Simplified Method for Estimating the Cost of Plant Equipment

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This article presents a method for calculating the value of various pieces of equipment installed in hydroelectric facilities, based on the parameters that define each component.

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This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.

Under Italian tax law, hydro plant components are included in the assets subject to estate tax. The value for taxation purposes must be declared by the plant owner. Hence, it is necessary to determine the value of installed machinery and civil works.

The value must be proven by documentation showing the cost of construction/installation or inferred using the comparative value procedure with documented similar plant components. Because of the lack of documentation showing the cost of construction, especially for older systems, ENEL personnel had to create a uniform and equalized calculation method based on a sample of cost data and documented on a classification that would allow for comparison in determining the cost of machinery. ENEL developed a similar procedure for determining the cost value of civil works.

ENEL is Italy's largest power company and one of Europe's main listed utilities. ENEL operates in 40 countries, has more than 97 GW of net installed capacity, and sells power and gas to about 61 million customers. The company operates a wide range of hydroelectric, thermal, nuclear, geothermal, wind, photovoltaic and other renewable plants. ENEL has an installed hydroelectric capacity of 30,265 MW in 780 plants, 430 of which have a capacity of less than 10 MW.

A cost estimate for feasibility studies or budgets cannot rely solely on market analysis and/or statistics. A close link between the technical and engineering departments should help determine the parameters that influence cost and to what extent. Existing documentation is not sufficiently reliable.

The data in this article is based on European prices for equipment of a reasonable quality. Higher and lower quality equipment and the region of the world will affect prices to some extent.

Objectives

The purpose of the study discussed in this article was to analyze the relationship between the cost of a component installed in a hydro plant and the main parameters that define it. Because the parameters that define cost are numerous, the objective was to identify the minimum set of parameters needed to estimate a good approximate cost. Often, not all parameters are known or defined. The procedure used was to examine orders for which the supply details were known and therefore it was possible to calculate a comparable price.

The figures and formulas presented in this article should be understood as a simplified model that is based on the known cost of a component. The rate of error increases as the known component and the component being compared to it become more parametrically distant.

It should be noted that even if costs are estimated in a non-uniform way through the assessment of overall weight, ENEL has confirmed that this approach is valid for many components as long as it is not extended to extremely different key parameters. By adding a feature that sees a higher unit cost for small pieces of equipment compared to larger ones, the approximation is acceptable.

The simplified model

A mathematical model of equipment cost is more accurate the greater the number of parameters that are available, but it is also often true that many parameters have a minor influence or may not be properly assessed (such as a significant increase in the price of raw materials).

The order price is influenced by the cost of raw materials and labor, marketing strategies (aggressive new competitors or closed markets), the size of competing businesses, and different companies' fixed costs. These parameters can change the price and are a source of uncertainty if the data has been collected without proper understanding of the context in which a bid should take place. In addition, data collection must be consistent and not spread over time, as changes in costs may introduce additional difficulties in deriving the standards in relation to the parameters already identified.

Evaluation models

Models were developed for the main pieces of equipment in hydro facilities.

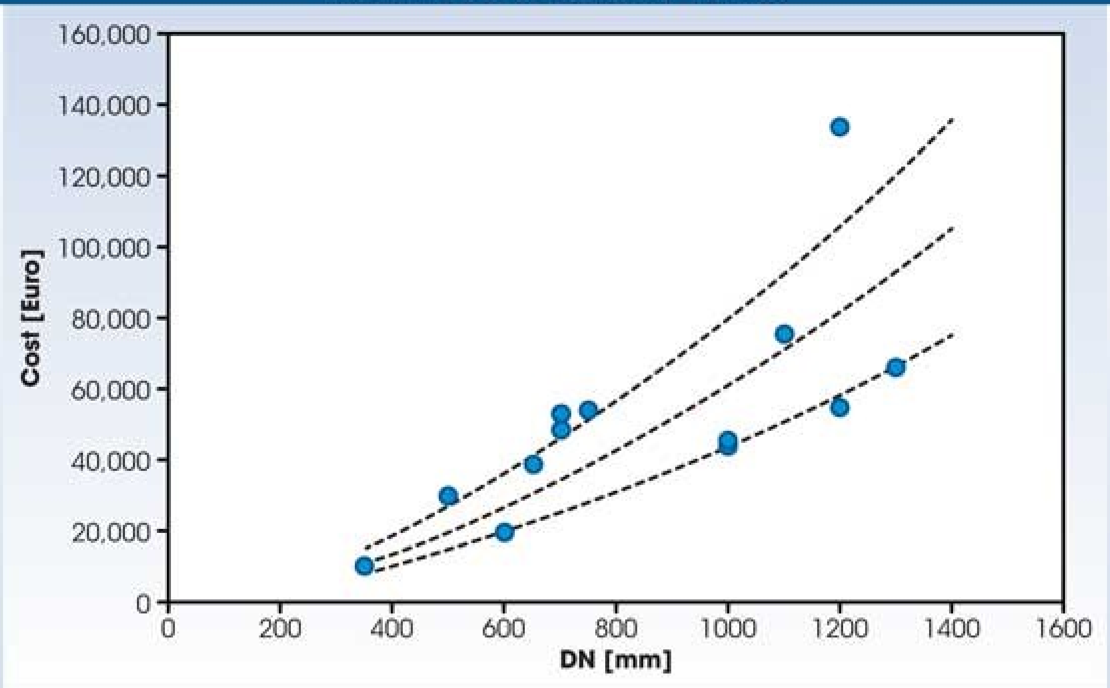
Gates

The cost of a gate is a function of its weight because the plant component is of secondary importance compared to the cost of the metallic structure. A thorough study of gate weights is available.[1]

Main inlet valves

The two categories of main inlet valves are butterfly and spherical valves. To find a relationship between weight and approximate cost, ENEL used the valve weights quoted in the manufacturers' catalogues. Diameter and maximum head are the main parameters that establish the weight and, consequently, the cost.

FIGURE 1 Cost of Butterfly Valves



The cost of a butterfly valve is highly dependent on its diameter, along with head.

Figure 1 equates ENEL's costs for butterfly valves to their diameter in millimeters. The analyses made are similar to those reported elsewhere for these valves.[2] An analysis also is available for the cost variation of rotating valves.[2] Using these curves, ENEL defined a constant for accurate estimation of valve prices. However, sufficient data was not available to make a similar analysis for spherical valves.

Penstocks

Because it is simple to find a preliminary total weight of the supply, ENEL did not refer to dimension parameters such as capacity and pressure, instead using the unitary price, which is linked to the material cost and is strongly related to quantity.

Hydraulic machines

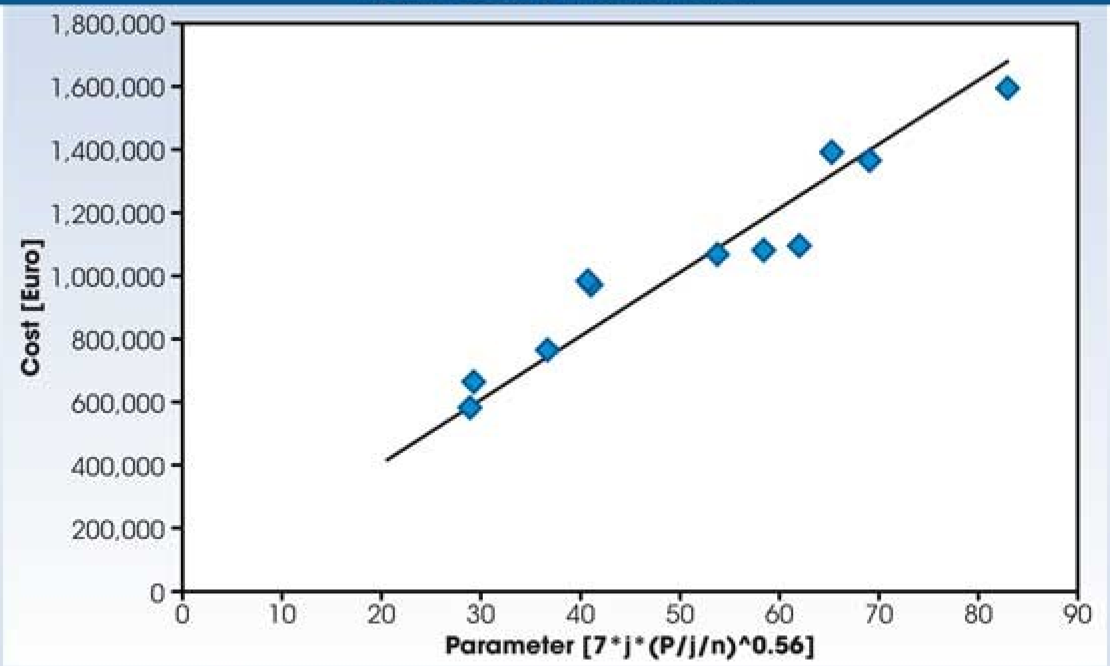
The various typologies and building technologies for the hydraulic machine (turbine or pump) make this component one of the most complicated when it comes to cost evaluation.

ENEL built many large plants from 1970 to 1990. The company's net installed hydroelectric capacity increased by 7,037 MW from 1970 to 1990. A total of 86 units were installed with an average capacity of 81 MW. The largest ENEL hydroelectric plant was commissioned in 1982 with a total installed capacity of 1,190 MW. From 2000 to 2010, many of these plants have been rebuilt, and the machines have been replaced as a result of the ‘green certificate' incentive mechanism. In these cases, the hydraulic machines had to be integrally replaced, with the exception of the cast iron parts.

In many instances, the plant was rebuilt because the configuration had changed from horizontal to vertical or complete replacement was more convenient.

— Pelton: Minimum parameters needed are the power, number of jets and speed. Studies carried out in the 1980s3 provide a relationship between the total turbine weight (including the main inlet valve) and the parameters of power, number of jets and rated speed. A similar relationship was discovered with regard to supply costs from 2000 to 2010 (see Figure 2).

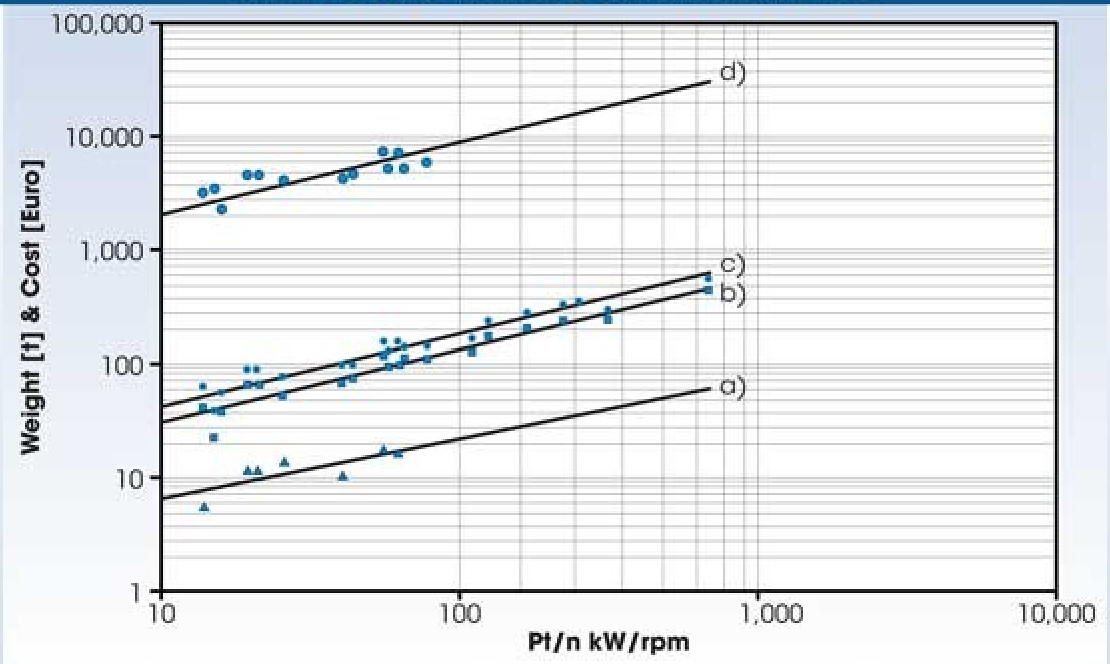
FIGURE 2 Cost of Pelton Units



For Pelton turbines, there is a direct relationship between the total turbine weight and the parameters of power, number of jets and rated speed.

— Francis and reversible single stage: Minimum parameters needed are power and speed. From the 1980s analysis,[3] a relationship between total weight and these parameters was found. A more recent analysis was carried out on Francis machines by evaluating a larger number of cases, and the validity of the previous model was confirmed (see Figure 3).

FIGURE 3 Cost of Francis and Reversible Units



The cost of a Francis or reversible turbine is based on a relationship between the total weight and the parameters of power and speed.

— Pumps and reversible multiple stage: Minimum parameters needed are power, number of stages and speed. Again, in the 1980s analysis,[3] a relationship between weight and these parameters was found. Because of the peculiarity of the machines and the small number of ENEL plants in which they are installed, the analysis of the historical results could not be confirmed.

— Kaplan: Minimum parameters are power and speed. From 2000 to 2010, by using the parameters obtained from plant renovation, it was possible to perform an analysis comparable to those of the other machines, obtaining a similar expression.

Generators

The synchronous generator (vertical axis) rotor weight may be expressed as:[4]

$$R = 50 \times (A/n^{0.5})^{0.74}$$

where:

— A is apparent power in kVA;

— n is rated speed in rpm; and

— R is rotor weight in tons.

The generator total weight estimate depends on the following relationship:[5]

$$W = 107.25 \times (A/n^{0.5})^{0.74}$$

A further analysis was made starting from a draft of an ENEL study from the 1990s. In a diagram of the cost by power unit in function of the power and of the cost by weight unit in function of the total weight of a series of vertical machines, ENEL found the following relationships:

$$\text{Cost/MVA} = k \times A^{-0.428}$$

$$\text{Cost/kg} = h \times M^{-0.229}$$

where:

— Proportion coefficients k and h are a function of the rotating speed.

Since:

$M/A = (k/h)^{1.297} \times A^{-0.428}/M^{-0.229}$

Then:

$M_{(t)} = K_j \times A_{(MVA)}^{0.742}$

where:

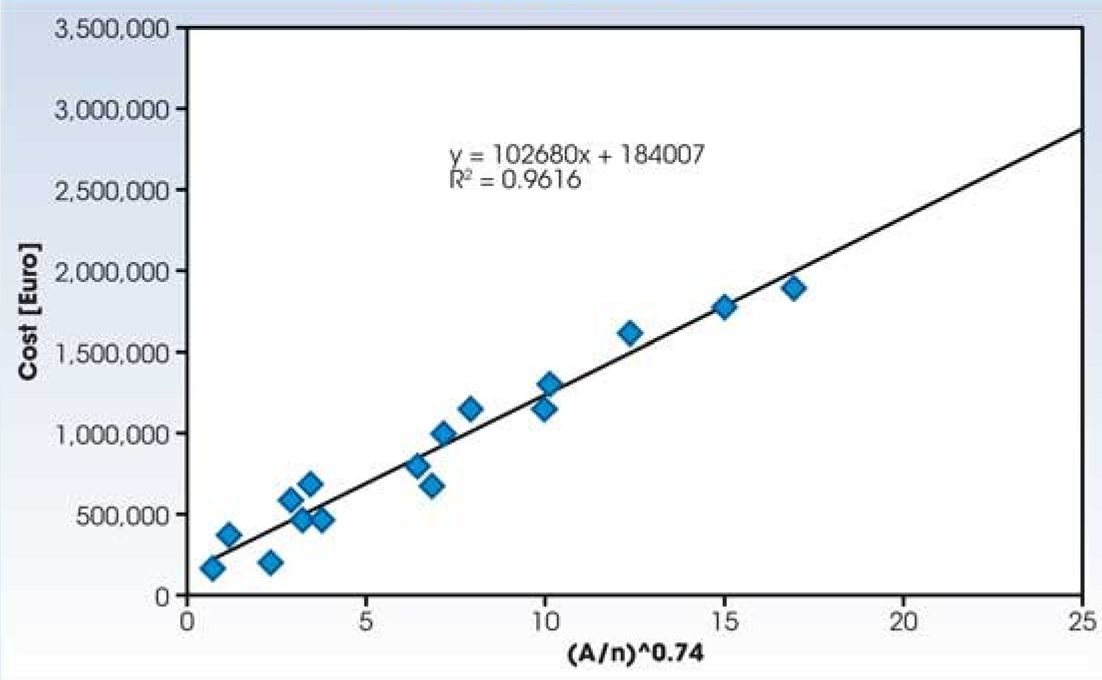
— K_j is a function of k and h and the speed. This parameter can be represented by $K_j = 1837 \times n^{-0.808}$

The total mass of the generator can be written again as:

$M_{(t)} = 1837 \times (A/n^{1.09})^{0.742} \approx (A/n)^{0.74}$

This expression places the total mass in relationship with the ratio A/n and consequently with the ratio P/n (torque), as it is for the hydraulic machines. By applying this relationship to the recent years' supplies, a better data interpolation results (see Figure 4).

FIGURE 4 Cost of Generators



For generators, cost is based on a relationship between apparent power and speed.

Secondary parameters include inertia, temperature class, power factor, short circuit ratio, sub-transient reactance and efficiency. An accurate analysis of the secondary parameters can be found.[6]

As a consequence of analyses carried out over many years, ENEL can summarize the simple method used to evaluate the costs as seen below.

For hydraulic machines, the functions found with interpolation are:

Francis: $Weight_F = K_F \times (Pmt/n)^{0.6}$

Kaplan: $Weight_K = K_K \times (Pmt/n)^{0.6}$

Pelton: $Weight_P = K_P \times j \times (Pmt/j/n)^{0.56}$

Reversible single stage: $Weight_{RS} = K_{RS} \times (Pmt/n)^{0.6} = 1.4\ Weight_F$

Reversible multistage and pumps: $Weight_{RP} = K_{RP} \times s \times (Pmp/s/n)^{0.54}$

where:

— Pmt is turbine power in kW;

— n is the rated speed in rpm;

— j is the number of jets;

— Pmp is mechanical pump power in kW; and

— s is number of stages for reversible machines or pumps.

The total weight is expressed in tons.

For electric machines, ENEL assumed as fundamental parameters the apparent power, speed and axis configuration (vertical or horizontal) and set the value of K = 40 for horizontal axis and K = 50 for vertical axis generators.

The total machine weight can be obtained as follows:

$Weight_{SG} = K \times (An/n^{0.5})^{0.74} \times 2.145$

For those models having the purpose of evaluating the total cost of the machines with the variation in power in a large field, it is necessary to consider that the specific cost by unit of weight or power is not a constant but increases with the decrease in power of the machine.

This function formulation has been deduced from what can be analyzed in previously published information.[7]

In a first approximation, this function was considered equal for the hydraulic machinery and electric machinery.

For the purpose of evaluating the cost of new machines with existing embedded parts in civil structures, it is necessary to introduce coefficient K_{conf} that considers the relative cost of the cast iron components compared to the whole ex novo supply. These coefficients, identified by analyzing the price composition of some supplies, can be estimated as 0.8 for Francis, 0.6 for Kaplan, 1 for horizontal Pelton and 0.85 to 0.9 for vertical Pelton units.

Similar considerations can be found in other literature.[8]

Curves of the weight for unit power for transformers were inferred from catalogues and purchase orders. With a reference,[9] ENEL can deduce analogous curves of the cost by unit power.

Taking as a reference the voltage level of 132 kV for oil transformers having an oil natural air natural (ONAN) cooling system, the curve of the cost in function of the power will have an exponent of 0.56. If the cost of some of ENEL's recent years' supplies are displayed on a diagram, the pattern is substantially confirmed.

It is necessary, particularly for the transformers, to underline that the price is very sensitive to the capitalization losses established in a tender. In fact, diagramming the price of several purchase orders including the capitalization losses, ENEL finds that the regression coefficient is close to 1. Further investigations have confirmed the transfer criteria published elsewhere[9] both for the high-voltage transfer level and for different cooling systems.

The simplified model for three levels for the step-up transformers shows:

220-230 kV, $Tr = K \times A_n^{0.45}$

132-150 kV, $Tr = 0.86 \times K \times A_n^{0.56}$

15-20 kV, $Tr = 0.74 \times Kx\ A_{n0.74}$

Secondary parameters include voltage level, cooling system, insulation level, short circuit voltage and losses.

Overhead cranes

The two parameters to estimate the cost of an overhead powerhouse crane are the capacity and span. From an analysis of the data coming from new supplies of powerhouse cranes carried out in recent years (22 supplies) and with a span varying from 7 meters to 20 meters, ENEL demonstrated that the parameter span in a simple model can be disregarded.

Among the secondary parameters that can affect the costs are, besides the span, lifting head, specification of test standard and operating mode. The cost of a gantry crane can be estimated from the cost of the overhead crane by adding the cost of the metallic structure of the stand.

Diesel generator

To find a simple model, ENEL referred to manufacturer price lists. The fundamental parameter is the apparent power and whether a soundproof enclosure is supplied. The quadratic model becomes linear for a diesel generator set with a limited power. Among the secondary parameters are the speed and typology of the diesel motor.

Turbine and generator cooling system

Cost of the cooling system of the turbine and generator unit in a closed circuit with water-water heat exchangers placed in the downstream channel, with oil-water heat exchangers for the bearings and air-water heat exchangers for the generator, can be expressed as a function of the power of the unit or of the cooling system nominal flow.

The second case is applied only when it is possible or when a preliminary project of the plant has already been done.

Among the secondary parameters that can cause a variation in costs are the materials used (e.g., carbon steel or stainless steel), length of the circuit, and difference of the temperature between the inlet and outlet.

Rectifiers and batteries

To evaluate the cost of rectifiers and batteries, ENEL assumes the rated current as a fundamental parameter. The direct current system of ENEL's power plants has a rated voltage of 110 V. It is evident that the cost is very sensitive to the variation of the cost of the raw materials, and over recent years this has seen a remarkable price increase.

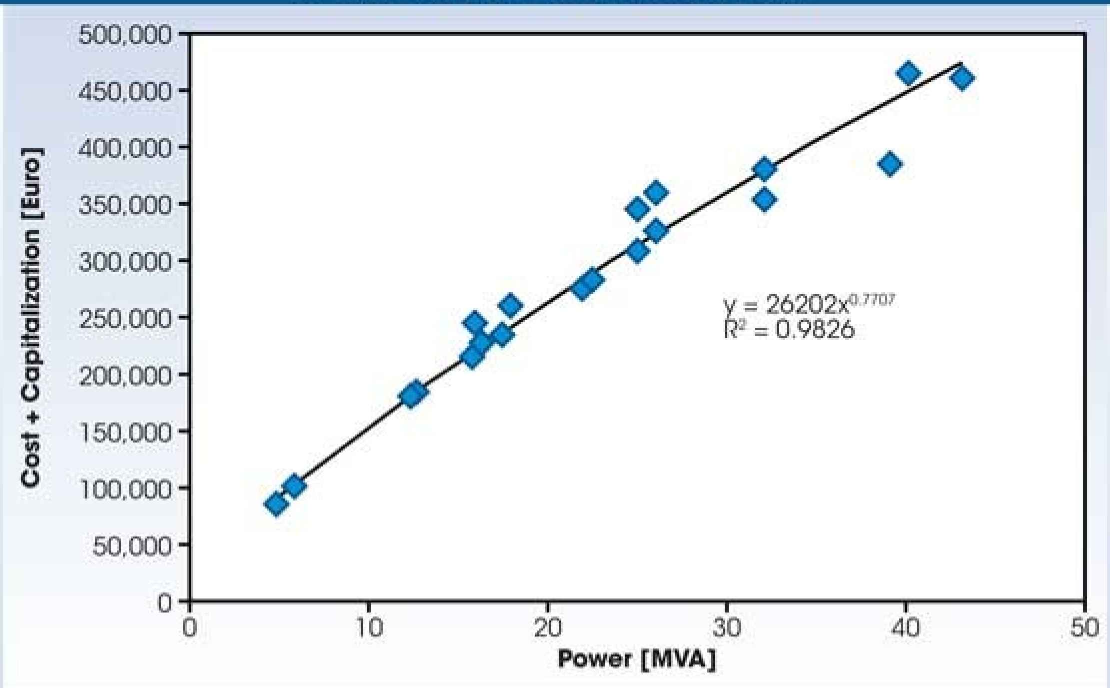
Cast resin transformers

For transformers dedicated to the auxiliary service (insulated cast resin transformers), the fundamental parameter to evaluate the cost is power. For this equipment, the linear relationship obtained for small power is not valid for higher power.

It is possible to verify that the variation of the weight and of the price in function of the power are analogous, in a relationship having 0.66 as the exponent of the power.

The weight variation and consequently the cost variation is also a function of the voltage level (see Figure 5).

FIGURE 5 Cost of Power Transformers



The cost of a transformer relies primarily on its power rating.

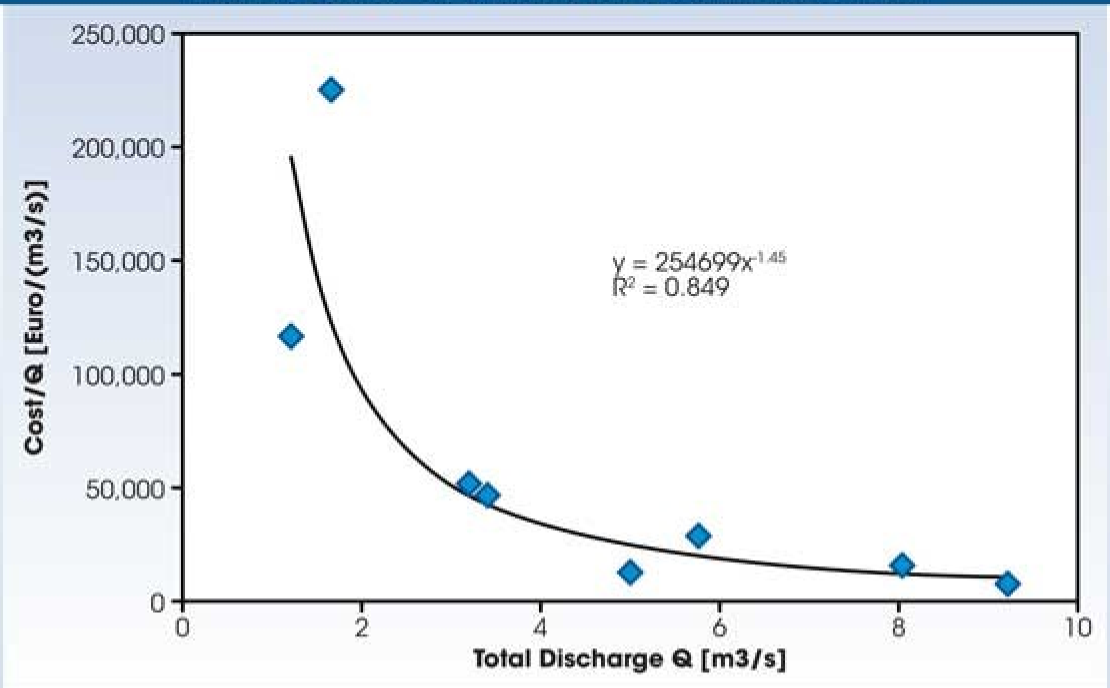
Among the secondary parameters that can contribute to a different cost are voltage level and short circuit voltage.

Hydraulic and civil works

The more complex aspect of the hydroelectric plant evaluation is estimating the civil works component. The latest modifications to the Italian fiscal policy caused a significant increase in the taxable real property value that now involves all plant components including the hydraulic works. For this reason, ENEL has established a procedure whereby there is a comparison of historical data available and comparisons between plants built in the past and those recently built or those being built, in order to evaluate the rebuilding cost. This has been created by establishing homogeneous and objective criteria to assess the costs, useful life of the works and consequent degradation due to ageing.

This article presents the initial results of this standardization study. In other countries, new taxation systems are being analyzed that could be fairer, be simpler and incentivize a better use of resources. This could push energy production companies to invest in renewable energy sources in a rational way, by managing the various requests of the system more efficiently, especially in the areas of energy production, tariff, incentives, various use of resources, and increases in ecologic emissions.

FIGURE 6 Cost of Civil Works for a Horizontal Pelton



Cost of civil works decreases greatly with increasing discharge.

Figure 6 shows the cost of civil works related to replacement of a horizontal Pelton turbine. The parameters considered for construction costs and residual value estimation are:

— Dam: type and volume;

— Tunnels: type and section area;

— Galleries: type and section area;

— Penstocks: type and weight

— Turbines: type, speed and power;

— Generators: type, speed and power.

Consider a statistical evaluation concerning 39 dams and works in roller-compacted concrete with volume greater than 30,000 m^3 for more than 6.3 million overall, with an average value in 2000 of €33.6/m^3 and a range of variability between €14.3 and €66.0 /m^3.[10]

The resulting component life and residual value is:

— Turbine: 45 years, 5% to 10%;

— Generator: 45 years, 5% to 10%;

— Automation system: 15 years, 0%;

— Auxiliary systems: 40 years, 5% to 10%;

— Dam: 90 years, 5% to 10%; and

— Penstock and hydraulic works: 65 years, 5% to 10%.

Conclusion

We have presented a methodology and a tool for carrying out cost estimates for hydroelectric plant components. This tool does not intend to establish a specific price which, as said before, is determined by market rules and tender strategies and methods.

The cost estimates remain a valuable guide for carrying out the assessment needed for the investment analysis and for the patrimonial evaluation of the goods present in a plant and inherent taxation implications.

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Notes

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