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Unit-sizing of hydro power plant

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Abstract. In developing countries with great and unexploited renewable energy potential, Governments can exploit local resources for electricity supply, substantial energy savings and sustainable socio-economic development of these own countries. The decision-making process regarding the choice of renewable energy sources for energy supply in these countries is multidimensional, made up of a number of aspects at different levels such as economic, technical, environmental, and social. Therefore, reaching clear and unambiguous solutions may be very difficult. It is from this difficulty that the need arises to develop a tool for the design of hydro energy sources for electricity. The work involved in seeking a compromise solution requires an adequate technical assessment based on multiple criteria methods. One of the criteria is the assessment of the appropriate size of the hydropower plant. This paper presents the state-of-art of preliminary sizing of hydropower plant for the given renewable energy potential. The main step consists of carefully selecting and sizing the innovative hydraulic units based upon the suitability of the flow and head range. Since the flow and head data have now been confirmed, the potential annual energy generation can be properly assessed.

1. Introduction

In developing countries with great and unexploited renewable energy potential, Governments can exploit local resources for electricity supply, substantial energy savings and sustainable socio-economic development of these own countries. The decision-making process regarding the choice of renewable energy sources for energy supply in these countries is multidimensional, made up of a number of aspects at different levels such as economic, technical, environmental, and social. Therefore, reaching clear and unambiguous solutions may be very difficult. It is from this difficulty that the need arises to develop a tool for the design of renewable energy sources for electricity. Such a tool should enable the decision maker as policy maker, regulatory authority, investor and electricity utility to draw up a series of alternatives and to choose the most acceptable compromise. The work involved in seeking a compromise solution requires an adequate technical assessment based on multiple criteria methods.

One of the criteria is the assessment of the appropriate size of the hydropower plant. This paper presents the state-of-art of preliminary sizing of Hydro Power Plant, HPP, for the given renewable energy potential. Various sizing proposals should be compared, on the basis of technical specifications and projected energy generation and consumption profiles, ability to minimize risk of system outages, total costs of the installation, operation and maintenance, and, most importantly, expected or agreed system performances, regarding the delivering of electrical energy to all users according to their expectations and needs.

The most important aspect of the assessment is the quality of the data required for input and assessment. A subsequent analysis of a site considers its location, catchment size, and flow and head parameters to perform an optimal installed capacity. The assessment refines the sitting of the scheme, calculates the potential generation and determines the potential cost of the scheme.

The analysis depicted in this paper, demonstrates the activities required from investigation through to implementation. Starting from scratch, this analysis includes reliable input data:

- Review of existing documentation and data collection: hydrology data, topographic data and geological data;
- Preliminary demand assessment: historical load profile, future typical load forecast and estimated demand;
- Hydropower assessment: flow duration curves, capacity, gross head, available discharge.

The following step consists of carefully selecting and sizing the innovative hydraulic units based upon the suitability of the flow and head ranges. Since the flows and heads data have now been confirmed, the potential annual energy generation and its distribution can be properly assessed.

2. Hydrology of the site and associated heads

2.1. Hydrology of the site

In this paper, a test case, called river FLOWCASE, issued from eDF database is taken into account to show how a new run-off flow HPP can be sized. The river flow is defined by the flow duration curve, Q_r, for one typical year. Sometimes, the utilities impose an ecological flow, Q_{eco}, for either agricultural use, and/or a water consumption prediction, Q_w. Thus, the available flow duration curve or available discharge, Q_a, used for the sizing process of the powerhouse is the difference between all previous flows, see equation(1).

$$Q_a = Q_r - Q_{eco} - Q_w \tag{1}$$

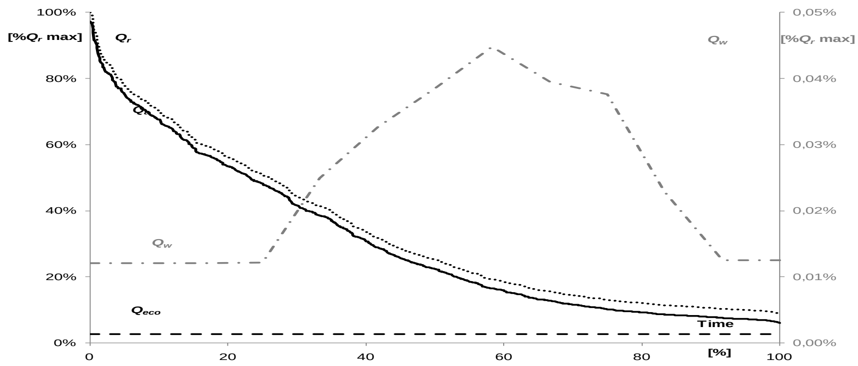

Figure 1. The river FLOWCASE flow duration curves versus the yearly time

2.2. Associated heads

The associated gross head, H_b, is the difference between the upstream water level, Z_{up}, and the tail water level, Z_{TW}. Furthermore the head water level and the tail water level depend on the river discharge law. Thus, the gross head becomes a function of the river flow Q_r. Head losses and river flow are linked to each other. They influence the operating range of the hydraulic machines. They can be roughly estimated in the preliminary first steps of the project. The current head losses are called ΔH_r and the corresponding net head H_n is defined by equation (2).

$$\begin{aligned} &H_n = H_b - \Delta H_r \\ &\text{with } \Delta H_r = f_1\left(Q_r^2\right) + f_2\left(Q_a^2\right) \end{aligned} \tag{2}$$

For the sizing the new powerhouse, a rated net head, $H_{n,rated}$ of turbines should be chosen in agreement with the permanence of the river flow. Due to dry season and flood season, this net head represents the maximal head which can be reached during the year. For this instance, frequency of 75% for gross head, which have been reached for 40% of the yearly time, is chosen as the rated net head for the project.

3. Modelling tools for electromechanical sizing

In order to complete modelling, necessary information must be reliable and well formatted. The flow of main information can be described in order to understand the role of these tools in the decision process, see Figure 2. The first feasibility study concludes to an estimated total capacity of the future hydropower plant depending on the topology and site hydrology. Civil Works engineering size the dam and the hydraulic design of the waterways. Then electromechanical studies can start.

3.1. Unit type and sizing tool

If the final unit sizing relies entirely on the turbine manufacturer, EDF needs to anticipate the technical tender answer of specialized constructors to evaluate the project feasibility and profitability. Indeed, after waterways characteristics, the modelling tools need units' characteristics and they are depending on the turbine type and preliminary sizing.

Depending on the head range, the choice of turbine type can be easy. For heads allowing more than one type of turbine, many different criteria can influence the turbine choice and sizing. The main ones are: Civil and Electro-Mechanical costs, performances and behaviour during transients; there are also: reliability, flexibility and maintenance.

Turbine pre-sizing main input data are:

- Rated net head, deduced from the dam water levels and the head losses calculation;
- Unit maximum discharge or output;
- Electric grid frequency at the powerhouse location;
- Minimum level of tail water level.

The turbine pre-sizing settles the following parameters:

- The rotation speed: with the capacity, it is an input parameter for the alternator design;
- The diameter and geometry;
- The unit setting level.

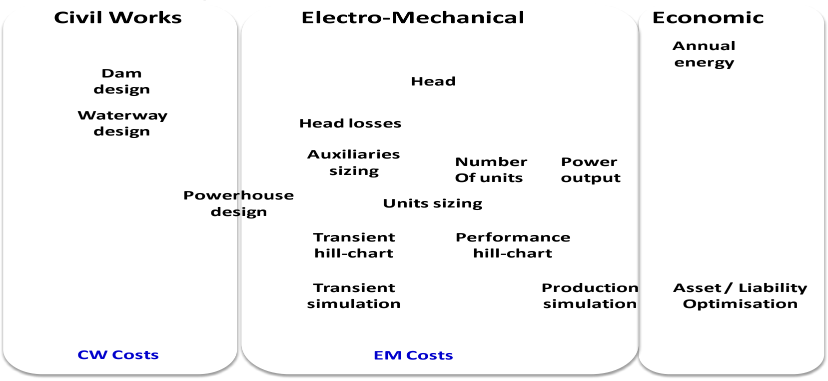

Figure 2. Hydro-electric project map from an electromechanical point of view

Through its involvement in numerous international hydro projects, EDF have developed dedicated software, called DEMHY, see Bellet *et al* [1]. It allows to quickly obtaining a pertinent unit pre-sizing compatible with the know-how of turbines manufacturers. In combination with a parametric 3D CAD model, it facilitates powerhouse design.

3.2. Performance hill chart tool

Hill charts, resulting of the manufacturer design, define the behaviour of the turbine in every operational configurations of the future hydraulic scheme arrangement. For instance, performance hill charts consist of a set of points and/or curves precisely describing the hydraulic performances of the turbine in a steady state operating range. EDF have developed a hill chart tool, called OUTPERF, to display and transform hill charts in view to use them in modelling, see Bourrilhon *et al* [2].

The main functions and their principle are summarized in the following points:

- Integration of an existing hill chart (data from site performance measurements or from model tests measurements of EDF projects) to the database;
- Creation of a new hill chart for the studying project;
- Translation of a hill chart;
- Computation and display of circuit characteristic ;
- Display of hill charts.

3.3. Annual energy production tool

The ability to predict the annual energy production capability is crucial to the development of a new powerhouse as it is the sale of energy that provides the income necessary to recoup the capital investment. This subsection provides guidance on the estimation of the energy output from a hydroelectric powerhouse.

The energy output is directly proportional to the flow of water, Q_r, available in the river. This will vary from year to year depending on the amount of rain falling and of the spring thaw on the river: during a wet period, more energy would be generated and for a dry period, the plant may fail to meet the predicted total output. This energy output is normally calculated using the flow duration curve, which expresses the percentage of the time for which a particular flow is exceeded.

However, as an ecological flow Q_{eco} and a water consumption flow Qw are considered, the available flow duration curve, Q_a, represents the flow data for the annual energy prediction. Thus, the area below the curve represents the volume of water available for hydropower generation and can therefore be combined with the net head and hydraulic and electrical efficiencies including mechanical losses to calculate the annual energy output. This procedure should be carried out in a stepwise fashion across the curve to take into account the increase in net head and reduction in turbine efficiency as the available flow reduces.

Thus, the annual energy production is defined by equation (4).

$$AE = \int_0^T \rho g \eta_g \eta_{turbine}(t) N(t) H_n(t) Q_{turbine}(t) dt \tag{3}$$

As shown in equation (3), the annual energy production depends on the number of turbines used for a current flow data, on the current flow data, on the corresponding net head and on the unit efficiency. Two strategies are developed: one, called ST1, for a powerhouse with only one type of turbines U1 and one, called ST2, for a powerhouse with two types of turbines U1 and U2.

3.3.1. *One type of turbines.*

The ST1 strategy of operating conditions for the best prediction of the annual energy production should be summarized as: find k such as equation (5).

$$\begin{cases} Q_{1,turbine}(t) = \begin{cases} \dfrac{Q_a(t)}{k} \text{ if } Q_a(t) \le N_{1,total} Q_{1,turbine,\max}(t) \\ \dfrac{N_{1,total} Q_{1,turbine,\max}(t)}{k} \text{ otherwise} \end{cases} \\ \max\left(\eta_{U1,turbine}(t)\right) \\ k \cdot P_{e,1}(t) \le P_{e,installed} \end{cases} \tag{4}$$

3.3.2. *Two types of turbines.*

For a new project of development of the powerhouse, a second type of turbines with a lower output is added to the previous ones. Furthermore, the operating range of the second type of turbines is supposed to be within the operating range of the previous one. Thus, the

ST2 strategy of operating conditions for two types of turbines for a better prediction of the annual energy production should be summarized as: find the couple (l;k) such as equation (6).

$$\begin{cases} Q_{2,turbine}(t) = Q_{2,turbine,\max}(t) \\ Q_{1,turbine}(t) = \begin{cases} \dfrac{Q_a(t) - l \cdot Q_{2,turbine}(t)}{k} & \text{if } Q_a(t) \le N_{1,total} Q_{1,turbine,\max}(t) + N_{2,total} Q_{2,turbine,\max}(t) \\ \dfrac{N_{1,total} Q_{1,turbine,\max}(t) + N_{2,total} Q_{2,turbine,\max}(t) - l \cdot Q_{2,turbine}(t)}{k} & \text{otherwise} \end{cases} \\ \max\left(\eta_{1,turbine}(t)\right) \\ k \cdot P_{e,1}(t) + l \cdot P_{e,2} \le P_{e,installed} \end{cases} \tag{5}$$

4. Results and analysis

An example using the previously described tools is presented below, through the study of a new HPP on the FLOWCASE River, for a maximum output of 1,000 MWe.

Two test cases are presented for the development of this project with a maximum of units equal to 10 available units:

- The PWH1 powerhouse with 10 double regulated turbines;
- The PWH2 powerhouse with N1 doubles regulated turbines and N2 single regulated turbines, so as to the total number of units' remains to 10 units.

For each case, unit sizing and annual energy production analysis are performed.

4.1. Unit type sizing

The input data required by DEMHY tool consists of the rated net head, $H_{n,rated}$ the corresponding maximal turbine power P_{rated}, the estimated rated turbine efficiency, $\eta_{t,rated}$ the tail water level Z_{TW} and thermodynamics properties of the site as the atmospheric pressure p_a the temperature of the water T_w the density of water ρ and the gravitational acceleration g.

The main output data issued from DEMHY for double and single regulated turbines used in both cases are summarized in the Table 1. DEMHY proposes different alternative turbines. These alternatives are different from the available and admissible number of pairs of poles issued from the synchronous speed. The selected turbine is the optimum compromise between the synchronous speed of the machine and the capacity of the existing generator.

4.2. Annual energy production for the PWH1 powerhouse

The PWH1 powerhouse consists of 10 double regulated turbines of 100 MWe each for a total installed capacity of 1,000 MWe as required. The flows through PWH1 powerhouse are shown in the top figure of Figure 3 with the river inflow in blue, the maximal available turbinated flow in red, the real turbinated flow in green and the outflow such as surplus flow and ecological flow in magenta.

The bottom figure of Figure 3 represents the generated total output versus the yearly time. Due to the river inflow, the PWH1 powerhouse generates the complete 1,000 MWe as requested during only 10% of the year.

The Figure 4 represents operating points for the generated annual energy during the year. The x-axis represents the ratio between the unitary discharge and the rated unitary discharge; whereas the y-axis the ratio between the net head and the rated net head. 20% of the annual energy are produced at lower heads than the rated head with all units in maximal operating range. The rest of the annual energy is produced by successively shutting down the units and running in the best efficiency area. Finally, all units run only 33% of the time and produce more than 54% of the annual energy, see Figure 3. The water has only been spilled at that time, as shown in magenta curve.

Table 1. Sizing of double and single regulated turbines.

Property	Value	Property	Value
Rated net head H_n [WCm]	$H_{1,n} = H_{2,n}$	Runner Diameter D [m]	$D_{1,r} < D_{2,r}$
Rated flow Q_n [m^3s^{-1}]	$Q_{1,n} < Q_{2,n}$	Rated turbine efficiency η_t [%]	$\eta_{1,t}$ / $\eta_{1,t}$
Maximal turbine output P [MW]	102	Thoma number plant σ_p	0.75 / 0.55
Synchronous speed n [rpm]	$n_1 > n_2$	Dimensions	Runner, Inlet and Outlet waterways, Generator
Runner setting level z_r [m]	-2.40 < -1.70		

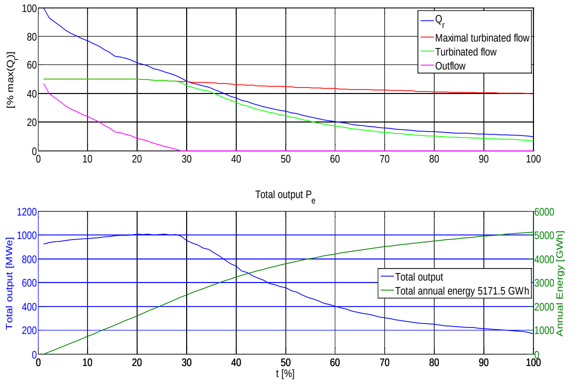

Figure 3. Inflow, outflow, turbinated flow and total generated output versus time

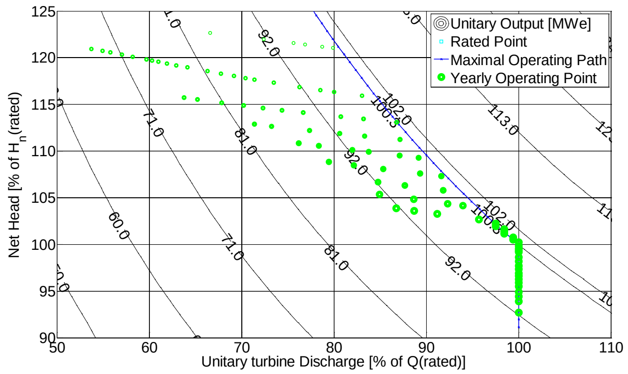

Figure 4. Hill chart of double regulated turbines versus output contours for PWH1

4.3. Annual energy production for the PWH2 powerhouse

The PWH2 powerhouse consists of a total of 10 units with single and double regulated turbines of 100 MWe each for a total installed capacity of 1,000 MWe as required. One goal of this case is to find the acceptable number of single regulated turbines and the number of the double regulated ones. Starting from 10 double regulated turbines and by decreasing the number of double regulated turbines, in black histograms, as well as increasing the number of single regulated ones, in grey histograms, and till keeping the total of units to 10, the corresponding annual energy is evaluated and presented in Figure 5. It is found that the couples *(k,l)* as presented in equation(5), (6;4) and (5;5) seem to be an acceptable compromise and keep the annual energy constant compared to the PWH1case.

For a local analysis of the distribution of the annual energy between both types of units, the case (6;4) is considered in the rest of the paper. Thus, 54% of the annual energy is produced by both of them and the last 46% of energy by only the double regulated units, as shown in Figure 6. Furthermore, all double regulated units have run in maximal operation range for 33% of the yearly time whereas all single regulated units during 36% of the time. And the single regulated units have successively been shutting down for 15% of the time. According to the ST2 strategy, the single regulated units run by following the maximal operating path, and the double regulated ones follow the same operating path as in the PWH1 case, see Figure 7 and Figure 8.

4.4. Analysis

For the case FLOWCASE river flow, corresponding heads are suitable for double or single regulated turbines. The emerging first idea has consisted of building the PHW1 powerhouse with only double regulated turbines. This kind of turbines keeps a better behaviour regarding cavitation phenomena compared to single regulated turbines. The corresponding annual energy production becomes the referent value and is the maximal value generated by the powerhouse. However, the major drawback concerns the need of an oil filled hub for the runner regulating mechanism.

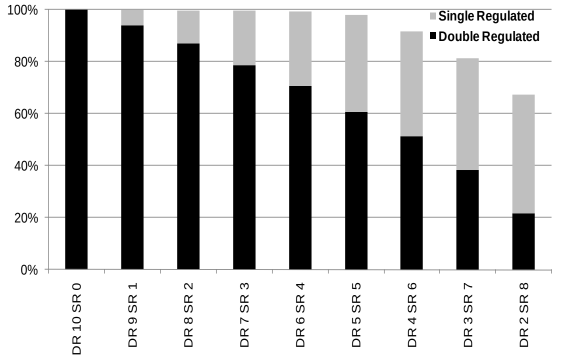

Figure 5. Annual energy production versus the number of double and single regulated turbines

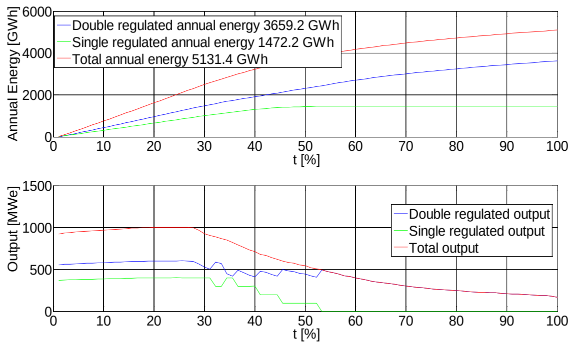

Figure 6. Annual energy production versus the number of double and single regulated turbines

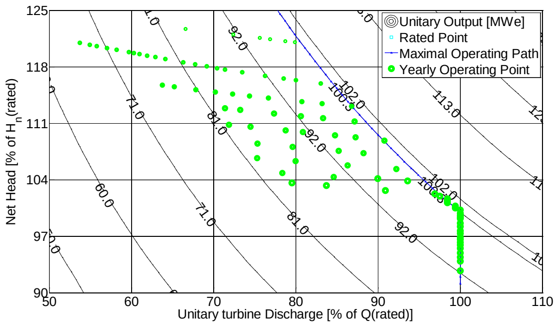

Figure 7. Hill chart of double regulated turbine versus output contours for PWH2

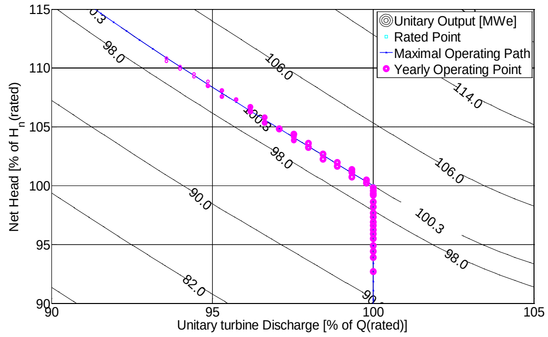

Figure 8. Hill chart of single regulated turbine versus output contours for PWH2

Moreover, in a second idea, the mix of double and single regulated turbines has been taken into account by building one powerhouse with only double regulated turbines and a second one with only single regulated turbines. It is supposed that all units keep the same output as in the first idea. But the diameter of the single regulated turbines slightly is increased whereas the synchronous speed is decreased. Using single regulated turbines allow reducing both: turbine and maintenance costs due to less equipment upkeep. Moreover, its oil free runner enables an environmental friendly communication. In previous subsection, it is demonstrated that the decrease of the generated annual energy is not so severe when using 40% of total units as single regulated units.

For the optimization of the total powerhouse, it is then necessary to add the civil work costs in a sensitivity analysis permitting the optimization of the total powerhouse costs. A lot of interfaces between civil cost, mechanical and hydraulic sizing and efficiency (including turbines efficiencies and head losses) have to be carefully studied. For instance, the units setting level, the length of draft tube or the shape of intake have to be clearly studied to lead to the best compromise of annual energy production versus costs. At this stage, a new iteration of the loop for annual energy calculation should be performed for each case. Evaluating the construction schedule associated to each option is also an important input data for the business plan, in fact, for a large number of units, a correct estimation of commissioning dates is a key factor.

Finally, from mechanical point of view, both cases fit with the initial request to equip the FLOWCASE River. After this first technical study, a lot of others studies reminds to be performed. Some of them are the following (not exhaustive):

- Sizing the corresponding generators, auxiliaries and transmissions lines;
- Sizing all the other HPP components as dam, spillway, access…

- Evaluating the environmental impact including, for instance, flooding, reduced oxygenation of the water, sedimentation upstream of the dam, erosion of draft tubes, electrical machinery noise and the social impact of the project;
- Elaborating a business plan by the Economist Department to finalize the decision making process.

5. Conclusions

This paper presents the state-of-art of preliminary sizing of hydropower plant for the given renewable energy potential. Various sizing proposals should be compared, on the basis of technical specifications and projected energy generation and consumption profiles, ability to minimize risk of system outages, total costs of the installation, operation and maintenance.

The mechanical aspects have showed that both configurations of powerhouse are viable economic for the realization of the project.

Acknowledgments

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Nomenclature

D_r	Runner diameter [m]	P	Hydraulic power [MW]	t	Time [hour]
g	Gravitational acceleration [ms^{-2}]	P_e	Electrical power [MWe]	Z	Water level [m]
H	Head [WCm]	p_a	Atmospheric pressure [Pa]	η	Efficiency [%]
N	Number of units [-]	Q	Flow [m^{3}s^{-1}]	ρ	Water density [kg m^{-3}]
n	Synchronous speed [rpm]	T	Temperature [°C]	σ_p	Thoma number [-]

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[2] Bourrilhon M and Lesage 2008 P-07-031- Outperf v2.1 *EDF Internal Note*