US Army Corps
of Engineers
Hydrologic Engineering Center

Potential for Increasing the Output of Existing Hydroelectric Plants

June 1981

TP-78

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
June 1981	Technical Paper	

4. TITLE AND SUBTITLE
Potential for Increasing the Output of Existing Hydroelectric Plants

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Darryl W. Davis, John J. Buckley

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
TP-78

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Presented at Waterpower '81, an International Conference on Hydropower, Washington, D.C., 22-24 June 1981.

14. ABSTRACT
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15. SUBJECT TERMS
hydropower, existing hydroelectric plants, renewable energy, uprating plants, efficiency increases

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER**
U	U	U	UU	26	

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POTENTIAL FOR INCREASING THE OUTPUT OF EXISTING HYDROELECTRIC PLANTS 1/

by
Darryl W. Davis* and John J. Buckley*

INTRODUCTION

The investigation reported herein (Hydrologic Engineering Center 1981) was undertaken to address the question of how much additional power might be generated at existing hydroelectric plants throughout the United States. The investigation was one of several special studies performed as part of the Corps of Engineers National Hydroelectric Power Study (NHS) (Institute for Water Resources 1979). The potential for increasing power output both through physical improvements in generating equipment and by changes in the manner that existing projects are operated were investigated and estimates of power increase prepared. The investigation was nationwide in scope, including Hawaii, Alaska, and Puerto Rico. All existing hydroelectric plants, regardless of ownership, were investigated for improvement in power output. The potential is identified by the type of improvement and is reported as aggregate regional values and national summaries.

The amount of power that can be generated at an existing hydroelectric power site is physically limited. The governing factors that determine this limit are: (1) the amount of flow volume that can pass through the powerhouse at a given time, (2) the "head" or elevation difference between the upstream and downstream water bodies acting at the time of power generation, and (3) the generation or "conversion" efficiency, i.e., the mechanical and electrical equipment efficiency in converting potential and kinetic energy of flowing water into electrical energy.

In order for there to be additional potential at an existing project, e.g., some "unused energy," an opportunity must exist for: (1) passing more of the annual volume through the powerhouse (there must be existing spill), (2) increasing the effective operating head (higher pool levels possible), or (3) technical opportunity to generate more efficiently from available head and flow. The option of increasing the storage capacity (raising the dam) was not considered in this study.

Short of this, all other measures that might be undertaken at a site that could effect the opportunities listed above and thereby increase energy output were considered. The primary measures for increasing energy output are: adding new generating units, rehabilitating or replacing existing units, modifying water handling facilities and, altering existing operating policies (reallocation of existing storage and/or change of annual and seasonal operation rule curves).

1/Presented at Waterpower '81, an International Conference on Hydropower, June 22-24, 1981, Washington, D.C.

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Excess flow or spill is by far the most important opportunity for increasing power output at an existing project. The measures available for capturing and routing additional flow volume through the powerhouse include: increasing the plant's generating capacity by adding additional generating units (expanding the powerhouse) or uprating existing units to higher generating capacity by rehabilitating, modifying or replacing turbines and/or generators; increasing the effective utilization of storage by reallocating additional storage to the power pool; and/or coordinating generation among a system of generating plants. For increasing the operating head, reallocation, or quasi-reallocation through modified rule curves and operating practices is necessary. Increasing the operating head may require that generating units be changed or modified to accommodate sustained operation at heads exceeding the design limits of the existing equipment. The measures available for increasing the conversion efficiency are those that can reduce the fluid energy loss in flow passage and energy loss in converting fluid energy (flow and head) to mechanical energy (turbine output) to electrical energy (generator output). The significant practical opportunity is improvement of the energy conversion efficiency of the hydraulic turbine since the energy conversion efficiency of electrical generators is quite high (about 95%) and modification of the water passage works of tunnels, penstocks, and draft tubes to reduce hydraulic energy loss would likely require significant and costly construction for minor increases. Table 1-1 summarizes the energy increase opportunities and candidate measures considered for capturing the potential.

Table 1-1.
MEASURES FOR INCREASING ENERGY OUTPUT OF EXISTING HYDROPOWER PLANTS

Measure	:	Spill Capture	Head Increase	Efficiency Increase
Add New Units	:	X		
Replace Existing Units	:	X		X
Modify Existing Units	:	X		X
Modify Water Passage	:			X
Reallocate Reservoir Storage	:	X	X	
Improve System Operation	:	X	X	

The main source of information for this study was the data base developed for the National Hydropower Study. The data base, compiled by the District offices of the Corps of Engineers, contains storage space for over 600 data items relevant to each site. There is selected incomplete information stored for more than 15,000 sites with detailed information on 6,000 sites. Those sites with existing hydropower facilities (1,288) were extracted from the file and an additional data item entitled "Equipment Information" (supplied by the Federal Energy Regulatory Commission) was added and a new separate "study" file created. Relevant data items in this computer file are shown in Table 1-2.

Table 1-2. STUDY FILE - PLANT AND REGIONAL DATA

Item	Percentage* of Sites	Percentage of** Total Capacity
Installed capacity in kilowatts	100	100
Average annual energy	99	99
Turbine type	27	66
Age of installation	59	96
Rating of turbine	27	76
Rating of generator	28	76
Design head	28	76
Number of units	28	76
Weighted net power head	100	100
Average annual inflow	93	96
Flow duration data	78	86
Depth of the flood-control space, feet	14***	28
Regional dependable capacity benefit in $/kW-yr	100	100
Regional average annual energy benefit in $/MWh-yr	100	100

* 1,288 sites catalogued in data file.
** Total installed capacity of sites in file is 63,375 MW.
***Represents all existing sites that have flood control storage.

EXISTING HYDROPOWER FACILITIES

The total installed capacity of the existing 1,288 sites that were identified and catalogued into the study file is 63,375 megawatts (MW) and they generate 272,552 gigawatt hours (GWh) of electrical energy per year. Tables 2-2 and 2-1 summarize types and ownership of existing hydropower development. Figures 2-1, 2-2, and 2-3 summarize information on installation date, head, and installed capacity of existing plants. A sampling of the types of turbines representing 80% of the total installed capacity indicates that reaction turbines (Francis) are the predominate type--66%, followed by propeller--25% (Kaplan--17%, fixed blade--8%), then impulse (Pelton)--5%, and other--4%.

Table 2-2. TYPES OF EXISTING HYDROELECTRIC PLANTS

Plant Type	Number of Plants	Capacity kW	Average Annual Energy MWh
1. Run-of-River	431	8,632,900	38,311,800
2. Diversion	160	2,332,900	12,899,300
3. Reservoir	501	44,790,800	190,417,000
4. Reservoir with Diversion	190	7,604,000	30,848,500
5. Other	6	14,800	75,400
Totals	1,288	63,375,400	272,552,000

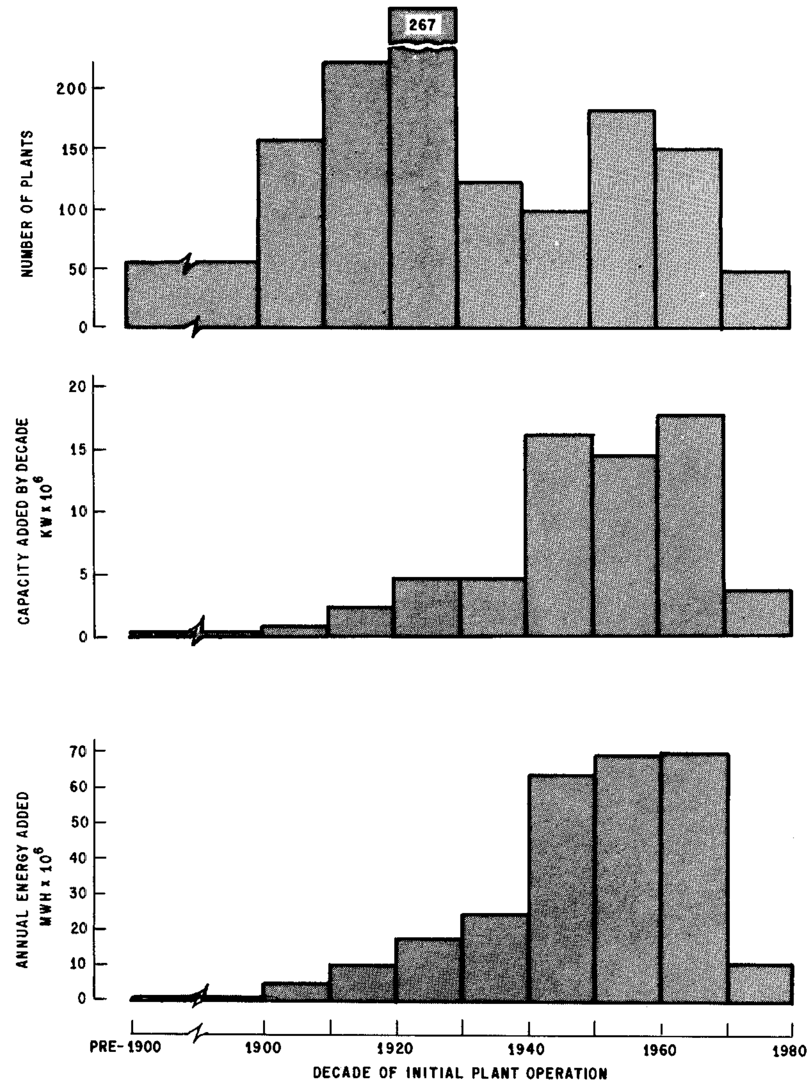


Figure 2-1. PLANT AGE VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

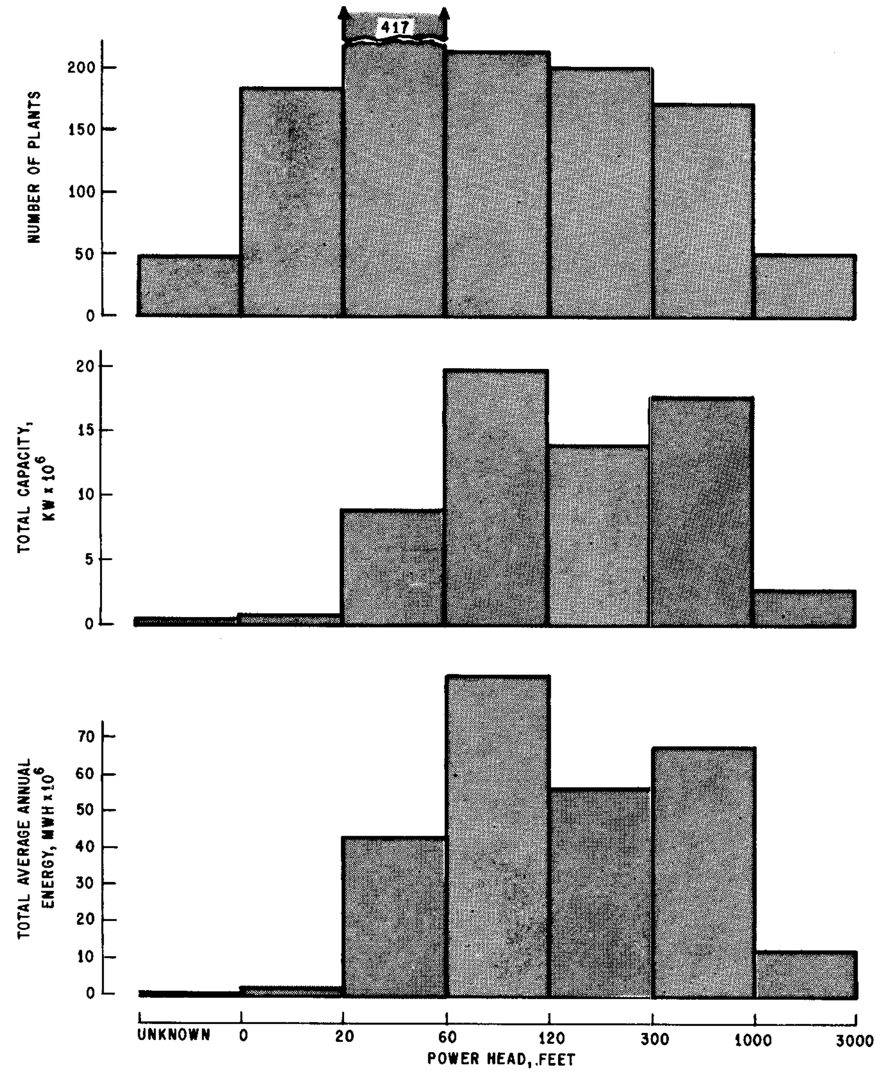


Figure 2-2. POWER HEAD VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

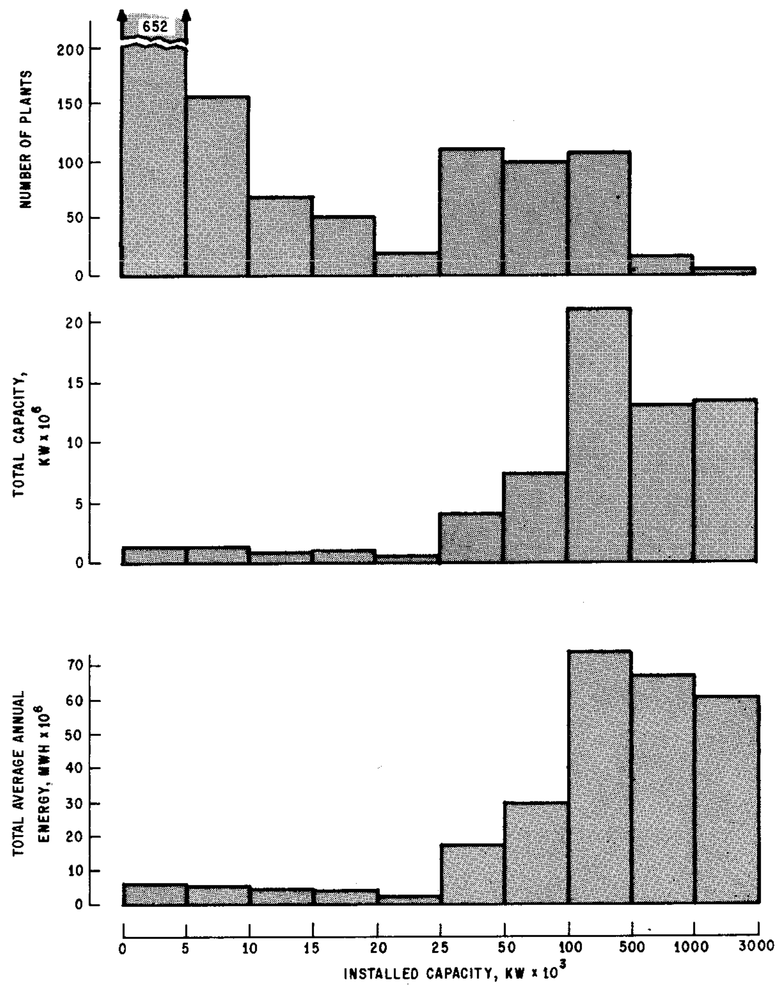


Figure 2-3.

INSTALLED CAPACITY VS. NUMBER OF PLANTS, CAPACITY, AND ENERGY

Table 2-1. OWNERSHIP OF EXISTING HYDROELECTRIC PLANTS *

Ownership Category	Number of Plants	Total Capacity kW	Total Average Annual Energy MWh
1. Corps	92	19,232,900	81,761,400
2. Other Federal	92	14,948,300	63,026,500
3. Non-Federal, Government	151	8,728,000	42,550,700
4. Investor Owned Utility	504	13,977,600	60,342,600
5. Cooperatively Owned Utility	57	2,330,100	8,353,500
6. Other Commercial or Industrial Firm	241	1,745,600	8,359,800
7. Private Citizen or Non-utility Cooperative	41	858,400	4,389,600
8. Unknown	110	1,554,500	3,767,900
Totals	1,288	63,375,400	272,552,000

* All information taken from study computer data file.

EQUIPMENT CHARACTERISTICS

Improvements due to research, materials, and design over the last 80 years have resulted in it being technically feasible to obtain substantial increases in capacity and to a lesser degree increases in efficiency from existing hydroelectrical equipment. When uprating an existing generating unit the amount of actual increase that can be obtained is limited by the specific design and manufacturing characteristics of the installed equipment. The year of manufacture or installation is used herein as an indicator of potential to assist in arriving at the capacity and/or efficiency gain possible.

Indications are that the generator is generally capable of being uprated to obtain a greater percentage capacity gain than can be developed from the turbine for an equivalent year of manufacturer. The turbine has been found in general to be the critical factor in determining the maximum output that can be developed. Figures 3-1, 3-2, 3-3 and 3-4 are examples of technical data compiled and used in this study for analyzing uprating potential. The reader is cautioned that these data were compiled to perform a nationally scoped study and should not therefore be used to make major decisions on a site specific basis. Also it must be emphasized that while these increases shown are within the capability of the machines, additional flow and/or head (beyond existing) must be developed through project changes before increased power output can result.

A major consideration in determining whether to uprate units of an existing hydroelectric powerplant is the question of the outage. Outage is the time the generating unit would be out of service undergoing replacement or modification. Opportunities for uprating appear to lend themselves more to powerplants with multiple units where outages can be scheduled to coincide with seasonal system power demand swings which would provide "windows" where a unit or units could be taken out of service without adversely affecting a system generating capability. This outage period can vary considerably depending on the uprating to be done. If only the turbine runner is replaced with minor structural adjustments, the outage time could be as low as two months. If more major changes are required, this time could be six to twelve months.

INCREASED OUTPUT FROM PHYSICAL MODIFICATIONS

Figure 4-2 is a schematic of the evaluation process that was adopted for this portion of the study. The existing 1,288 plants were separated into one of thirty-two categories based on whether or not the reservoir had flood control storage, whether or not there was spill occurring at the site, the ratio of potential head to existing, and the age of the plant. The following measures were designated as action categories that were studied to enhance the energy output at existing plants.

- Addition of new units for capacity increase
- Replacement of older units for capacity increase
- Uprating of older units for capacity increase
- Replacement of older units for efficiency increase
- Modification of older units for efficiency increase

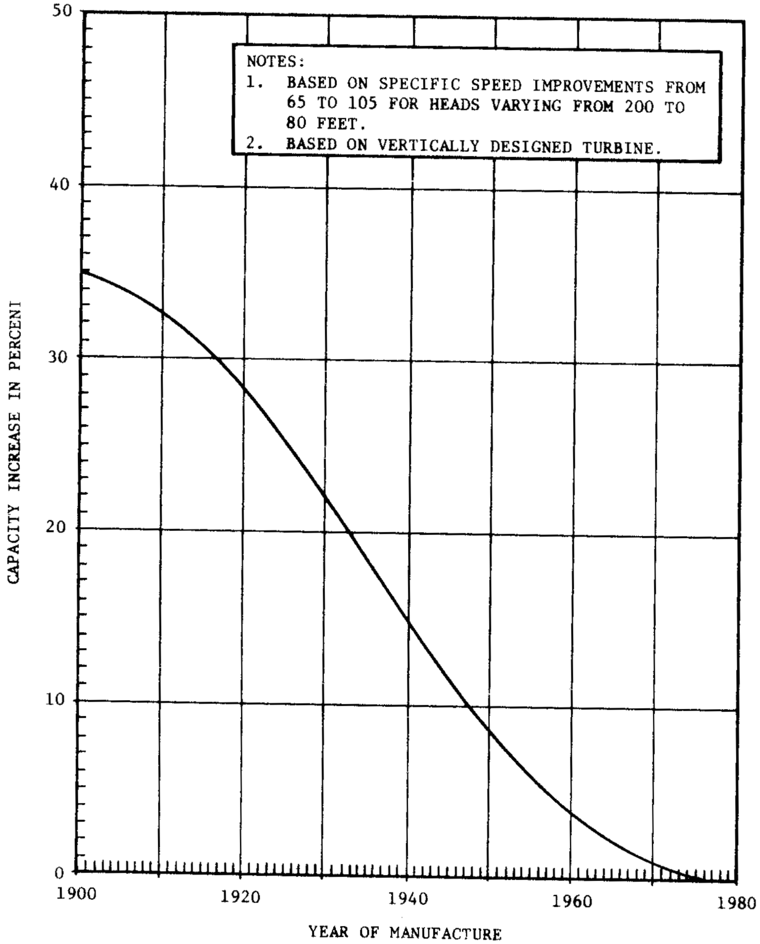


Figure 3-1.

POTENTIAL FOR CAPACITY INCREASE - FRANCIS TURBINE

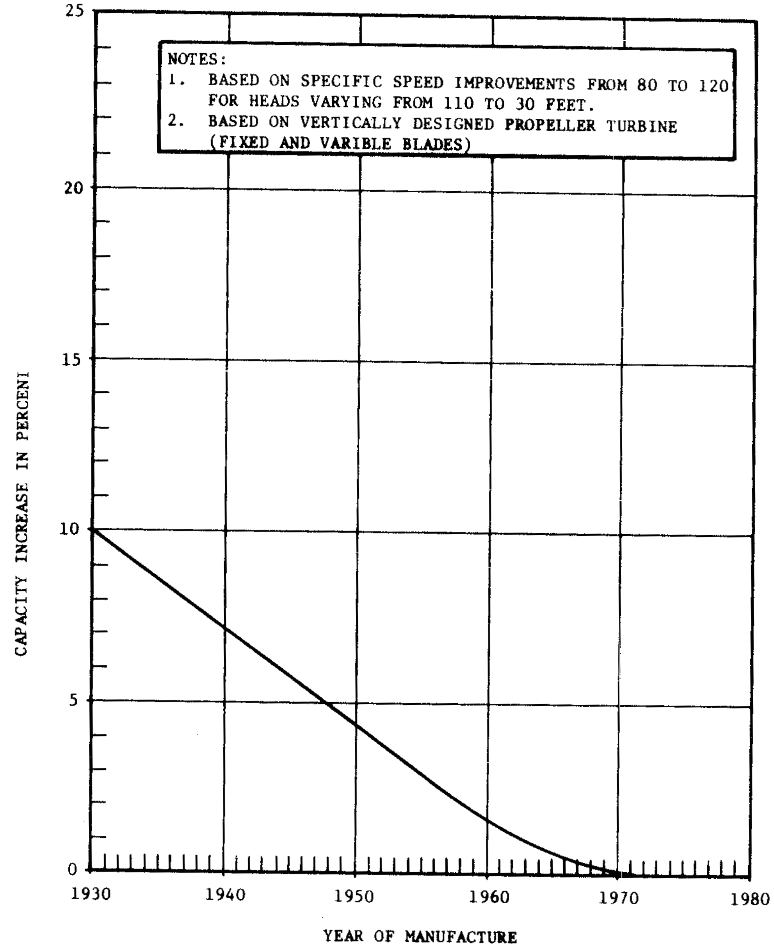


Figure 3-2.

POTENTIAL FOR CAPACITY INCREASE - PROPELLER TURBINE

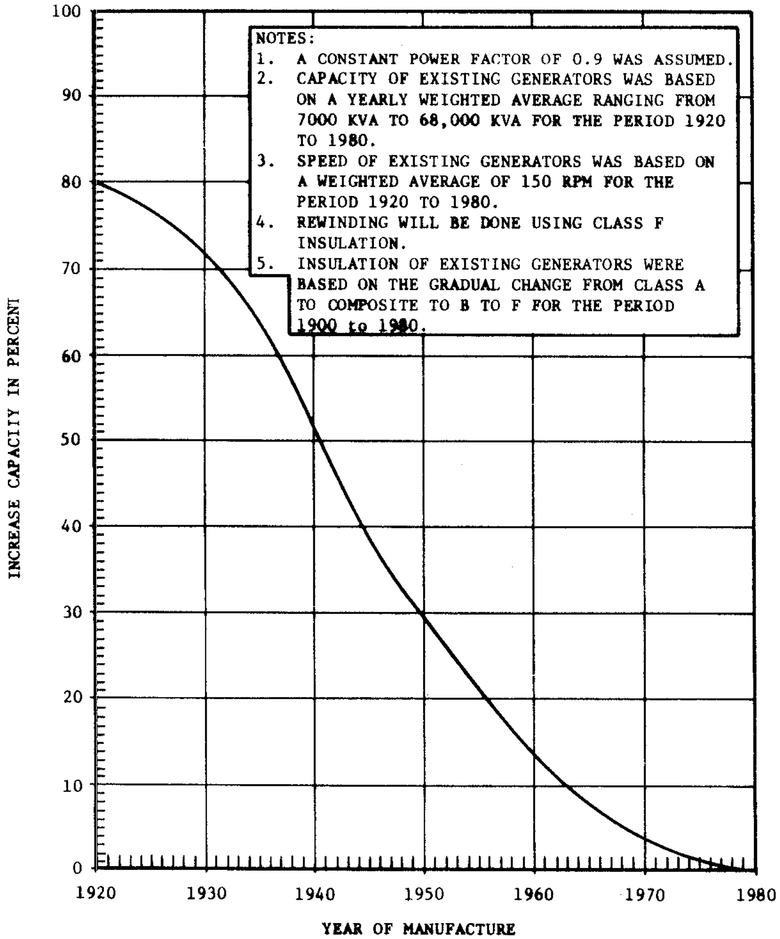


Figure 3-3.

POTENTIAL FOR CAPACITY INCREASE

- REWINDING OF STATOR

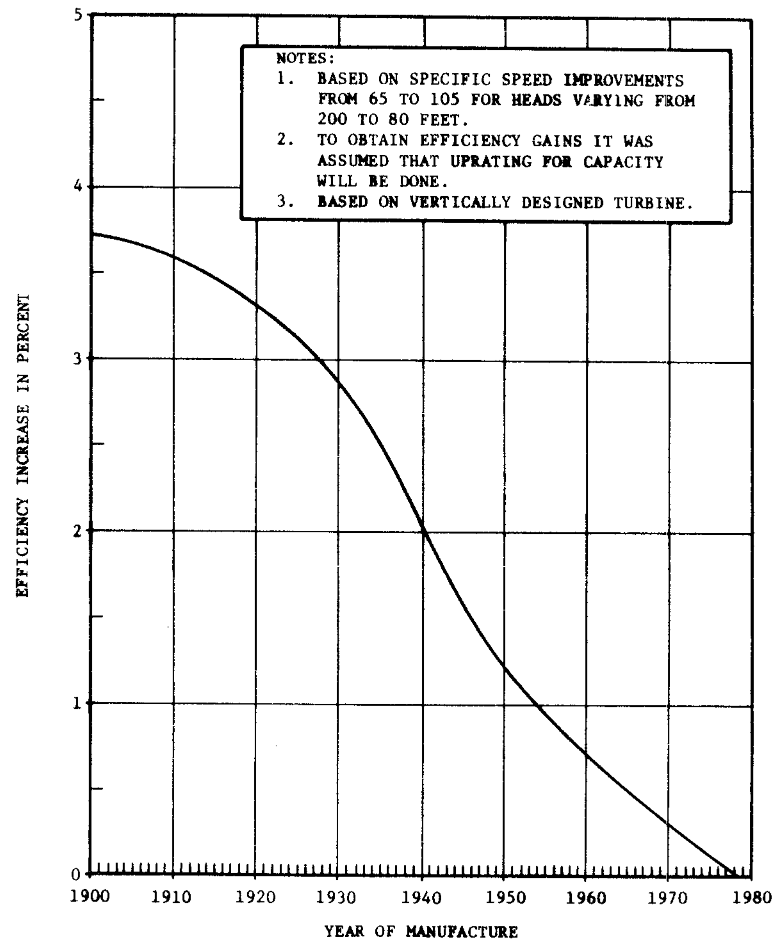
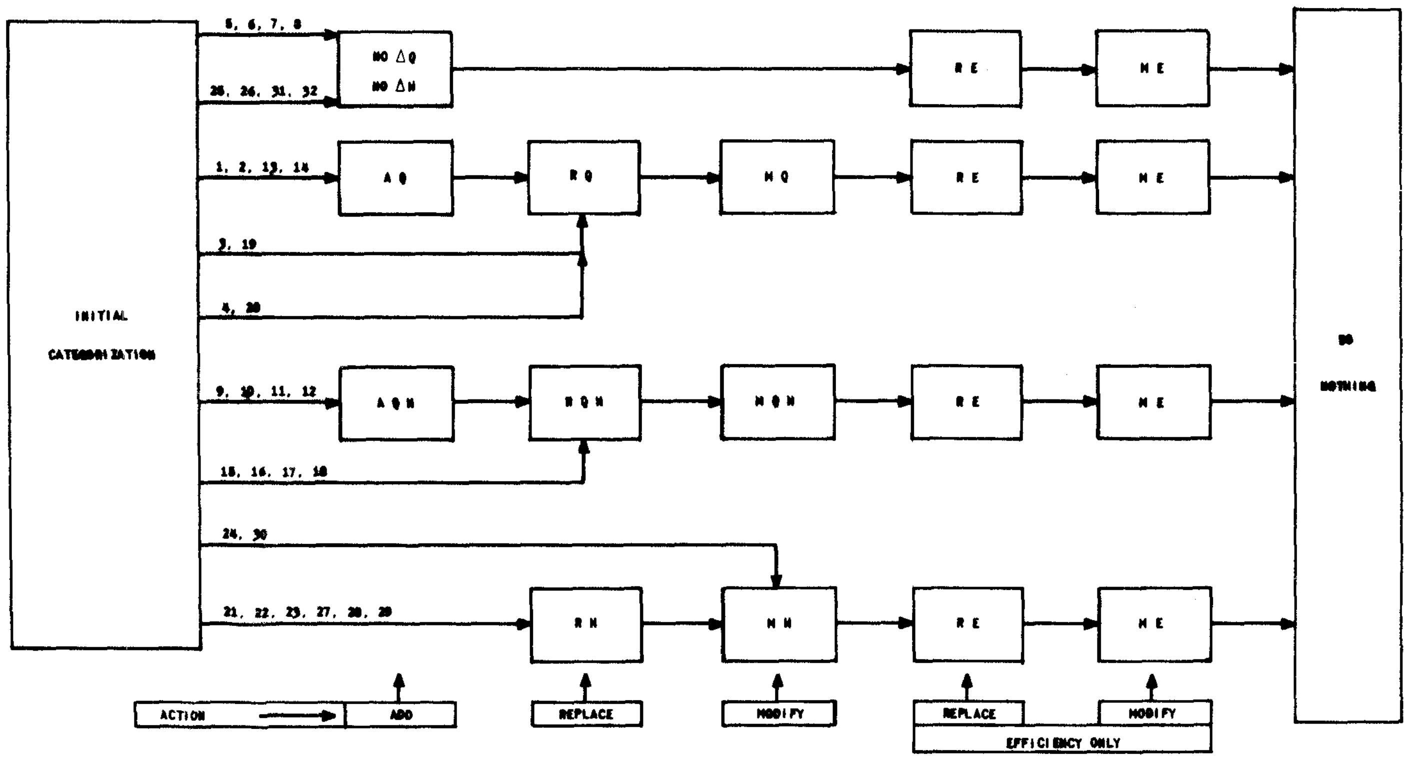


Figure 3-4.

POTENTIAL FOR EFFICIENCY INCREASE

- FRANCIS TURBINE



LEGEND:

ΔQ Increase in Flow.
ΔH Increase in Head.

CLASSIFICATION

FIRST TERM (ACTION)

A - Add Units.
R - Replace Units.
M - Modify Units.

SECOND TERM (SOURCE)

Q - Flow Only.
QH - Flow and Head.
H - Head Only.
E - Efficiency Only.

Figure 4-2. SCHEMATIC - EVALUATION PROCESS

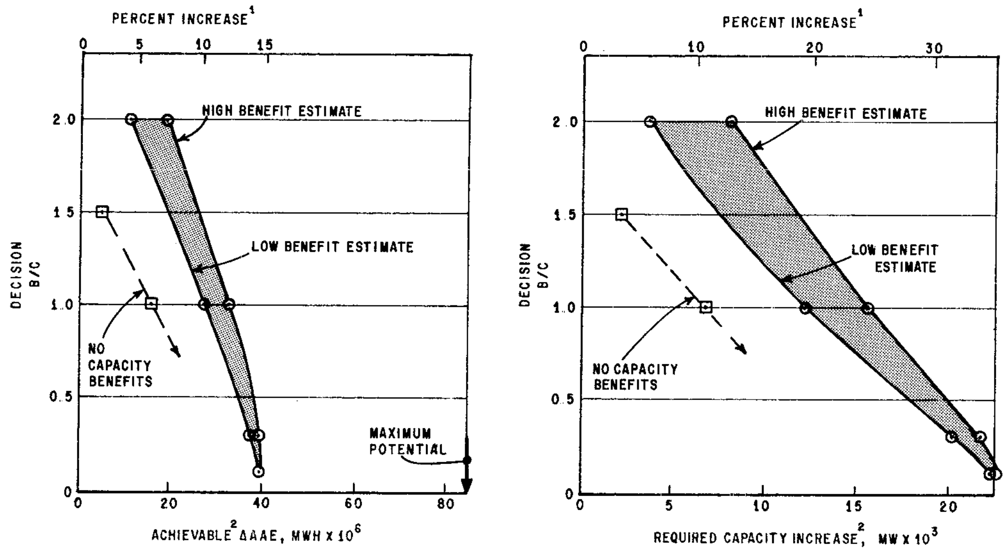
The total gross physical potential increase in energy and corresponding increase in capacity was estimated for each site and appropriate action categories. An indicator of benefit was estimated for the improvement by application of the Federal Energy Regulatory Commission (FERC) regional power values developed for the NHS study. Costs were estimated based on technical data compiled for this study. The test for "achievability" of the energy increase consisted of comparing the calculated benefit to cost (B/C) ratio for each action category to a specified decision B/C ratio. The decision B/C ratio was the decision device used to study the sensitivity of results to a range of acceptable economic criteria. The energy increase of each site that ended up in an action category with a B/C value equal to or greater than the specified decision B/C ratio was considered "achievable".

As an illustration of the evaluation process, consider those sites (Figure 4-2) that were initially classified as "add" categories 9, 10, 11, or 12. All of these sites have potential due to additional flow and head above existing conditions. First the costs and benefits at each site are evaluated for the add (AQH) conditions to see if the calculated B/C ratio is equal to or greater than the specified decision B/C value. If the site does meet this condition the developed information is stored in the AQH category. If the site does not meet the decision B/C ratio at the initially calculated capacity and energy increase, the site is completely re-evaluated at 75 percent of that capacity increase. If required, two more trials are made at 50 percent and 25 percent of the initial value before going on to the next potential action category - RQH. The processing of each site either meets the decision B/C ratio or ends up in the "do nothing" category. Therefore, before sites in categories 9, 10, 11 or 12 are considered "do nothing" sites they could conceivably be tested for achievability for up to twenty different conditions - four conditions for each of the five action categories.

Figures 4-5 and 4-6 present the results of the analysis on an aggregate national scale. Note the maximum physical potential is estimated at slightly over 80 million MWh with a more realistic estimate of physical potential of 40 million MWh. For a decision B/C ratio of 1.0, the achievable energy increase is about 11% (mid range of band) requiring about a 22% capacity increase to accomplish the energy output. Sensitivity results of benefit estimates (HIGH = capacity increase valued as dependable, LOW = capacity increase valued as intermittent), decision B/C ratio (uncertainty in costs and power values), and project life and discount rate (private sector criteria) are shown to provide a complete picture of the potential.

Table 4-4 is a summary computer printout of the computations for the HIGH benefit estimate and decision B/C ratio of 1.0. Note that essentially all the increase is found to be from adding new units (expanding the existing powerhouse). The Northwest accounts for about half of the increase estimated, the Northeast for about 30% of the increase and the Southeast about 10% of the increase.

An analysis was performed with the add category removed from the evaluation process to provide some insight into the potential energy increase from the options of only rehabilitating existing plants. The potential increase achievable dropped to 1.4% (from 11%) nationwide.

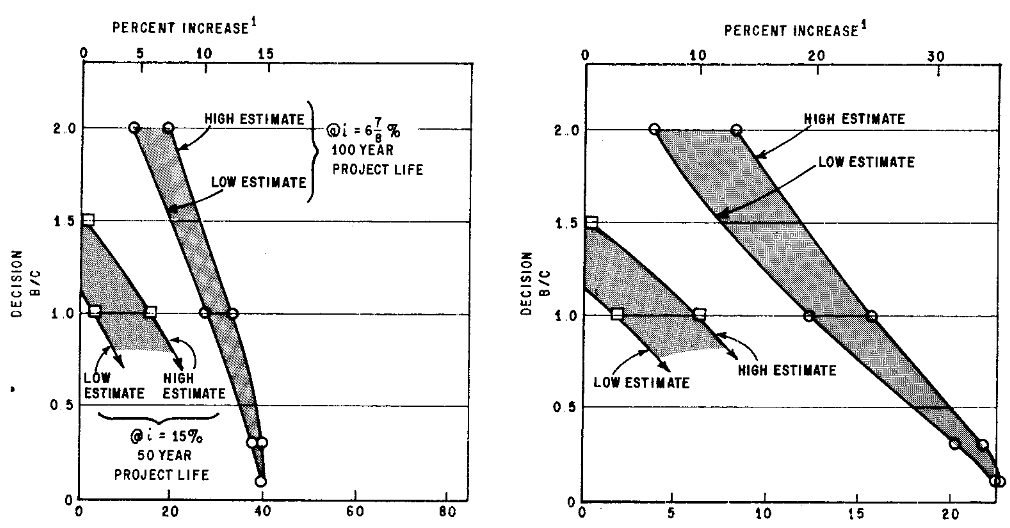


1 Based on existing installed capacity and average annual energy

2 Costs and benefits are based on 1978 price levels and 6 7/8% interest

Figure 4-5.

ACHIEVABILITY ANALYSES - SENSITIVITY RESULTS



1 Based on existing installed capacity and average annual energy

Figure 4-6.

ACHIEVABILITY ANALYSES - SENSITIVITY RESULTS

- INTEREST RATE AND PROJECT LIFE

Table 4-4. SUMMARY
ACHIEVABILITY EVALUATION OF EXISTING HYDROELECTRIC PLANTS, HIGH BENEFIT ESTIMATE, DECISION B/C= 1.0.

ACTIVITY	NUMBER OF PLANTS	INSTALLED CAPACITY	CAPACITY INCREASE	AVERAGE ANNUAL ENERGY	AVERAGE ANNUAL ENERGY INCREASE	INVESTMENT COSTS	AVERAGE ANNUAL COSTS	AVERAGE ANNUAL BENEFITS
		MW		MILLION MWH		MILLION DOLLARS		
ADD UNITS								
AQ	253	9923.0	14491.5	52.284	30.420	12362.7	945.12	1631.41
AQH	15	714.1	961.5	4.045	1.971	766.2	58.52	104.67
ADD SUBTOTAL	268	10637.1	15452.9	56.329	32.391	13128.9	1003.64	1736.07
REPLACE UNITS								
RQ	0	0.	0.	0.	0.	0.	0.	0.
RQH	0	0.	0.	0.	0.	0.	0.	0.
RH	0	0.	0.	0.	0.	0.	0.	0.
RE	4	355.6	10.3	1.930	.019	13.8	1.10	1.79
REPLACE SUBTOTAL	4	355.6	10.3	1.930	.019	13.8	1.10	1.79
MODIFY UNITS								
MQ	10	707.2	70.6	3.549	.092	99.2	7.93	9.28
MQH	1	474.5	111.1	1.719	.138	111.1	8.99	12.53
MH	1	22.5	3.2	.082	.002	.9	.09	.14
ME	15	1605.6	47.1	5.702	.056	67.3	5.40	7.43
MODIFY SUBTOTAL	27	2809.7	232.1	11.052	.288	278.5	22.40	29.39
A,R,M SUBTOTAL	299	13802.3	15695.3	69.312	32.698	13421.1	1027.14	1767.25
DO NOTHING								
DN	989	49573.1	0.	203.240	0.	0.	0.	0.
TOTALS	1288	63375.4	15695.3	272.552	32.698	13421.1	1027.14	1767.25

INCREASED OUTPUT FROM OPERATIONAL CHANGES

Operational changes to existing plants that could potentially increase the energy output are possible. By reallocating a portion of the flood control storage to power storage there is the potential to increase the energy output by capturing and routing additional flow through the powerhouse and by increasing the head available for power generation by keeping the pool level higher. The additional energy increase may be possible without necessarily increasing the plants installed capacity. The loss to the existing project would be reduced flood control protection. It is unlikely that a significant reduction in flood control storage would be found to be acceptable. However, in some cases only a small portion of the flood control space may be needed to capture and control a significant amount of reservoir inflow volume.

Altering the reservoir operation policies is another potential way to increase energy output. Typically, there is a set of operating rules by which a reservoir is operated. The thesis is that there may be opportunities to increase power output such as reducing flood control releases during and following flood events to allow more volume to be passed through the plant; allowing seasonal power pool elevations to remain at higher elevations for longer periods of time; and minimizing all releases that do not go through the plant. In effect this might amount to a quasi-storage reallocation in that some of the goals of reallocation might be achieved without formally modifying the designated storage zones.

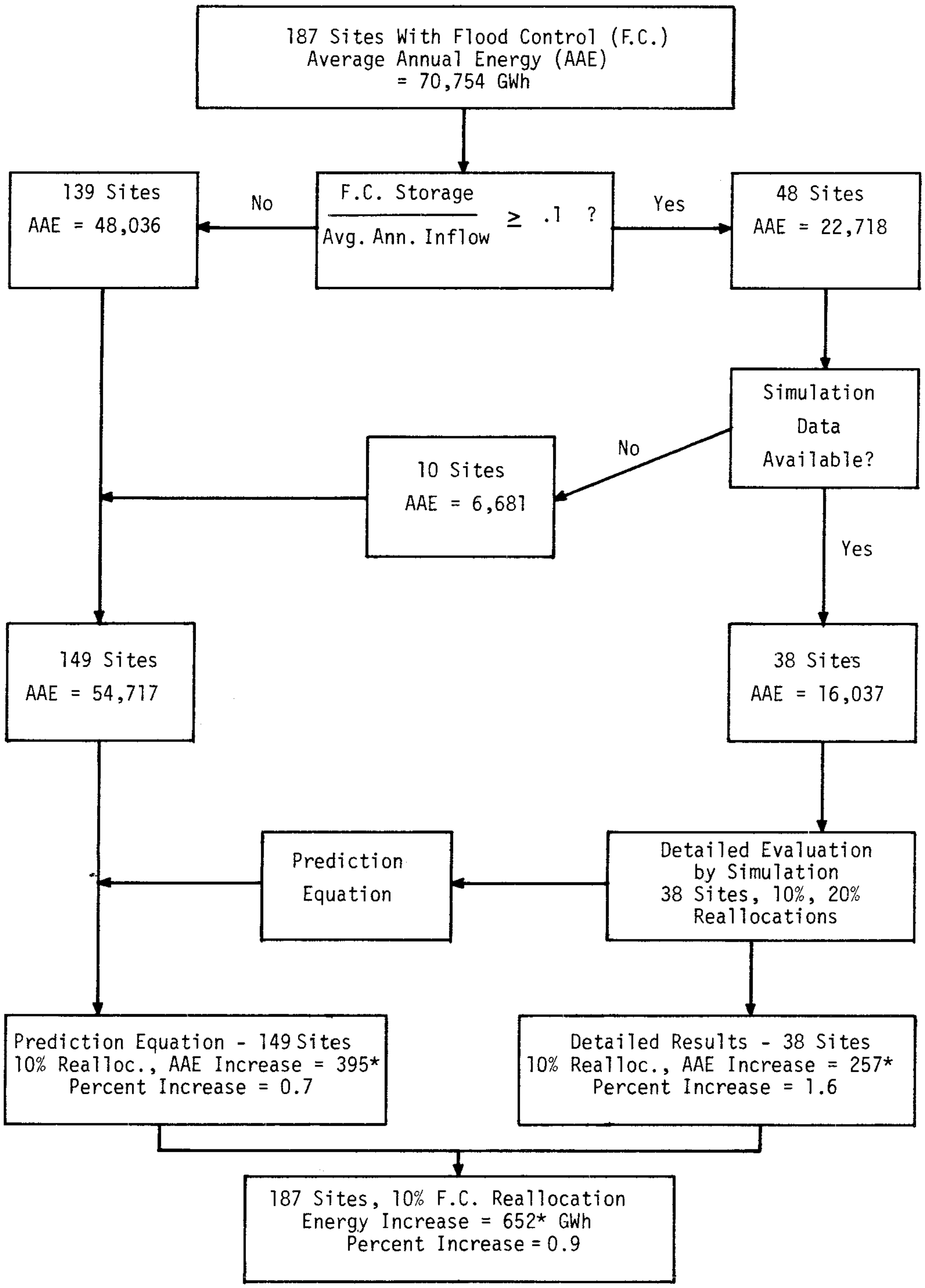
Storage in a multiple-purpose reservoir is usually allocated into flood control space, conservation storage (including hydropower), and inactive or dead storage. Flood control operation requires reservation of storage space in the event a flood might occur thus potentially releasing water that might have been later used for power generation. The hydropower reallocation question for all practical purposes reduces to allocating portions of existing flood control space to hydropower storage. The potential contribution to increased energy output of allocating from one conservation purpose to another is insignificant in comparison. The candidate projects for reallocation of flood control storage are therefore those existing hydropower projects that also have flood control storage. A total of 187 projects were found that met the criteria. Forty-eight (48) of these projects have flood control storage equivalent to 10% of the annual flow volume.

The reallocation analysis was accomplished by performing detailed sequential, hydropower analysis on 38 of the 48 project previously identified, developing a prediction equation from the results obtained, and applying the prediction equation to the remaining sites. Computer simulations were made based on existing storage allocations, then repeated for reallocation of 10% and 20% of flood control storage to power storage. Figure 5-1 is a schematic of the analysis flow and includes the results for the 10% flood control storage reallocation option.

The estimated increase in energy output for reallocation only (installed capacity remains at existing) is 10% reallocation - 652 GWh (.9% increase for all reallocation sites) and 20% reallocation - 1,225 GWh (1.7% increase for all reallocation sites). If the installed capacity is increased commensurate with the increased dependable capacity made possible by the increased power storage and decreased plant factor, an additional 1.7% increase in average annual energy for a 10% reallocation may be possible. The major factor in increased energy output was found to be increased head (pool levels). The contribution due to capturing additional spill was negligible. By adding to the power storage through reallocation, projects are able to meet increased power demands during critical low flow periods. The percentage increase in firm annual energy (conversion of non-firm energy to firm energy) was approximately 3 times the increase in average annual energy.

The likely acceptable reallocation project development would require formulation and implementation of mitigation measures to offset the loss in flood control performance by the reservoir. The benefits from increased power production would have to be greater than the cost of the mitigation measures needed to assure the same (or nearly so) flood control performance for reallocation to be economically justified.

Analysis of the potential for increased output by operational (rule curve) changes indicated that the potential was minor and in fact is included within the estimates made for reallocation analysis. Project operators appear to be diligent in operating their projects to extract the greatest amount of energy that is practical and reasonable.



* Installed capacity maintained at existing values.

Figure 5-1. ESTIMATE OF POTENTIAL ENERGY INCREASE FROM STORAGE REALLOCATION

SUMMARY OF FINDINGS

The hydroelectric power generation system of the United States is comprised of 1,288 individual plants, totaling about 3,000 individual generating units, with installed capacity (exclusive of pumped storage) of 63,375 megawatts (MW), generating 272,552 gigawatt hours of electrical energy per year. The data documenting characteristics of the 1,288 plants have been catalogued into a computer file for use in the evaluation of the potential for increasing output from existing plants. There is modest potential for increasing energy output from these plants (11%) with virtually all the increase due to capturing existing spill through enlargement of the existing powerplant. Equipment uprating and improvements would likely contribute no more than 1.4% increase over existing output. Potential for increased energy output from operational improvements and storage reallocation is possible at sites with existing flood storage and is optimistically estimated to average 2% for the sites with flood control storage (a national increase of about 0.6%). While the total national potential for increasing energy output at existing plants is modest, the opportunities are real and in specific instances could be significant and important on a local scale. The existing hydropower generation system on the whole is making quite efficient use of the energy resources available at the existing sites.

Specifically, the investigation has found:

- The upper physical limit estimate of potential increase in energy output at existing hydropower sites is approximately 86,000 (GWh). A more realistic value for physical potential developed through detailed study in this investigation is a maximum practical limit of about 40,000 GWh (15% increase over existing) indicating that current utilization of potential energy at these sites is 87 percent on a nationwide basis. Based on present day cost and power benefit values as decision criteria, the potential energy increase that is achievable is estimated to be about 30,000 GWh or an 11 percent increase.

- 1,288 sites have been identified and catalogued into the basic data files of the national hydropower study. This data base provides an adequate basis for a national study of potential energy increases at existing sites.

- Existing federal plants (14 percent of total) contain a little over 50 percent of total installed capacity.

- There is flood control storage at about 15 percent of existing sites with a total installed capacity of 17,774 MW (28 percent of the national total).

- There are 431 (33 percent of total) sites with capacity of 8,633 MW (14 percent of national total) that are classified as run-of-the-river locations.

- Approximately 80 percent of the total existing capacity has been added since 1940.

- Two-thirds of existing plants were constructed prior to 1940 and contain only about 20 percent of the existing capacity.

- Approximately 75 percent of existing plants are less than 25 MW installed capacity yet these plants account for only 7 percent of the total installed capacity.

- There can be significant increases of up to 35 percent in turbine output capacity due to modifications to older turbines, if additional head and/or flow are available.

- Improvements in insulating material over the past 50 years allows significant generator capacity increases through uprating.

For summary purposes the values used in the following items are taken from analyses based on costs and benefits in present day values and a decision threshold benefit to cost ratio of 1.0.

- The major source of potential increase in energy at existing plants is the flow that is currently bypassing the existing powerplant and not being captured for power generation. Specific measures of adding additional units, replacing or modifying units to achieve higher output, or storage reallocation would be required to capture portions of the presently passed flows (spill). Utilization of this spillage through addition of units accounts for more than 94 percent of the estimated achievable potential energy output increase at existing sites.

- The increase in energy due to head increases, even using all of the flood control space, accounts for less than 6 percent of the total potential energy increase at existing sites.

- The achievable average annual energy based on the capacity and energy power values used herein and the federal interest rate of 6-7/8% is about 30,000 GWh or an 11 percent increase in energy above existing hydropower output. Development of this additional energy would require adding about 14,000 MW of capacity, an increase of 22 percent over existing capacity.

- If power benefit credit for dependable capacity is omitted from the evaluation (because not all additional capacity could be reasonably expected to be dependable), the achievable annual energy increase drops to about 18,000 GWh or a 6 percent increase over existing output.

- If the interest rate for the implementation decision criteria is raised to 15 percent from the 6-7/8 percent utilized in this study and the project evaluation period is decreased from 100 years to 50 years and the value of power is held constant, the achievable annual energy increase drops to about 10,000 GWh or a 4 percent increase over existing output.

- If adding units were not being considered as an alternative, (e.g., only existing unit uprates and improvements are considered) the potential increase in annual energy due to replacement of and/or modifications to existing units would be about 3,750 GWh or an energy increase of 1.4 percent over existing.

- The loss in energy (and thus revenue) from removing a unit from service to uprate through modification is presently seldom economically justified. Uprates through improvements are more attractive for implementation when the plant must be taken out of service for some other compelling reason.

- The Western Systems Coordinating Council (WSCC), Northeast Power Coordinating Council (NPCC), and Southeastern Electric Reliability Council (SERC) regions contain 88 percent of the estimated achievable annual energy increase.

- The potential energy development due to reallocation of flood control storage in existing power reservoirs - will likely contribute less than a one percent increase in hydroelectric energy output on a national basis. The conversion of non-firm energy to firm energy made significant - up to 3 times the increase that was estimated for annual energy. Substantial gains in average annual energy can be obtained at those projects where the reservoir power operation can be based on zero firm energy due to the higher heads resulting from the decreased reservoir drawdown.

- It would require about 60 million barrels of fuel oil annually, to produce the equivalent amount of electrical energy (30,000 GWh) that has been found in this investigation to be achievable.

ACKNOWLEDGEMENTS

The investigation reported herein was performed by The Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers, as a service to The Institute for Water Resources (IWR), U.S. Army Corps of Engineers, managers of the National Hydropower Study. Mr. Michael Walsh was the IWR contact for the study. Mr. Darryl W. Davis was the principal-in-charge and Mr. John J. Buckley was the study manager. HEC staff that performed significant tasks for the study were Messrs. Vernon R. Bonner, Dale R. Burnett, Robert C. Luethy, Gary M. Franc, and Brian W. Smith. Mr. Bill S. Eichert, Director of the HEC, provided guidance and participated in the technical performance of the reallocation analysis. Parsons, Brinkerhoff, Quade and Douglas, Inc. (PBQ&D) prepared technical data on equipment uprate potential and cost while under contract to HEC. Principals for PBQ&D were Messrs. Clarence E. Korhonen and Richard L. Hearth.

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