utilizable discharge varies from 1.75 Q_M to 4 Q_M . The lowest figure - 1.75 Q_M - corresponds to the daily network operation of a purely hydraulic system.

Next to be determined is the utilizable discharge below which water will be lost in high water periods. By studying the annual discharge curve, the value of the Q_M daily maximum average discharge capacity of the turbines can be calculated, the natural discharge above that figure being used to replenish the reserves.

For instance, in the case of a river which has both a dry and a wet season, the operation can take place as indicated in figure IV in which the horizontal line Q_M is drawn so that $V_1 = V_0$.^{1/}

During the period D_1 to D_2 in figure IV, the hydro plant will operate as the basis of the diagram.

The daily hydro output is then:

$$E_H = E_{y2} (x)$$

The same calculation shows that:

$$\frac{Q}{Q_M} = 1.75 \frac{x}{y2}$$

For:

$\frac{P_H}{P} =$	50%	60%	70%	80%	90%	100%
$\frac{Q}{Q_M} =$	1.12	1.16	1.27	1.42	1.58	1.75
$\frac{Q_M}{Q_M} = \frac{y2}{y1}$	is the dotted curve in figure III.					

^{1/} Figure IV does not perhaps accurately show the maximum value sought for Q_M because the shaded area V_1 may, strictly speaking, be less than V_0 as part of the replenishing can be done during the intermediary periods D_0 to D_1 and D_2 to D_3 where the rate of operation of the plant is indefinite and may be regulated below the natural flow. However, the method advocated gives a suitable approximate value for Q_M .

/In fact,

In fact, the logical way in which to find the best solution is as follows:

(a) The curve representing the natural flow of the section of the river will be traced on the basis of studies at the site of the setting. The selected curve will not be that of an actual year nor will it be an average curve. It will be a fictitious curve that takes into consideration, for the dry season, the minimum flow on which calculations can be made on a high probability basis (say, 90 per cent) so as to ensure the minimum flow discharge. (Should there be an even drier season, some or all of the thermal groups kept in reserve for maintenance purposes will be used, and this simply means that maintenance work would not take place during dry periods). For the wet period, the curve drawn will relate to a year in which hydro output was high, in order to reduce losses of water as much as possible.

(b) Three or four possible dam heights will be considered initially. Once their capacity has been determined, the specified daily minimum discharge - Q_m - can be calculated for each case. Q_M will be determined (on the basis of $V_1 = V_0$ if the discharge curve follows the curve in figure IV).

(c) The $\frac{Q_M}{Q_m} = \frac{y_2}{y_1}$ relationship will, if read directly on Diagram III, give the $\frac{P_H}{P}$ value corresponding to the fully specified output without losses of water during the wet season. The value y_1 and y_2 will also be read. This will also give the utilizable discharge corresponding to the solution, i.e. for a given value of the dam height:

$$Q = 1.75 Q_m \frac{x}{y_1}$$

If, for instance, $\frac{Q_M}{Q_m} = 2.73$, then $\frac{P_H}{P} = 60\%$; in other words $\frac{40}{60} = 66\%$ of thermal power and $Q = 3.18 Q_m$ will have to be added to the hydro output.

(d) Since total output without loss of water may not be the most economic solution, tests will be made with smaller utilizable discharges corresponding to lower percentages of thermal power.

/The following

The following tests will be made in the preceding example:

$$\frac{P_H}{P} = \begin{matrix} 70\% & 80\% & 90\% \end{matrix}$$

$$\frac{Q}{Q_m} = \begin{matrix} 2.58 & 2.15 & 1.91 \end{matrix}$$

These variations provide for water losses during the wet season.

(e) An increase in the output of the plant beyond the limits indicated may be considered desirable but then the excess power is no longer guaranteed and as will be seen later, the corresponding output is only involved in estimating fuel savings. Tests might also be carried out along these lines. This sort of situation might very well arise if an increase in the plant's output requires relatively little civil engineering work (plant at the foot of the dam or short tunnel).

(f) These different variations will be calculated, bearing in mind that consideration will be given to the potential yield of each of them on the basis of the principles laid down below.

The number of variations should not discourage the economist since prices can be shown on diagrams obtained with the help of a limited number of values of the two parameters and on which it will be easy to work by interpolation.

To facilitate a comparative study the price of the works should be divided into categories, investments being classified separately on the basis of their probable duration, i.e. in three groups:

- Purchase of land, restoration of communications, etc.,
- Civil engineering work,
- Metals, mechanical and electrical equipment.

(g) Whether or not the thermal output needed by the combination is already part of the network will also have to be considered for each variation studied. If not, the cost of building the missing thermal units will have to be included in the estimates of potential yield.

(h) It will be noted that the specified output produced by the harnessing of a section of the river is not a fixed figure. Each variation supplies the network with a new output which differs from one variation to another.

/The time

The time required to absorb the new output will be studied for each variation on the curve representing the future expansion of consumption by the network under consideration.

The interest that will have to be paid while the dam is under construction, plus the additional interest in proportion to the plant's non-absorbed output until the full output is utilized, must be added to the investment.

If the plant's full capacity cannot be used for a long time, the possibility of building the dam by successive stages should be considered.

(i) The advantage of the method advocated is that it is based on rational and orderly research; it will ensure that the river section under consideration will be developed in the best national interest and on the basis of the simplest calculations.

No attempt has been made in this study to discuss the most rational method of segmenting the waterway since each particular case will have to be examined separately. A warning should nevertheless be issued against undue selectivity in choosing the sites by harnessing only the steepest segments since this would impede full harnessing of the waterway at some future stage.

However, as noted earlier, the work can be done by stages on the basis of rates of discharge below the final rate; this would not be unduly selective in so far as the final rate is clearly established and the preliminary work is so planned as to allow for expansion without having to interrupt operations.

(b) Second case

The head remains virtually constant (high-head) but several hydro plants are linked to the network.

Two possible situations might arise:

(a) The developed rivers have the same régime; the high and low water mark for each river occurs virtually at the same time, as happens very often in tropical climates.

Each project may be studied separately by the method previously advocated and the results need merely be added. Each involves an optimum related thermal power.

/It will

It will be necessary to check whether the various thermal units to be related to the hydro power are already part of the network. If not, additional sources of thermal power will have to be provided and this must be taken into consideration in calculating yields. Obviously the order in which the various hydro plants will be built affects the yield of each plant. Those built first should be linked to existing thermal units, with the new thermal units being linked to the hydro plants built later.

(b) The régimes are different and compensations can be effected from one season to another. In this case, the method outlined above will not be the best from the economic point of view since the total obtained for the thermal units linked to the network will be too high.

We nevertheless propose to calculate these thermal units in the same way in order to get a rough idea and then to attempt to reduce the cost by combining operations with hydro plants functioning under different régimes. However, no general rule can be applied for this purpose.

(c) Third case

The height of the head is variable. This applies to plants at the foot of dams. The tests will be carried out according to the procedure previously mentioned but a third parameter, which will be the maximum variation of the reservoir's water level, must be added to the two parameters Q_m and $\frac{P_H}{P}$.

For a specified dam height, the minimum water level taken as a third parameter will make it possible to calculate V_0 (desirable volume) and Q_m . The difference between this level and the water level downstream corresponding to the operation of the units at full capacity will indicate the height of the head related to the specified output P_{1H} , the calculations being effected as in the first case.^{2/}

2/ If the water is at the flood level - full reservoir - the downstream level is at a height h above the level at which all the units operate at full capacity. In estimating variations of the level of the lake it is therefore unnecessary to consider variations below h since the specified head height would then appear during periods of run-off - full reservoir - and not when the reservoir is empty.

In estimating earnings this case differs somewhat from that of a high head in that the hydro power is higher than P_{iH} when the level of the lake is above the minimum and some of the thermal units can be shut off. The maintenance reserve can thus be reduced.

Lastly, the question of additional régimes will arise particularly for proposed irrigation dams, the role of which is to conserve water during the wet season in order to make it available in dry periods. Operation rules which would apply both to electric power production and to irrigation must be carefully studied beforehand as they are very delicate but essential to the preparation of a rational plan.

The revenue from the operation of the plant is often necessary to ensure a yield from irrigation. However, the plant at the foot of the dam will have to play a useful part in supplying the specified output. Small daily losses of water will thus have to be provided for during the replenishing period in order to ensure peak service. The amount must be calculated by comparing the value of the specified output with that of the land which cannot be irrigated because of these losses of water.

The combination of a purely hydro dam and a multi-purpose dam may reduce these losses of water in view of the phenomenon mentioned above, since the former may during certain periods exceed the minimum specified daily output.

3. Method of estimating the economic merits of the variations under consideration

We do not propose, in this study, to explain the method which would give the different variations value co-efficients by which they could be compared. We shall merely indicate the principle of the method.

It has been shown that each variation, in order to ensure the supply to a network the peak load of which is P , includes a combination of hydro power - P_H - and related thermal power - P_T .

In order to compare these variations with one another, we shall compare them to a system of reference consisting only of a thermal power capacity of value P .

/Since the

Since the type of investment differs, as do the term of the investment and the consumption it represents, the best method is to project the expenses to the infinite, i.e. to estimate in each case the hypothetical or total capital required at a given date - i.e. the day service starts, for the following purpose:

- (a) to build the works;
- (b) to operate, maintain and renew them indefinitely by means of the interest on the funds still available.

The difference between the total capital of one variation and the total capital of the system of reference will provide the extent to which the construction of the hydro plant will contribute to the national economy.

The variation with the highest yield from the network's additional power will be selected.

In order to evaluate the total capital of the system of reference and that of the variation under consideration, the investment made in the reserve units will have to be taken into consideration in both cases. If the number of reserve units in a system is high, the reserve power may be represented by a percentage. If it is low, the reserve power will be indicated in the form of one or more actual additional units. Since the cost of these units will have to be supported by the variation under consideration, the first few installations of a network will naturally be adversely affected and their yield may thus be slightly lower. However, another procedure may be adopted by providing the proposed project with a percentage reserve below the individual power capacity of the units, the difference being carried over to the subsequent projects together with the interest that has to be met during the interim period.

One final point should be mentioned in connexion with the minimum technical or economic level of operation of the thermal plants.

During the periods when the thermal plants must operate at capacity according to the design at the bottom of figure II (c), they cannot always be shut off completely during non-peak periods. While this does not apply to gas turbines, it would be the case for steam turbines. If ,

/on the

on the other hand, the plant operates on natural gas, the gas supply contract will always include a consumption minimum ensuring a yield on the gas supply system. In either case, therefore, there will be a fuel consumption or a payment on non-consumed fuel that must be taken into account.

While this does not apply to a purely thermal system of reference, it will have to be included in an estimate of the cost of the variations, i.e. by capitalization in determining the total capital.

We propose to base our calculations on what we consider to be a very difficult case - that of thermal plants operating on natural gas, with a minimum consumption equal to 250 hours of peak operation per month.

The monthly quantity of thermal power that can be produced at this specific minimum is $250 P_T$.

For a specific value of $P_H = x$ the monthly quantity of thermal power calculated in theory for peak operation is:

$$30 E_T = 30 E_{y_1} (1-x)$$

$y_1 (1-x)$ being the ordinate of curve y_1 in figure III corresponding to the absciss $1-x$.

If lm_3 of gas produces 3.5 kWh and p is the marginal price of a cubic metre of gas, the monthly value of gas paid for but not consumed is thus:

$$(250P_T - 30E_T) \frac{p}{3.5}$$

with

$$P_T = P(1-x)$$

$$E = \frac{24P}{1.75}$$

thus:

$$P \left[250 (1-x) - 411y_1 (1-x) \right] \frac{p}{3.5}$$

Which gives the following table:

x	=	40%	50%	60%	70%	80%	90%
$y_1 (1-x)$	=	0.33	0.22	0.10	0.035	0.015	0.005
<u>Value of gas</u> Pp	=	4.0	10.0	17.0	17.4	12.5	6.6

/If it

If it is assumed that this system continues for four months every year, the total loss per kW of specific power will be for:

x	=	40%	50%	60%	70%	80%	90%
Annual value	=	16p	40p	68p	69.6p	50p	26.4p
Value capitalised at 6%	=	270p	670p	1130p	1160p	830p	440p

If, for instance, $p = 0.007$ dollars, the additional capital to be provided for each variation per kW of specific output:

for x	=	40%	50%	60%	70%	80%	90%
dollars/kW	=	1.9	4.7	7.9	8.1	5.8	3.1

In any case these figures represent only a small percentage of the total capital and do not affect the principle of the methods described. They nevertheless had to be taken into consideration and calculated.

Conclusion

This study, after having explained the desirability of and procedure for the combined operation of hydro and thermal plants, offers a rational method by which the harnessing of a specified watercourse can best be determined. By a few simple calculations it enables the section concerned to be included in an expanding network and ensures that the solution will contribute most to the economy of the country.