Chapter 3 HYDROPOWER

Content

2.1 General view

From ancient times water courses were harnessed to obtain mechanical energy for milling cereals or to operate different working tools. Nowadays, this energy resource is utilized only to generate electricity.

All the hydrosphere of the earth presents potential or kinetic energy. This energy originates from the solar radiation which maintains the cyclic circulation of the water in the earth nature. Besides the solar radiation, the sun and moon attraction contribute to the ocean tides, one of the components of the hydrosphere energy.

Owing to its origin, the hydropower is renewable, although having a limited potential. In every location on the earth, the time gap for water energy restoration is the same like for the solar radiation, what is a year.

The hydrosphere energy can be divided in two major sections:

- Water courses energy, known as *conventional source*, which is currently utilized to generate electricity,
- Ocean water energy (waves, tides, currents, thermal)which is slightly utilized, because of technological and economic problems; consequently, these forms of water energy are classified as *unconventional*.

Water courses energy is full accessible and measurable, being situated at the earth surface. This energy must be exploited in the river bed or very close to it. There are important possibilities to store water in reservoirs. Water energy resources have a single utilization: the generation of electricity.

Other usefulness of the water than the electricity generation is very important: drinking water for people, domestic and wild fauna and vegetation, industrial water, transport etc. All these utilizations must be considered when a hydropower project is to be elaborated.

2.2 The hydropower potential

The notion "*hydropower potential*" is utilized to evaluate the potential energy what a water stock presents. There are in use several definitions for the hydropower potential.

a) The ***theoretical potential***, with three levels:

- theoretical potential of precipitations
- surface theoretical potential
- linear theoretical potential

b) The ***exploitable hydropower*** potential, with two levels:

- technical potential
- economical potential

2.2.1 The theoretical hydropower potential

This represents the potential energy of a water stock without considering the technical and economic limits and losses to exploit it. The theoretical potential is evaluated taking into account the total available head and flow rate as well as a conversion efficiency of 100%.

The theoretical potential of precipitations represents the potential energy of the water stock originated from precipitations on a defined territory (river basin, region, state etc.), during 1 year and related to a reference level (the sea level, the lowest altitude of the territory, state border etc.). Because the precipitation abundance is variable on the earth, the large territories are divided in smaller area, homogeneous from this point of view.

$$W_p = k\rho g \sum_{i=1}^{n} \Delta S_i x_i \Delta h_i \,, \qquad (2.1)$$

Where:
- ρ is the water density (1000 kg/m^3),
- g is the gravitational acceleration (9.81 m/s^2),
- x_i is rainfall depth during a year (mm),
- ΔS_i is the area of a surface with uniform rainfall depth (km^2),
- Δh_i is the medium head, namely the altitude difference between the considered surface and the reference level (m),
- k is a constant which is introduced to express the water stock in TWh/an. If all the factors in eq. (2.1) are expressed in the above mentioned unities of measurement, than the constant k is:

$$k = 10^6 * 10^{-3} * 10^{-12} / 3600 = 2.778 * 10^{-13}$$

For Romanian national territory, in a normal hydrological year, the theoretical potential of precipitations reaches

$$W_p = 240 \; TWh / yr .$$

The ***surface theoretical potential*** represents the potential energy of the water stock originated from precipitations, which flows on a territory surface during the year, until a defined reference level. This potential may be expressed by:

$$W_s = k\rho g \sum_{i=1}^{n} \Delta S_i x_i \Delta h_i \left(1 - p_i\right) \qquad (2.2)$$

All the above definitions for the constituent factors are valid here. p_i is the soil permeability. Its value depends on relief, soil structure, temperature, precipitation rate etc. Because p_i is dimensionless, the value of constant k does not change.

For the territory of Romania, in a normal hydrological year:

$$W_s = 81\ TWh / yr,$$

what represents 33.75% of W_p.

The ***linear theoretical potential*** represents the potential energy of the water stock which flows on all the rivers, until a defined reference level, during 1 year. Because the flow rate grows along the river from the source until the mouth, the river length is divided in many sectors which have constant flow rate (e.g. sectors between confluence points):

$$W_l = k\rho g T \sum_{i=1}^{n} Q_i \Delta h_i, \qquad (2.3)$$

where

T is the yearly number of hours (365*24=8760 h),

Q_i is the mean flow rate on the sector i (m^3/s),

Δh_i is the altitude difference (head) on the sector i (m).

With these units of measurement, the value of constant k becomes:

$$k = 10^{-12}.$$

For Romania

$$W_l = 70\ TWh / yr,$$

which represents 86,4 % from W_s, respectively 29,16 % from W_p.

2.2.2 The exploitable hydropower potential

This is the amount of electricity delivered yearly by all the hydropower plants, which can be built up on a defined territory. Both the water and energy losses which happen owing to the hydropower development structure and plants operation are taken into account.

The ***technical potential*** represents the share from the linear theoretical potential which can be included in water development works. Some linear potential losses appear during the development works:

- Incomplete utilization of the water courses length *(f)* because of the territory shape or geological structure which does not allow the emplacement of the dam, reservoir, channels etc.

- Incomplete utilization of the extreme flow rates (e), which appear aleatory and cannot be stored in reservoirs.
- Head losses (η_h) by water flowing through channels, tunnels, pipes, penstocks, valves etc.).
- Mechanical losses in hydraulic turbine (η_{th})
- Mechanical and electrical losses in the electrical generator (η_g).

The technical potential can be evaluated with:

$$W_t = W_l * f * e * \eta_h * \eta_{th} * \eta_g . \qquad (2.4)$$

For Romania, the result is

$$W_t = 36.1 \; TWh / yr ,$$

where the contribution of the Danube is approximately of 13.3 TWh/yr.

The ***economical potential*** represents the share of the technical potential which can be developed to be competitive on the energy market. However, the hydropower has a special position among the energy resources because the energy carrier is costless and remains unchanged after the power generation. Owing its national and renewable character this resource must be entirely developed, but the specific investment cost (lei/kW) is much greater than for other types of power plants. The national energy policy decides about the economical hydro potential. The continue growth of the fuels prices and the environmental damages induced by those utilization encourage the water energy development.

All the types of hydro power potential can be considered as proved, because it can long term observed and measured. An acceptable evaluation error, of ±5% can be reached after 15-20 years of observations about the precipitations and flow rates of the rivers.

The water resources which build up, during a medium hydrological year and flow on the inner water courses of Romania reach 35.10^9 m^3, what means 1520 m^3/capita, while the European figure is 4800 m^3/capita. From this point of view, Romania is situated on the 21st place in Europe. Taking into account the water resources which come from the neighboring countries and flow on Romanian territory, results a quantity of 200.10^3 m^3 that represents 8700 m^3/capita, the 11th place in Europe respectively.

The water resources build up on the Romanian territory depending on the territorial zone (table 2.1).

The hydropower resources of the earth are evaluated as follows:

- The theoretical linear potential, app. 40000 TWh/yr.
- The technical potential, app. 16000 TWh/yr.

Table 2.1 Water resources building up in Romania

Relief zone	Water resources share	Territory share
Mountains (over 1000m)	66 %	21 %
Hills, plateau	24 %	31 %
Plains	10 %	48 %

At the world scale, app.20% of the total technical potential was in use, in the 2008 year.

This potential is developed in different proportions, depending on the economic possibilities of the countries. At a continental scale, the water resources are utilized as follows: 75% in Europe, 69% in the North America, 49% in Australia, 33% in the South America, 22% in Asia and 7% in Africa.

The participation of the hydropower to the electricity production of the country varies from 99% in Norway, 89% in Brazil and 66% in Canada to 17% in China, 13% in India and so on.

Romania reported an installed capacity of 6375 MW, which generated app. 17 TWh in 2008.

2.3 Hydropower developments

Many factors are to be considered when a hydropower project is starting. Every water course can be characterized by the *hydrological regime*, what is the water flow rate dependence with time, usually 1 year. This function may be various enough, depending on climate, relief, configuration of the river basin, forestation degree, supplying sources of the river.

Two main categories may be defined:

- *Simple regime*, when de flow rate presents only a minimum and a maximum value during the year. This regime is specific when the supplying source is only a glacier or the snow stored during winter.
- *Complex regime* if there are more maximum and minimum values of the flow rate. This is the situation in Romania, because the rivers are supplied both from the winter snow and from rain.

Other factors of interest for the economic effectiveness of the project are the population denseness, the presence of consumer agglomerations, the presence of electric lines and roads in the proximity and others.

2.3.1. Water reservoirs

The presence of a dam and a water reservoir is a common feature of every hydropower project. This reservoir accomplishes two main functions: concentrates the head from a river sector by the dam and allows the water stock management according to the consumer’s demands and the flow rate of the river.

The relief slope along the river is various; from high values on the upper course (tens of meters per kilometer) to very small values on the lower course (some centimeters per kilometer). The dam equalizes upstream the water level on a distance depending on its height and of the slope of the river bed. Only a concentrated water head can be utilized by a hydro power plant.

The existing water developments utilize water heads from some ten meters (e.g. Danube Iron Gates I and II) until 200-300 m. In Romania, the highest dam is Gura Apei on the Riul Mare river, having 168 meters.

The diagram of the river flow rate versus time is named "hydrograph" (fig.2.1a). On this base, can be build up another diagram of the flow rate, representing it in descending order versus to the number of hours every flow rate exists during the year (fig. 2.1b).

a) b)

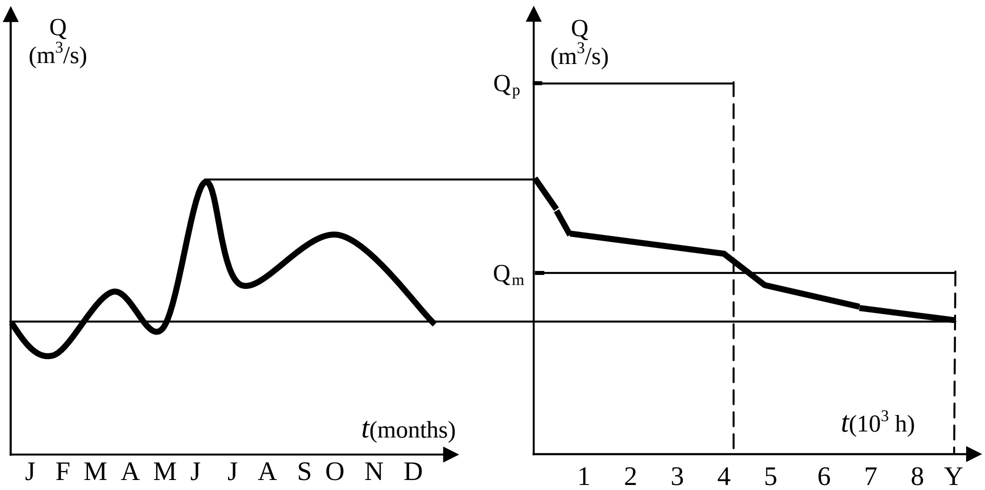

Fig.2.1. The hydrograph (a) and the descending diagram (b)

The areas of the surfaces between the axes and the curves in fig.2.1a and 2.1b must be equal and represent the annual water stock of the examined river.

The descending diagram allows pointing out the possibilities offered by the reservoir to utilize the entire water stock according to the size the installed power of the hydro plant.

Thus, if the flow rate of the hydro plant is equal to the medium annual value of the river, Q_m, the plant can work continuously at the rated power ("*basic regime*"). It is possible to increase the installed flow rate of the plant, Q_p, so that the installed power increases too. Because the water stock remains the same, the work period of the hydro plant will be longer as much as the installed flow rate is smaller. If the work period is of 25-30% of the year, the hydro plant has a "*peak regime*"

The reservoir is sized taking into account many factors related to its role in the power system, the relief and other utilizations of the water. This volume is directly correlated with the time dependences of the natural flow rate of the river and the utilized flow rate. Another important factor is the annual trend of the energy demand and of the natural flow rate of the river. If both graphs have close shapes, the volume of the reservoir will be smaller than in the case when the two trends are opposite.

Depending on the regulation degree realized by the reservoir, four categories were defined:

- *Small size reservoirs* which can accomplish a daily regulation. The natural flow rate, near constant during 24 hours, may be distributed for the period of peak demand of electricity, which has 6 to 8 hours. The volume of the reservoir must be sized considering for the winter season when the demand for electricity is higher.
- *Medium size reservoir*, which allows both a daily and a weekly regulation of the water flow rate. The water stock of the non-working days will be utilized in the rest of the week. The volume of the reservoir will be sized taking into account the gaps with small demand in the non-working days. A non-working day allows increasing the available water stock for the other days with 15-20%.
- *Large reservoir,* which allows a seasonal-annual regulation of the water flow rate, besides the previous possibilities. The excess of water from the rainy periods is stored to be utilized in the droughty periods or in the winter when the precipitations are in solid form. For Romania, the volume of the reservoir is pushed to the superior size owing to the opposite trends of the flow rate of the rivers and the electricity demand during the year period.
- *Very large reservoir,* which allows an over-yearly regulation of the water flow rate. The reservoir size becomes very large and the occupied territory too, as only some countries like Canada, Brazil, Russia, China, a.o. can accept such project.

The greatest reservoirs on the Romanian territory are of "*large*" type.

2.3.2. Principles to realize the water developments

The continental water resources have much other utilization besides the energetic one. In order to obtain a great economic effectiveness, all these utilizations must be considered and correlated, having regard for a systemic conception.

The Romanian specialists have synthesized their studies and experience in four principles, which materialization is proved by many water developments now working.

1. *Conceiving the project of the water development for an entire basin of for some neighboring basins.*

The main objective is to provide the complete utilization of the available potential as well as satisfying the water demands from the inhabitants, agriculture, industry etc. Such a project allows the emplacements of the hydro power works in the best locations. The share of the other utilizations of the water, which depend on the population denseness, industry and the land utilization, grow when the altitude become lower and the hydro potential decrease too.

In Romania there are many water developments which cover large surfaces: entire basin-Bistrita, Arges, Sebes or neighboring basins like Cerna-Motru –Tismana.

2. *On the upper course of the river are to be realized large size reservoirs and hydro plants which work in a peak regime.*

The upper segment of the river is situated in a mountain zone, where the linear potential is high and the population denseness is small. The main utilization of the water may be generating electricity.

To achieve a maximum economic result, some methods can be applied:

- locating the reservoir at higher possible altitude;
- sizing the reservoir to be able for annual or over annual flow rate compensation;
- collecting water resources from as larger as possible areas belonging the river basin or even from neighboring basins by catch works and conveyances;
- concentrating of the head from a much longer segment of the river in the power plant, even resorting to an underground location;
- dimensioning as higher as possible the installed power of the hydro plant by increasing the flow rate of the penstocks;
- planning a peak regime for the power plant, because the higher energy price in this regime.

These methods were applied at the hydro plants of Arges, Lotru, Tismana, which are underground located.

3. *Realizing on the middle segment of the water course of power plants arranged in waterfall scheme, working in middle and basic regimes.*

At these lower altitude zones, the terrain near the river bed is often occupied by settlements, industrial or agricultural unities or other destinations. Here the energy utilization of the water must be combined with the drinkable or industrial use.

The waterfall arrangement is mandatory; higher dams could not be admitted because the flood danger for the near zone.

The water plants in the middle course of the river may benefit by the regulation effect of the reservoir in the upper course (if any). That makes possible installing higher power and producing more electricity.

The economic result may be improved by some means like:

- inserting in the cascade of the hydro plants of small or middle size reservoirs to ensure an daily independent work regime relating to the upper course hydro plant;
- dividing the entire head of the sector in equal sections in order to typify the projects for dams, buildings, turbines, generators and other equipment, what diminishes considerably the investment costs;
- positioning the power plant in the river bed in order to not affect the neighboring terrain;
- contribution of the hydro technical works to the flood proofing of the populated areas and agricultural cultures.

The application of this principle may be recognized by many examples in Romania. For example there are 12 small hydro plants on the Bistrita river down stream of Stejaru main station. These plants utilize water heads of 15 and 20 m, having a totalized installed power greater than the upstream station and delivering more electricity than that one.

On the Arges river, 14 small plants were build up in waterfall scheme, utilizing three steps of head: 10,5 m; 14,5 m; 20,5 m.

4. *On the lower segment of the water course will be build up hydro plants by the side of water reservoirs dedicated to irrigations or water supply for all the demands.*

The number of such plants is very small in Romania.

Table 2.2 presents some parameters of the greatest water developments in Romania, allowing to identify the above principles materialization.

The linear potential of the Danube is used in two plants: Iron Gates I and II; another project (Turnu Magurele-Nicopol) was not materialized (Table 2.3).

Table 2.4 presents a general draft of water developments in Romania, drawn up by professor Dorin Pavel. Until 1989 were build up 5600 MW which can deliver 12.6 TWh/yr. In 2008 the installed power was 6375 MW.

2.4 Small hydro power plants

The installed power of the existing hydro plants varies from some tens kW up to over 10,000 MW. Although all the hydro plants utilize a renewable resource, only those having rated power under 10 MW are included among the renewable sources.

Table 2.2 Water developments in Romania

River	Bistrita	Arges	Sebes	Lotru	Somes	Raul Mare
0	1	2	3	4	5	6
The main reservoir	Izvorul Muntelui	Vidraru	Oasa	Vidra	Mari-selu	Gura Apei
Water level (mASL*)	513	830	1255	**1289**	990	1072
Useful water capacity (*10^6 m^3)	**930**	320	125	300	200	200
Downstream level of the main plant(mASL)	364	506	790	480	520	490
Main plant head (m)	149	324	565	**809**	470	582
Downstream level of the cascade (mASL)	141	253	214	296	367	295
Cascade head (m)	223	253	**576**	184	153	195
Natural flow rate (m^3/s): - droughty year - rainy year	 25 55	 14.5 25.55	 5.1 10.2	 9.9 20.1	 7.4 14.3	 7.0 18.5
- summer time - winter time	58.6 22.6	26.4 12.6	11.2 5.3	22.6 10.5	15.3 8.1	20.7 7.9
Regulated flow rate (m^3/s): - droughty year - rainy year - summer time - winter time	 **27** **54** **35.5** **45.7**	 15.1 23 18.5 20.5	 5.6 10 66.5 10.0	 11.4 19.8 12.5 20.7	 8.1 13.7 9.1 14.3	 7.9 17.5 12.9 16.1
Inflow (m^3/s): - main river - conveyances - total	 **40.6** 0 **40.6**	 7.2 12.3 19.5	 3.9 4.3 8.2	 4.2 **12.4** 16.6	 6.6 5.1 11.7	 8.5 6.0 14.5
Installed power (MW):	210 **244** 454	220 180 400	300 80 380	**510** 133 **643**	220 75 295	335 205 540
Electricity production (GWh/yr): - main plant - downstream cascade - total	 370 **770** 1140	 400 350 750	 520 155 675	 **1000** 252 **1252**	 390 140 530	 605 480 1085
Medium operating time (h/yr)	1760	1820	1735	1960	1770	1800
Main plant: name and location	Stejaru, ground level	Arefu, under-round	Galceag, under-ground	Ciunget, under-ground	Mariselu, under-ground	Retezat, under-ground

*)mASL = meters above sea level

Table 2.3. Hydro developments on the Danube

Hydro plant	Instaled power (MW)	Electricity production (TWh/yr)	Reservoir length (km)	Year of commissioning
Iron Gates I	12*175=2100	10.5	272	1970
Iron Gates II	16*27=432	2.4	80	1985
Turnu Magurele-Nicopol	20*39=780	4.4	282	Project

Table 2.4 General draft of Romanian water developments

Plant work regime	Economic rank	Number of plants	Installed power (MW)	electricity production (TWh/yr)	Operating time (h/yr)
Peak	I	10	1117	2.235	2001
	II	10	439	0.953	2171
	III	111	894	2.772	3101
Midlle and basic	IV	42	740	3.088	4173
	V	487	2930	14.202	4847
Danube	VI	4	2770	10.770	3888
Total		664	8890	34.020	3827

The small power hydro plants harness some categories of water potential, as follows:

- the linear potential of water courses what was not included in the large development projects or downstream of these, where the natural flow has restored to a suitable size;
- the residual heads at existing hydrotechnical works like evacuation gallery of a underground hydro plant, locks, open cooling circuits of thermal power plants etc.;
- the head on the feeding pipes for drinkable or industrial water.

These hydro plants may be utilized to supply remote consumers or to be connected to the public grid. Those hydraulic and electric equipments are as simpler as possible as well as the afferent hydrotechnical works, in order to reduce the investment cost.

Many countries, even developed countries, give a big attention to small hydro plants, releasing important projects in this respect. Some examples: Japan - 7000 MW in 1350 units; Sweden – 550 MW in 5050 units; Russia – 2200 MW in 21000 units; French – 1170 units; Germany – 30000 units.

For Romania, the small technical potential is evaluated at 3.8 TWh/yr, which may be utilized in 4700 units. The economic potential reaches 2,2 TWh/yr electricity from an installed power of 900 MW. The higher resources are in the counties Valcea (17% from total), Brasov (9.2%). The Iasi county is poor in this respect, the little potential being evaluated at some 10 GWh/yr.

2.5 Environmental aspects of the water developments

Comparatively with other energy processes, the hydro power seems to be the least injurious for the environment because after finishing the works, the zone comes back to the previous normal condition. Often, the new landscape with a big reservoir contributes to the economic development of the area with industrial units, tourism etc.

In fact, during the construction works, appear some negative consequences like noise, dust, exhaust gases, solid and liquid wastes etc.

Studies about the economic efficiency of the water developments reveal that the positive consequences are social and economic but the negative consequences are predominately the environmental ones.

These negative effects are mostly local and can be prevented or amended:

- degradations of forests or agricultural areas by landslide or raising of the freatic water because of the hydrostatic pressure of the water in reservoir;
- potential possibilities for large damages downstream the dam if destroyed;
- laying down of the alluvial material in the reservoir, causing siltation;
- breaking the route of the migratory fish;

The consequences on the biological ecosystems are considered uncertain, being positive or negative:

- changes of the local flora and fauna;
- alteration of the local climate.