SMALL HYDRO

Some Practical Planning and Design Considerations

by

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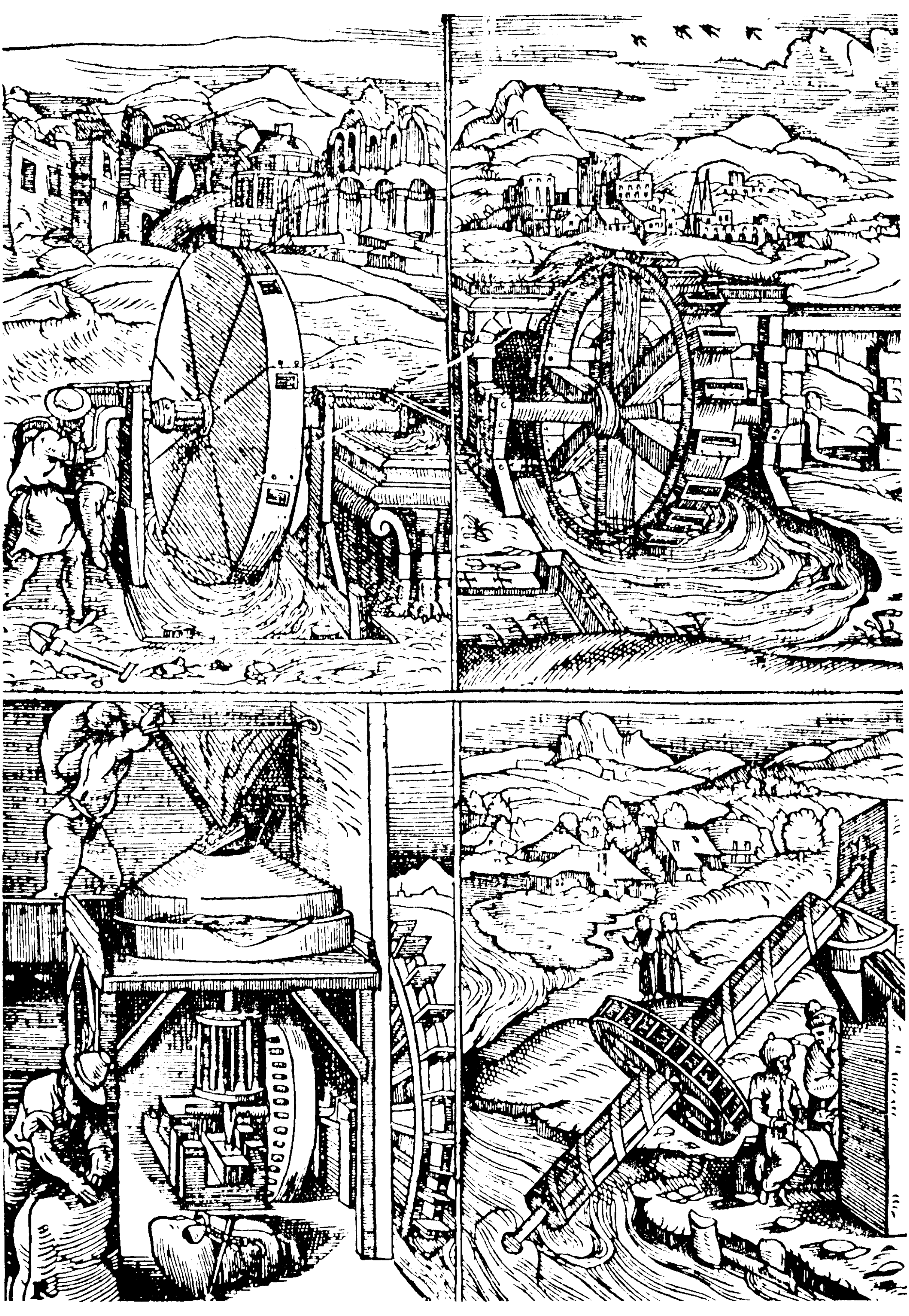

Waterwheels and Irrigation. Woodcut by Vitruv 1567

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I. INTRODUCTION

General Considerations

The electricity supply business throughout the world has, as most people are well aware, been undergoing some revolutionary changes in attitude. We have on the one hand the call for increased development of extremely large blocks of power capacity -- a tendency that I have, perhaps not too generously, entitled the "single fix" mentality. On the other extreme we have those who would ignore the large energy developments entirely in favor of what they see as the "alternatives" of conservation, solar, small hydro, etc.

Each group of advocates has its own set of "proof" to show they are correct in their assumptions. I believe the more rational approach, and the great challenge for the world today is to develop a balanced energy future, taking into account the most appropriate and reasoned use of all of its resources.

Hydro is one source of energy. It may not always be the source that needs to be developed first -- but then to arbitrarily cast it aside because it doesn't completely solve the problem is an incredibly naive view of this world's energy situation. The fact is that with the rapidly escalating costs of "fueled" energy, the economic opportunity for expanded development of the alternative sources using renewable resources is greatly increased.

In some areas of the world the importance of small hydro may not be quantitatively or yet economically advantageous to warrant its serious consideration at this time. But in many areas, even though the overall percentage of that guaranteed by small hydro may be small, its marginal value may be much greater. In some areas of the world hydro, particularly small hydro, offers a substantial and practical contribution to energy problems. Furthermore, because hydro systems are capital intensive relative to operational costs they tend to have built-in inflationary protection. Once built, the fuel -- river water -- is essentially free.

An important fact that must be remembered is that approximately 650 kwh production at a hydro plant almost anywhere will reduce the requirement for oil (or its fuel equivalent) by one barrel. If you are an oil-rich nation, that should be significant. If you have oil reserves it means they will last longer. Furthermore, although the rapidly rising cost of oil certainly reflects inflation to some extent, an important factor not to be overlooked is that oil is a limited non-renewable resource with a large demand. There is no way, in the long run, that the price can realistically be expected to do anything but increase.

Which brings me to the point that there is an alternative that must be considered by all nations -- that of being responsible for their own energy futures, or, on the other hand, of being forced to depend upon external powers .... possibly unreasonably. Each country must consider the total situation in deciding upon its course of action.

There is, of course, nothing wrong with using external energy sources or expertise as long as it is to your advantage. Yet countries should not become overly committed to importation or "rediscovery of the wheel" without looking at the long-run costs of so doing. Nevertheless, a nation should carefully consider those key resources that could cause social and economic disruptions should the supplying nation make an unfortunate decision concerning the supply. Energy resources certainly fit that description.

Energy Requirements -- How Much Is Needed?

Before seriously beginning on a major program to develop energy resources a nation or region should consider very carefully how much it will need -- and in particular -- when it will be needed.

To be studiously avoided is the concept that a simple increase in available energy will necessarily be closely followed by economic prosperity. While it is true that there have been many studies made that show a positive correlation between energy and economy, it does not follow automatically that a slow or deliberate growth in energy need necessarily be linked with a slow economic growth. Correlation does not mean necessary causation. One needs only to look at countries like Sweden or West Germany to see that they enjoy economic prosperity every bit as high as that of the United States -- but consume much less energy. Capital, labor and better technology can all be substituted for energy in providing equally high levels of development. The rising cost of oil is rapidly illuminating this point for many who once felt that "more energy" was the simple and necessary solution.

It is important, then, to determine where a nation wants to go, and based upon that decision to objectively determine where energy fits into the picture. It is every bit as important to be realistic in making goals for the future -- with full consideration being given to the limitations of demographic, economic and technologic forces that will be the ultimate factors in power demand. As Butcher (1978) makes the point, "Electricity consumption ought to be determined by a decision to use power in all applications and usage rates for which value gained or cost saved by the user is greater than the cost of supply. Underbuilding or overbuilding because of plans based on erroneous or biased forecasts should not be a factor."

How Much Hydro Potential Remains?

In the United States we began several years ago to talk about "low-head" hydro. We now realize that although in general we are talking about small dams, it is not necessarily low "head". For governmental grants and loans, we now generally consider developments of less than 15 Mw as "small hydro".

In Europe these projects are often called "mini-hydro", although manufacturers do not restrict themselves to any predetermined limits. Nevertheless, in general "mini" and "low-head" overlap by most definitions, except for one very glaring exception that occurs where we have high heads, but low capacities.

In order to include these high-head low-capacity plants, the term "small hydro" is more appropriate.

But all is not quite so simple. We have yet another category of small hydro -- the ultra-small that can range down to a few watts. Used quite frequently for individual homes or small groups of homes, or for villages in developing areas, these units generally provide relatively minute amounts of energy (although they can range up to the megawatts size). These have commonly been called "micro-hydro" units, although as with all the various names "micro-hydro" is sometimes used to designate the region more commonly known as "small".

Although there is no physical reason for restraints, this paper will be limited to heads less than about 30-40 meters, excluding the ultra-small "micro-hydro" installation. What is more important, however, is to realize that what is really being discussed is small power capacities.

Numerous surveys of various levels of detail have been undertaken in recent years to determine the hydro potential -- nationally and worldwide.

To begin with it must be realized that the hydroelectric potential essentially depends upon two factors: the characteristics of streamflow and the developable head. Whether or not a specific site could or would in fact be developed depends upon a number of other factors, including the economics of alternative energy sources. Viessman (1978) reports that current estimates place the practical limit in the U.S. at about 50 percent of the theoretical maximum due to technological, environmental and political contraints alone. He also notes that because of increased depletions by water uses such as irrigated agriculture the average annual streamflows in many streams are shrinking. In the Upper Missouri basin, for example, it is estimated that from 1975-2000 a 20 percent reduction in the average annual streamflow will occur. This aspect must certainly be considered in any hydro development plan. Nevertheless, the world's hydro potential is far from fully developed.

The increasing cost of alternative energy fuels will make hydroelectric projects more economically attractive. Many projects once considered to be infeasible have already or may soon become competitive. This is particularly true of small scale hydro plants.

On a worldwide basis, Armstrong (1978) reports that hydraulic energy provides about 23 percent of the total electrical generation, with the installed capacity now approximating 375,000 Mw. The 1976 World Energy Conference Survey (1978) of energy resources indicated that this is about 17 percent of the total estimated potential likely to be developed. That survey found also that the total potential considered likely to be developed amounts to approximately 2.2 million Mw at 50 percent plant capacity factor, about 12 percent of the total hypothetical world potential.

In 1977 the U.S. Army Corps of Engineers (1978) completed a study in which it was estimated that 54,600 Mw of additional electrical generating capacity is available for development now in existing dam structures. Of that amount 5,100 Mw it was estimated could be achieved through improved efficiency of existing turbine-generator installations; 15,900 Mw were estimated to be available by adding turbine generators to existing hydroelectric plants; and 33,600 Mw could be developed by installing turbine-generators at existing dams presently not used to generate electricity. Of the total, 27,000 Mw were estimated for sites with individual potential capacities of less that 5 Mw, generally low-head.

The Corps of Engineers is now doing a more detailed follow-up study of original "National Hydropower Survey". Many hydro experts felt that the original study overstated the extent to which small scale hydroelectric power could be commercially developed. Nevertheless, it is important to begin hydro surveys by studying carefully the potential for increasing present capabilities.

In New York State a preliminary assessment of the regional marketing potential of low-head hydropower for the northeastern states was undertaken. Those findings indicated that a definite market exists for low-head hydroelectric technology in that area. Of 5,300 dams studied, 1600 were selected on the basis that they were estimated to have the capacity of producing hydroelectric power in the range of 50 to 5000 Kw. Heads of 15 to 45 feet were examined. Using a sampling technique, the investigators estimated that perhaps 750 low-head dams would be candidates for re-development.

In the Pacific Northwest, a U.S. Department of Energy funded study coordinated by the Idaho Water Resources Research Institute has recently been completed. The study progressed in two phases:

Phase I, a theoretical assessment of the energy potential if every stream were dammed up with a series of small hydro projects (the "reach" analysis), and Phase II, the potential at existing dams without generation, all previously identified damsites and at sites in irrigation systems. Table 1 summarizes the results of Phase I for the region.* Clearly, the region has a large theoretical potential of hydropower remaining. Of course, much of this potential has, at least at present, been effectively eliminated by virtue of such activities as "wild and scenic river" designation, and other institutional constraints.

In a study undertaken by the World Bank, Moore (1978) points out that in many developing countries hydro power surveys have not been undertaken. Nevertheless he sees hydro as continuing to be an important (although decreasing relative to others) source of energy in 97 developing countries. Table 2 shows that the installed hydro capacity is forecast to nearly triple and by 1990 will comprise about one-third of all the additions. In

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*A flow-duration curve procedure was used in this study, as described in Section III.

terms of actual overall energy capacity, however, hydro will be reduced from 40.7% in 1976 to about 35.5% in 1990.

STATE	Power (MW)		Energy (GWH)	
	P_{30}	P_{50}	E_{30}	E_{50}
Washington	13928	8862	80124	61314
Oregon	12105	6786	64951	46324
Idaho	9147	5443	53365	38338
Montana	3576	2044	19848	14689
Wyoming	620	295	3345	2205
Nevada	15	8	76	53
Total	39391	23439	221709	162923

Table 1. Theoretical Maxium Developable Hydroelectrical Potential in the Streams of the Pacific Northwest Region of the United States.

Type	1976	1980	1985	1990	1977-1990 Additions	
hydro	70.4	101.0	149.5	205.8	135.4	(33.3%)
geothermal	0.1	0.4	1.4	2.3	2.2	(0.5%)
nuclear	1.2	4.3	22.1	62.4	61.2	(15.1%)
thermal	101.6	149.6	217.0	308.8	207.2	(51.1%)
TOTAL	173.3	255.3	390.0	579.3	406.0	

Table 2. 1976-1990 Installed Capacity Breakdown - GW In 97 Developing Countries.

It must be kept in mind constantly that "averages" mean almost nothing in hydro -- this is a field that is <u>extremely</u> site and time specific. It either exists or it does not. Costa Rica, for example, is seriously considering going almost 100% hydro -- a shift from thermal. The Pacific Northwest of the U.S. has traditionally been hydro -- but is now considering increased thermal.

Is Anyone Thinking Seriously About Small Hydro?

It is, unfortunately, all too "common knowledge" that hydro is passe'. After all, if it were really worth discussing we would be doing something about it. We all "know" that there won't be any more big dams -- and those small ones don't produce enough energy to bother with. We've all heard comments like that -- although I must say that they are decreasing.

From the number of studies completed or underway it would seem obvious that there are people who do take small hydro seriously. And, if one listens too seriously to some of the staunch advocates of small hydro (similar to those of nuclear, coal, synfuels, solar, etc.) one might begin to feel that small hydro is <u>the</u> answer to our energy problems.

It is not.

In fact, in most regions it does not come close to being the answer.

Hydro is but <u>one</u> source of energy. It may not always be the source that needs to be developed first -- but to cast it aside because it does not totally solve the problem is unthinkable. More and more decisionmakers are beginning to realize this, and are considering many options.

In many countries the options are available now. When we get serious about energy developments we will see that the problems of integrating small hydro and other energy sources into large systems, where it is advantageous, will be solvable without the predicted overwhelming complications. Shown a "profit" from an operation, energy organizations will begin to give it more serious consideration. Granted, small hydro will not be quantitatively or economically justifiable in all areas of the world. But in some parts, even though the overall percentage of that guaranteed by small hydro may be small, its incremental value will be much greater.

To be sure, the greatest first interest is in the possibility of retrofitting existing dams. Why? For two basic reasons: (1) use of existing dams clearly reduces the cost of generating the power, and (2) if there has been environmental desecration, it has already been done, and little additional would be expected. (Note: all is not quite so simple, however, as will be discussed later). Even using old dams, however, not all sites appear to be presently economical -- but with the rising cost of alternative sources they may soon become so.

Engineers are learning to be very resourceful in the field of small hydro. There simply isn't the level of funding or investment in the individual projects to warrant a great deal of time-consuming (and thus dollar consuming) special studies. This also, as will be discussed later, is a problem.

The previous discussion would lead us to believe that small hydro has not been considered too seriously until recent years. That certainly is true in the U.S., but internationally it is simply not the case. In the modernization of small hydro the U.S. is presently behind other technically developed countries -- although we are rapidly trying to catch up.

Why should this be so?

It seems evident that small hydro has until only recent times been generally bypassed by planners who have been pressed by an interesting and (they are accused) self-fostered supply-demand relationship. To produce the required energy and satisfy the rapidly growing demand, it has been necessary for them to develop large blocks of power capability.

I am not certain that this trend toward large blocks of power will, or even can be totally turned around. Whether it should be, some would contend, is yet another question.

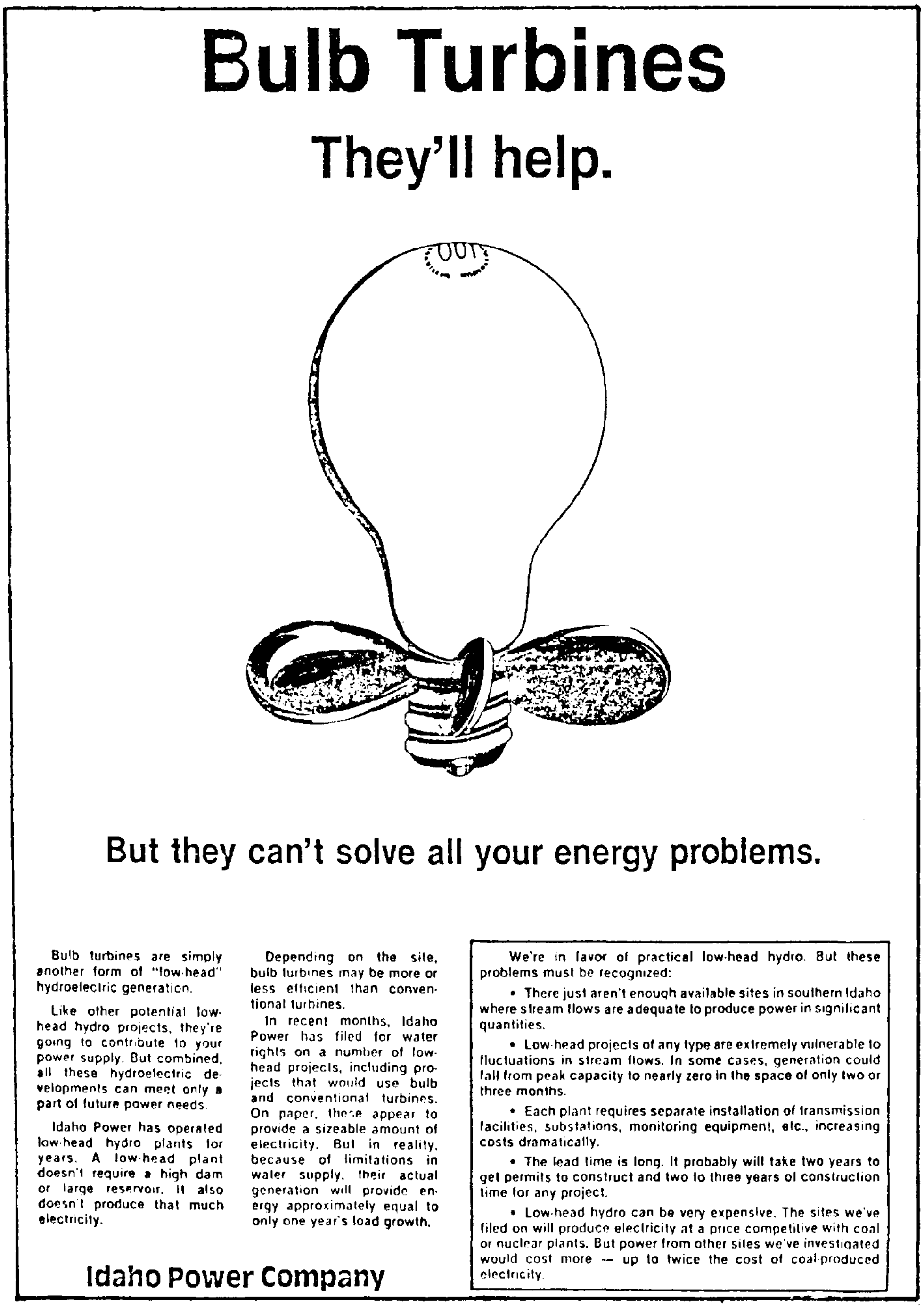
The development of small hydro, it would seem, will continue to depend upon those persons and organizations who as a matter of conscience feel that a nation must increase the use of its renewable resources in working toward the solution of its energy problems. . .and those whose studies show it to be economically worthwhile.

Is Small Hydro Interesting to Utilities?

Some facts are clear. Justifiably or not, in the U.S.A. utilities in general have not been enthusiastic in their endorsement of small hydro. And, as the installed capacity of the hydro plants decreases the interest of utilities anywhere in the world has tended to decrease proportionally.

Figure 1 is a reproduction of a newspaper advertisement that appeared in several southern Idaho newspapers about the time my Institute was sponsoring a national symposium on low-head hydro. (The buzz-word around the non-initiated in small hydro is "bulb turbines". As we will see later, bulb turbines are but one of several available configurations). The Idaho Power Company, as do most large utilities, has had a much greater interest in new large scale thermal plants.

A serious problem does exist, however, in that some utilities have actively discouraged the development of small hydro units by non-utilities



Bulb Turbines

They'll help.

But they can't solve all your energy problems.

Bulb turbines are simply another form of "low-head" hydroelectric generation.

Like other potential low-head hydro projects, they're going to contribute to your power supply. But combined, all these hydroelectric developments can meet only a part of future power needs.

Idaho Power has operated low-head hydro plants for years. A low-head plant doesn't require a high dam or large reservoir. It also doesn't produce that much electricity.

Depending on the site, bulb turbines may be more or less efficient than conventional turbines.

In recent months, Idaho Power has filed for water rights on a number of low-head projects, including projects that would use bulb and conventional turbines. On paper, these appear to provide a sizeable amount of electricity. But in reality, because of limitations in water supply, their actual generation will provide energy approximately equal to only one year's load growth.

We're in favor of practical low-head hydro. But these problems must be recognized:

- There just aren't enough available sites in southern Idaho where stream flows are adequate to produce power in significant quantities.
- Low-head projects of any type are extremely vulnerable to fluctuations in stream flows. In some cases, generation could fall from peak capacity to nearly zero in the space of only two or three months.
- Each plant requires separate installation of transmission facilities, substations, monitoring equipment, etc., increasing costs dramatically.
- The lead time is long. It probably will take two years to get permits to construct and two to three years of construction time for any project.
- Low-head hydro can be very expensive. The sites we've filed on will produce electricity at a price competitive with coal or nuclear plants. But power from other sites we've investigated would cost more — up to twice the cost of coal-produced electricity.

Idaho Power Company

Figure 1. One utilities opinion of low-head hydro.

by refusing to pay "reasonable" rates for the generated power. Institutional arrangements must be made to ensure that pricing is not used as a means of unfairly restricting small hydro development, because the fact is that in many cases the economics of hydro developments are definitely positive. And the consumer has the right to know that protected public and private utilities are providing the most economic product.

What, specifically, do utilities say about small hydro? The following arguments were presented at our symposium on low-head hydro:

* Sites are not generally available where stream flows are adequate to produce power in significant quantities.

* Low-head projects of any type are extremely vulnerable to fluctuations in stream flows. In some cases, generation could fall from peak capacity to nearly zero in the space of only two to three months. This is a very important consideration.

* Each plant requires separate installation of transmission facilities, substations and monitoring equipment. This increases costs dramatically and complicates the every day management and operation of the overall system.

* Lead time can be long. It can take two years to get permits to construct and two to three years of construction time for any project. You do not merely grab a bulb turbine off the shelf and plug it into your system.

* Low-head hydro can be very expensive. The sites filed on at Idaho Power hopefully will produce electricity at prices competitive with coal or nuclear plants. But power from other sites investigated would cost more -- up to twice the cost of coal-produced electricity.

* Utility systems having 500 to 1300 Mw plants of single units cannot afford to allocate very much manpower in operating small, low-head plants of 15 to 75 Mw capacity. It takes almost as many people to operate a 15 Mw low-head hydro plant as it does to operate a 1500 Mw high-head hydro plant.

* The protection that goes into keeping a small plant operating is approximately the same protection that goes into keeping a large plant operating.

* Through federal legislation and pressure by minority environmentalists, two of the major sources of hydro electric power in the State of Idaho have been "locked-out" of production.

I will not attempt to refute those points at this time, on the other hand, since it is clear (in my mind, at least) that there are also a number of positive aspects in favor of small hydro), I feel compelled to comment that those arguments do seem to give a "non-positive" approach to the possible benefits of considering small hydro as an alternative energy source worthy of consideration. As a consumer I do not insist on "hydro" power, but I do insist on proper economic analyses. Furthermore, as consumers (the ones who eventually pay the bills) we have the right to expect our utilities to develop the most economic energy first. If hydro cannot compete, then we should not become messianic.

It may very well be true in some parts of the world that the importance of small hydro may not be quantitatively or economically sufficient to warrant its serious consideration at this time. But in many areas, even though without a doubt the overall percentage of that guaranteed by small hydro may be small, its incremental value and its use of a renewable resource make its serious consideration a must. Reduction in our dependence upon fossil-fuels, may turn out to be a most important need in the preservation of our environment.

Certainly the use of hydro (small hydro in particular) has not been disregarded nearly as much by foreign utilities. Developing countries in particular are realizing that they want to be responsible for their own energy futures. If for no other reason, the use of hydro in these countries is a logically simple step. Although the individual hydro outputs may be small, the system is one that can be comprehended and can be depended upon to produce with high and consistant efficiency. An it uses the countries' own resources.

II. SMALL HYDRO TECHNOLOGY

Basic Hydraulics

Hydroelectric energy technology has been around for a long time. The basics are rather simple:

$$P_{kw} = \frac{QHe}{11.8}$$

where P_{kw} is power in kilowatts, Q is water flow rate in c.f.s., H is the net head available to the turbine/generator in feet, and e is efficiency.

Thus, some of the first things an engineer must determine are (1) how much water is available in a river (and when), and (2) how much head (drop) is potentially available (and when). From the basic information he will begin to try various configurations of dams, penstocks, etc. -- including the type of turbine -- in order to minimize the cost while producing as much power as possible. He usually conceives a number of possible configurations, each of which must be evaluated in more or less detail.

Turbines basically fall into two categories: Impulse and reaction.

Impulse Turbines:

On this kind of turbine "buckets" on the periphery of a wheel are moved by the force of a jet (or sets of jets). The available (net) head is converted to kinetic energy, of which a portion creates the torque. Generally, impulse turbines are used for high heads, although one modern design is efficiently used in the low-head range.

Impulse turbines are enclosed in a case, but operate under atmospheric pressure in air. There is, therefore, some unused head because they must effectively be set above the tailwater level (they can be operated below tailwater levels, but then only under positive pressure), Figure 2.

Reaction Turbines:

Reaction turbines are generally of two kinds -- mixed flow and axial flow. Energy is imparted to the turbine from the flowing water by a reduction of pressure and velocity. On Francis type turbines, water enters radially, continually impacting the "buckets" and discharges (usually vertically) down (axially) the center into an expanding draft tube. Effective head range is quite large, from low - to high-head. Propeller type turbines can be serviced by the flow much as a Francis turbine (radially

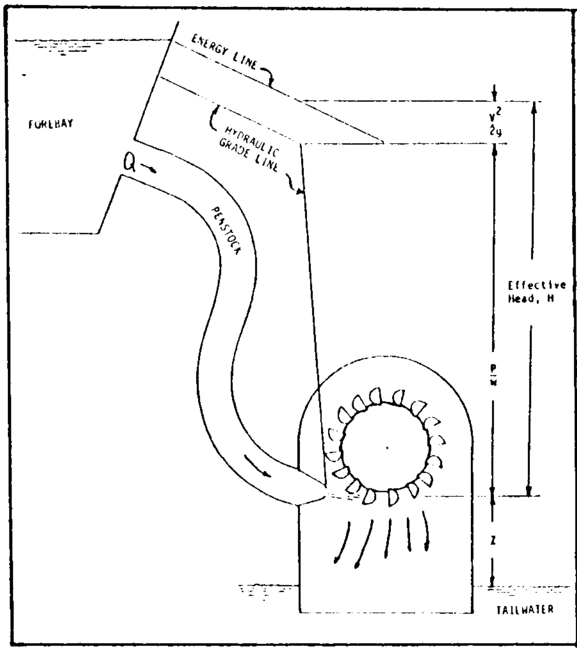


Figure 2. Hydraulics of Impulse turbines -- definition sketch.

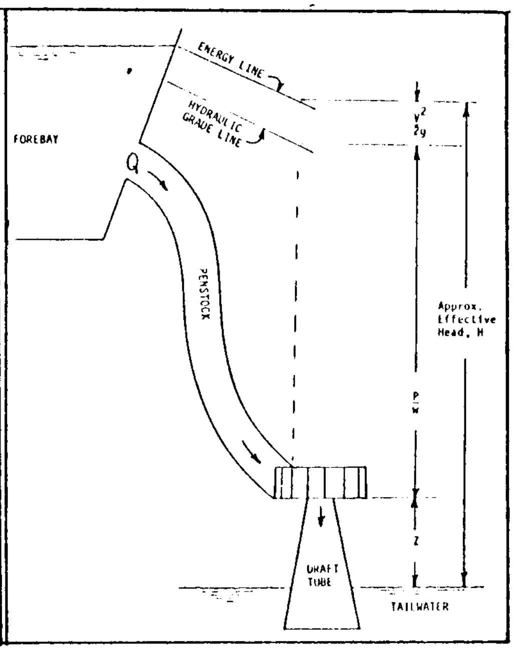


Figure 3. Hydraulics of Reaction turbines -- definition sketch.

then axially), or in more modern applications (tubular) by designing the water passage purely axially. In any case, the flow to the propellers is axial. Effective heads are in the lower to middle ranges. Reaction turbines take advantage of the total head available to the tailwater level (see Figure 3). As a result, however, the setting of the turbines must be very carefully designed to avoid cavitation.

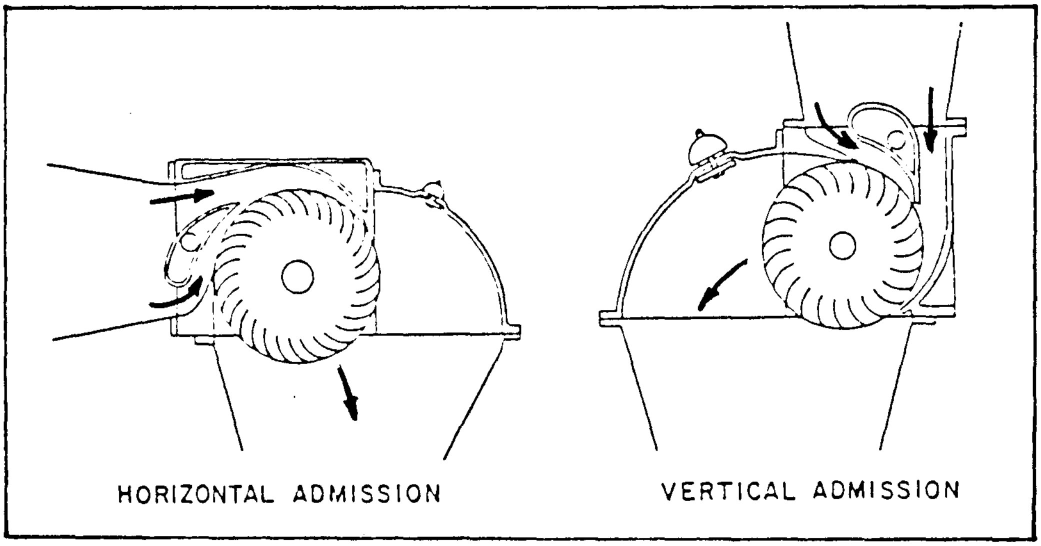
Examples of Turbines

The following is not intended to be an exhaustive discussion of all manufacturers, but rather to cover the range of types of turbines.

Impulse Turbines:

Perhaps the most commonly thought of impulse turbine is the Pelton-type. Figure 2 illustrates such an installation. Each "bucket" is in fact divided into two identical parts, separated by a thin edge, or "splitter" when the jet strikes a bucket, the splitter divides it into two equal portions which are then deflected by the curved sections in opposite directions, nearly opposite to the direction of entry. Pelton-type impulse turbines are normally considered for high-head installations. They have found wide use in small hydro programs where high heads combine with low flows.

The Ossberger turbine is a radial, impulse-type low-speed turbine, often referred to as cross-flow. The intake water is forced through a rectangular cross-section and guide-vane system through the blades of the cylindrical runner, first from outside to inside and then, after passing through the interior of the runner, from inside to outside, as illustrated in Figure 4.


HORIZONTAL ADMISSION

VERTICAL ADMISSION

Figure 4. Ossberger Cross-flow turbine.

Flow can be restricted by two balanced guide vanes (1/3 or 2/3) so that the arrangement permits the use of any water quantity in the range of 16% to 100% with optimum efficiency in all ranges, as shown in Figure 5.

"Common knowledge" has it that impulse turbines are generally eliminated from consideration in the very low-head range. However, the Ossberger unit has been satisfactorily installed at heads as low as 18 feet, and operated ideally with heads up to 650 feet -- a broad range of applicable head. Both the Pelton and Banki (a "crossflow" turbine very similar to the Ossberger) have found wide application in micro-hydro application.

Reaction Turbines:

Reaction type turbines under consideration for small hydro projects are varied, and are manufactured by a number of different companies. Following is a brief description of each of three turbine types: (1) Francis, (2) Kaplan and (3) tubular. Tubular turbines are subdivided into Tube-

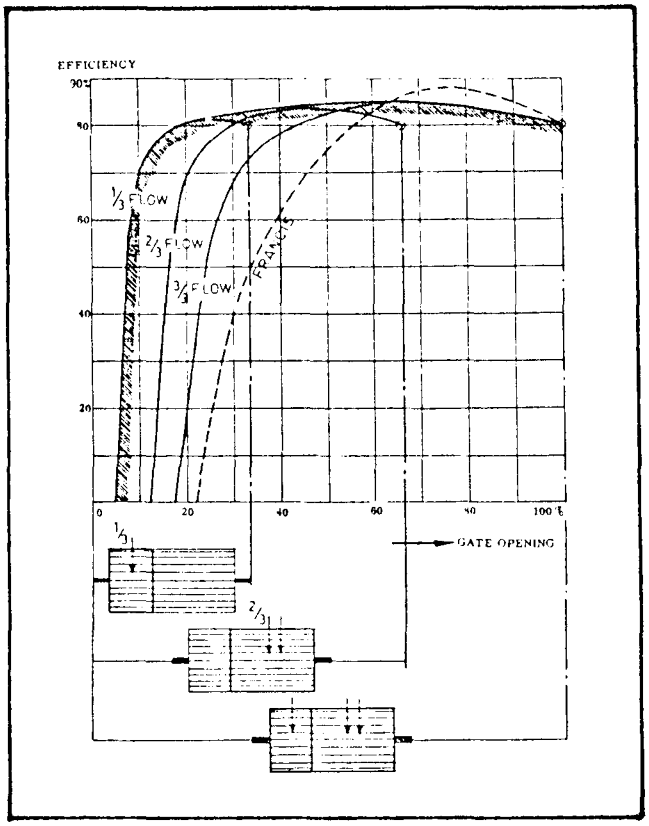


Figure 5. Ossberger vs. Francis Turbine operating efficiencies.

type Bulb, and Rim. In practice the penstock and draft tubes must be considered an integral part of the design.

Francis:

The Francis turbine is a mixed flow turbine. Water enters this turbine flowing toward the axis; it then flows through passages caused by vanes and by families of curved buckets and exits flowing axially. The actual flow path through the runners, depends on the design, and there are wide variations in design for various flow and head conditions.

High head Francis runners are characterized by large entrance diameters and low heights -- followed by a small discharge diameter. They have been designed and used for heads exceeding 1500 feet. For medium heads the inlet and discharge diameters are practically the same.

For low-head Francis runners the inlet diameter is characteristically considerably smaller than the discharge diameter, and in order to provide greater entrance area the entrance height is substantially increased.

Francis turbines can be installed vertically or horizontally, and are available for operation at heads of 16 feet and above.

Generally, the hydraulics of a Francis turbine are such that their operating speeds are lower than comparable propeller runners, and as a result have higher generator costs. They may not be as competitive in the lower head range.

In the vertical installation the turbine shaft can be connected directly to the generator by a coupling that drives the generator at turbine speed. The use of a speed increaser permits use of higher speed, and thus lower cost, generators.

In horizontal settings the turbine shaft is parallel to the powerhouse floor, with similar generator couplings available as with the vertical installations (see Figure 6).

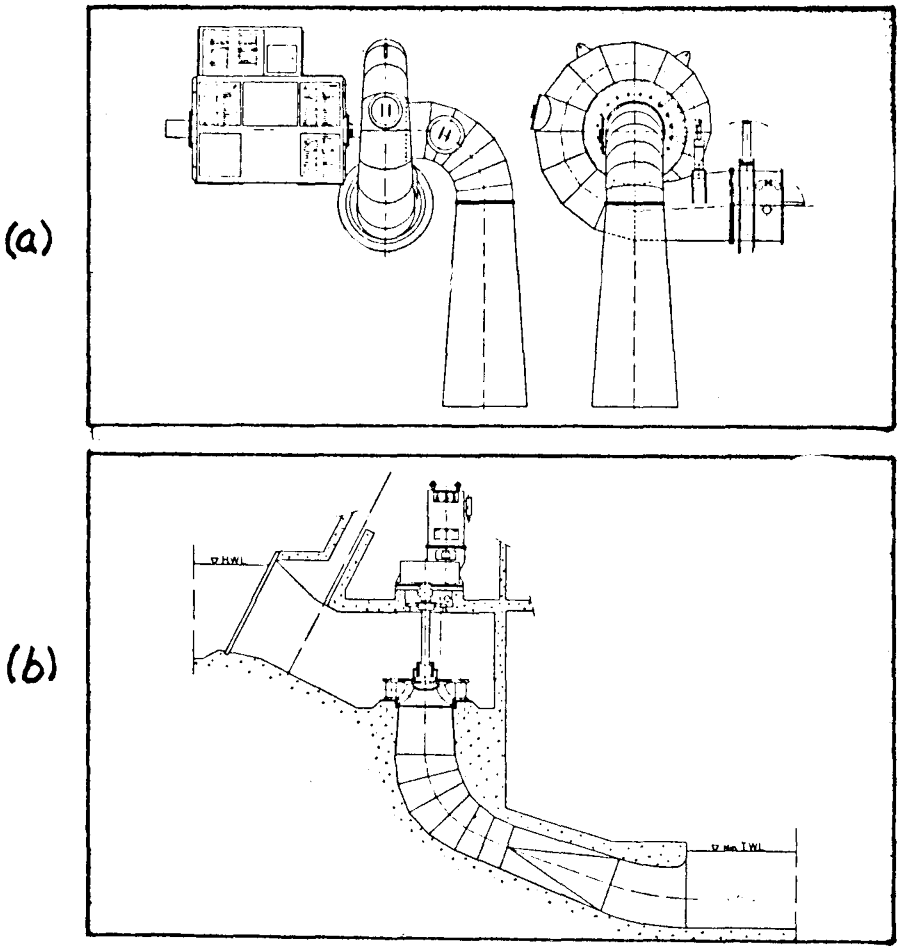


Figure 6. Francis turbines: (a) horizontal, (b) vertical installations.

Even though the cost of the generators may be less for the horizontal installation (because of the smaller thrust bearings required), it will require greater floor space. And although the performance characteristics are the same as the vertical setting, the horizontal installation capacity of the spiral case causes inherent problems in powerhouse arrangements.

Efficiencies of the Francis turbine can be quite high, but in low-head range they will not be as "flat" as some of the other designs. Figure 5 compares the cross-flow and a typical Francis efficiency curve.

Kaplan:

The advantage of adjustable runner blade propeller turbines in combination with wicket gate control to provide optimum hydraulic performance were realized early. The Kaplan turbine maintains good efficiency under part load (Figure 7) -- it was the original in the application of adjustable blade settings and wicket gate control.

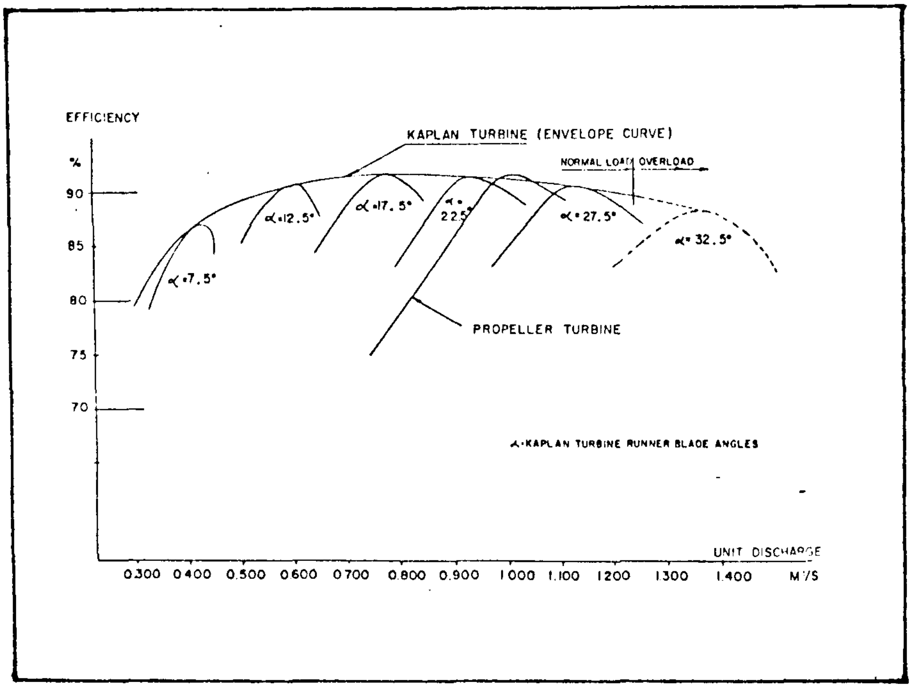


Figure 7. Comparative efficiency curves: Kaplan vs. fixed blade propeller turbines.

For heads below 150 feet a propeller type turbine is usually chosen, and the Kaplan type (adjustable blade) is generally preferred because of its greater flexibility in operation. The adjustment capabilities of the Kaplan turbine permit it to be used efficiently at locations where the unit operates at various flows and heads. Their additional cost, however, makes their use in very small developments somewhat doubtful. As will be discussed later, high overall efficiency can also be obtained by unequal sizing of turbines. Figure 8 illustrates a typical large vertical shaft Kaplan turbine installation.

Propellers runners with adjustable blades are also used in tubular turbines and are often referred to as "Kaplan" runners.

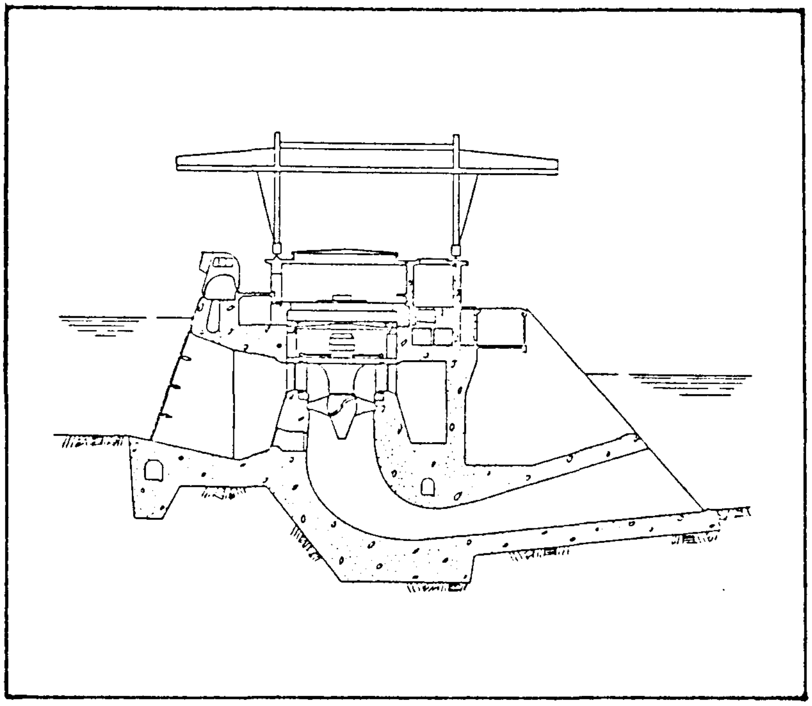


Figure 8. Vertical Kaplan turbine installation.

Tubular:

Turbines in which the water flow is conducted to the runners coaxially with the shaft are called tubular as well as axial-flow turbines. Tubular turbines include tube-type ("TUBE" is a registered name of the Allis-Chalmers Corporation) bulb and rim turbines.

All tubular turbines have propeller-type runners, each having individual characteristics concerning generator placement. They can be located in any of a number of shaft configurations, as will be seen, and may be either fixed or adjustable runners.

Those with adjustable blade runners, as noted before, are able to maintain optimum efficiency over a broad operating range. Fixed-blade runners have good efficiency within a narrow range, dropping off rapidly for other flows. Because of its simpler design, however, the fixed-blade propeller runners will have lower capital costs. Figure 7 compares efficiencies of the adjustable (Kaplan) and fixed blade runner turbines.

Tubular turbines have several general advantages over Francis or vertical Kaplan installations: (1) flow pattern deviation in spiral casings and the necessity for substantial draft tube bends are eliminated or greatly reduced. This can result in efficiency gains of up to several percent, (2) axial flow conditions increase flow capacity and thus energy output, for the same runner diameter this increase may be in the 5-20% range: (3) the dimensions of the tubular units are usually considerably less than the Francis or vertical Kaplan, resulting in smaller housing requirements; (4) if draft tube bends can be eliminated there should be considerably reduced excavation requirements, and (5) straighter flow passages require less concrete form costs.

Tube-type turbines are manufactured by a number of companies worldwide. The distinguishing feature is that the generators are located outside the water passages, either directly coupled with turbine shaft or with speed increasers. Figure 9 illustrates several typical installations.

The Allis-Chalmers Corporation expresses the merits of its TUBE turbine as recommending it for use for two principal applications: (1) in standardized form for low-head hydro installations which would generally operate unattended and for which more efficient and more elaborate bulb or rim type units are either not available or not economical, and (2) for the rehabilitation of old low-head plants where in many instances the physical constraints favor the TUBE concept.

Advantages of tube-type turbines include a relatively simple seal arrangement and the fact that the generator is easily accessible for maintenance and repair. Disadvantages include the typical necessity for a long drive-shaft to connect the turbine with the generator, and because of the distance between turbine and generator a large powerhouse is sometimes required to accomodate and service both components.

Bulb turbines have become very popular for low-head hydro application. As has been noted before, to some "low-head" and "bulb turbine" have

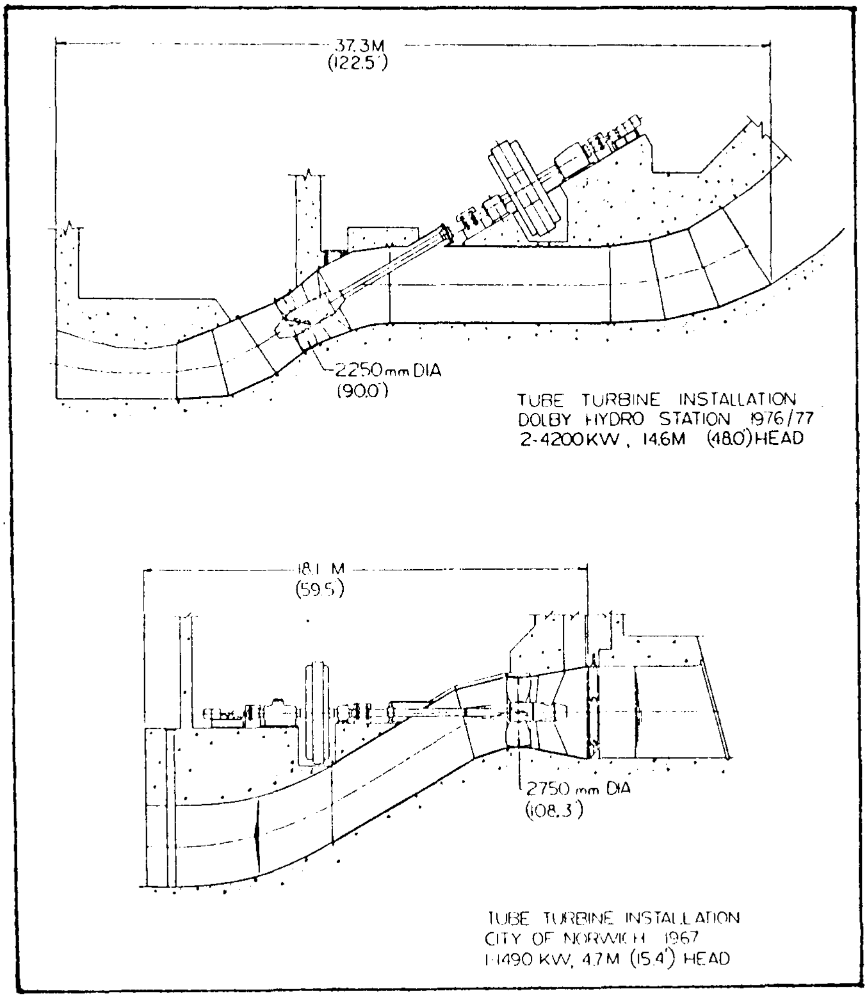


Figure 9. Two Tube turbine installations.

erroneously become almost synonymous. In this configuration the generator (driven directly by the turbine or with speed increasing gears) is encapsulated in a bulb-like housing directly in the flow passageway. For maximum efficiency it is attached upstream from the turbine runners.

Because the bulb turbine/generator is directly in the flow passageway, it must be streamlined, the passageway must be as compact as possible. The compactness of the generator area means that the rotor diameter may be considerably smaller than the turbine runner diameter, which is compensated for by an increase in the generator length. Cooling is a problem that must be overcome.

The small rotor also has inherently low inertia; not a desirable consideration. The compactness can also lead to problems of access to the generator. Access to bulb turbines is usually provided by shafts, which, depending upon the bulb size, may permit full installation and removal of components. However, if such access is not available, long delays may be necessitated for removal of generators for repair.

In addition to all the advantages generally attributed to tubular-type turbines, bulb turbines have one advantage concerning the electromechanical equipment. Because of the compactness and location, although for an equivalent vertical Kaplan turbine these equipment costs do not vary appreciably, construction costs can be as much as 30% lower. It has been suggested that the use of bulb turbines should be most effective in the higher capacity installations where the improved turbine efficiency resulting from long conical draft tubes would be most valuable. Figure 10 illustrates a typical bulb turbine installation and cross-section.

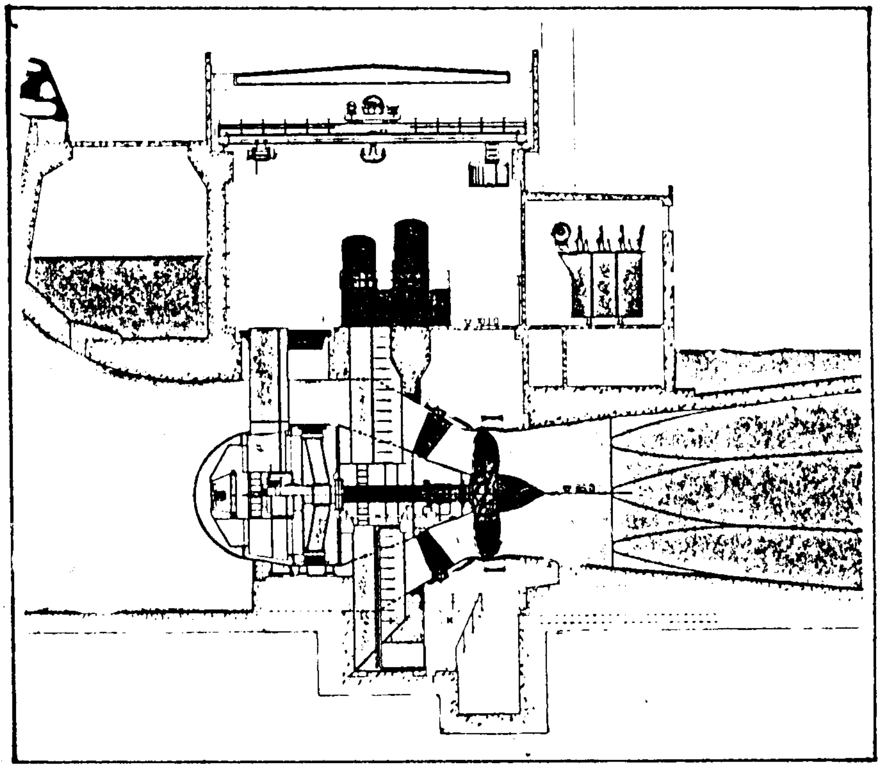


Figure 10. Section through a bulb unit.

Bulb turbine performance has been suggested to be the same as for a vertical Kaplan unit; overall efficiencies, however, may be one to two percent higher due to the straight flow passageways and the reduction in the head losses at the entrance.

Rim generating unit installations are unique in that the generator rotor is mechanically attached to the periphery of the propeller runner blades and carries the poles. The generator itself surrounds the entire passageway at the runner, see Figure 11.

The "torpedo" container of the rim generating unit is considerably smaller than the bulb turbine capsule; Figure 12 compares a "bulb" and "rim" installation.

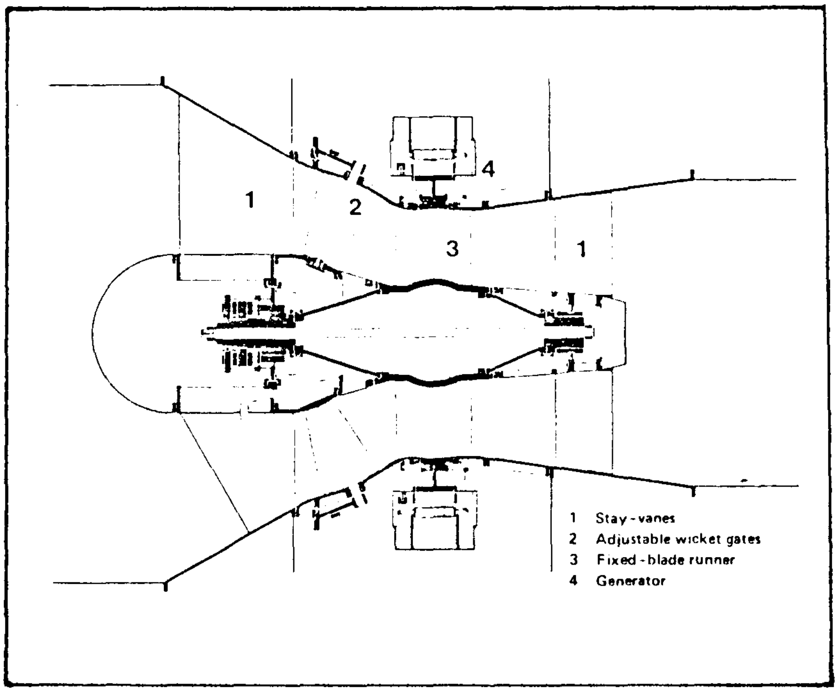
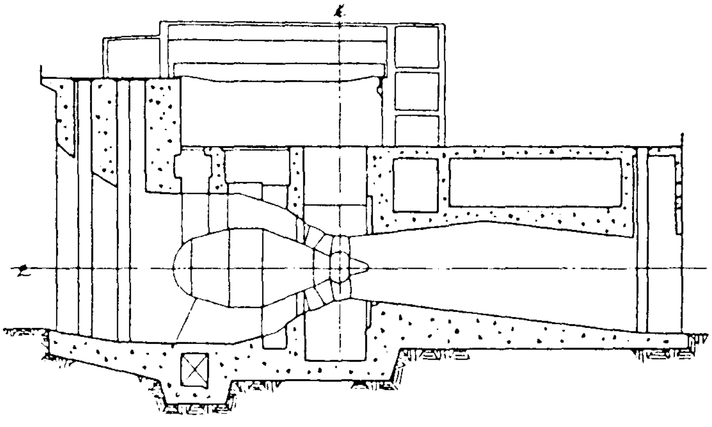


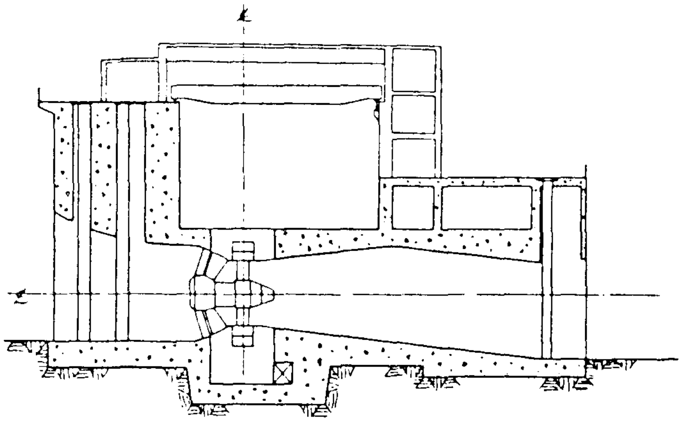
Figure 11. Typical cross-section of Straflo (rim) turbine.

Despite the compactness of this unit, the manufacturer (Escher Wyss of Switzerland currently manufactures the only rim units -- called STRAFLO) suggests that all the disadvantages of the bulb turbine previously mentioned, have been eliminated.

* The generator diameter is about 50% larger than for the bulb turbine which removes all difficulties connected with rotational speed, output, compactness factor, reactive power factor, and cooling.
* As far as is possible from the manufacturer's point of view, there is no limitation to the size of turbine and generator.
* Three to four times as much inertia.



BULB TURBINE



STRAFLO TURBINE

Figure 12. Comparative sections of bulb and Straflo (rim) units.

- Turbine and generator are in the same vertical plane which thus makes only one erection pit necessary.
- Good accessibility to the generator. By moving the stator axially, poles and stator windings are completely accessible.

The difficulty of providing a satisfactory runner seal to prevent water from reaching the generator has been stressed by speakers and writers. Such problems, according to the manufacturer, are apparently overly exaggerated. It is stated that with the development of hydrostatic seals preventing the entrance of water to the generator and bearings, the unit is particularly suitable for medium and large outputs.

Although no rim generator units have been installed to date (1980) in the United States, 73 were installed in Germany and Austria between 1937 and 1950. It is suspected that with increased marketing efforts, the rim generator units will see increase popularity.

III. DETERMINING THE HYDROELECTRIC POTENTIAL

Site Hydrology

The characterization of flows at a specific site can be made with varying degrees of sophistication, dictated to a great extent by the availability and type of data. In general the only "given" in hydrology is that there will almost never have been data accumulated precisely where it is needed. Thus, almost any hydrologic analysis will require transposition, regionalization, statistical generalization or some other technique for deriving information at a specific site from data gathered at other locations.

The ultimate goal in the hydrologic analysis would be to develop an appropriate time series of flows at the specific site. From that time series will ultimately be determined the potential installed capacity and the energy which can be developed therefrom.

Although not the only way the time series can be used, the flow-duration approach is perhaps the most easily understood -- and is widely used in practice. In this procedure the data must be condensed in order to provide working curves. The very act of condensing can influence the annual energy values calculated.

In a flow-duration analysis the time series is rank ordered by annual, monthly, weekly or daily mean flows according to magnitude. The use to which the information is to be put determines the choice of time interval. The rank ordered values are then assigned order numbers, thelargest beginning with order 1. The order numbers are then divided by the total number in the record and multiplied by 100 -- representing the percent of time intervals (days, weeks, etc....) that a particular mean flow has been equaled or exceeded during the period of record analyzed. As in any statistical analysis, the value of the information contained is a function of the length of record. References to flow-duration curves are usually made as Q_{50}, Q_{30}, Q_{10}, etc., indicating the flow values at the percentage point subscripted.

As noted before, the choice of time interval or analysis procedure will be governed by the use to which the results will be put. A very simple energy model, used for preliminary potential analysis, can be made on the basis of the daily flow observation over the period of record (approximately 365N days, where N is year of record). It must be realized, however, that this "daily" method of analysis submerges low-flow years and low-flow within-year periods in one overall record. Thus, the percentages indicate the average relative frequency over the period of record only. It is helpful when using such a procedure to show typical annual hydrographs as well so that critical within-year periods will be identified.

The same procedure, with the same limitation can be done using monthly mean values. The record in that case will consist of 12N items of data. Because the monthly mean values will camouflage within-month variations, the flow-duration curve will look somewhat different from a daily flow analysis, and as a result will be less useful in design consideration. Of course, the same arguments would hold for flow-duration curves developed from annual mean values.

Because flows at specific sites generally follow some cyclical variations as a function of within-year periods, greater value can be derived if the analysis is based on monthly flow-durations. This may be done in at least two manners. In one, all the January means (for example) are listed as a data series of N values, and the analysis made. The monthly averages used, however, will mask the within-month variations. Thus, an analysis of all the daily January flows (in this example) will provide a better basis for design consideration. Depending upon the purpose for the analysis, it may only be necessary to evaluate the critical monthly periods (which for small hydro as we will see later will probably include the high-flow as well as the obvious low-flow months).

Another procedure might be to attempt to provide "index" years. In this procedure the yearly average flow duration curve is prepared first. From this the K-th percentile index year may be identified. By using the historic monthly and daily flows occurring during the selected index years, the capacity and energy characteristic can be determined. Although this procedure has been called "probabilistic", it is only the index year that has any true probabilistic inference. There is nothing certain about the probability of that year's within-year distribution of flow. It is thus very important to inspect that year for any perceived anomalies, and since the acceptance of an "index" year concept is a subjective decision, there may be some advantage to purposely "normalizing" the within-year distribution. By ordering the index year daily flows a more realistic and useful flow duration curve for determining capacity and annual energy will be available for that selected year. It has been suggested that the Q_{50} index year can offer a good estimate of primary energy, anything above that value being secondary. Figures 13 through 15 show some of the various flow-duration techniques by example. Table 3 shows the calculated values.

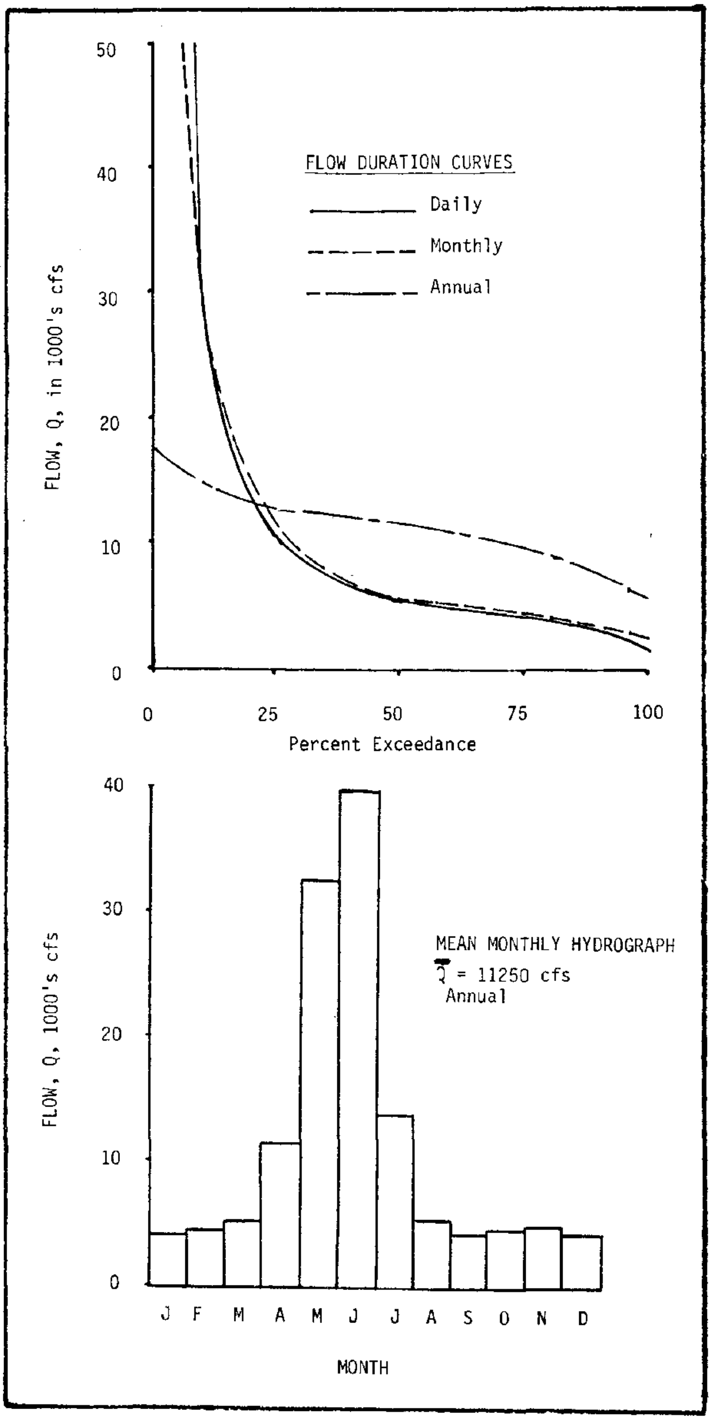


Figure 13.

Daily, Monthly, and Annual Flow Analyses; Salmon River at Whitebird, Idaho.

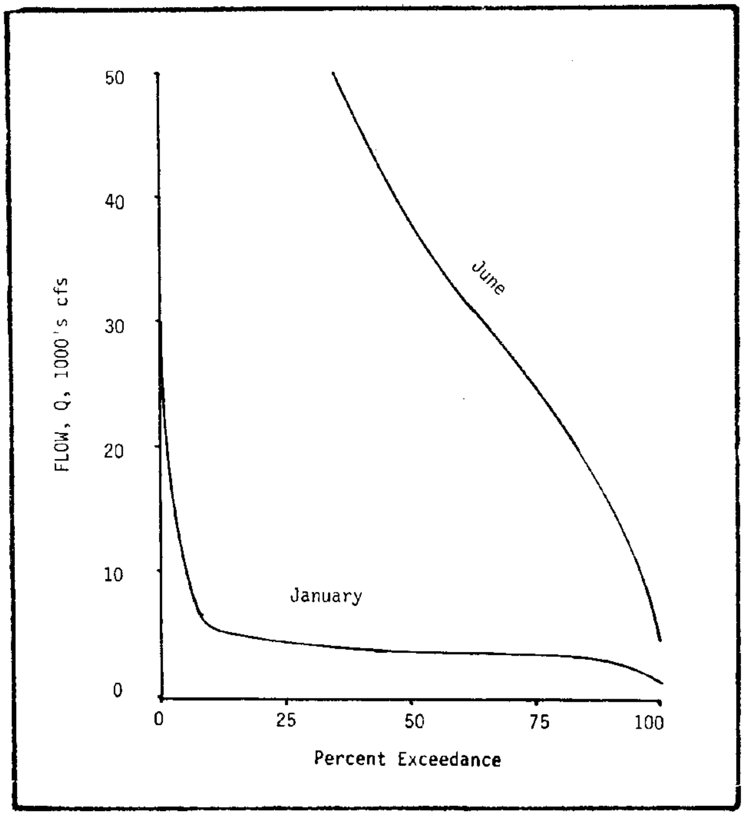
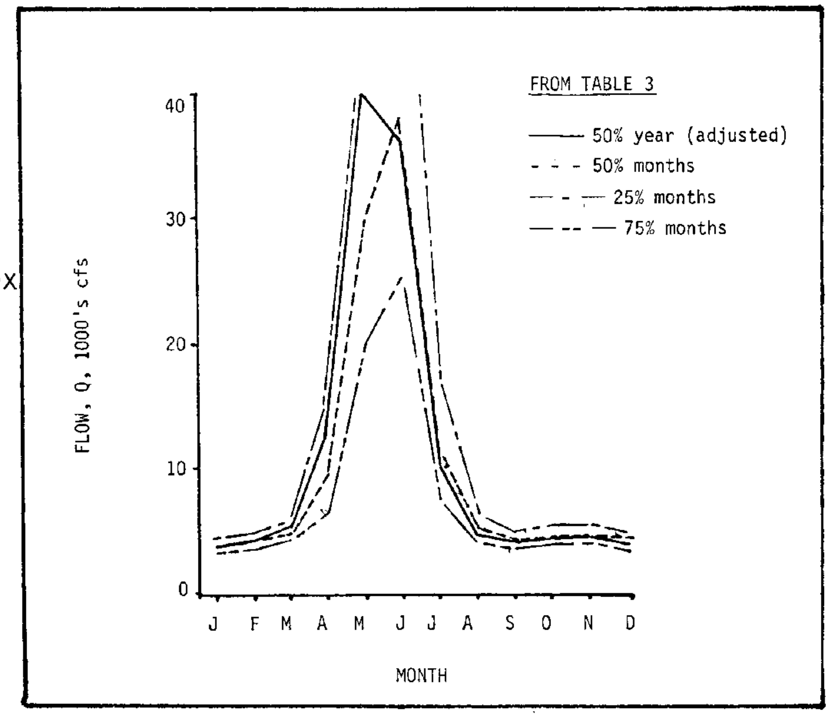


Figure 14.

Daily Flow Duration Curves for June and January; Salmon River at Whitebird, Idaho.

Figure 15.

Monthly Flow Values from 50% Index Year and Monthly Flow Duration Curve Analyses.



	PERCENT EXCEEDANCE							
Period	100	90	75	50	25	10	0	$\bar{Q}$
			(DAILY RECORDS WY 1911-1974)					
Daily	1500	3300	4100	5300	10,300	30,300	129,000	11,255
			(MONTHLY RECORDS WY 1911-1917, 1920-1977)					
Monthly	2500	3500	4200	5300	11,400	30,000	82,600	11,247
			(ANNUAL RECORDS WY 1911-1974)					
Annual	5800	7700	9200	11,400	12,900	14,700	17,480	
			(DAILY FLOW DURATION ANALYSES BY MONTHS)					
Jan	1800	3000	3400	3900	4600	5800	27,800	4,166
Feb	2000	3200	3600	4200	4800	5700	14,100	4,365
Mar	2500	3600	4100	4800	5800	7500	18,200	5,258
Apr	3000	5300	6700	9300	14,800	21,700	46,100	11,555
May	5000	13,800	20,000	29,200	42,900	70,200	104,000	32,687
June	5000	15,700	25,400	38,100	60,900	101,800	129,000	39,963
July	2000	5300	7600	11,300	17,100	26,300	62,000	13,955
Aug	2000	3100	4100	5200	6400	8000	13,000	5,438
Sept	2000	3100	3800	4400	5000	5900	10,500	4,441
Oct	2500	3300	4000	4600	5400	6200	20,400	4,810
Nov	1800	3400	4100	4700	5500	6600	17,100	4,917
Dec	1500	3000	3600	4200	4900	6200	25,900	4,519

50% INDEX YEAR MONTHLY AVERAGES
("ADJUSTED" IS AVERAGE OF THREE)

	1925	1949	1922	Adjusted
Oct	3280	5172	4610	4354
Nov	3950	5057	4810	4606
Dec	3500	4042	4600	4047
Jan	3400	3684	3740	3608
Feb	4780	4094	3890	4255
Mar	4870	6232	4760	5287
Apr	15,900	14,370	7990	12,753
May	42,700	47,860	29,500	40,020
June	31,600	28,780	48,800	36,393
July	11,900	8316	11,100	10,439
Aug	5000	4234	5590	4941
Sept	4530	3677	4090	4099
MEAN	11,300	11,330	11,100	
min. day	3020	2760	2900	
max. day	58,600	73,900	67,200	

Table 3. FLOW ANALYSES, Salmon River at Whitebird, Idaho (cfs)

Traditionally the Q_{20} or Q_{30} values have been found to be good starting places for sizing equipment.

In some areas of the world experience may have shown, or hydrologic studies may suggest, that average annual flows may be estimated based on some key variables. In New England, for example, it has been found that the precipitation varies between 20" to 30" per year. A useful rule of thumb is to assume 2 cfs per square mile drainage area as the corresponding 20 to 30 percentage flow.

A more comprehensive analysis of capacity and energy can be made by using the entire daily flow sequence coupled with a rapid procedure for calculating energy output on a daily basis. Variations in installed capacity and numbers of units can be analyzed. If historical records are used only one sequence will be available, and thus no range of reliability can be established except by the assumption of a repetition of historical flows -- highly unlikely, though very commonly used. However, by analyzing the historical sequences for their statistical characteristics it is possible to develop "stochastic" models for design use. It is also possible under the assumption of the model used, to establish confidence levels.

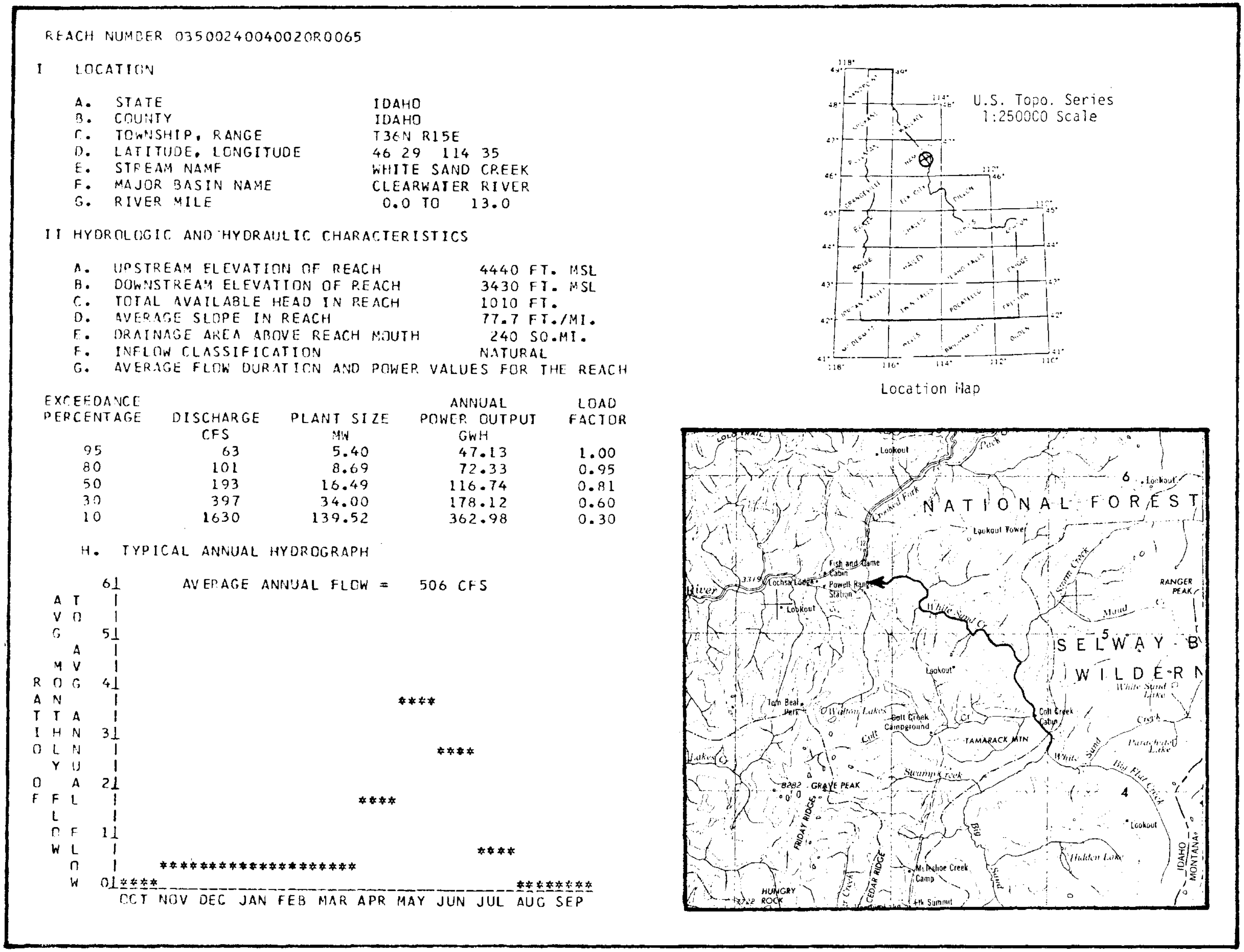
More often than not in developing countries the data for site hydrologic analyses will be quite limited. Even in the United States, a country that by general standards could be considered to have a wealth of data, it is almost always necessary to adjust remote information.

A recently completed study at the Idaho Water Resources Research Institute (Gladwell, et.al, 1979) had as one of its goals a complete hydroelectric potential analysis of the Columbia River system in the United States. We chose to use the daily flow-duration procedure, with accompanying average annual hydrographs. Since it appeared evident that such a task would greatly exceed our capability to depend upon "nearby" gages, a different approach was called for. Without going into details, a regionalized approach was developed that included the availability of an estimate of mean annual precipitation values. The procedures developed permitted us to develop synthetic flow-duration curves at any point on any stream in the region, within the constraints of the process. This, in combination with the site physical data allowed us to develop the potential energy under a series of assumed installed capacity levels. Figure 16 illustrates the method of data presentation used in that study.

Other techniques for developing hydrologic information will be limited by the types of data available. Regression analyses using precipitation, river flow at various gages and watershed physical characteristics are commonly used. If flow gages are located reasonably close to the site, a simple adjustment based on relative drainage areas is sometimes possible.

Site Hydraulic and Physical Characteristics

It should be understood that the hydrologic, hydraulic and physical characteristics referred to in this paper are limited in general to those influencing the hydroelectric generation. Considerable engineering work



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REACH NUMBER 03500240040020R0065

I    LOCATION

     A.  STATE                          IDAHO
     B.  COUNTY                         IDAHO
     C.  TOWNSHIP, RANGE                T36N R15E
     D.  LATITUDE, LONGITUDE            46 29  114 35
     E.  STREAM NAME                    WHITE SAND CREEK
     F.  MAJOR BASIN NAME               CLEARWATER RIVER
     G.  RIVER MILE                      0.0 TO   13.0

II HYDROLOGIC AND HYDRAULIC CHARACTERISTICS

     A.  UPSTREAM ELEVATION OF REACH               4440 FT. MSL
     B.  DOWNSTREAM ELEVATION OF REACH             3430 FT. MSL
     C.  TOTAL AVAILABLE HEAD IN REACH             1010 FT.
     D.  AVERAGE SLOPE IN REACH                    77.7 FT./MI.
     E.  DRAINAGE AREA ABOVE REACH MOUTH            240 SQ.MI.
     F.  INFLOW CLASSIFICATION                     NATURAL
     G.  AVERAGE FLOW DURATION AND POWER VALUES FOR THE REACH

EXCEEDANCE                                   ANNUAL        LOAD
PERCENTAGE    DISCHARGE    PLANT SIZE     POWER OUTPUT    FACTOR
                 CFS           MW             GWH
     95           63          5.40           47.13         1.00
     80          101          8.69           72.33         0.95
     50          193         16.49          116.74         0.81
     30          397         34.00          178.12         0.60
     10         1630        139.52          362.98         0.30

      H.  TYPICAL ANNUAL HYDROGRAPH

        6⊥       AVERAGE ANNUAL FLOW =   506 CFS
  A T    |
  V O    |
  G     5⊥
    A    |
  M V    |
R O G   4⊥
A N      |                            ****
T T A    |
I H N   3⊥
O L N    |                                ****
  Y U    |
O   A   2⊥
F F L    |                        ****
  L      |
  O F   1⊥
  W L    |                                    ****
    O    |    ********************
    W   0⊥****____________________________________********
          OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP
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Figure 16. Sample Reach Hydro-Potential Characteristics Sheet.

will also be necessary for dam design and general safety consideration -- including safe and economic flood flow passage. Where an existing dam is being considered it is particularly important that a satisfactory safety inspection be made by a competent engineer.

The hydraulic head available for generation of hydro power is, of course, related closely to this development scheme devised. Where high heads are being developed the variation may be minimal. However, in lower head systems it is important to study the site and proposed development scheme to determine the relationship of head to discharge. In this case, the maximum head will be available at lowest flows, whereas it is quite possible for the available head to be so small at extremely high flows as to make negligible the amount of power produced. Figure 17 illustrates some of the head/flow relationships that must be developed for a site. Table 4 illustrates how the information can be used to determine energy output. The unit energy cost for various levels of capacity installed can be compared. This is discussed further in Section VI.

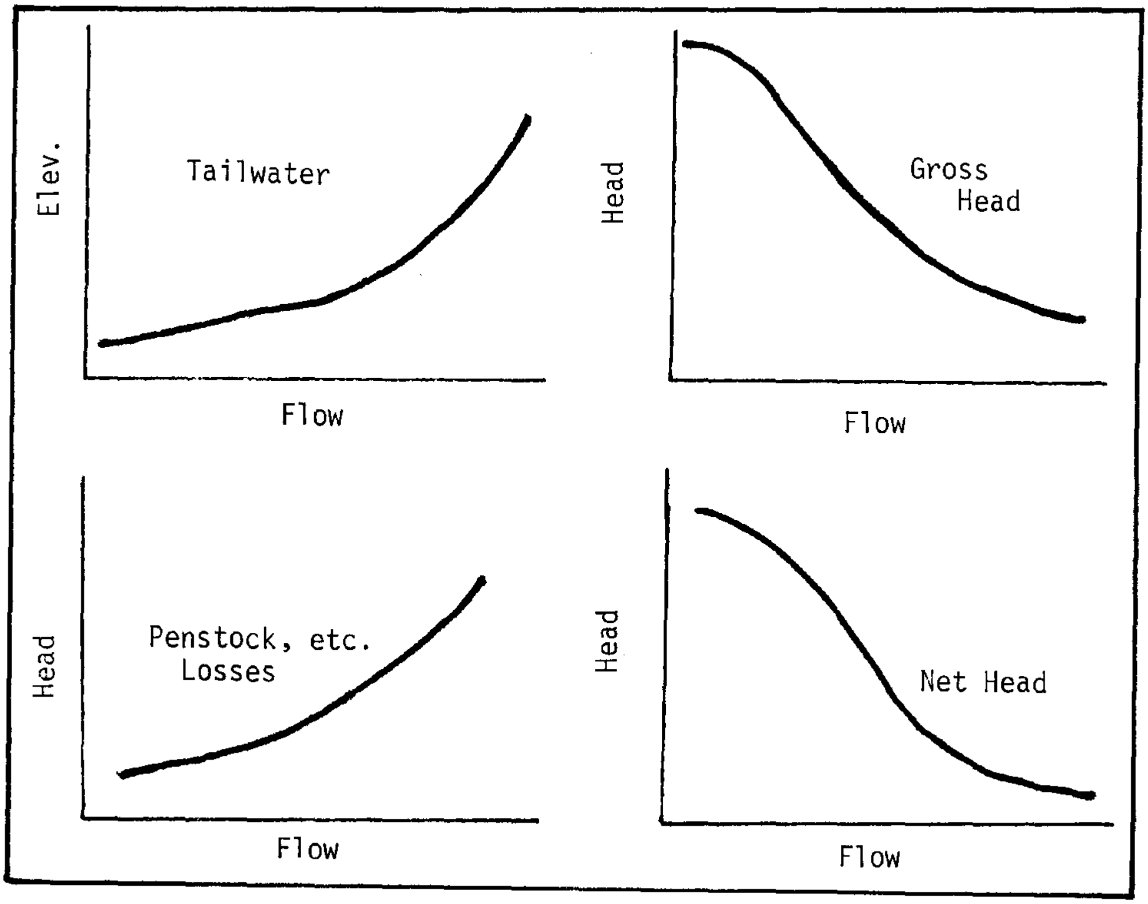


Figure 17. Typical Head/Flow Relationships.

Percent Exceedance	0	10	20	30	40	50	60	70	80	90	100	(1)
Q, 1000 cfs	130	30	15	8	7	6	5	4	3	2	1.5	(1)
Net head ft., ft	48	50	52	54	56	58	60	65	70	75	80	(2)
Turb. Disch., Q_t, cfs	14.4	14.7	15	8	7	6	5	4	3	2	1.5	(3)
Assumed Eff., e	87	87	87	87	87	87	87	87	87	87	87	(4)
Dev. Power, kw	51,150	54,390	57,720	31,970	29,000	25,750	22,200	19,240	15,540	11,100	8,880	(5)
Percent of time		10	10	10	10	10	10	10	10	10	10	
Dev. Energy, Mwh		46,230	49,100	39,280	26,700	23,980	21,000	18,150	15,230	11,670	8,750	(6)
Annual Energy, Mwh	260,090											(7)

Notes:

(1) from flow duration analyses

(2) from hydraulic analyses of site and development

(3) In this example the turbine is designed for Q_{20} = 15,000 cfs. Flow through turbines for lesser discharges is river flow. Flow for higher flows (Q_{10}, Q_0) is assumed to be "orifice flow" controlled, or proportional to the square root of relative net heads: flow at 20% is $15\sqrt{\frac{50}{52}} = 14{,}700$ cfs.

(4) Efficiency assumed to be constant for this example only. The value combines turbine(s) and generator(s) efficiencies.

(5) Use the power equation $P_{kw} = \frac{HQ_t e}{11.81} = .074\ HQ_t$

(6) $$\text{Energy} = \left(\frac{P_1 + P_2}{2}\right)\left(\frac{\text{Percent of time}}{100}\right)\left(8760\ \frac{\text{hrs.}}{\text{yr.}}\right)\left(\frac{1}{1000}\right) = .438\ (P_1 + P_2)\ \text{Mwh}$$

(7) Sum of the incremental developed energies

Table 4. Annual Energy Calculations Using Daily Flow Duration Analysis Plant Installed Capacity Designed for Q_{20}.

Numerous site factors may control the eventual consideration of the potential development scheme. Many of these deal not so much with the specific site as they do with its relationship to other considerations. In the previously mentioned University of Idaho study we considered the following in attempting to preliminarily rank the sites according to their potential feasibility.

(1) Transmission Line Characteristics
    distance to nearest power line
    capacity of nearest power line
    owner of nearest power line

(2) Local Load Characteristics
    local residential load
    local Industrial load
    local pumping load
    distance to nearest city

(3) Land Use Restrictions
    - Wild and Scenic River designation
    - National recreation area
    - National Parks
    - National Wilderness area
    - Identified archeological sites

(4) Utility and Building Displacement
    - major highways
    - railroads
    - utility lines
    - buildings

(5) Fish Problems
    - supports run of salmonids
    - supports sturgeon population

The factors considered will vary depending upon the country or region, but a list of considerations should definitely be developed.

Although most small hydro developments will tend to be run-of-river, it is quite possible that the reservoir produced may be of sufficient volume to offer some regulation. It is, in any case, necessary to study the reservoir characteristics to determine the area to be inundated. Characteristics to be determined will include volume/elevation relationships, areal extent, and backwater effects.

IV. SELECTING THE RIGHT EQUIPMENT

Although the consulting engineer will be responsible for system design he will inevitably be dealing with equipment manufacturers. Those dealers can and will be very helpful in providing suggested equipment selection, and will often work with the engineers in suggesting system design considerations. In order to receive maximum benefit from the manufacturers, however, it is necessary to provide them with sufficient and accurate information. The following list of data required by manufacturer's was suggested by Mayo (1979a) of the Allis-Chalmers Corporation.

1. The name of the firm or corporation and individual with address and preferably phone number in order to provide a reply and/or obtain additional information.
2. Location and name of the plant or dam site. Most inquiries are cross-referenced by project name and frequently additional information is available on specific sites. If an old plant is involved, drawings of the original equipment will be filed under the purchaser's name and frequently plant name.
3. Approximate elevation of the plant above sea level is needed to obtain barometric pressure which is used in establishing the cavitation limits and also becomes significant in establishing generator cooling requirements.
4. Total quantity of water is required preferably in the form of a flow duration curve corrected for the drainage area at the particular site involved. The shape of the flow duration curve can have a substantial effect upon not only the size of the equipment, but also the number of units that may be selected.
5. The quality of the water becomes important primarily from the standpoint of erosion and whether or not the water is suitable for bearing lubrication. Corrosive water can substantially accelerate pitting damage caused by cavitation as can the effects of erosive materials.
6. Gross head becomes important from the standpoint of mechanical design of the hardware, however, just as important are correlated head duration and tailwater elevation duration curves. Not only will an extremely wide variation in head influence the equipment type of selection, but a wide variation in tailwater elevation

6. May necessitate a sumberged or waterproof powerhouse or a vertical turbine shaft arrangement.
7. The net effective head is the basis of all turbine power guarantees and is basically the responsibility of the equipment purchaser. This will be estimated by the turbine manufacturer if not specified.
8. The amount of power desired or required may only be significant if it is only a very small part of that available or is substantially greater than that available. Such situations will affect the value of the energy generated or the cost/value of the additional power.
9. Discharge or load at which maximum efficiency is desired becomes important primarily when it is not consistent with conventional turbine efficiency curves. It may be necessary or desirable to oversize or undersize the turbine or adjust the number of units.
10. Number and size of the units contemplated or required, now and for future installation, may only relate to existing structures. On the other hand, if the project schedule is to be compatible with a load schedule, this may be important. It is extremely important in order to minimize civil construction that complete information be provided concerning any given space limitations as well as details of existing foundations and superstructures. Existing crane capacities may limit the size or pieces as well as the installation schedule. Existing foundations may substantially reduce the civil construction costs or may be a substantial hindrance to the most economical development of a particular site.
11. The distance from normal tailwater levels to the powerhouse floor as well as correlated information with respect to tailwater elevations becomes particularly important when selecting the type turbine if the floor elevations will affect the location of the turbine with respect to tailwater. While a propeller type turbine would normally be used for low heads, it may be necessary to use a Francis type turbine if the runner must be set at a substantial distance above tailwater. Existing powerhouse floor elevations may influence access to the turbine.

11. Also, the cross sectional area and length of the tailrace will influence tailwater elevations and they may become a limitation on the plant capacity.
12. Proposed length, diameter and material of the supply pipe (penstock) if required or if existing, becomes very important from a head loss standpoint as well as water hammer and speed regulation considerations. As a rule-of-thumb, if the water passageway length exceeds three times the head, it becomes particularly important to investigate water hammer and speed regulation. The penstock or tunnel material will affect the velocity at which a pressure wave travels, therefore, will affect the water hammer calculations.
13. If a surge tank is installed or contemplated on the pipeline, the distance along the penstock from the surge tank data become vital to water hammer and speed regulation calculations.
14. Whether or not the plant operates separately or in parallel with an existing power system, will also affect speed regulation characteristics and the type of generator that may be used. If there are any particularly large motors to be started or severe load changes to be accommodated, these also will make a substantial difference with respect to the equipment supplied. In some cases it may be necessary to add a fly wheel to the equipment if it is not tied into a system and yet rather substantial load changes are expected.
15. The method of intended operation becomes important in selecting the control systems. Hydro units may be operated manually, semi-automatically, or fully automatically and may also have remote controls. For most small plants it is not practical to have a fully manned, manual plant. It is also usually not necessary to have a governor to control generator frequency, particularly if the unit is tied to a large system. Many of the small installations may be most economically operated from head water level control with automatic shutdown in emergencies and manual start-up so that in event of shutdown, an individual must visit the plant to make sure it is in proper working order before start-up.

16. Supplementary information with drawings or sketches are of substantial assistance in interpreting specific site situations. Topographical survey maps help provide precise locations and in many cases will identify transmission lines, gauging station locations, potential loads, access, interference with roadways and railroads, etc. Drawings of existing structures most easily communicate the potential interference or benefits of using such structures. Even a sketch relating the dam location to proposed powerhouse location, river bed and flood plan can be of substantial help in identifying factors that can substantially influence the turbine selection.

As noted in Section II on Small Hydro Technology, the typical development will probably consider variable pitch propellers ("Kaplan Turbines") very carefully because of the increased cost in spite of the vastly superior maintained efficiency. As shown, the efficiency curve for a fixed blade system will show a peak, at which point the best use of the water occurs. A hydro plant with a single non-adjustable turbine will then have only one flow with peak efficiency. For a run-of-river situation where there is some storage, it is possible that a single unit may be acceptable.

Where no storage exists, better use of the flow may be made if multiple units are incorporated. Multiple units may be of equal size or, for greater overall efficiency, of unequal size. As Purdy (1980) explains, "A plant with two unequal size turbines has three peak efficiency points, a plant with three unequal size units has seven peak efficiency points. The ideal sizing is approximately 70-30 and 57-28-15, respectively." As he notes, the important advantage is the much improved operation during low flow. Also because a large portion of the flow duration curve is used the system can be operated much closer to run-of-river, with little reservoir drawdown and consequently a high average head, see Figure 18.

The efficiency characteristics and operational limitations of the proposed installed systems are required to predict energy production.

Figure 19 and 20 show a simplified example of four equally sized turbines, the operation of which is superimposed first on a typical annual hydrograph, and second on a flow duration curve. As Fisher (1979) explains, (Figure 19) in periods of high water flow the full capacity of all four units is exceeded -- and presumably excess water is being discharged via spillways.

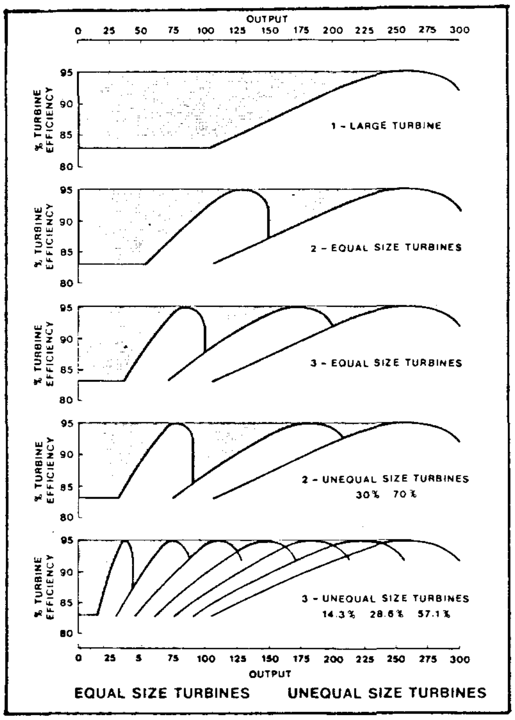


Figure 18. Comparison of Efficiencies With Various Turbine Size Combinations.

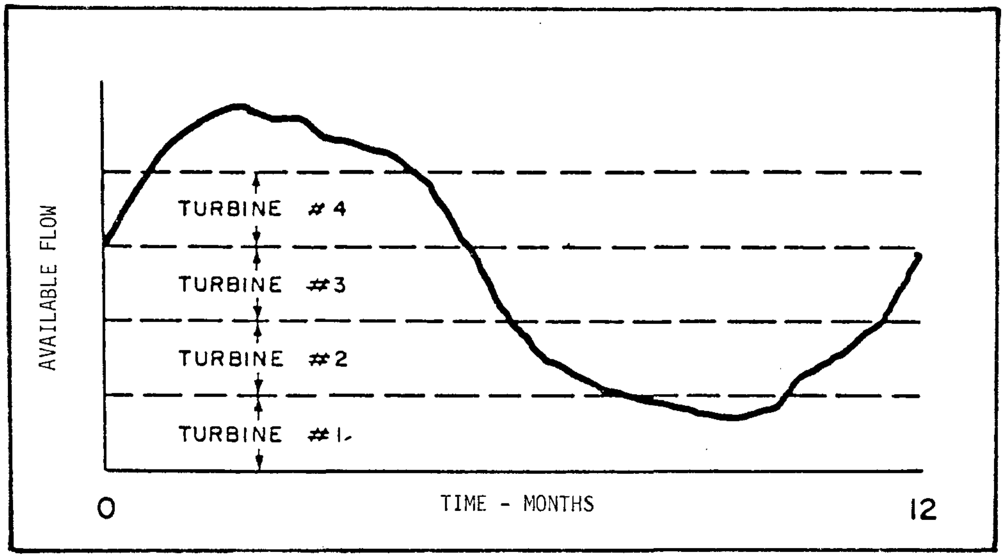


Figure 19. Monthly Average Flows At Site.

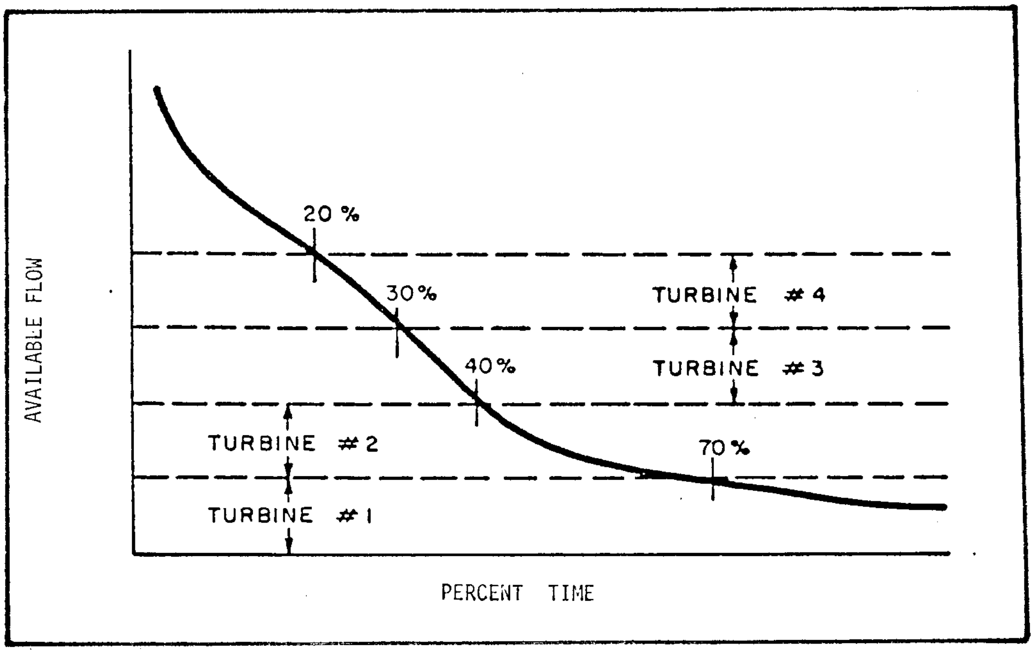


Figure 20. Typical Presentation of Flow Duration Data.

On the other hand, during the period of low flows one unit is used, and then only partially. Where the flow-duration curve is used (Figure 20) it can be seen that (in this example) one unit will operate 70 percent of the time at full capacity, two units will operate 40 percent of the time at full capacity, three units will operate 30 percent of the time at full capacity, and four units will operate only 20 percent of the time at full capacity. In this example for 20 percent of the time the flows exceed the turbine capacity and are not available for energy production.

As noted previously, the efficiency curve is considerably flattened with three unequally sized turbines as compared to three equally sized turbines. Note that Figure 18 shows the complete range of optimum efficiencies whereas Figure 20 indicates only the flows at which three equally sized turbines are being fully utilized. Figure 20 does not show how the turbines would be combined for intermediate flows for maximum overall efficiency.

Purdy (undated) also points out that principally for economic purposes, to allow the use of small high speed generators rather than large slow speed generators, speed increasers have often been used between the turbines and generators. He points out that the speed increaser can also be advantageously applied at sites where a large variation in head exists. It is quite possible under such circumstances that efficiencies may be so low at the extremes that the unit must be shut down. A suggested way of improving this situation is to provide for a change in turbine speed by installing more than one gear ratio in the speed increaser. In the synchronous generator arrangement, in which generator speed remains relatively constant, the variable gear ratio will then force a change in turbine speed, thus permitting the turbine to operate more efficiently. Purdy claims increases of average annual energy of as much as 15 percent by such arrangements. He also suggests that combination of variable gear ratios and unequal turbine sizes will result in an even higher operating range of peak efficiency.

V. ENVIRONMENTAL AND SOCIAL CONSIDERATIONS

The creation of an impoundment on a river changes the natural system. Small/low-head installations, in spite of the fact that they will typically be operated as run-of-river, will be no exception. Of course, changes will be expected to be comparatively small.

Because of their characteristically small physical size, and generally pollution-free operation, this essentially noiseless system should not be a threat to plants or animals of the surrounding ecological communities. Fish passage, of course, is a definite factor which planning must accomodate -- and from which controversy can be expected to arise. Likewise, recreational or visual use of the river can be expected to change -- another aspect which may raise the ire of some river enthusiasts.

A recent feature article in the Boise Statesman (Idaho) entitled, "Kilowatts or Kayaks?" sets a typical stage by beginning..., "A battle is brewing between a small band of whitewater enthusiasts and one of Idaho's largest corporations over a turbulent stretch of the North Fork of the Payette River..."

New impoundments (not all small hydro installations will require "dams" as we commonly think of that term) will clearly make changes on existing river systems. On the other hand in the U.S.A., at least, thousands of existing dams and impoundments have been identified where hydro power could be developed. In those situations the environmental changes have already taken place. There may be some stress during retrofitting (depending on the degree of effort required) but in general neither the existence of the new generating capability nor its operating characteristics should create any unreasonable change in environmental quality.

The use of existing facilities is not without the need for concern, however. For example, in the U.S.A. some developers are finding that they are being required to install fish-passage facilities on dams that for many years existed without them. This presents an interesting social complexity, for if the damsite is not used for hydro power it will presumably continue to "block" fish passage without any required change. In addition, it is quite possible that the new flow pattern created in the reservoir will temporarily disturb silt deposition that has accumulated and result in a temporary, at least, change in downstream water quality. Such a prospect would need to be carefully investigated.

Regarding safety of the structures, it is assumed that the quality and safety of a new installation will be ensured by modern design and construction methods -- sensational examples to the contrary, modern hydroelectric installations have an admirable record of safety. On the other hand, dams being considered for retrofitting were often designed and built at a time when modern codes and methods were not available. It is obvious that investigations of the structural stability, safety and concealed deterioration of these sites will be necessary. It is important to note, however, that those existing dams pose potential problems in their present form, and that the very consideration of them for retrofitting can only be considered a positive approach to safety, even though the result of the study may be a conclusion of economic infeasibility.

Even though it may be expected that the environmental and/or social effects of a small hydro project may be minimal it is important that the inquiries be systematic and thorough. Among the various topics suggested for consideration and discussion by the U.S. Department of Energy (Magleby, 1980) are:

Environmental Impact

1. The effects and available information on water quality in the impoundment and tailwater areas.
2. Anticipated or potential effects within the reservoir or downstream of flow and/or water level fluctuations due to daily and seasonal operations of the hydro facility.
3. The anticipated effect on known resident and migrating fish in the vicinity, and height of potential fish passage facilities.
4. The effect and extent of any dredging that might be required during development.
5. Review and discussion of previous environmental studies completed in the vicinity of the site.
6. Any anticipated changes in environmental conditions resulting from retrofitting or rehabilitating existing hydro plants.
7. Known or potential environmental issues at the site, such as past, present or planned designation as Wild or Scenic river or existence of any threatened or endangered species.

Safety Assessment

When an existing structure is to be used it is important that its safety be established. The assessment should discuss the safety hazard, if any, either existing or introduced by the development, and processes by which such conditions would be overcome.

Socio-Institutional Assessment

Any legal, social or institutional situations or constraints associated (or potentially associated) with the project should be investigated.

VI. ECONOMIC ASPECTS

Costs and Construction Schedules

Hydroelectric energy development is extremely site specific. Thus, it is not possible to generalize easily on the competitiveness of low-head hydro plants. Nevertheless, many small upgraded plants are producing energy for as little as 20 to 35 mills per kilowatt-hour.

With the technical advances being made in the design of turbines and more efficient construction methods (including a move to greater standardization) the competitive position is being increased.

The single greatest economic factor favoring hydro generation is that it is capital intensive -- there essentially being no fuel cost. Compared to the rapidly escalating cost of fossil fuels, the annual costs in hydro plant operations are a much less significant factor.

Hydroelectric equipment also has a history of being relatively problem-free. Downtime for maintenance can usually be scheduled.

As noted before, where dams already exist, the potential for economically upgrading or retrofitting is greatly enhanced. Economic studies have shown that moderate increases in efficiencies can often justify the additional investment.

Factors that will influence the investment of capital in existing facilities include: (1) the condition and useability of existing facilities, (2) the cost of safety and deficiency correction, (3) size and number of existing or potential units, (4) whether the plant can operate as "base load" or for "peaking", (5) the market potential for the generated energy, and (6) the environmental restraints for handling fish.

A report recently prepared for the U.S. Bureau of Reclamation by Tudor Engineering Co. as a guideline for the preparation of feasibility studies included a number of graphical illustrations of costs of the various factors. Figure 21, from that report, estimates the costs for bulb and rim turbine-generator installations.

Construction times for completion of small hydro installation depends entirely upon the site specifications. In general, however, two or three years is not an unreasonable estimate, depending upon what has to be accomplished. Mayo (1979b) compares construction schedules between a relatively large hydro expansion (Bonneville second powerhouse) and a small plant (Barker's Mill Lower Dam), Figure 22. The times do not, of course, include

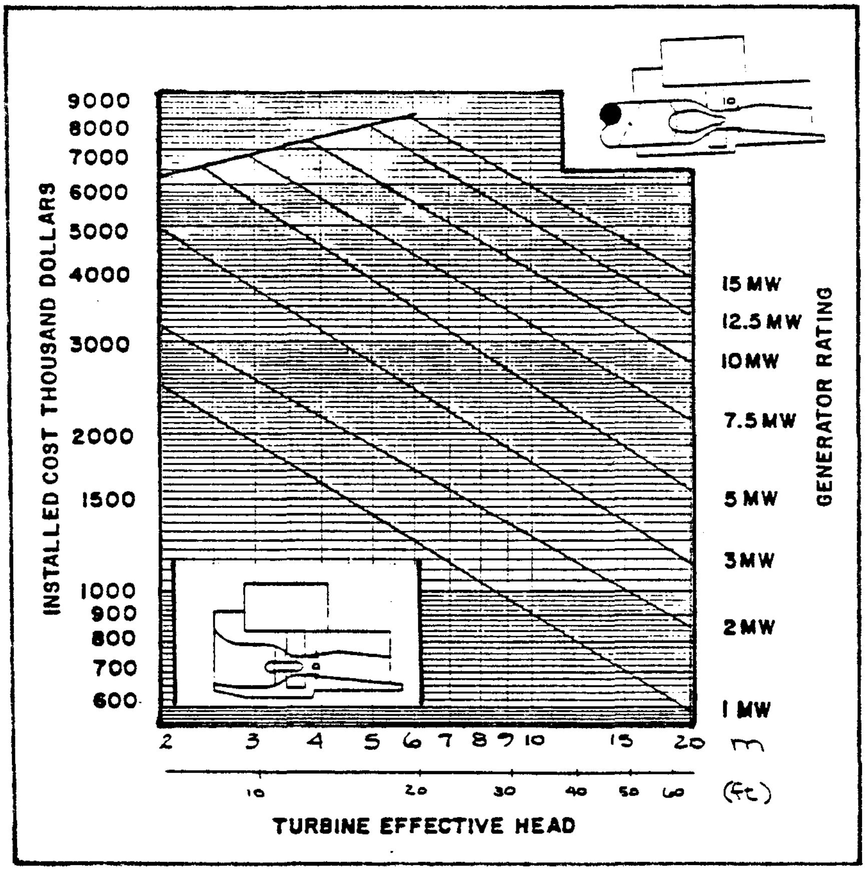


Figure 21. Estimated bulb and rim turbine generator costs, July, 1978 (TUDOR).

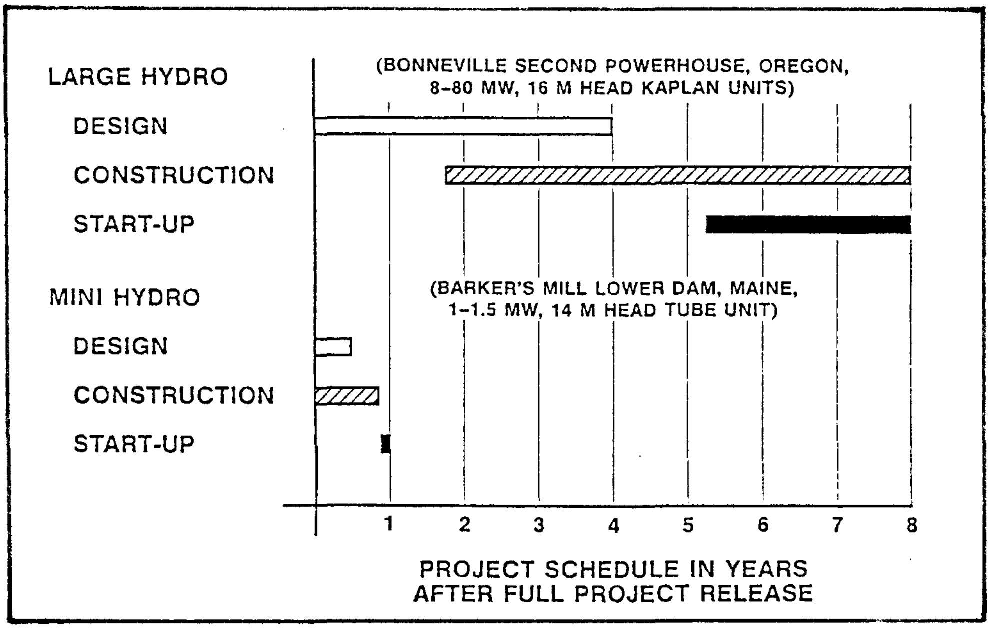


Figure 22. Comparison of Schedules for Large Hydro VS Small Projects.

the preliminary pre-design phase. As is the case in almost all energy developments these days in the U.S.A., furthermore, one has no way of predicting the existence of or the resulting delays from possible court suits.

Certainly one of the major factors hindering private investments in small hydro developments in the United States is the potential for interminable delays by court action. Particularly where the investments may be "close" in terms of payback, investors will be reluctant to provide the up-front funds for projects that might be killed through delays. As a result, the U.S. Government has established several programs to assist in the feasibility studies -- loans which, should the projects prove to be infeasible, would be forgiven.

Technical Problems and Solutions

If there are problems in the design of small hydro projects they are those of fitting the "mental" approach to the scale of operation. The economics of small hydro simply do not allow the luxury of time and funds characteristic of larger installations. In small hydro the feasibility study alone must often be viewed as a significant financial burden warranting an investment type decision by the potential project sponsor. Thus a systematic approach in the identification of alternative schemes is extremely important.

Although the selection methodology can be straightforward, the identification and conceptualization of alternative arrangements can be surprisingly difficult. According to a recent paper by Broome and Mayo (1979), the best approach seems to be to check every possible alternative for each major portion of the system against the governing constraints. They suggest the following principles apply when developing the candidate concepts:

- Minimize new construction and use as much of what is existing as can be relied upon and will serve the purpose.
- Avoid or minimize the use of temporary works such as cofferdams and bulkheads whenever possible.
- Eliminate buildings needed primarily for weather protections. (It can be provided more economically by integral equipment housing.)
- Eliminate personnel facilities (These stations will be unattended most of the time.)

- Eliminate permanent cranes. (Mobile cranes are quite suitable for installation and infrequent overhauls.)
- Increase the available head and power generating potential by use of collapsible flashboards that do not increase upstream flood damage exposure.
- Increase project benefits by the inclusion of water supply improvements, the addition of recreational facilities, or the enchancement of downstream aquatic habitats by low flow augmentation and/or regulation.

Economic Factors -- How Does Small Hydro Fit In?

Although there is nothing very new in the application of economic analysis to small hydro, I would like to begin by indicating that I will not include financial analysis, except incidentally. If a country wishes to encourage small hydro it may give special forgiveable loans for feasibility studies, or it may give tax-exempt status for certain kinds of bonds, or it may choose to give credit for reductions in imported fuels. In analyzing the feasibility of small hydro all of these factors may play an important role in the financial decision process. Whatever the incentives might be, however, it still remains that one way or another the small hdyro option must eventually be compared against alternative energy sources.

Let us look at one very simple case (see Figure 23). Since the Arab oil embargo of 1973, the cost of purchased electricity to the city of Ukiah, California increased from 9 mills per killowatt-hour in May, 1973 to 33 mills in May, 1977 (at that point the supplier was paying $15 per barrel of oil). A study by TUDOR Engineering Company (Willer, 1978) resulted in a suggestion that they satisfy a portion of their electrical needs by constructing a small hydroelectric plant at an existing flood control and water conservation dam nearby. The proposed 4,000 kw plant, it was determined, would supply about one-fourth to one-third of the city's needs at that time, at a cost of about 16-19 mills per killowatt-hour. The investigation of alternative energy sources was certainly worthwhile.

As Willer points out, the development of small hydroelectric projects versus continuing to purchase power wholesale has a potential advantage of hedging against inflation in power costs in that the cost of small hydro power should remain fairly constant over the life of the project.

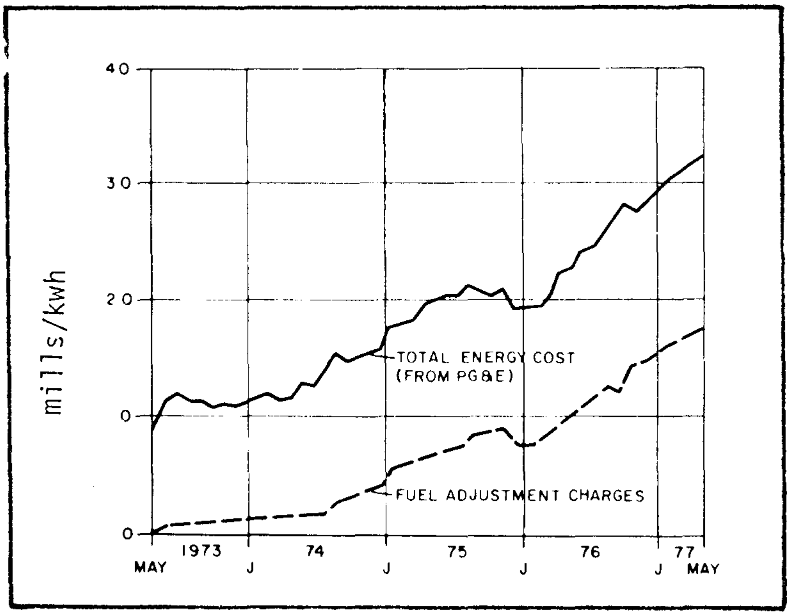


Figure 23. Cost of Purchasing Power, Ukiah, California, 1973-1976

To illustrate that point I have constructed a series of hypothetical situations regarding the cost of alternative power and capital cost of a small hydropower development. Three aspects are intended to be illustrated by this example:

(1) because hydro is capital intensive it is relatively free from the effects of inflation or increasing fuel costs.

(2) the cost of alternative energy sources is an important factor, and

(3) because money has value in alternative uses an interest rate must be assigned. The interest rate is also a very important consideration.

The hypothetical example assumes the following:

(1) installed generating capacity is 6 Mw.

(2) capital costs are assumed to be from $1000 to $3500 per installed kw, in $500 increments.

(3) capital costs are funded by a 40-year loan (alternatively at 7%, 10% and 15% interest).

(4) O & M costs assumed to be $50,000 the first year for all conditions.

(5) energy output is 20,000,000 kwh/year (all of which is used).

(6) energy value during the first year is assumed to vary between 20 and 50 mills/kwh (in 5 mill increments) -- this can be assumed, for example, to be the cost of purchasing energy from an alternative non-hydro source.

(7) Inflation rate of 5% per year is applied to the Hydro O & M and Energy value only.

(8) present worth is calculated using the assumed interest rate for the 40-year loan (7%, 10%, 15%).

Table 5 shows a typical computer output for the hypothetical Hydro Example. Information for the various combinations of assumptions is shown in Figure 24. They clearly show the advantage of heavy capital costs as compared to a heavy O & M and fuel burden during times of inflationary pressures. It should be noted that the value of 5% inflation assumption has been very conservative in the last several years.

The effect of increased interest is quite evident. This is further illustrated in Figure 25 in which the effect on the Benefit-Cost Ratio (present worth) is shown both as a function of interest rates, and cost of alternative energy. The three parts of Figure 25 are then summarized in Figure 26 which shows the break point for a Benefit-Cost Ratio of unity as a function of interest rate, cost of alternative energy, and the hydro capital cost.

And, finally, because proper financing must consider cash-flow, Figure 27 illustrates the periods of time before which a development's benefits can be expected to exceed the costs (for the 7% case).

It should be noted that the variability of interest rates is very much a function of the borrowing entity. It is thus quite possible for a particular site to be "unfeasible" to one group while being an excellent investment to another. As a result, the "financing" arrangements can be very important in hydro development.

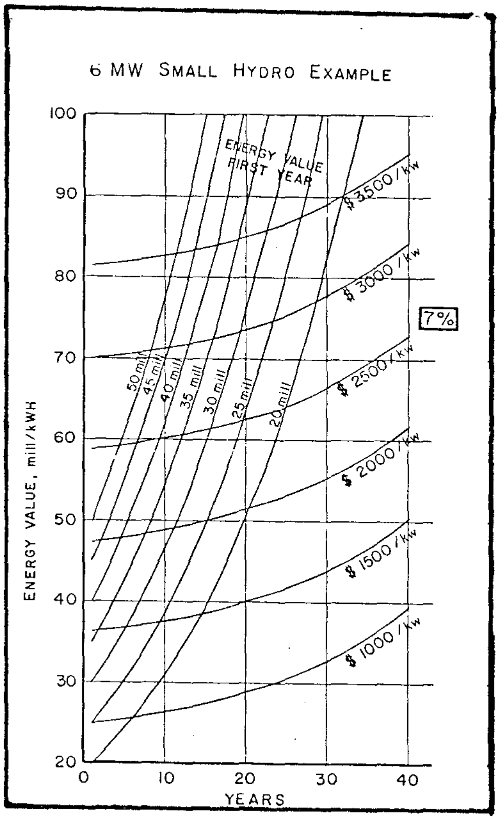
In the case of a small hydro development in which it is desired to wholesale the energy produced, the economic value of that energy depends directly upon the kind of energy that it would displace (oil, coal, etc.) in the elecrical load for the utility. However, because of uncertain water conditions -- small hydroelectric projects are typically run-of-river types with limited reservoir storage (and thus "dependable" capacity) -- their

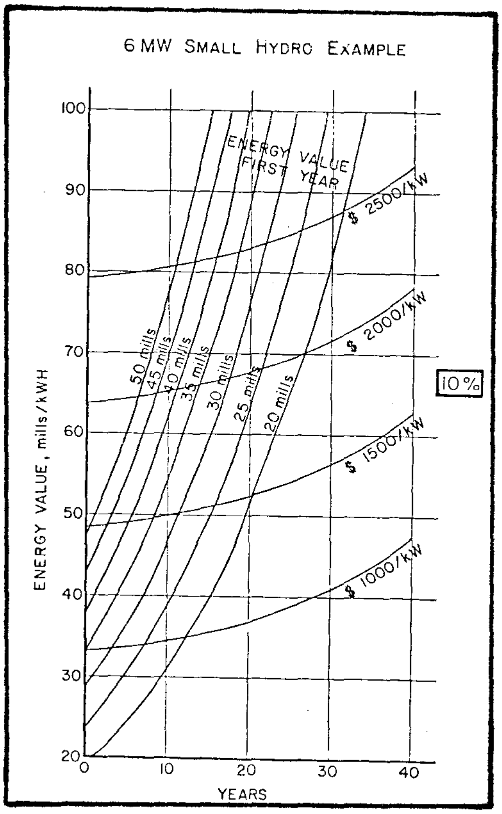
YEAR	REPAY ($) (40-year/10%)	O & M ($)	TOTAL ($)	HYDRO Mill rate (mills/kwh)	ENERGY PURCHASE ($)	PURCHASE Mill rate (mills/kwh)	PWF (10%)	PW COST ($)	PW BENEFIT ($)	PW SURPLUS ($)
1	920335.00	50000.00	970335.00	48.52	800000.00	40.00	0.9090914	882123.13	727273.06	-154850.06
2	920335.00	52500.00	972834.94	48.64	839999.94	42.00	0.8264475	803997.00	694215.88	-109781.13
3	920335.00	55124.99	975459.94	48.77	881999.88	44.10	0.7513167	732879.31	662661.25	-70218.06
4	920335.00	57881.24	978216.19	48.91	926099.81	46.30	0.6830157	668137.00	632540.69	-35596.31
5	920335.00	60775.30	981110.25	49.06	972404.75	48.62	0.6209239	609194.81	603789.38	-5405.44
6	920335.00	63814.06	984149.00	49.21	1021024.94	51.05	0.5644767	555529.19	576344.81	20815.63
7	920335.00	67004.75	987339.75	49.37	1072076.00	53.60	0.5131614	506664.56	550147.94	43483.38
8	920335.00	70354.94	990689.94	49.53	1125679.00	56.28	0.4665107	462167.38	525141.19	62973.81
9	920335.00	73872.63	994207.62	49.71	1181962.00	59.10	0.4241009	421644.38	501271.19	79626.81
10	920335.00	77566.25	997901.25	49.90	1241060.00	62.05	0.3855467	384737.50	478486.56	93749.06
11	920335.00	81444.50	1001779.50	50.09	1303112.00	65.16	0.3504974	351121.06	456737.31	105616.25
12	920335.00	85516.69	1005851.69	50.29	1368267.00	68.41	0.3186342	320498.69	435976.56	115477.88
13	920335.00	89792.50	1010127.50	50.51	1436680.00	71.83	0.2896676	292601.19	416159.63	123558.44
14	920335.00	94282.06	1014617.06	50.73	1508513.00	75.43	0.2633345	267183.63	397243.44	130059.81
15	920335.00	98996.13	1019331.13	50.97	1583938.00	79.20	0.2393953	244023.00	379187.25	135164.25
16	920335.00	103945.88	1024280.88	51.21	1663134.00	83.16	0.2176322	222916.44	361951.44	139035.00
17	920335.00	109143.13	1029478.13	51.47	1746290.00	87.31	0.1978475	203679.69	345499.19	141819.50
18	920335.00	114600.25	1034935.25	51.75	1833604.00	91.68	0.1798616	186145.06	329794.94	143649.88
19	920335.00	120330.25	1040665.25	52.03	1925284.00	96.26	0.1635107	170159.94	314804.56	144644.63
20	920335.00	126346.75	1046681.75	52.33	2021548.00	101.08	0.1486462	155585.25	300495.50	144910.25
21	920335.00	132664.06	1052999.00	52.65	2122625.00	106.13	0.1351330	142294.94	286836.69	144541.75
22	920335.00	139297.25	1059632.00	52.98	2228756.00	111.44	0.1228483	130174.00	273798.94	143624.94
23	920335.00	146262.06	1066597.00	53.33	2340193.00	117.01	0.1116804	119118.00	261353.75	142235.75
24	920335.00	153575.13	1073910.00	53.70	2457202.00	122.86	0.1015278	109031.63	249474.19	140442.56
25	920335.00	161253.88	1081588.00	54.08	2580062.00	129.00	0.0922980	99828.44	238134.63	138306.19
26	920335.00	169316.56	1089651.00	54.48	2709065.00	135.45	0.0839074	91429.69	227310.50	135880.81
27	920335.00	177782.38	1098117.00	54.91	2844518.00	142.23	0.0762795	83763.81	216978.44	133214.63
28	920335.00	186671.44	1107006.00	55.35	2986743.00	149.34	0.0693451	76765.38	207115.81	130350.44
29	920335.00	196005.00	1116340.00	55.82	3136080.00	156.80	0.0630410	70375.13	197701.50	127326.38
30	920335.00	205805.19	1126140.00	56.31	3292883.00	164.64	0.0573101	64539.20	188715.44	124176.19
31	920335.00	216095.44	1136430.00	56.82	3457527.00	172.88	0.0521002	59208.17	180137.63	120929.44
32	920335.00	226900.19	1147235.00	57.36	3630403.00	181.52	0.0473638	54337.40	171949.63	117612.19
33	920335.00	238245.19	1158580.00	57.93	3811923.00	190.60	0.0430580	49886.17	164133.88	114247.69
34	920335.00	250157.44	1170492.00	58.52	4002519.00	200.13	0.0391437	45817.39	156673.38	110855.94
35	920335.00	262665.25	1183000.00	59.15	4202644.00	210.13	0.0355852	42097.32	149552.00	107454.63
36	920335.00	275798.50	1196133.00	59.81	4412776.00	220.64	0.0323502	38695.17	142754.25	104059.06
37	920335.00	289588.38	1209923.00	60.50	4633414.00	231.67	0.0294093	35583.02	136265.56	100682.50
38	920335.00	304067.75	1224402.00	61.22	4865084.00	243.26	0.0267358	32735.32	130071.75	97336.38
39	920335.00	319271.13	1239606.00	61.98	5108338.00	255.42	0.0243053	30128.96	124159.50	94030.50
40	920335.00	335234.63	1255569.00	62.78	5363754.00	268.19	0.0220957	27742.69	118515.94	90773.19

BENEFIT/COST RATIO (PW) = 1.37

6 Mw/20,000,000 kwh Annual Energy
40 mill/kwh Thermal Energy Purchase Alternatives
Capital Cost: $1500/kw installed
Assumed interest rate: 10%
Assumed 5% annual inflationary rate on O & M and Purchase Energy

Table 5. Hydro Example - Calculation Sheet





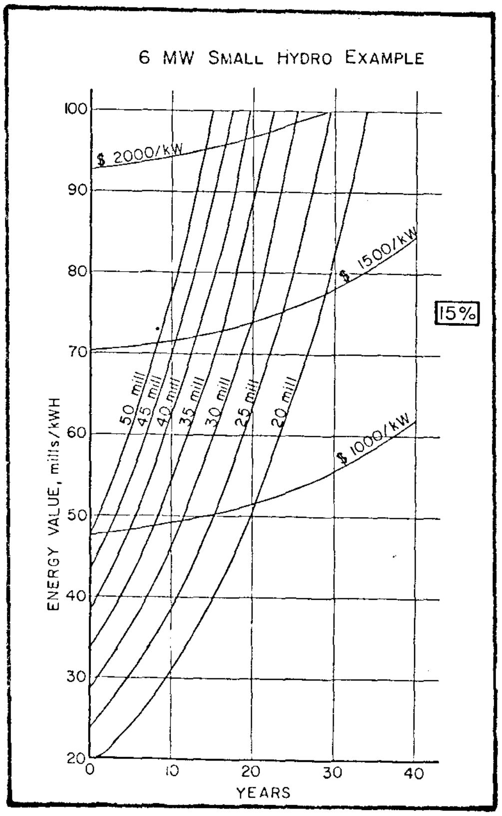
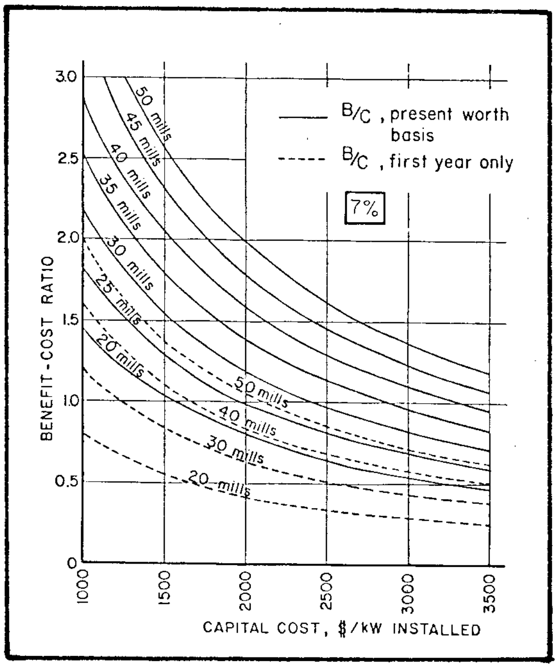
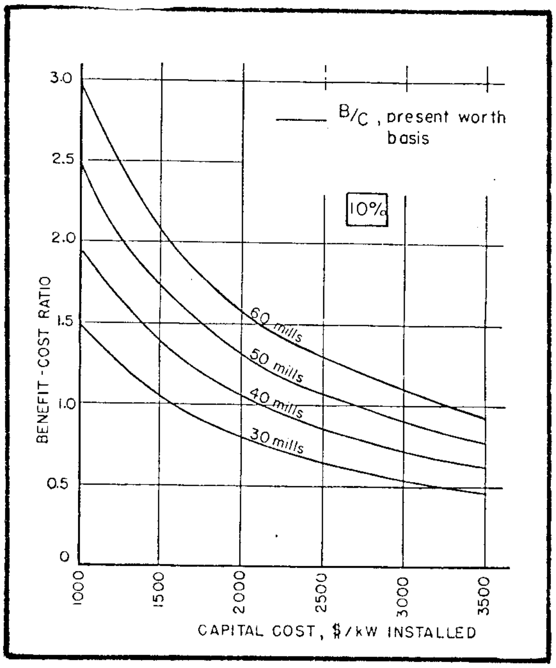


Figure 24. Cost of Hydro/ Purchase Energy -- Example Hydro





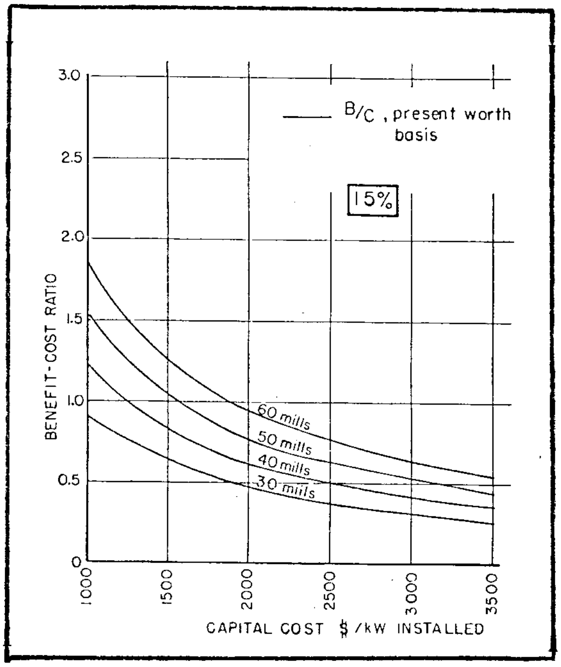


Figure 25. Benefit-Cost Ratio -- Example Hydro

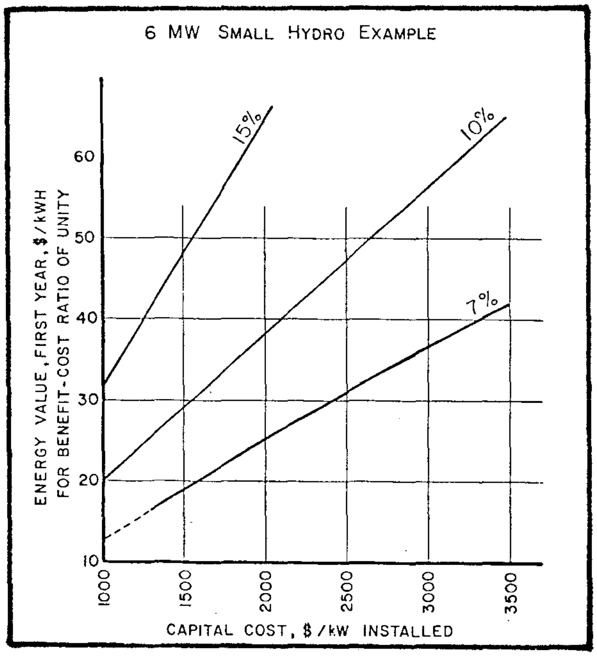


Figure 26. Benefit-Cost Ratio -- Example Hydro, Summary.

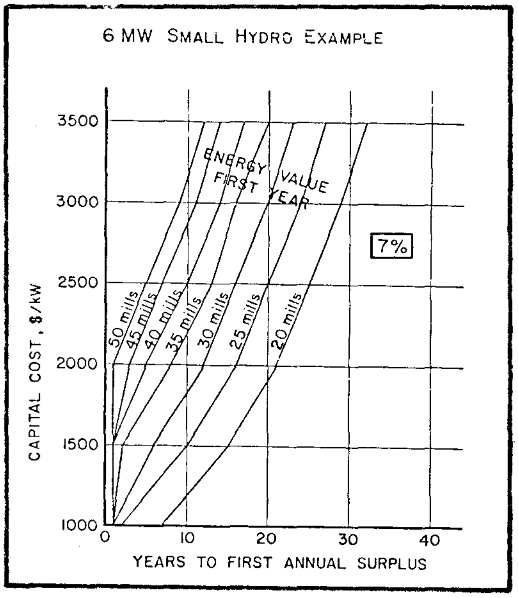


Figure 27. Year to first Positive Surplus -- Example Hydro, 7%.

role in the electric system is sometimes difficult to define. Nevertheless, a realistic estimate of capacity and energy benefits is essential.

Dependable capacity can be developed during low stream conditions; however, by-and-large the energy output can be expected to be used in the upper portion of the load curve for maximum economy rather than by displacing base power from the large thermal plants. Nevertheless, it is possible, even with a small reservoir, that dependable capacity can be developed in the upper portion of the load curve and thereby add to its value. As will be discussed later, one should not be too quick to categorize the value of the small hydro output if there is a system within which it may operate with some optimization.

Figure 28 (Willer, 1978) shows the power demand for a typical week for a U.S. utility. It shows that 6 Mw of capacity which is available for only five days a week for 12 hours a day can be considered dependable. The value of the capacity is normally expressed (in the U.S.) as dollars per killowatt-year and, as noted before, will vary depending upon the kind of generator being displaced.

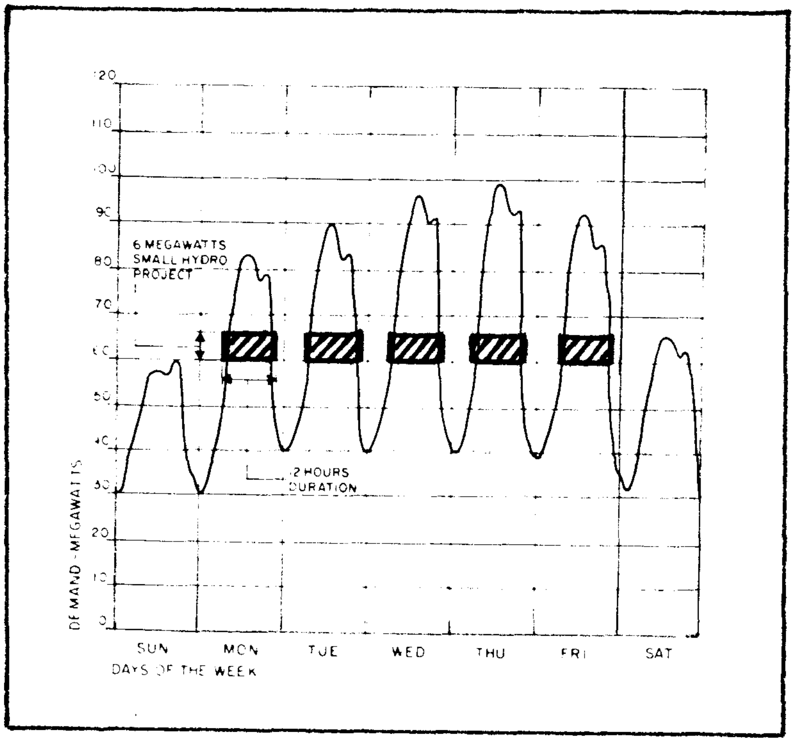


Figure 28. Small hydro use possibility on a typical weekly demand.

As Chen (1978) indicates, the proper way to select the installed capacity is to go through an optimization analysis, comparing incremental benefits to incremental costs. The economic analysis for isolated developments is conducted by comparing the hydro project with alternative generators providing the same service.

Where large electrical systems are involved they are often supplied by a number of generating units. In that case it is the combination of capabilities that determines the adequacy or reliability of the system. Thus, although a hydro plant may be unavailable during certain times for hydrologic reasons, the system will rely on other sources of power. As has been noted many times, hydro plants are more reliable than thermal plants and require less time for maintenance. Chen (1978) suggests that if a powerplant is available for only 80 percent of the time, it should be assigned a capacity value equal only to 80 percent of the full capacity value. Particularly where hydro plants are added to a thermal system this approach should be seriously considered inasmuch as it gives a more realistic comparison of capacity availability.

In considering "energy" value in an electrical system it would be important to be able to evaluate the "incremental system fuel cost" with and without the hydro plants added to the system. Clearly such costs would depend upon the generation mix of the system.

As Chen (1978) states: In essence, the hydro plant is dispatched in the system to achieve optimum operation or minimum energy cost of the system as a whole. Thus the optimum mode of a realistic operation of the hydro plant under existing and expanded conditions would be developed, and an estimate of the future benefits of hydro energy production is obtained.

When all the benefits and costs for the alternative power producing arrangements are identified and estimated, the economic analysis can be performed. Much as was illustrated before in this paper, the time value of energy is analyzed, appropriately by using present worth, and a life-cycle costing, approach. If the analysis is to be realistic, proper introduction of inflation and real cost increases should be accounted for. Without such considerations it has been shown that small hydro will too often, and incorrectly, appear to be non-competitive.

The optimum plant size is found when the difference between yearly costs and benefits is maximized. Figure 5 was used to show the calculation of the Benefit Cost Ratio. However, it is not the B/C ratio that is maximized. Nevertheless, using this procedure of Table 5, and following the example of energy calculation described in Table 4 (Section III) it is possible by incrementally enlarging the theoretical installed capacity (Q_{30}, Q_{25}, Q_{20}, ...) to find the maximum Benefit Minus Cost. An example of the typical curves that will be found are shown in Figure 29. The installed capacity that would be chosen, barring other non-economic factors, would be at the apex of the Benefit Minus Cost curve.

Figure 30 illustrates the difference in project cost allocation between large and small hydro where dams already exist (Mayo, 1979b).

Planning for Proper Management

Whenever I am asked for my opinion on small hydro I try to respond very carefully. Not because I have doubts about my facts, but because there are so many cases around where hydro's capabilities have been oversold. I spent one 2-hour period listening to a very knowledgeable

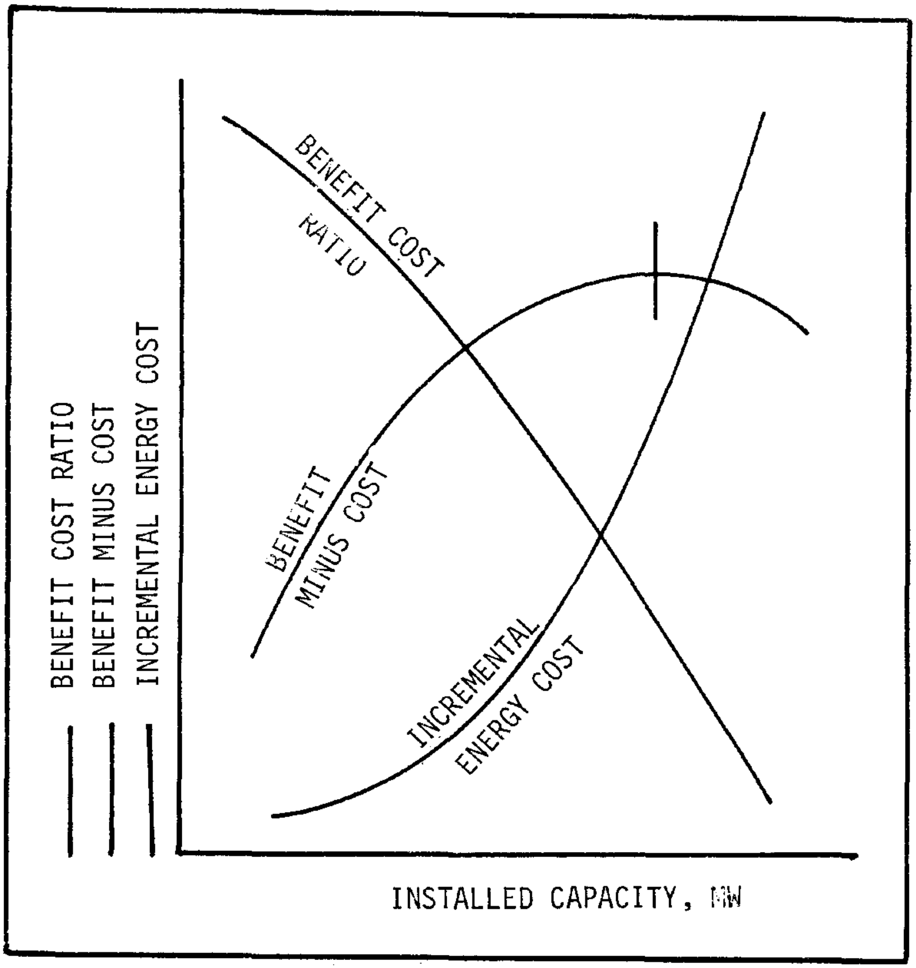


Figure 29. Analyses for Selecting Installed Capacity.

engineer tell me how stupid it was to develop these plants in remote areas and expect local "politicos" to run them properly. And, of course, he was absolutely correct -- except for one point: It was not the hydro system that failed, it was the lack of planning for proper management. The proper management of the system must be considered no matter what installed capacity is being considered.

In a discussion of micro-hydro installations Armstrong-Evans (1979) suggested some excellent ideas for consideration by planners, particularly if it is expected that local expertise will be used in the plant operations. As he notes, "If you build one large plant and it is a failure you lose everything, but with smaller units you can afford many more so you disseminate the technology faster and it is extremely unlikely that all your plants will fail. Even those plants that have failed can be moved on to new sites

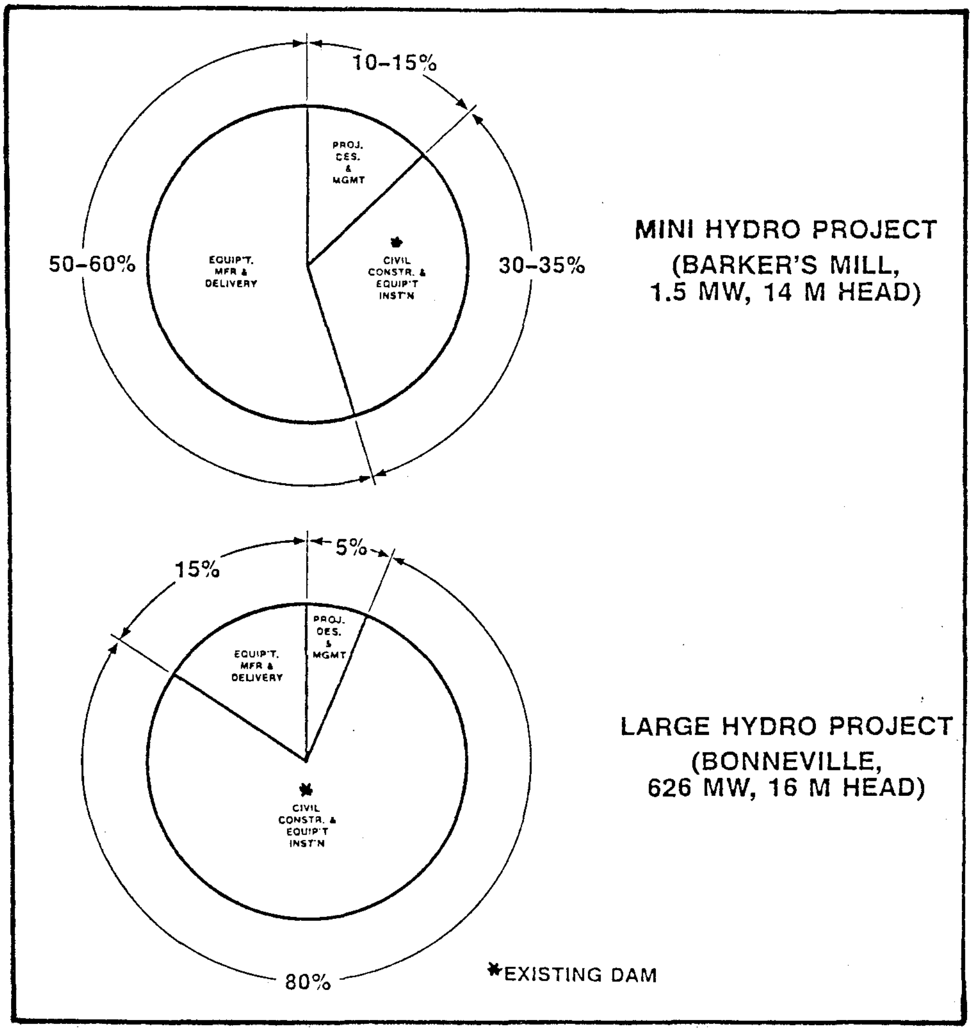


Figure 30. Comparison of Cost Breakdown for Large Hydro VS Small Hydro.

or rebuilt by those people who have made a success of other schemes, so all may not be lost even with initial failures. Large schemes, however, train few people and any mistakes in engineering tend to be very permanent and expensive to rectify."

He suggests that developments be planned for expansion and that "training" be a very important part of the total package. Several specific points for consideration are listed:

(1) In the expansion of a system will the existing plants simply lose their present consumers to a new project or will they be worked into the new system?

(2) Who will control water diversion and water rights?

(3) What standards of voltage and frequency will be adopted?

(4) Is it possible to use alternative energy sources (such as diesel) temporarily before a major water power scheme is constructed?

(5) What kinds of tariff structures can be used to stop peak load problems from developing?

(6) What industries can be promoted to use surplus power during wet seasons?

Finally, it must be realized that in those areas where electricity is being introduced for the first time, the early years of operation are very likely to be unprofitable. It will take time for the people to adjust to the use of electricity and for small industries to develop to use the newly available power. It is important that this be carefully evaluated and proper considerations be made to ensure the development's solvency.

VII. SUMMARY

With the increasing cost of alternative energy sources, small hydro is becoming an energy resource worth serious consideration. Many sites are economical now. Although small hydro has many positive attributes, it has negative aspects as well. Some of these positive and negative aspects of small/low-head hydro are summarized below.

Positive Aspects

* Hydropower uses a renewable resource.
* Capital expenditure is a one-time expense and not subject to inflationary factors.
* "Fuel" and operating costs are small compared to other energy alternatives.
* Hydropower is relatively non-polluting by almost any standard.
* The state-of-the-art is fully developed. We know what hydropower can and cannot do.
* The use of its water resource means that a country is less dependent upon external sources for its fuels.
* Many dams already exist without installed hydroelectric production capabilities. Installation at these sites will cause almost no additional environmental stresses and produce electricity at considerably lower unit cost.
* The simple fact is that in most parts of the world the hydroelectric potential far exceeds that which has been developed.

Negative Aspects

* Construction sites may not be available where stream flows are adequate to produce power in significant quantities.
* Because small/low-head plants will often be run-of-river the energy produced is extremely vulnerable to fluctuation in stream flows. Generation could fall to zero, requiring some back-up system.
* Unless the energy is to be used nearby, each plant may require separate installations of transmission facilities, substations and monitoring equipment. This could increase costs dramatically.
* Because of its small energy output, the unit cost of production may be high.

* Although it is claimed that environmental degradation will be smaller because of the obvious small scale of operation, the reaction of environmentalists and recreationalists has not yet been well tested. If it should prove to be as difficult to develop small hydro plants as to develop larger alternative energy sources it will be difficult to convince investors of the value of considering them.
* A large number of small plants implies a possibility of coordination and operation problems.

It is my opinion that if properly addressed, the negative aspects should not represent serious obstacles.

As stressed repeatedly, small hydroelectric energy generation will be but a small part of a total energy package. But the use of renewable water resources for electricity generation in conjunction with other development projects makes sense. It could make a significant positive contribution to any country's energy difficulties.

Finally, although this presentation may have given the impression that the planning and design of small hydroelectric plants is straightforward, it is not. Experience is extremely important, and knowing where efficiencies can be economically maximized for overall impact can be critical. As a result, I would like to finish by stressing the need for the careful selection of consulting engineering firms. Rediscovery of the wheel goes on all the time -- but it is an extremely costly business, which fortunately has a simple solution.

DEFINITIONS

Anadromous Fish -- fish, such as salmon, which ascend rivers from the sea at certain seasons to spawn.

Average Load -- the hypothetical constant load over a specified time period that would produce the same energy as the actual load would produce for the same period.

Base Load -- base load is that portion of the load curve where demand is continuous or nearly continuous 100 percent of the time.

Benefits (Economic) -- the increase in economic value produced by the hydropower addition project, typically represented as a time stream of value produced by the generation of hydroelectric power. In small hydro projects this is often limited for analysis purposes to the stream of costs that would be representative of the least costly alternative source of equivalent power.

Capacity -- the maximum power output or load for which a turbine-generator, station, or system is rated.

Capacity Value -- that part of the market value of electric power which is assigned to dependable capacity.

Capital Recovery Factor -- a mathematics of finance value used to convert a lump sum amount to an equivalent uniform annual stream of values.

Cost (Economic) -- the stream of value required to produce the hydroelectric power. In small hydro projects, this is often limited to the management and construction cost required to develop the power plant, and the administration, operations, maintenance and replacement costs required to continue the power plant in service.

Cost of Service -- cost of producing electric energy at the point of the ownership transfer.

Critical Streamflow -- the amount of streamflow available for hydroelectric power generation during the most adverse streamflow period.

Demand -- see Load.

Debt Service -- principal and interest payments on the debt used to finance the project.

Dependable Capacity -- the load carrying ability of a hydropower plant under adverse hydrologic conditions for the time interval and period specified of a particular system load.

Energy -- the capacity for performing work. The electrical energy term generally used is kilowatt-hours and represents power (kilowatts) operating for some time period (hours.)

Energy Value -- that part of the market value of electric power which is assigned to energy generated.

Feasibility Study -- an investigation performed to formulate a hydropower project and assess its desirability for implementation.

Firm Energy -- the energy generation ability of a hydropower plant under adverse hydrologic conditions for the time interval and period specified of a particular system load.

Firm Power -- in marketing, the energy from a hydroelectric project, the seller cannot assume delivery of any more power than is continuously available in minimal or critical water years. This power on which delivery can be assumed, even under worst-case circumstance, is called firm power.

Fossile Fuels -- refers to coal, oil, and natural gas.

Generator -- a machine which converts mechanical energy into electric energy.

Gigawatt (GW) -- one million kilowatts.

Head, Gross (H) -- the difference in elevation between the headwater surface above and the tailwater surface below a hydroelectric power plant, under specified conditions.

Hydroelectric Plant or Hydropower Plant -- an electric power plant in which the turbine/generators are driven by water.

Installed Capacity -- the total capacities shown on the nameplates of the generating units in a hydropower plant.

Interval Rate of Return on Investment -- the interest rate at which the present worth of annual benefits equals the present worth of annual costs.

Kilowatt (kW) -- one thousand watts.

Kilowatt-Hour (kWh) -- the amount of electrical energy involved with a one-kilowatt demand over a period of one hour. It is equivalent to 3,413 Btu of heat energy.

Load -- the amount of power needed to be delivered at a given point on an electric system.

Load Curve -- a curve showing power (kilowatts) supplied, plotted against time of occurrence, and illustrating the varying magnitude of the load during the period covered.

Load Factor -- the ratio of the average load during a designated period to the peak or maximum load occurring in that period.

Magawatt (MW) -- one thousand kilowatts.

Megawatt-Hour (MWh) -- one thousand kilowatt-hours.

Multi-Purpose River Basin Program -- programs for the development of rivers with dams and related structures which serve more than one purpose, such as - hydroelectric power, irrigation, water supply, water quality control, and fish and wildlife enhancement.

Outage -- the period in which a generating unit, transmission line, or other facility, is out of service.

Peaking Demand -- peak demand is the maximum demand in kilowatts for a given period. For example the annual peak demand is the maximum demand in kilowatts that occurs within a year; the daily peak demand is the maximum demand in kilowatts that occurs within a given day.

Peak Load -- the maximum load in a stated period of time.

Plant Factor -- ratio of the average load to the plants' installed capacity expressed as an annual percentage.

Pondage -- the amount of water stored behind a hydroelectric dam of relatively small storage capacity used for daily or weekly regulation of the flow of a river.

Power -- the rate of work done. Electric power refers to the generation or use of electric energy, usually measured in kilowatts.

Power Factor -- the percentage ratio of the amount of power, measured in kilowatts, used by a consuming electric facility to the apparent power measured in kilovolt-amperes.

Project Sponsor -- the entity controlling the small hydro site and promoting the construction of the facility.

Pumped Storage -- an arrangement whereby electric power is generated during peak load periods by using water previously pumped into a storage reservoir during off-peak periods.

Reconnaissance Study -- a preliminary feasibility study designed to ascertain whether a feasibility study is warranted.

Secondary Energy -- all hydroelectric energy other than Firm Energy.

Service Outage -- the shut-down of a generating unit, transmission line or other facility for inspection, maintenance, or repair.

Spinning Reserve -- generating units operating at no load or at partial load with excess capacity readily available to support additional load.

System, Electric -- the physically connected generation, transmission, distribution, and other facilities operated as an integral unit under one control, management or operating supervision.

Thermal Plant -- a generating plant which uses heat to produce electricity Such plants may burn coal, gas, oil, or use nuclear energy to produce thermal energy.

Turbine -- the part of a generating unit which is spun by the force of water or steam to drive an electric generator. The turbine usually consists of a series of curved-vanes or blades on a central spindle.

Turbine/Generator -- a rotary-type unit consisting of a turbine and an electric generator.

Turbine Efficiency -- turbine efficiency refers to the ratio between the actual power output of the turbine and the theoretical power output for a "perfect" turbine. Efficiency can refer to the turbine by itself, or to the plant as a whole, including the generator and any gear box, clutch or similar unit. In this report, efficiency refers to the power production of the plant as a whole.

Vertical Integrated System -- refers to power systems which combine generation, transmission, and distribution functions.

Watt -- the rate of energy transfer equivalent to one ampere under a pressure of one volt at unity power factor.

Wheeling -- transportation of electricity by a utility over its lines for another utility; also includes the receipt from and delivery to another system of like amounts but not necessarily the same energy.

BIBLIOGRAPHY

Armstrong, E.L., 1978, "The Impact of the World's Energy Problems on Low-Head Hydroelectric Power," Low-Head Hydro by Gladwell and Warnick, 1978, pp. 13-20.

Armstrong-Evans, R., 1979, "Micro-Hydro as an Appropriate Technology in Developing Countries," paper presented at Waterpower '79, International Conference on Small Scale Hydro, Washington, D.C., Oct. 1-3, 1979.

Broome, K.R. and Mayo, H.A., 1979, "The Optimization of Civil Works Design for Small-Scale Hydropower Projects," paper presented at Waterpower '79, International Conference on Small Scale Hydro, Washington, D.C., Oct. 1-3, 1979.

Butcher, W.R., 1978, "The Need for Better Forecasting," Low-Head Hydro by Gladwell and Warnick, 1978, pp. 45-50.

Carlson, J.L. and Samuelson, R.S., 1977, "Low Head Generation with Bulb Turbines," paper presented to Northwest Public Power Association, Engineering and Operation Conference, Coeur d'Alene, Idaho

Chen, H.H., 1978, "Economics of Low-Head Hydro: U.S. Case Studies," Low-Head Hydro, by Gladwell and Warnick, 1978, pp. 65-69.

Corps of Engineers, North Pacific Division (1979), "Hydropower Cost Estimating Manual," prepared for Institute of Water Resources National Hydropower Study, May, 1979.

Davis, D.W., 1979 (a), "Technical Factors in Small Hydropower Planning," paper presented at Water Systems Specialty Conference, American Society of Civil Engineers, February, 1979, Houston, Texas. Published as U.S. Corps of Engineers, Hydrologic Engineering Center Technical Paper No. 61.

Davis, D.W., 1979, (b) "Planning Small Scale Hydropower Additions," paper presented at Waterpower '79, International Conference on Small Scale Hydro, Washington, D.C., Oct. 1-3, 1979.

Fisher, R.K., 1979, "Optimization and Selection of Hydro-Turbines Based on Considerations of Annual Energy," paper prepared for University of Wisconsin Low-Head Hydropower Development Seminar, April 30-May 3, 1979.

Frick, P.A. and G.C. Alexander, 1979, "Cost of Controls for 'Small Hydroelectric Plants' or River Systems," report to U.S. Department of Energy, DOE/ET/28310-1, Oregon State University, February, 1979.

F.W.E. Stapenhorst, Inc., undated, "Ossberger Turbine Generating Sets," (company brochure).

Gladwell, J.S., 1980 (a), "Low-Head Hydro -- A State-Of-The-Art Discussion," Proceedings, American Nuclear Society Meeting, Feb. 27-29, 1980, Los Angeles, California, pp. III-4-1 to III-4-26.

Gladwell, J.S., 1980 (b), "Small Hydroelectric Energy Generation -- Some Technical Considerations," paper prepared for presentation at the Costa Rican Workshop on Energy and Development, San Jose, Costa Rica, March 17-21, 1980. Workshop co-sponsored by the National Academy of Sciences (USA) and the National Research Council of Costa Rica.

Gladwell, J.S., 1980 (c), "Small Hydroelectric Energy Generation -- Some Economic and Planning Considerations," paper prepared for presentation at the Costa Rican Workshop on Energy and Development, San Jose, Costa Rica, March 17-21, 1980. Workshop co-sponsored by the National Academy of Sciences (USA) and the National Research Council of Costa Rica.

Gladwell, J.S. and Warnick, C.C., 1978, LOW-HEAD HYDRO, Idaho Water Resources Research Institute, University of Idaho, Moscow, Idaho, 206 pp.

Gladwell, J.S. and Warnick, C.C., 1979, "Small Hydro -- A Viable 'Alternative' Now," paper presented at Waterpower '79, International Conference on Small Scale Hydro, Washington, D.C., Oct. 1-3, 1979.

Gladwell, J.S. and Warnick C.C., 1979, "Small Hydro -- A Second Chance," Water International (March), pp. 9-21, 24.

Gladwell, J.S., et. al., 1979, "A Resource Survey of Low-Head Hydroelectric Potential in the Pacific Northwest Region - Phase I and II," project completion reports to U.S. Department of Energy, Idaho Water Resources Research Institute, University of Idaho.

Höller, K. and Miller, H., 1977, "Bulb and Straflo Turbines for Low Head Power Stations," Escher Wyss News, 2/1977.

Hopper, H.R., Mayer, H.W., and Severn, B., 1978, "Manitoba Hydro and Straflo Units," paper presented at 92nd EIC Conference, St. Johns Newfoundland.

Klotz, L.H. and Manasse, F.K., 1977, "Low-Head/Small Hydroelectric Workshop," New England Center for Continuing Education, University of New Hampshire.

Magleby, H.L., 1980, "Hydro Power Assessment and DOE Loan Applications," paper prepared for Small Hydroelectric Workshop, sponsored by U.S. Department of Energy, Spokane, Washington, March, 1980.

Mayo, H.A., Jr., undated, "Low Head Hydroelectric Fundamentals," Allis-Chalmers, Hydro-Turbine Division, York, Pennsylvania.

Mayo, H.A., Jr., 1979 (a), "Turbine Selection," paper presented at short-course on Small Scale Hydro Power Feasibility, Planning and Design, University of Idaho.

Mayo, H.A., Jr., 1979 (b), "Standardization of Hydroelectric Generating Units for Low-Head Hydropower Development," paper presented by Department of Engineering, University of Wisconsin.

Mayo, H.A. and Smith, C.W., 1979, "Small Hydro Control and Operation," paper presented at short-course on Small Scale Hydro Power Feasibility, Planning and Design, University of Idaho.

Mercer, A.G., 1978, "Very-Low-Head Hydroelectric Generation," Low-Head Hydro, by Gladwell and Warnick, pp. 103-113.

Miller, H., 1978, "Choice of Hydro-Electric Equipment for Tidal Energy," paper presented at the Korea Tidal Power Symposium.

Moore, B. and Gladwell, J.S., "Micro-Hydro, A Bibliography," Idaho Water Resources Research Institute, University of Idaho.

Moore, E.A., 1978, "Electricity Supply and Demand Forecast for Developing Countries," Energy, Water and Telecommunication Departments, World Bank.

Morrison-Knudsen Co., undated, "Hydroelectric Comeback -- A Competitive Response," (Company brochure).

Pugh, C.A., 1979, "Standardized Intakes and Outlets for Low-Head Hydropower Developments, State-Of-The-Art Report," U.S. Bureau of Reclamation, Engineering and Research Center.

Purdy, C.C., 1979, "Energy Losses at Hydroelectric Power Plants," paper presented at Waterpower '79, International Conference on Small Scale Hydro, Washington, D.C., Oct. 1-3, 1979.

Purdy, C.C., undated, "Speed Change Results in Improved Turbine Performance," published by TAMS, Consulting Engineering Company.

TUDOR ENGINEERING COMPANY, 1979, "Lower Limits -- Low-Head Hydroelectric Installations," Interim Report - Preliminary Construction Costs, prepared for Division of Research Engineering, U.S. Bureau of Reclamation, April, 1979. (draft).

U.S. Army Corps of Engineers, 1977, "Estimate of National Hydroelectric Power Potential at Existing Dams," Institute for Water Resources, Ft. Belvoir, Virginia.

Viessman, W., 1978, "Federal Legislative Considerations," Low-Head Hydro, by Gladwell and Warnick, pp. 124-128.

Willer, D.C., 1978, "Some Basic Considerations," Low-Head Hydro, by Gladwell and Warnick, 1978, pp. 58-64.

World Energy Conference, 1978, "World Energy Resources 1985-2000," Executive Summaries on Resources, Conservation and Demand, to the Conservation Commission of the World Energy Conferences, IPC Technology Press, London, 250 pp.

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