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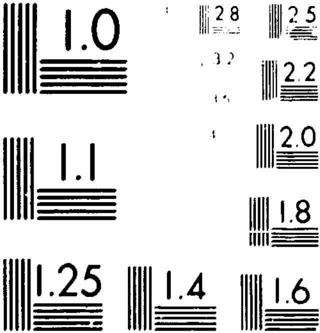

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CASE STUDY OF THE PLANNING AND CONSTRUCTION OF A MINI HYDRO POWER PLANT*

by

Norwegian Water Resources and Electricity Board (NVE)
Oslo
Norway

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SYNOPSIS

The reconstruction of an existing Norwegian mini hydro power plant dating back from 1911 is now (1979) under way. With an installed capacity of 1700 kVA the annual power production is estimated at 6.7 GWh and the total cost of reconstruction at US$ 1 mill. Since the regulating reservoir, the intake dam and the intake canal already exist, the required civil works are limited. Therefore the bulk of the expenditures mainly pertains to the mechanical and electrical equipment. The new asynchronous unit will feed into a large regional grid.

INTRODUCTION

South-eastern Norway, where the plant is located, is reasonably flat, with rolling hills, partly forested and partly farmland, and with numerous lakes and rivers. The privately owned power potencial of Andelven river in the Municipality of Eidsvoll, 70 km from Oslo, was early utilised for industrial purposes; first sawmilling, later pulp production, and today exclusively production of electricity. The Andelven is a minor tributary of the Vorma river, one of the two main branches of Glomma, Norway's largest river.

Andelven river originates from the lake of Hurdalsjöen with a drainage area of 600 km^2 and a regulating reservoir 121 mill. m^3. Normal annual runoff at the power station site is 430 mill. m^3. This corresponds to a mean flow of about 12 m^3/s, utilised entirely for industrial purposes. In addition, short yearly floods reach about 30-50 m^3/s.

The total head of 53 m of this 10 km long river has been developed in five power stations, the head of each being in the range of 8 to 18 m.

In the latter half of the nineteenth century the water was used to run water-wheels, mills and sawmills, and later on, cellulose and papermills. Around 1910 most of these factories were extended and modernised and new turbines were put in. The power was taken directly from the shaft using belts. Later on, during the 1950s and 1960s the cellulose production dropped - generators were put in - and the production of electricity took over completely.

The turbines are now 60-70 years old, the generators nearly 30, most of the buildings are in a bad condition, and the overall efficiency is dropping very low. The installations are designed for a smaller river flow than is now economically feasible.

The first power plant to be rehabilitated was the station called MAGO C (A.D.1898), which is now equipped with a 900 kVA horizontal unit placed in a new powerhouse. This enterprise took place in 1978, lasted for ten months and cost a total of US$ 1 mill. The annual power production is now approximately 5 GWh.

The second plant to be modernised is MAGO D, located at the downstream end of the river. Here the larger of the two installed units broke down in September 1978. The fieldwork started in April 1979 and the new unit is expected to be on line by March 1980.

BACKGROUND DATA OF THE OLD MAGO D

The existing dam, inlet canal, gates, trash rack, steel tube, powerhouse and two turbines of 800 and 250 kW are from 1911, and were at first used for the direct running of grinding stones in the production of cellulose pulp and for the generation of local power. The factory was rebuilt to only produce electric power in 1963, and two generators, together with other mechanical and electrical equipment, were put in and connected to the existing turbines. The steel penstock was renewed only a couple of years ago.

On September 1st, 1978, the turbine shaft broke due to fatigue.

RECONSTRUCTION CONSIDERATIONS

A few days later the building and machinery were inspected by civil and mechanical engineers and an assessment of the damage, and of the plant's general condition, was made. The turbine proved to be in a bad condition. The electrical equipment was also oldfashioned and worn. The draft tube was inspected by a diver and found to be in a very bad state.

Due to the breakdown and to the poor general condition of the plant the turbine was not worth repairing. This taken into account, the Owner wanted to look into the possibility of installing a new turbine and new electrical equipment in the existing building.

About one week after the breakdown the Consultant for mechanical engineering obtained (from a turbine manufacturer) an outline design of a new installation including turbine, gear, generator, etc., together with a rough cost estimate.

FEASIBILITY STUDY

The design of a new arrangement started in September/October 1978. Old drawings from 1911 showing the original features of the plant did in fact exist, but did not show later structural and inventory changes.

It became immediately clear that if new machinery were to be installed, the manufacture and delivery of this would be the governing time factor. Consequently it was necessary first to establish the design criteria for the new installation, i.e.:

1) Upper and lower water levels and their variations

2) Flow and flood conditions

3) Production potential (i.e. the function of flow, turbine capacity, head, efficiency, power prices - variable with time throughout the year)

4) Economy (i.e. cost/benefit, financing, etc.)

Some three weeks after the breakdown three turbine manufacturers were contacted and asked to give binding offers of their particular machinery by October 11th. They all answered and came up with three possible arrangements:

1) 4 immersible propeller turbines with built-in generators

2) 1 vertical propeller turbine with stationary guide vanes and adjustable propeller blades

3) 1 vertical Francis turbine with adjustable guide vanes.

A first comparison of costs appeared as follows
(approximate rate US$ 1 = NKr 5.00):

Tender No.	1	2	3
Turbines	392,000	331,000	266,000
Gear and electrical equipment	158,000	163,000	238,000
Civil works estimates	145,000	175,000	155,000
Sum US$	695,000	669,000	659,000

Adding fees, administration, and interest during construction, the total cost would increase to about US$ 800,000. Mean annual production was estimated at about 6.7 GWh, at present worth roughly

$$6.5 \cdot 10^6 \times \text{US\$ } 0.02 = \text{US\$ } 128{,}000.$$

Assuming a 40 years depreciation time, a 7% interest rate and 1% annual maintenance, the annual costs amount to

8.5% x US$ 800,000 = US$ 68,000.

The cost per kW is $\frac{\text{US\$ 800,000}}{6.7 \cdot 10^6}$ = US$ 0.12

As the turbines vary in design and characteristics, the efficiencies also vary. These factors must also be taken into consideration.

CHOICE OF HYDRAULIC AND ELECTRICAL EQUIPMENT

Turbine

On this basis, and after having evaluated the advantages and disadvantages of the three offers, contract was negotiated with Company No. 3 offering a vertical Francis turbine.

One good reason for choosing the Francis turbine is the high suction head (5.7 m) tolerated by the runner without suffering cavitation. On this particular site the downstream water level varies normally about 4 or 5 m over the year, with the possibility of extreme floods in addition. By placing the centre of the turbine 5.5 m over the lowest water table (LWT) access to the turbine could always be secured by closing the inlet gate. Tailrace gate and drainage system with pumps could therefore be waived.

Generator

Background for the choice of the 1700 kVA generator is as follows:

MACO D is located in an area well covered with electric power from a very reliable main grid. It therefore should not be required to consider the station as a vital energy supplier. Hence it was possible to choose an asynchronous generator and cheaper type of governor equipment than would otherwise have been necessary if the power station were to deliver to a separate system without connections to the main grid. Therefore the turbine is not fitted with speed regulating devices, but only with a servo motor and a hydraulic system which permits automatic regulation of the load as a function of the upstream water level. An asynchronous generator was chosen since this is cheaper than a synchronous generator of this size. In order to partly magnetise the asynchronous generator a shunt capacitor battery of approximately 250 kVAr is being installed. This will increase the power factor from 0.38 to 0.94.

The generator is automatically connected to the main grid with the aid of a speed registration device.

A gear is fitted between the turbine shaft and the generator in order to increase the rotating speed of the generator thereby reducing the total cost. The water-cooled gear is delivered together with the electrical equipment. The cooler is placed in the turbine tank.

The items included in the delivery are listed in Appendix 2.

Transformer

The generator will deliver 660 V to a 2000 kVA transformer. The outgoing voltage will be 17,500 V with the option of 22,000 V which will be required in a few years. The station will be connected to an existing high-voltage line with an underground cable.

REHABILITATION OF THE OLD STATION VERSUS THE CONSTRUCTION OF A NEW ONE

While measuring up the old station it became clear that there had been turbines (mill-wheels) and waterways in operation elsewhere on the site before 1911. Existing buildings and the terrain itself also pointed to this, and historical records confirmed it later on. It also became clear that the existing station was in more need of repair than initially thought.

As an alternative to rehabilitating the old power station, the Consultant now looked into the possibility of constructing an entirely new power plant. Design of a new station was outlined, and costs and benefits compared.

The alternatives now were:

A. Use of the existing building. Uncertain total estimate of US$ 870,000. (The necessary extent of the cofferdam outside the draft tube was not easily predictable.)

B. New building and tailrace channel. A more reliable total estimate than 'A': US$ 970,000.

Alternative 'B' was recommended and decided upon as being the better solution altogether. At times of very low downstream water level one would also utilise a minor fall of about 0.3 m just downstream of the old station. Besides, during the first few years of operation one could possibly keep the remaining old unit running in periods of sufficient flow.

A preliminary time schedule was prepared as shown below, the limiting factor being the turbine design and production.

Initial turbine drawings ready by	20th Feb., 1979
Tender documents ready (civil works)	15th March
Start construction	1st May
Start mechanical installations	3rd Dec.
Start testing	1st Feb., 1980

STATION ARRANGEMENT

The station consists of a waterway and a house for mechanical and electrical equipment.

The waterway:

1) Trash rack, constructed of flat, galvanised steel bars spanning from top to bottom and inclined at 2:1. The inclination, and the narrow footpath not more than 0.5 m above the water at the top, have by experience been found to give the best performance with regard to cleaning of ice and trash. The water velocity through the rack is less than 1 m/s.

2) Road bridge, designed to take any regular traffic load. This will be the only access to the building housing the old unit.

3) Inlet gate with hydraulic hoist. An air inlet duct for emptying and a water pipe with valve for filling of the turbine tank is also included. Attached to the water pipe is a pressure-meter, which senses the upstream water level.

4) Turbine tank. Inspection possibility of the underside of the runner through a small manhole with hatch.

5) Draft tube, with steel lining of the upper part. At the outlet there is a possibility of closing the tube by placing vertical stop logs ('needles') between the top and bottom. An earthing-mesh, connected to all embedded steel, is distributed over the station area before concreting. It is made of 70 mm^2 Cu wire.

6) Turbine. Runner, shaft, bearing, water-cooled gear and air-ventilated generator. Over head runs an 8 ton capacity crane on a single track beam.

7) Machine hall. The floor is under water pressure and must be impermeable. Drains are carried to the downstream side.

8) Main transformer room, separately ventilated and equipped with oil ditch in case of leakage.

9) High-voltage room.

10) The roof is made of pre-cast light-weight concrete beams, grouted together to form a slab and placed on the supports on continuous rubber bearings. On top is glued an asphaltic membrane covered by sheet metal.

FINAL COSTS OF MECHANICAL AND ELECTRICAL EQUIPMENT

The equipment was supplied by a joint venture of a manufacturer of electrical equipment and a turbine producer, with the turbine producer as sponsor.

The final cost of the equipment was US$ 490,000, approximately equally divided between mechanical and electrical equipment.

The total delivery included in this price is listed in detail in Appendices 1 and 2. It consists of a Francis turbine, asynchronous generator, gear and electrical components.

Auxiliary Equipment not included in the Main Delivery (approximate prices)

Trash rack	:	US$ 14,000
Inlet gate with guides, sill and lintel, etc.:		US$ 23,000
Hydraulic aggregate and cylinder for the gate:		US$ 9,000
8 ton capacity electric crane on a single track beam	:	US$ 10,000
Total		US$ 56,000

COST OF CIVIL WORKS

Six tenders were received at the expiration date, 29th March. The gap between the highest and the lowest was 33%.

Various limitations and reservations in the lowest tender made the second lowest the most attractive one, and the contract was awarded to the tenderer of this.

TOTAL COSTS

The total costs now seemed to be:

Mechanical and electrical equipment	:	US$	490,000
Other installations	:	US$	56 000
Civil works	:	US$	310,000
Channel outlet, excavated before contract	:	US$	10,000
Administration, fees, interest, etc.	:	US$	134,000
Sum		US$	1,000,000

APPROVAL FROM NATIONAL AND LOCAL AUTHORITIES

Since the work actually was a reconditioning of an old plant and since no new water regulations were establised or new waterfalls utilised, no public approval was required according to Norwegian law.

However, approval by the Norwegian Water Resources and Electricity Board of the electrical parts was mandatory since the voltage exceeds 1000 V. The application included a technical and economical presentation of the project and was submitted by the Consultant on behalf of the Owner.

The Owner himself applied for a 'building approval' by the local authority. The required permits were issued in a week's time.

FIELDWORK AND PLANNING

Shortly after the breakdown of the old 800 kW turbine the existing buildings were inspected, detailed measurements taken and arrangement drawings made. When the switch to the other site was conceived by mid-winter, the ground was covered with snow and ice, and very little was known of the geology of the site. Trial pits had to be dug along the line of the tailrace channel in order to investigate the soil properties and to find the depth of overburden. The amount of rock to be blasted and soil to be removed would of course affect the feasibility of the plan.

A set of trial pits were dug in mid-February, using a large hydraulic excavator. Samples were taken from the trial pits and analysed in the Consultant's laboratory. The soil varied widely over the site, from coarse gravel and stones near the proposed station site, to hard clay in the middle and soft mud at the outlet of the river. The mud was so soft and deep that the excavator had to rely on the bearing capacity of the thick ice sheet and the frozen ground. Still, it was impossible to reach the end of the proposed channel. It became obvious that the outlet part of the channel had to be excavated as quickly as possible, while it was still winter. The idea was to excavate using the ice and frozen ground as a platform. The alternative would be to dredge out the channel in the summer, using a drag-line, a more costly and uncertain procedure. However, the success of a drag-line seemed dubious, since the mud was filled with sunken timber, ropes, chains, etc.

The work had to be done before the tenders were due, and the Owner hired a local contractor to excavate the outlet part of the channel. Still, by the time he got started, the winter had culminated and the ice and the frozen ground had become weaker. Ice and ground alone could not carry the excavator. The problem was overcome by placing thick layers of bark on the ground, and by using large wooden rafts to drive on. As a further safety measure the excavator was anchored to a 30 ton standby bulldozer.

THE MAIN CONTRACT

The tender documents were distributed to the tenderers on the 8th of March. The tendering contractors attended a site visit on the 13th, and the tenders were received on the 29th. The Contractor was selected a few days later and started work the following week - even prior to the scheduled starting date (13th April).

Regular meetings are arranged on site, where both the Contractor, the Owner and the Consultant are present. When necessary, the turbine manufacturer or other suppliers of hardware attend. Meetings have been held every fortnight, but with extraordinary meetings and site visits whenever necessary.

All the reinforcement comes 'pre-cut' and 'ready-bent' from the Contractor's supplier. This means that reinforcement drawings have to be ready by an earlier date than normally, due to the procuring time.

Retrospectively, this system seems to be impractical, especially for the bottom parts of the construction, where the reinforcement has to be bent according to the actual shape of the blasted rock. The usual procedure is to have the reinforcing bars delivered on site in lengths of 12 m, and to do the cutting and bending there. Thereby one can easily adjust the lengths, number of bars, etc., whenever required.

Rigging

The Owner supplied electric power, water and telephone on the site, and lodging quarters near by. An area at the site was reserved for the Contractor's rig (barracks, etc.).

The Contractor started by clearing the site and building up his own rig and manpower. At the same time excavation started at the station site in order to clear the rock surface for the drilling rig as soon as possible.

Floods

A critical date was supposed to be around 1st May, when the downstream water level would normally begin to rise quickly and it would be imperative to have a cofferdam in place.

This year's flood turned out to be the largest in a great many years. The cofferdam was just high enough and held tight, except for a few small local breaches which were easily dealt with. The leakage was small.

Spoil Deposits

The excavated materials were placed on both sides of the channel, the soft mud from the downstream end in a depression (ancient channel) to the south, and the firmer soil and rock on the river bank to the north. The rock was distributed to form a closed wall retaining the soil and preventing it from erosion by the river. The channel sides were also covered with a 0.3 m layer of rock riprap as erosion protection.

The Consultant performed vane tests on the outer channel sides and in the spoil deposit area, and the soil conditions were found to be safe.

Rock Blasting

All the blasting had to be done carefully since the site is located very close to existing buildings and other structures. The Contractor was required to place a 'shock-recorder' on the wall of the intake channel. A maximum allowable amplitude was decided on (300 μm) and a table showing the recommended amount of explosives versus distance from the channel was included in the tender documents. Shock records were taken from the very beginning.

The channel sides were pre-split prior to the actual blasting, using holes at approximately 0.6 m intervals.

However, the rock was split by crossing faults and cracks and some large rocks seemed to be loosening. The Consultant visited the site and prescribed safety measures' i.e. rock bolts and anchors. Deteriorated rock on one side of the pit made it necessary to construct a concrete supporting wall above the roof of the draft tube.

Inlet Cofferdam

The inlet channel was to be drained by the Owner in August, after the flood season. The Contractor wanted this done prior to the spring flood. This would be an advantage for the Contractor in the job planning and execution and would also benefit the Owner since the small turbine in the old station could be running continuously during the whole construction process. A cofferdam in the inlet channel was then built as a joint venture between the Owner and the Contractor.

Due to the limited space, this dam, a steel frame support with vertical timber stop logs, had to be placed so close to the new intake that it became necessary to move the station 0.25 m in the downstream direction.

Breakthrough in the Channel Wall

The old inlet channel wall was not reinforced. Careful blasting was prescribed using a 'seam' of holes at 100 mm intervals, and small amounts of explosives in every second hole. A few cracks developed in the side walls, but these can easily be grouted.

Installation of the Draft Tube Lining

Using a mobile crane, the draft tube steel lining was installed only a few days after the initially scheduled date. Concreting operations started immediately afterwards.

Design of Concrete Mix, Delivery, Concreting

The concrete was to be delivered from a concrete factory some 18 km away. Since the draft tube lining was to be wholly embedded in mass concrete, it would be of importance to keep the cement content as low as possible to avoid heat and shrinkage cracking. The following mix was used, based on the experience gained from the construction of MAGO C a year ago:

Cement	280 kg	
Water	140 kg	(5% water in sand included)
Sand	930 kg	
Gravel	920 kg	
Admixture (LP)	2-3 kg	(air-entraining and plasticising effect)

This gives a water/cement ratio of 0.5.

The steel lining was sprinkled with water to keep it cool and to avoid increase in circumference of the steel lining due to temperature rise during the hydration of the cement. The lining might otherwise shrink and loosen under normal working conditions at lower temperatures.

Construction Planning

According to his production plan the Contractor will finish the riprap in the tailrace channel by the end of November. At the same time, all the main concreting operations will be completed.

Installation of trash rack, inlet gate, single-track crane, governing ring (turbine), roof elements, etc., will take place during October and November.

Installation of the main machinery is scheduled to start on 3rd December. The installation period is planned to last about 9 weeks until the scheduled starting date, i.e. 11th February 1980. After trial running the station will formally be taken over by the Owner on 23rd March, 1980, less than 15 months after the decision to rebuild was taken.

SPECIFICATION, HYDRAULIC EQUIPMENT

1. Vertical Francis turbine, arranged in a concrete tank.

Head (m)	Discharge (m^3/s)	Max. output (kW)
6	11.2	610
7	12.9	825
8		1000
9	14.9	1210
10	16.0	1390
10.5	17.0	1500

Efficiency (Load 1.0 = 1000 kW)

Load	0.5	0.6	0.7	0.8	0.9	1.0
Efficiency	81.6	84.9	87.6	90.5	93.1	91.4

Maximum efficiency is 93.5%, obtained at a load of 0.93.

The turbine consists of:

1.1 Running wheel with stainless steel blades of 13/6 Cr Ni, statically balanced and connected to the axle flange with bolts.

1.2 Inside mounted guide vanes of cast iron mounted on stainless steel bolts. The vanes are regulated through a connection between the vanes and the regulating ring. The ring is seated on the upper turbine lids, and is moved by a hydraulic servomotor.

1.3 Upper and lower turbine lids, made as monolithic plate constructions in mild steel.

1.4 Turbine shaft in rolled mild steel.

1.5 Spherical axial roller bearing designed to take all axial forces from the turbine.

1.6 Water lubricated rubber bearing for the positioning of the turbine shaft.

1.7 Conical draft tube in welded mild steel plates, with laid-in brass ring against the stainless steel part of the running wheel.

1.8 Various steel plates, embedded steel fundaments, valves, spare parts and gaskets, etc.

SPECIFICATION, ELECTRICAL EQUIPMENT

1. 3-phase synchronous generator.
   Rated output 1700 kVA at 660 V, 50 Hz.
   Efficiency 95.7%, 765/1721 rpm, weight about 6.3 tonnes.

2. Gear, running effect 1500 kW.
   Efficiency 99%, water cooled, 150/765 (315/1721) rpm,
   weight about 5.0 tonnes.

3. Main transformer, 3-phase, oil-immersed, self-cooled,
   rated output about 2000 kVA. Voltage ratio 660/22,000 (17,500)
   ± 2 x 3.1%, 50 Hz, weight about 4.9 tonnes.

4. Local transformer, 3-phase, oil-immersed, rated output 30 kVA.
   Voltage ratio 22,000 (17,500) ± 5%/240 V, 50 Hz, weight 375 kg.

5. High-voltage equipment consisting of 3 cubicles:

5.1 Cubicle 1: For outgoing cable
1 earthing switch
3 voltage transformers connected to the busbars
3 voltmeters showing voltage on the busbars

Cubicle 2: For power transformer
1 disconnecting switch 630 A, Fuse 400 A

Cubicle 3: For plant transformer
1 disconnecting switch with fuses, Fuse 4 A.

5.2 Generator panel equipped with the following instruments:

1 pc.	voltmeter	0-500 V
3 "	amperemeters	0-4000 A
1 "	wattmeter	100-0-2000 kW
1 "	frequencymeter	46-50-53 Hz
1 "	ohm-meter for control of isolation	
1 "	kWh-meter	

Relays:

3 pc.	control relays for temperature protection of generator and gear
1 "	overvoltage relay
2 "	runaway indication relays
1 "	insulation level indication relay
10 "	signal relays, turbine side
10 "	signal relays, generator side

Disconnecting switch:

3 transformers for instruments and guard.

5.3 Turbine panel incorporating all electrical equipment for the turbine, i.e. main and reserve pump for the turbine regulator, necessary relays, push-buttons, etc.

1 pc.	rpm-meter	0-2500 rpm, marked red at 765 rpm
1 "	water head meter	0-12 m
1 "	turbine gate opening	0-100%
1 "	hour counter	4 digits.

In this panel the 230 V, 50 Hz distribution is also incorporated, i.e.,

1 pc.	voltmeter 0-250 V
1 "	main disconnecting switch
2 "	3 x 63 A fuse courses
2 "	3 x 25 A element automats
10 "	2 x 10 A element automats

6. Batteries

6.1 24 V batteries for signal governing, consisting of:

battery with accessories
battery charger
battery watch with signal for minimum voltage.

6.2 Shunt capacitor for increasing the power factor from 0.88 to 0.94.

7. Water level and turbine regulating

Level indicator,	measures upstream water level by pressure, and indicates this on an instrument in the turbine panel
Regulator,	regulates the turbine gate opening to keep a constant water level.

8. All cables and accessories necessary for a complete assembly are also included.

9. The complete electrical erection and assembly of machines delivered are included. Necessary extra manpower must be supplied by the Owner. Local transport and handling are the responsibility of the Owner.

10. Earthing.
It is assumed that the station is equipped with negative earth which must be available in several places.

11. Engineering.
The supplier of hardware also supplies detailed drawings and plans for fundaments of his equipment. The supplier puts the station into operation.

6

MAGO D.

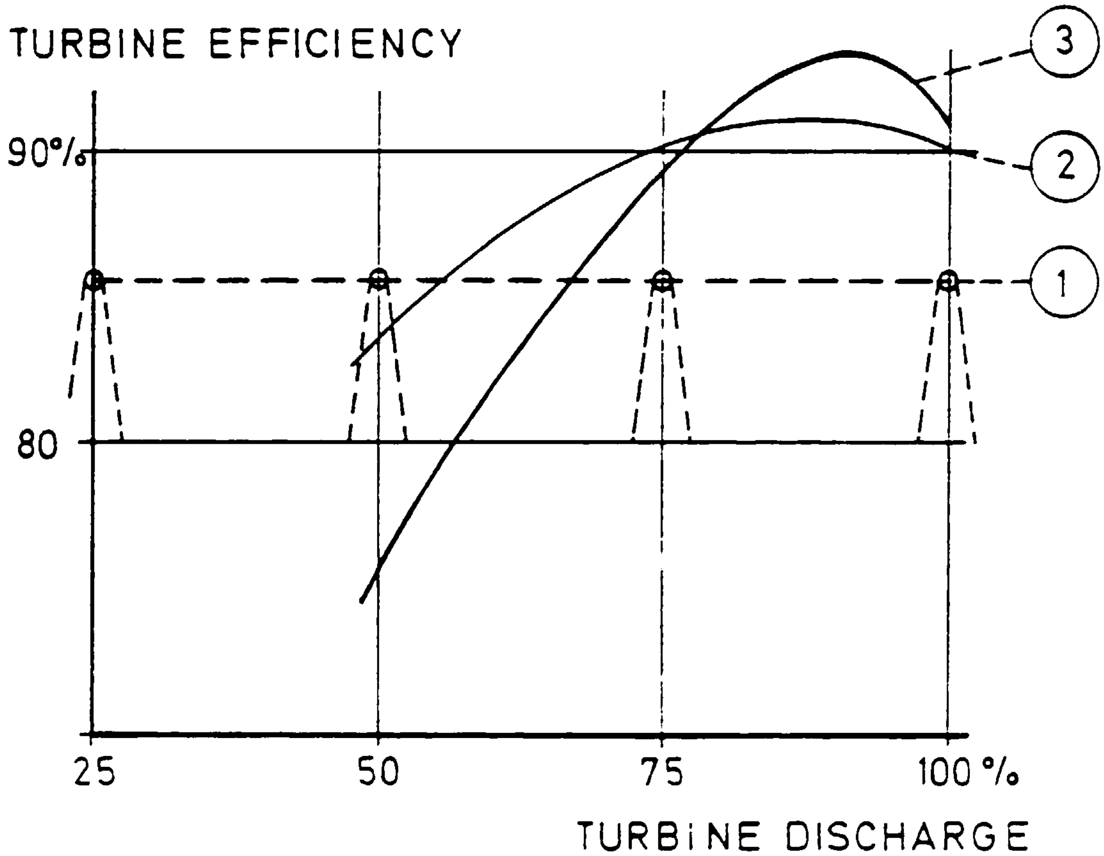
MINI HYDRO POWER PLANT.

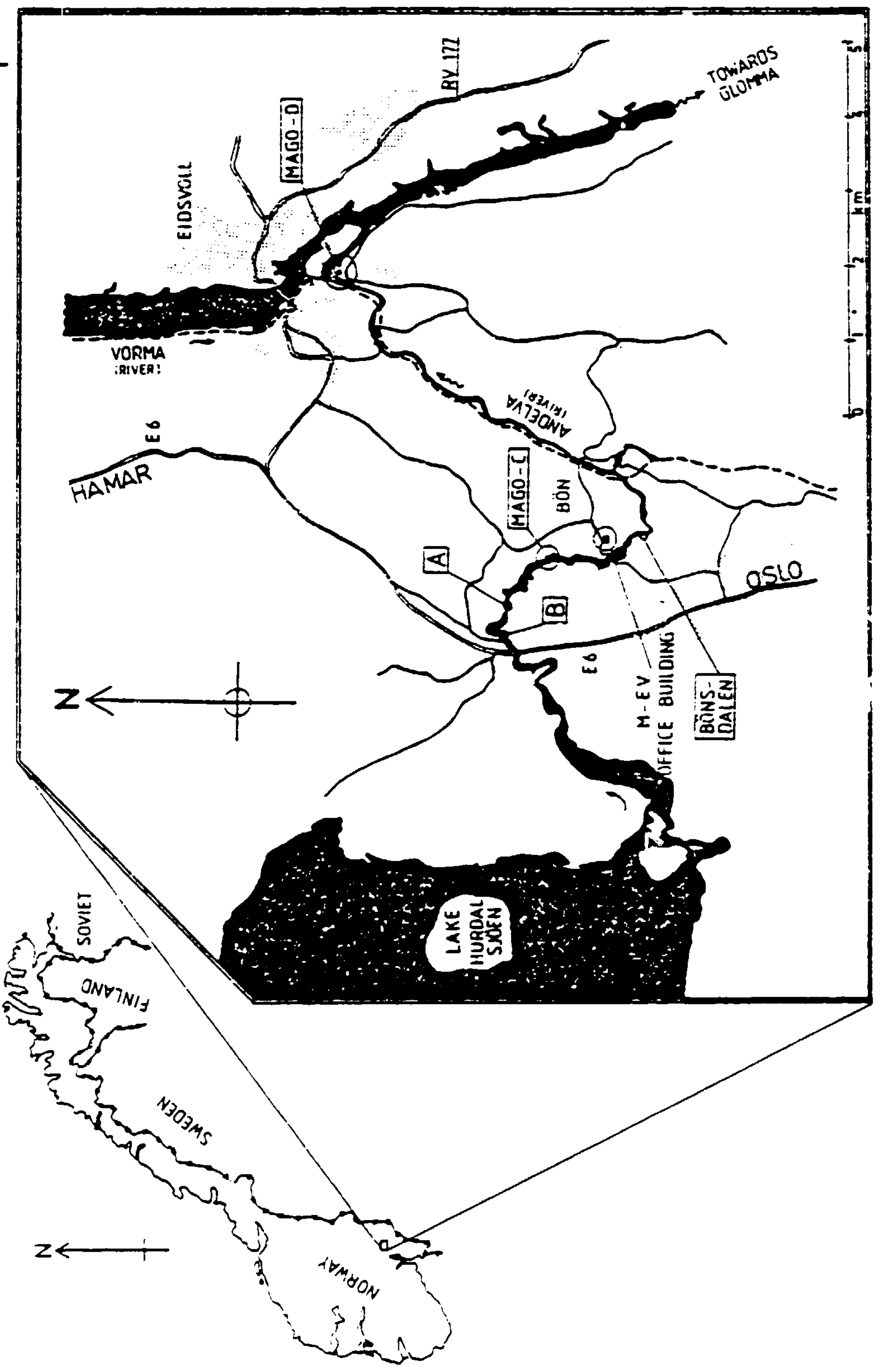
TURBINE EFFICIENCY AT NET HEAD 8m BY:

(1) 4 no. of propeller turbine units.

(2) Kapland turbine with fixed guide vanes.

(3) Francis turbine




TOWARDS GLOMMA
RV 177
MAGO-D
EIDSVOLL
VORMA (RIVER)
E6
HAMAR
ANDELVA (RIVER)
MAGO-C
BÖN
A
B
OSLO
E6
M-EV OFFICE BUILDING
BÖNS-DALEN
N
LAKE HURDAL SJÖEN
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SOVIET
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