TECHNICAL CHANGE IN THE SWEDISH HYDRO POWER SECTOR 1900–1975*

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A hydro power station has two functions from an energy point of view, on the one hand to make the potential energy of the water available for energy conversion (energy gathering) and on the other hand to perform the energy conversion from kinetic energy to electric power. The aim of this paper is to point out some main characteristics of the development of the energy conversion stage and to give some quantitative measures of the energy saving technical change in this stage.

Even though the energy gathering stage and the energy conversion stage are constructed interdependently we shall, however, at first discuss the energy gathering stage. The easiest way to do this is to start with the physical relationship that expresses the relation between energy (E) quantity of water (m-kilogrammes) and head (h-meters)[1] in a waterborne energy resource.

$$E = m \cdot h \cdot g \text{ (Ws = Wattseconds)} \qquad (1)$$

where g = acceleration of gravity force 9.81 (m/s^2).

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[1] Drop.

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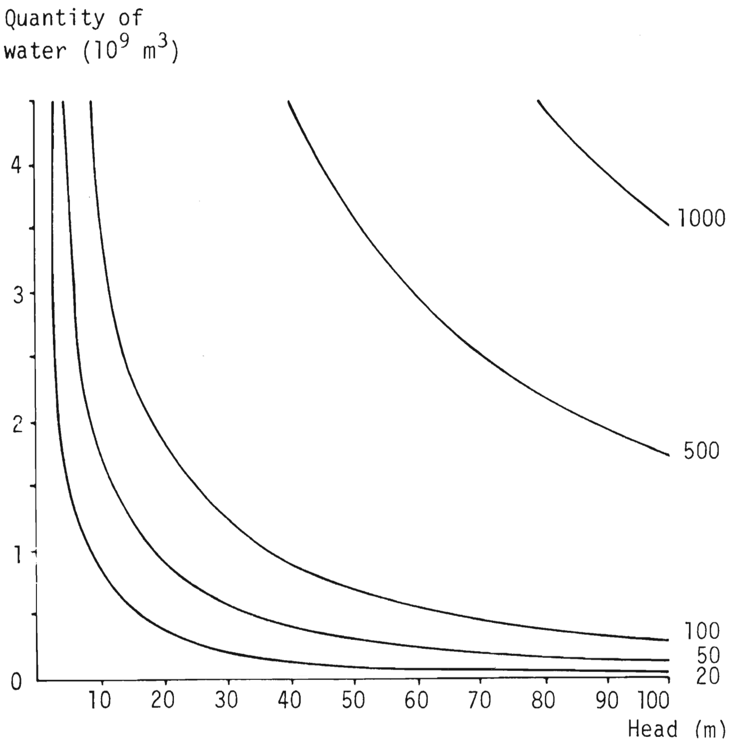
This relation can also be seen in Diagram 1. The isoquants unite different combinations of m and h, which give the same energy (E). We can think of this relation as an equation expressing the energy quantity in a shallow lake with m-kilograms of water h-meters above a lake. In principle there exists full interchangeability between increasing the quantities of water (m) on the one hand, and increasing head (h) on the other in order to gather a certain quantity of natural energy resources. Natural conditions are very important in determining whether a certain quantity of energy is going to be produced in a power station, say with large quantities of water and a low head.

When blasting and constructing techniques were undeveloped, the dimensions of a power station were more restricted by natural con-

Diagram 1. Isoquants (in Gwh=10^6kWh) referring to different combinations of head and quantities of water



ditions than is the case today. Economic possibilities now exist for blasting long tunnels and building large water accumulating systems.

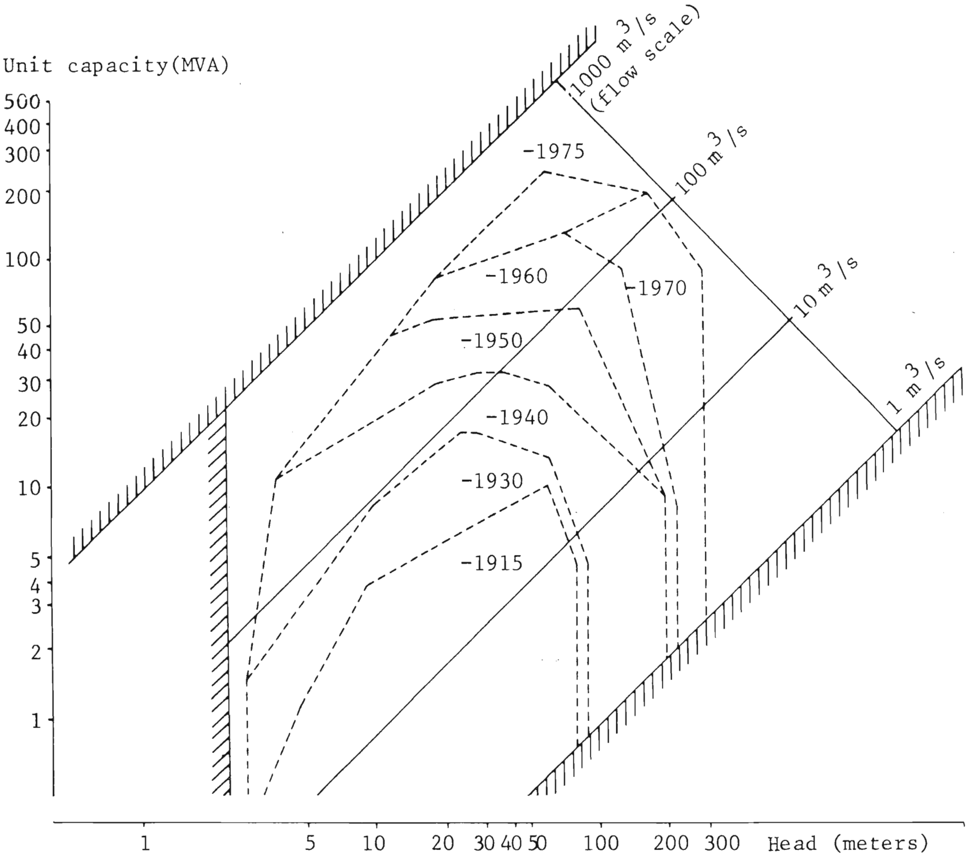
The energy conversion technique chosen for a power station thus depends greatly upon the "energy gathering" technique, in combination with the natural conditions. Therefore we cannot speak of a "best practice" plant for energy conversion in the traditional sense. It is usually assumed that the best practice plant is optimal in scale and technique with respect to present price and technology expectations. Hydro power energy conversion is furthermore restricted as regards inputs into the process. Input to the energy conversion stage does not consist of the homogeneous input "hydro energy" but rather of "hydro energy at a certain pressure". Since energy in different forms requires different construction of the energy converting equipment, different heads (h) will demand different turbine and alternator designs - with a given state of technology and capacity. The best practice energy conversion plant will thus be the plant that with given capacity and head demands the lowest amount of resources, mainly in the form of energy- and capital inputs because modern hydro-electric power plants are mostly unmanned.

TECHNICAL CHANGE IN THE ENERGY-CONVERSION STAGE

Since every new combination of capacity and head (and therefore also quantity of water) for a hydro-power unit represents a new mode or technique of production, one aspect of the technical change in the energy-conversion stage is therefore how the "frontier" of these combinations has moved over time. The other aspect is how input of resources has varied over time, given these combinations.

To start with we shall study how this technical frontier has developed. (See Diagram 2.) We have used data from 841 units installed between 1900 and 1974. Their total capacity is

Diagram 2. Limits to flow, head and capacity-characteristics for hydro-power units installed 1900-1975



14 823 MVA[1], which includes most of total installed capacity during this period. In Diagram 2, which is double logarithmic, head (in meters) is along the x-axis and installed unit capacity along the y-axis. Because E, h and m are multiplicatively related, points with the same flow will form straight lines in this diagram (iso-flow lines). The scale on the right refers to the flow (m^3/s). To give an impression of the possible space of

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[1] MVA (Megavolt ampères) is equivalent to MW corrected for a coefficient expressing the offset in phase between current (in ampères) and voltage. This offset is measured as an angle ϕ. The correction coefficient becomes $\cos(\phi)$ and usually takes values around 0.9.

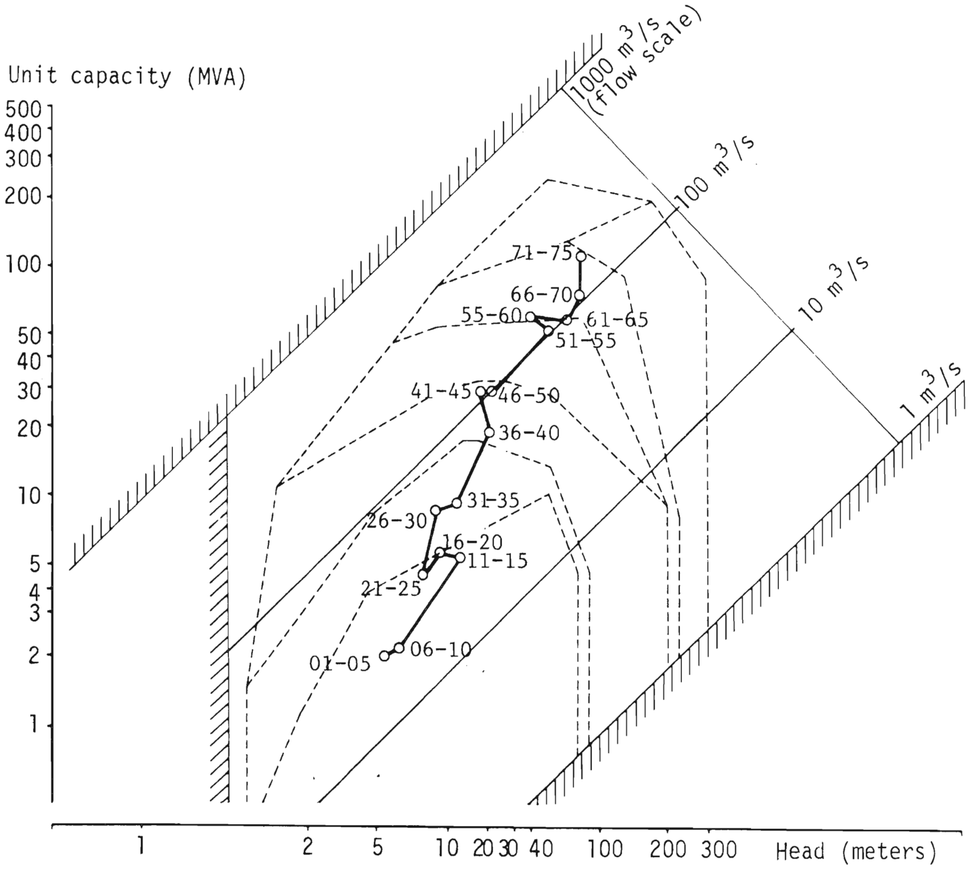
existence for units we have marked the present space of existence for power plants with limitation lines. (A power plant can consist of one or more units.) Thus, e.g., the lowest head was 2.5 m and the largets and the lowest flows were 1000 m^3/s and 1 m^3/s, respectively. These "limits" should, however, not be considered as absolute in the sense that they cannot be crossed. Within this region we have marked the combinations of head, waterflows and unit scale installed up to a certain period. The material has been subdivided into the following periods: 1900-1915, 1916-1930, 1931-1940, 1941-1950, 1951-1960, 1961-1970 and 1971-1975.

As can be seen in Diagram 2, the most pronounced characteristic of the development is the increase of the unit scale. This can be seen as an upward shift of the maximum attainable Megawattage for each period. The vertical distance between the upper point of each period is roughly the same for all the chosen periods. This indicates that the rate of growth in the maximum scale has been approximately constant over a long period, even though it has been slightly quicker during the fifties. The average of these vertical distances implies a near doubling of maximum scale during each period. Analogously an increase in the maximum flows can be seen as a shift of the limitational lines perpendicularly with respect to the iso-flow lines. The relative growth of the maximal flow stops almost completely already after the 1940's.

Changes in maximum head are seen as a shift in the rightmost limitation lines along the x-axis. The quickest growth of head occurred between 1930 and 1940. Already during the 1930's high heads were used for hydro power production. This picture of the development can be complemented by studying the characteristics of the average capacity installed. For the sake of clarity these can be seen in a new diagram (Diagram 3).

Every circle in the diagram represents the average unit characteristics (scale, head, flow) during each five year period between 1900-1975. (Every five year period consists of 25 to 114 observations.) The averages have been calculated by weighting with the unit capacities.

Diagram 3. Average flow, head and capacity of units installed 1900-1975



To begin with we can see that average installed head has increased from 10-20 meters in the beginning of the century to 80-90 meters during the seventies. Average unit rating has increased from 2-3 MW to 100-150 MW during the same period. From a capital productivity point of view this means that during this period the volume of water handling per unit of production has decreased substantially.

If we study the pattern of development from period to period, we can, however, note some irregularities. Between 1916-25 no increase in neither the unit rating nor the head does occur. One explanation may be the large increase in construction costs which ocurred in connection with the first world war. Therefore, the construction of hydro power stations which required more building work was avoided. A similar tendency can be seen during the second world war. During the period 1925-1940 construction costs decreased, which is also reflected in a substantial increase towards larger waterflows and higher heads.

During the period 1950-1955 capacity expansion was almost solely achieved by higher heads, that is, parallell to the iso-flow lines. After 1955 the pattern is more irregular. During 1955-1960 a worsening of the head conditions occurs. Between 1961 and 1965 erection of capacity with favourable heads takes place but with lower average natural energy resources. During the following 10-year period, 1966-1975, an increase in the average rating of units occurs, however, without the usual simultaneous improvement in head conditions.

This could be related to a strong change in the relative cost of expanding energy capacity from increasing heads to increasing quantities of water. Such a relative change in costs could occur if topographic conditions are altered in such a manner that it is less costly to expand water accumulation capacity,(e.g. by connecting adjoining precipitation regions) than to blast long mountain tunnels to attain heads. (After 1960 capacity expansion took place mainly in the northern Norrland region which has more favourable topographic and hydrological conditions than southern Sweden in this sense.) The above mentioned shift in relative costs can be viewed as a change in price of <u>water</u> relative to <u>head</u>. As can be seen in Diagram 4 a drastical increase in average dam volume (weighted by size in MW) took place after 1955. An increase in dam volume can be seen as a rough proxy for the size of interconnected water systems. Furthermore, it can be seen in Diagram 5 how average tunnel length per head meter has developed. Until the end of the 1960's this ratio increased relatively slowly compared to the

Diagram 4. Average dam-capacity per MW installed 1941-74

Index for period before 1941 = 100

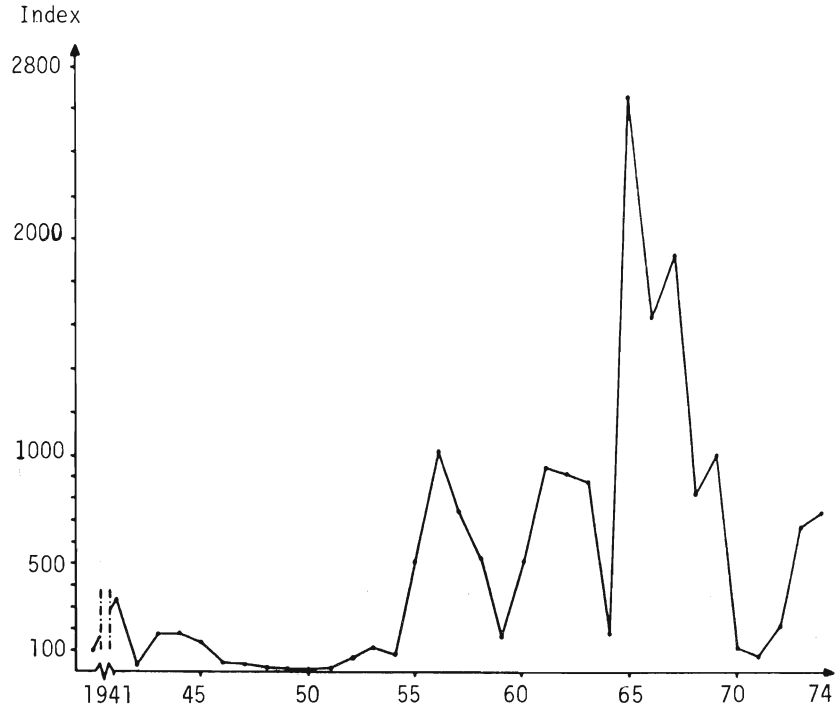
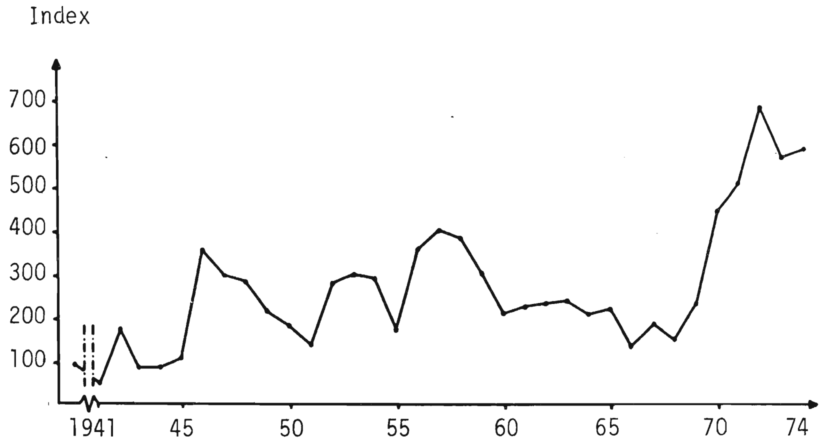


Diagram 5. Tunnel-length per head-meter and MW installed 1941-74

Index for period before 1941 = 100



period 1969-1975, when it grew from approximately 200 to a high of 700. In order to achieve the 1972 average head of 85 meters (see Diagram 3) one had to blast 6.5 km of tunnels. (All other waterways, canals etc. not included.) This can be compared with 1.8 km of mountain tunnels to achieve an average head of 65 meters during the 50ies.

This very rapid change (worsening) of the conditions for expansion is probably one of the main reasons why expansion of hydro power in Sweden has almost halted during the 70ies.

ENERGY PRODUCTIVITY AND TECHNICAL CHANGE

In the following section we shall give an account of an attempt to measure and quantify the energy-saving technical change in the hydro-power sector. The data refer to 263 plants built between 1900 and 1974. Efficiency measures refer to cross-section data in 1974. The long life of hydro-power units has made it possible to make estimations for plants of high age. (Plants built before 1900 are still used for commercial production.)

Successive repairs and improvements, however, have increased efficiency in the oldest plants in such a manner that their efficiency in 1974 does not reflect their efficiency at the date of construction. There is, though, no good way to know how much this error affects our estimates. The technique of measuring efficiency in hydro-power stations is much younger than the technique of producing hydro power. Some complementary investigations seem to suggest that even if the cross section analysis biases our estimates of the speed of growth in energy efficiency downwards this bias is of minor importance due to a strong "embodiedness" of the technique for each vintage.

Specification of a partial engineering production function

We shall view technical progress as the shift over time of the (ex-ante) function expressing the relation between input and output of energy. The energy saving technical progress analysis will be performed by studying energy conditions solely at the unit level. In order to refer to the measured increase in energy efficiency (that is, the ratio between input and output of energy) as technical progress, we have to make the assumption that the possibility of substitution between energy and capital at the unit level is small. This implies that substitution between energy and capital at the plant level takes place by choosing the number of units in a station. This type of substitution is possible due to the rather surprising fact (which shall be demonstrated later in this paper) that gross capital requirements of the energy conversion equipment at the plant levels decrease with the number of units given the capacity of the plant. An increase in the number of units, given plant capacity, will, however, reduce plant energy efficiency due to scale effects at the unit level. Therefore there will be a tradeoff at the plant level between energy and capital, but not at the unit level.

The general production function relation for a hydro power unit is assumed to be expressed in the following way

$$f(x, y, k_1, \dots, k_n) = 0, \qquad (2)$$

where x = input in the form of natural energy (motive power)
y = output in the form of electric energy (power)
$k_1, \dots, k_n$ are design parameters.

The function could most adequately be described as an "engineering production function", because it includes the effect on energy productivity of among other factors, the design of water systems and type of turbines.

In the following these variables will be used:

C = capital (investment)
E = energy of a waterborne energy resource in Wattseconds
g = acceleration of gravity force = 9.81 (meter/sec^2)
h = gross head in meters
l_v = length of tunnels in meters
l_v/h = length of tunnels l_v relative head h
$\ln P_e$ = scale parameter expressed in logarithmic form in order to take account of decreasing $\Delta\eta/\eta$ with increasing unit scale. (Decreasing elasticity of scale.)
m = quantity of water in kilogrammes
$\dot{m}$ = flow of water in kilogrammes per second
P_e = Unit capacity in MW or MVA
R = Dummy variable taking value 1 if turbine can be regulated (Kaplan) and 0 if it cannot (Francis). Since we do not know if the installed turbines are of the Kaplan or of the Francis type, we have assumed that if the unit was installed after 1935 (year of introduction of Kaplan turbines) and the head is lower than 15 meters, then the turbine is of the Kaplan type. When this proxy variable was compared with the true value for a smaller sample of units, however, we achieved a correlation of only 0.28.
t = unit age
β_1 = capital coefficient
β_2 = head coefficient
γ = shift coefficient
$*$ expresses conditions during maximum production in a plant.

The statistical model

The energy-loss function used as a starting point for the statistical estimations is

$$\frac{P_e}{\dot{m}^*h^*g} = \eta(l_v/h,\ \ln P_e,\ t,\ R)^{1} \tag{3}$$

* signifies conditions under maximum production. The left-hand side term is the actually observed energy-efficiency of the plant under maximum-production conditions. After differentiation the relation between the loss function η and changes in the relative length of tunnels variable (l_v/h), unit scale variable ($\ln P_e$), unit age variable (t) and type of turbine variable (R) can be expressed:

$$\eta_j = \eta_{oj} + d\eta_s = \eta_{oj} + \frac{\partial\eta_j}{\partial(l_v/h)} d(l_v/h) + \frac{\partial\eta_j}{\partial(\ln P_e)} d(\ln P_e) + \frac{\partial\eta_j}{\partial t} dt \tag{4}$$

where j attains different values for Francis and Kaplan turbines, respectively.

For statistical estimation of the partial derivatives of this equation we write the statistical model:

$$\eta_i = \alpha + \beta_1(l_v/h)_i + \beta_2(\ln P_e)_i + \beta_3 t_i + \beta_4 R_i + u_i, \tag{5}$$

where u_i is an error term with $F(u_i) = 0$ and $E(u_i^2) = \sigma^2$.

Thus we have taken care of the two different techniques (R = 1 and 0) with a dummy variable and by assuming equal coefficients for the other independent variables. In this model technical change is included as a linear function of time. Since we cannot assume

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[1] To go from the energy relation (1) to the momentaneous power relation (3) one takes the time derivative of (1) assuming constant head (h) that is $P_e = \frac{dE}{dt} \approx \frac{dm}{dt} \cdot h \cdot g \cdot \eta$, where dm/dt is massflow per unit of time, that is kg/s, (density of water is assumed to be 1 ton/m^3) and multiplied by the loss factor η.

a linear relationship over a longer period of time we have, besides the above regression equation, also estimated an equation in which every vintage has its own dummy variable (48 vintages between 1900 and 1974).

The results of estimations

The estimates of the coefficients according to equation (5) can be seen in Table 1.

Table 1. Energy productivity in the hydro-power sector 1900-1974
Explanatory variables and regression results

	Regression coefficients					
Intercept	Unit scale ($\ln P_e$)	Unit age (t)	Relative length of tunnels (l_v/h)	Type of turbine (R)	R^2	Degrees of freedom
0.8013	17.5×10^{-3}*** (11.6)	-10.5×10^{-4}*** (-7.1)	-24.2×10^{-6} (-0.3)	-20.7×10^{-5} (-0.04)	0.60	258

Note: t-value within parenthesis. *** = significance at the 1% level.

The coefficients for unit scale ($\ln P_e$) and unit age (t) are both significant and of the correct sign. The coefficient for relative length of tunnels (l_v/h) has the proper sign but does not significantly differ from 0. It is also doubtful whether the coefficient is of the correct magnitude. Its size implies that head losses in tunnels are 0.024 meters per kilometer of tunnel, whereas direct measurements of the losses show that they should lie around 0.5 meters per mountain tunnel kilometer[1]. The coefficient of type of

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[1] Elfman, S., Vattenledande bergtunnlar vid kraftverk. Statens Vattenfallsverk. Stockholm 1975. Technical report.
In a mountain tunnel, friction losses are a function of the velocity of waterflow. With a given flow (in m^3/s) the velocity of flow will be a function of the cross sectional area. Since cost per tunnel km increases with increasing cross section one is usually forced to make a trade-off between tunnel cross section and energy losses, or generally speaking between capital and energy.

Cont.

turbine (R) is also insignificant, but not therefore, uninteresting. It implies an aspect of the relation between natural conditions and energy productivity, namely that energy productivity under stationary conditions is not importantly altered if plants are built to make use of high or low heads. The value of this coefficient could, however, depend largely upon the chosen proxy. The scale coefficient ($\ln P_e$) implies that with otherwise equal (natural) conditions a doubling of unit scale leads to an increase in energy productivity with 1.3 percentage units. The unit age coefficient (t) shows that energy productivity, on the average, has increased with 1 percentage unit every 10 year.

As an example we can calculate with these values that a plant that was built in the beginning of the thirties with a unit size of 6 MW without tunnels should have had an energy productivity of approximately 0.79, while a unit built in 1967 of 220 MW with 5 km tunnels should on the average have an energy productivity of 0.89, both being operated at full capacity production.

We return to the matter of the coefficient for relative length of tunnels (l_v/h). Our estimate has a 20 times lower value than would be expected from physical measurements of tunnel losses. The reason we have this error is probably that it is difficult to separate the effects of unit scale ($\ln P_e$) and unit age (t) from the effects of relative length of tunnels (l_v/h) in the regres-

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Footnote 1 cont.

(There is, besides the possibility of increasing cross-sections, also the possibility of reducing flow losses by improving the surface conditions of the tunnel.) The point one chooses depends largely upon the natural rock-conditions (hardness, crackformations, etc.). These factors imply that losses per unit of tunnel length will vary between tunnels. The spread in friction does, however, not seem to be very significant. The average flow velocities at maximum production conditions lie around 1-1.5 m/s. The corresponding friction losses are on the average 0.5 m/km.

sions, because during a relatively short period (approximately since the middle of the 1960's) there has been simultaneous increases in both tunnel lengths and unit scale. Therefore the unit scale ($\ln P_e$) and age (t) variables have "explained" a part of the energy productivity decrease which undoubtedly has taken place as a result of increased tunnel lengths. We should for this reason assume that the unit scale ($\ln P_e$) and unit age (t) coefficients have been underestimated. One way to reduce the effect of this multicollinearity problem is to specify a new dependent variable $\hat{\eta}$, which is the observed energy efficiency at maximum production plus the expected value of the waterway losses that is

$$\hat{\eta} = \eta + \frac{l_v}{h} \cdot 0.5 \cdot 10^{-3} . \qquad (6)$$

Due to this we now have only unit scale ($\ln P_e$), unit age (t) and type of turbine (R) as independent variables. The results of this new regression can be seen in Table 2.

Table 2. Energy productivity in the hydro-power sector 1900-1974
Explanatory variables and regression results.
$\hat{\eta}$ = dependent variable

	Regression coefficients				
Intercept	Unit scale ($\ln P_e$)	Unit age (t)	Type of turbine (R)	R^2	Degrees of freedom
0.8133	19.2×10^{-3}*** (12.0)	-12.5×10^{-4}*** (-8.0)	-75.7×10^{-4}* (1.5)	0.64	259

Note: t-value within parenthesis. *** and * = significances at the 1% and 10% level, respectively.

As we see in Table 2 the coefficients of unit scale ($\ln P_e$) and unit age (t) increase somewhat with this operation as could be expected.

The results of the regressions with dummy variables for each vintage group can be seen in Table 3. The results also are suitable for graphic representation. We have plotted the intercept terms for the 47 vintage groups in Diagram 6. Not unexpectedly the linear trend through these intercept terms has the same slope as the OLS regression coefficients (see Table 2). We have plotted this trend in Diagram 6. Perpendicularly from this trend line we have drawn the lines which show the effect of (increasing) scale upon energy productivity. Clearly the increase in unit scale has meant roughly as much for the energy productivity development as has the general trend of the energy saving technical change.

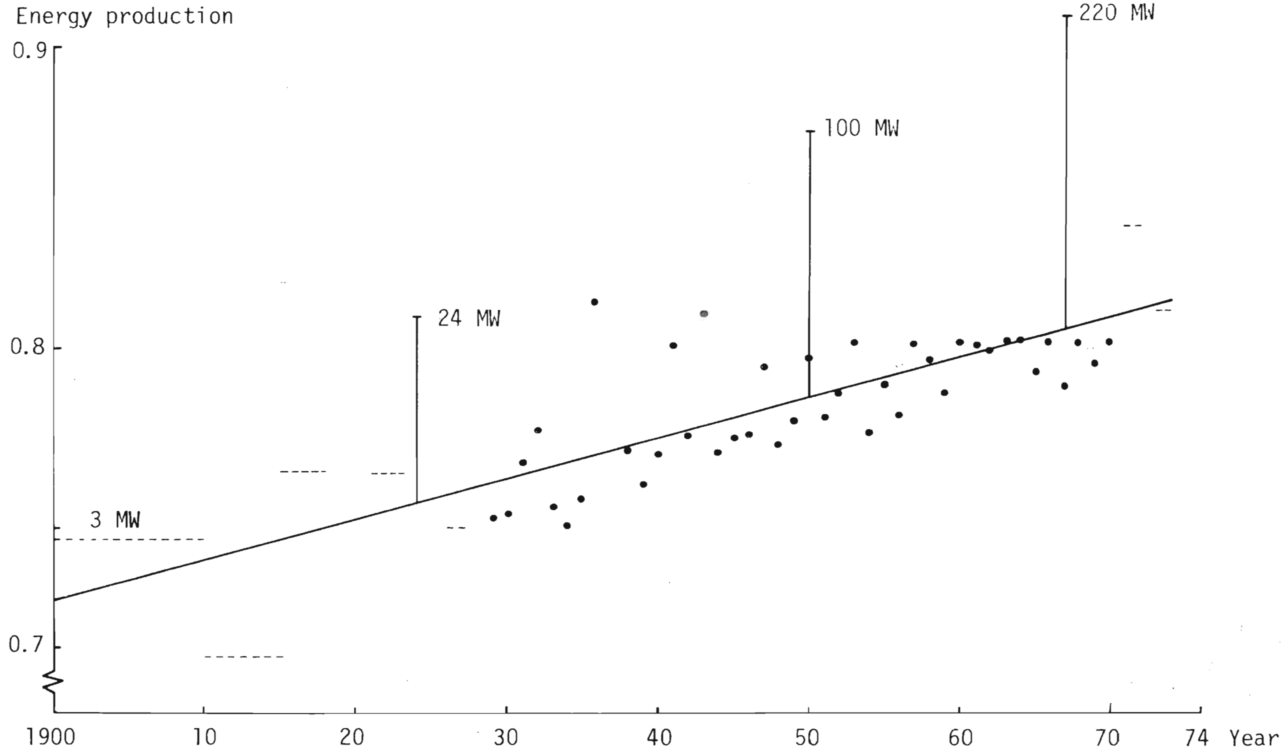
Table 3. Energy productivity in the hydro-power sector 1900-1974 Explanatory variables and regression results. Statistical model with individual term for each vintage
$\hat{\eta}$ = dependent variable

Regression coefficients			
Unit scale ($\ln P_e$)	Type of turbine (R)	R^2	Degrees of freedom
19.4×10^{-3}*** (10.8)	-105.2×10^{-4}** (-1.9)	0.43	213

Note: t-value within parenthesis. Intercept term, see Diagram 4.
*** and ** = significance at the 1% and 5% level, respectively.

Diagram 6. Energy-productivity, unit scale and technical change 1900-1974

Every dot or line represents an intercept



AN ASSESSMENT OF THE ENERGY-SAVING TECHNICAL CHANGE IN THE HYDRO-ELECTRIC POWER SECTOR

We shall ultimately try to calculate how much this energy saving development could be worth.

Suppose that we build a power plant with a capacity of 200 MW. We can build it with one unit and with an average utilization of 5 000 hours per year. Yearly production will then be 1 TWh (= one terawatthour which is equal to 10^9 kilowatthours), or we build it with two units of 100 MW each. According to our findings the two smaller units will produce with a 1.3 percentage units lower efficiency. Since energy efficiency in the first case will be on the average 0.90 (1970-vintage) the relative decrease in energy productivity will be 1.4 %. This means that for a given amount of supplied energy the two-unit station will produce 14 GWh (gigawatthours = 10^6 kilowatthours) less per year. The yearly worth of this production is in 1968 prices (0.032 Skr/kWh high voltage price excluding distribution costs) approximately 0.45 million Skr. Calculated with an average length of life of 30 years at an interest rate of 8 % this represents a capitalized value of 5.0 million Skr. This is to be compared with the average investment of approximately 10 million Skr in turbines and alternators in the one unit case. The investment in the two unit case thus has to be approximately 50 % lower in costs in order to justify the use of two units.

How do capital requirements vary with scale and head in the conversion stage? Some preliminary results referring to investments in the energy conversion stage suggest that the adequate specification of the relation between capacity and capital (unit capacity cost) is

$$P_e = C^{\beta_1} h^{\beta_2} e^{\gamma t} A, \qquad (7)$$

i.e., a Cobb-Douglas type of function where A is the intercept, the β's are the "marginal production elasticities" of capital and head and γ is a shift factor which expresses the rate of shift in this investment relation, due to, among other factors, inflation and capital saving technical change. We have estimated this relation using data referring only to turbines (49 observations) and to plants (25 observations). The turbines estimation gave the following coefficients (see Table 4). Note that capital is measured as investment in current prices, which leads (if prices have increased substantially on this type of equipment) to a negative sign on the shift coefficient γ.

Table 4. Turbine investment function. Estimated coefficients Turbines installed 1934-1975

Regression coefficients				
Capital coefficient (β_1)	Head coefficient (β_2)	Shift coefficient (γ)	R^2	Degrees of freedom
0.75*** (10.9)	0.54*** (10.6)	-0.008 (-1.43)	0.99	44

Note: t-values within parenthesis. *** = significance at the 1% level.

The unit regression is similar, but investment in this case refers to total investment in machinery per unit in the plant and not only to the energy conversion equipment.

Table 5. Machinery per unit investment function. Estimated coefficients. Units installed 1950-1974

Regression coefficients				
Capital coefficient (β_1)	Head coefficient (β_2)	Shift coefficient (γ)	R^2	Degrees of freedom
0.52** (2.3)	0.44*** (5.1)	-0.0159 (-0.9)	0.99	21

Note: t-value within parenthesis. *** and ** = significance at the 1% and 5% level.

Both regressions suggest that with given head and total capacity, capital requirements decrease with the amount of units installed, since the capital coefficients (β_1) are less than 1. Note, however, that in this step we have not considered the fact that capital requirements increase if building capital is included, since machinery takes more space if divided into more units. This is, however, important only in cases where machine rooms have to be blasted in the mountain.

Returning to our example, if we use two units instead of one, investments in machinery will decline (head is constant). If we use the results from Tables 4 and 5 investment requirement would decrease by between 50 and 25 % depending upon which of the capital coefficients (β_1) is considered the most reliable estimate. These investment reductions imply, with the figures given in our example, that investment could be reduced by 2.5-5.0 million Skr by using two units. If this is compared with the capitalized value of energy savings of 5.0 million Skr we arrive at a situation in which the choice very much depends upon the price assumptions we have made. The example, however, shows the great importance of energy productivity increase in the hydro-power sector. It also shows that energy productivity has played an important role in the process of increasing unit scale of production.

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