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# Past and future of water turbines in Romania

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## ABSTRACT

Water wheels have been known since Antiquity, being primarily used to raise water from rivers, and to generate mechanical power for mills. Water wheels spread during Middle Ages, being widely used till the 19<sup>th</sup> century. Some water wheels, entirely built in wood, dated from the 18<sup>th</sup> and 19<sup>th</sup> centuries and in use till the mid 20<sup>th</sup> century, are well preserved in Romanian museums where they have been transferred. With the widespread introduction of Hydro-Power Plants for generating electricity, in the late 19<sup>th</sup> century, water turbines have largely replaced the water wheels. A brief overview of the concepts and evolution of water turbines is realised within this paper, being illustrated with pictures from Romania. As the need of renewable energy sources increases, new concepts of turbines adapted for marine currents or hydropower farms are emerging. Water-current turbines or collections of such turbines (farms) use directly the kinetic energy of the water current to produce electricity. Water-current turbines only need minor civil works and are easy to transport and relocate.

## INTRODUCTION

The hydraulic energy has been used for thousands of years. The *water wheel* is considered the first rotary system for extracting power from water flow, by transforming the hydraulic energy of the water entering the wheel into mechanical energy at the wheel's spinning shaft. Water wheels appear to have been invented by the Ancient Greeks, being primarily used to raise water from rivers. By Roman times, *watermills* appear after realising that the spinning shaft can be used to turn millstones. In Ancient China, in the 2<sup>nd</sup> century BC, about the same time as in Europe, large rotary mills for grinding grain appeared. Watermills spread during Middle Ages, being widely used till 19<sup>th</sup> century (Hansen 2007). Washing and fulling woollen cloth in hydraulic installations (*whirlpool*) powered by water wheels were developed from the early 1<sup>st</sup> century (Bucur et al. 1996). Many other applications were developed during the last 900 years, the most common being fulling cloth in hot water in *fulling-mills* (from the beginning of the 12<sup>th</sup> century), and sawing lumber in *sawmills* (from the mid 13<sup>th</sup> century, then widely spread in the 16<sup>th</sup> century). By the late Middle Ages, water wheels were used in

mining, to pump water from the mines, to grind ore, operate hammers at the metal smith's forge etc. The water powered *cotton spinning mills* (based on the *water frame* perfected by Arkwright in 1771) become the wonder of the late 18<sup>th</sup> century.

With the widespread introduction of *Hydro-Power Plants* (HPP) for generating electricity, in the late 19<sup>th</sup> century, *water turbines* have largely replaced the water wheels. Within that context, by the mid 20<sup>th</sup> century, only few water wheels were still used, especially in isolated areas, in less industrialized countries. Today, all over the world, the main classical water energy sources are already exploited, and HPPs produce about a quarter of the world's electricity. To respond to the renewable energy increasing demand, new concepts of turbines adapted for marine currents or *hydropower river farms* are studied.

## WATER WHEELS

There are five types of water wheels (Georgescu & Georgescu 2007; Hansen 2007):

① The *undershot wheel*, also called *noria*, is one of the most ancient and less efficient water wheel (below 20% efficiency). It uses the kinetic energy of the flow. Marcus Vitruvius Pollio, Roman engineer and architect in the 1<sup>st</sup> century BC, describes such a wheel. It is a vertically mounted wheel, so its horizontal shaft requires gears to drive a typical millstone. That's why the undershot wheel was primarily used to raise water from rivers to aqueducts, and only later to *watermills*. The wooden wheel consists of many straight paddles or blades, and water enters the wheel below the axis. The largest existing water wheel is a *noria* with a diameter up to 20 m, located in the Syrian city of Hama (Monzur 2007). An old *noria* of 12 m is still used for irrigation in China, in Jiangxi's Nankang City (*Ancient Water Wheel in Jiangxi* 2005).

② The *overshot wheel* is more efficient (70% efficiency). It is vertically mounted, and receives water from above, very near the top, often from a mill race. It uses mainly the potential energy of the flow. The wheel rotates in the same direction as the incoming water flow, but opposite to the downstream flow. The wheel consists of many backward curved blades that receive the water at its natural angle of fall, and then retain it as long as possible.

③ The *backshot wheel*, or *pitchback wheel*, is the most efficient water wheel (about 90% efficiency). It's similar to an overshot wheel, but it is mounted in mirror position. The wheel rotates opposite to the incoming water, while the exhaust water flows in the direction of the rotating wheel. That wheel needs a *penstock* or mill race to bring water above the wheel.

④ The *breastshot wheel* design and mounting is similar to the pitchback type, but it has a smaller diameter, it's very wide (figure 1a) and less efficient (about 50% efficiency). The water enters the wheel about half way up, above the shaft, and it flows out with the rotation of the wheel. That wheel is the precursor of the *Bánki turbine*.

⑤ The *Norse wheel* (or *tub wheel*) is generally mounted horizontally and its vertical shaft turns a millstone directly. It uses the kinetic energy of the flow, and has great efficiency. The wooden wheel has several straight blades or curved buckets at the outer circumference of the hub, and a water jet strikes the blades and turns the runner. The water jet is directed to the wheel by an inclined mill race (*tub*). A Norse wheel can equally be mounted vertically, like in figure 1b, to gain power by adding the potential energy of the flow to the kinetic energy.

Watermills were known in Dacia (ancient Romania): millstones were discovered in Apulum, Napoca, and Micia. The Latin terminology of the entire technical structure of watermills proves that these installations were continually used by the native population throughout the first millennium (Bucur et al. 1996; *Museum of Traditional Folk Civilization ASTRA Sibiu* 2007). On both sides of the Carpathian mountain chain of Dacia, most of the ancient watermills combined two functions: flour-milling inside the mill house, and washing and thickening the woollen cloth downstream the mill.



(a)



(b)

**Figure 1.** Wooden water wheels from the Village National Museum "Dimitrie Gusti" of Bucharest: (a) breastshot wheel; (b) vertical Norse wheel.

Within the hydraulic installation for washing and fulling cloth, the water jet arrives through an inclined mill race, and is projected at the base of a *whirlpool*, to create a vortex, which carries the cloth that is introduced into the pool. That whirlpool is called in Romanian *vultor* or *valtoare*, but also *steaza*. Those names originated from ancient times and they are unchanged till present! They have two linguistic origins: *vultor* or *valtoare* comes from the Latin *\*vultoria* (unattested, so recovered on etymological basis); the term *\*vultoria* derives from *volutus* (attested, derived from the verb *volvo*, *volvare*). Thus, the Romanian words *vultor* and *valtoare* are related to the *act of swirling* (whirling), and they are used on the territory of Dacia that was occupied by Romans (western, south-western and central Romania). In mountain areas not incorporated in the Roman province of Dacia, the Romanian term of the whirlpool is *steaza*, a pure Thracian-Illyrian name.



(a)



(b)

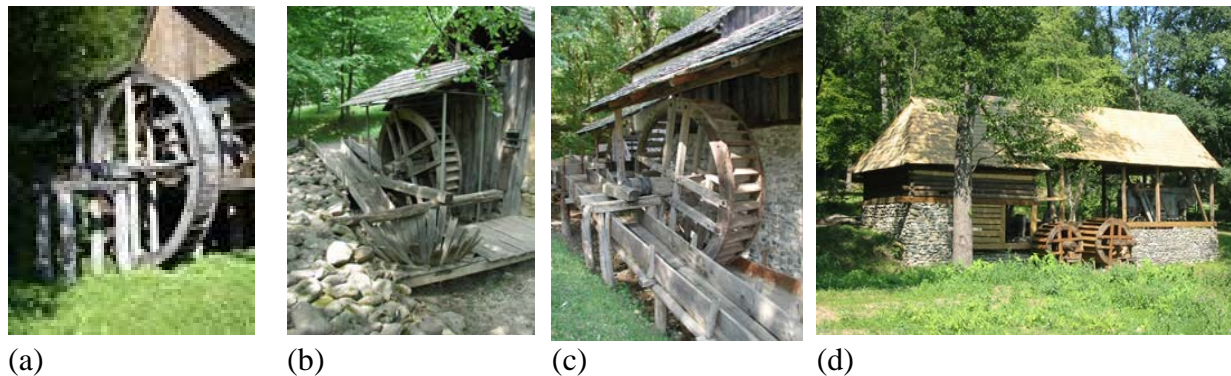


(c)

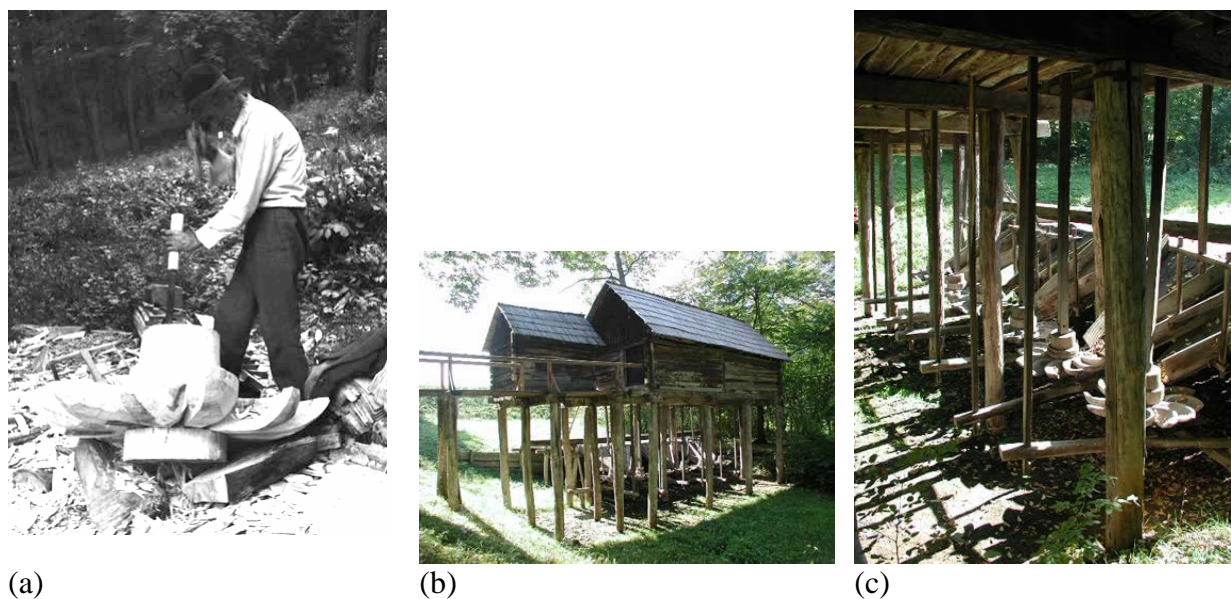
**Figure 2.** Romanian fulling-mills: (a) whirlpool in situ, at Moeciu de Sus; (b) mill race and whirlpool at Sichevita; (c) wooden undershot wheel with button-admission, from Sichevita (*Museum of Traditional Folk Civilization ASTRA Sibiu 2007*)

Some whirlpools are still functional: see the picture taken in situ (figure 2a) at the fulling-mill of Moeciu de Sus Village, Brasov County (central Romania), built in 1925. The *fulling-mills* involve hackling and thickening large woollen cloth in hot water (Bucur et al. 1996). In figure

2b we present the mill race and whirlpool from the fulling-mill of Sichevita Village, Caras-Severin County (south-western Romania), built in 1926. In figure 2c is the undershot wheel of the same mill. A very inclined penstock brings water to the lower part of the wheel; the water jet strikes the buckets placed on the wheel periphery, thus resulting a *button-admission*.



**Figure 3.** Romanian undershot wheels: (a) flour-mill with 4.3 m wheel from Rogojelu; (b) wheel and whirlpool at Nistoresti fulling-mill; (c) fulling-mill with 3 wheels from Rucar; (d) fulling-mill from Sarbi (*Museum of Traditional Folk Civilization ASTRA Sibiu 2007*)



**Figure 4.** Romanian Norse wheels at Galesoia watermill: (a) the reconstruction of the wheel by a local artisan; (b) landscape view of the watermill; (c) parallel arrangement of the 6 vertical axis wheels (*Museum of traditional folk civilization ASTRA – Sibiu 2007*)

The biggest water wheel that exists in Romanian museums is an undershot wheel of 4.3 m diameter (figure 3a), from Rogojelu Village flour-mill, Cluj County (central-northern Romania). The mill installation dates from 1853 and was recovered in 1981, during its demolition in situ. In figure 3b we present the fulling-mill equipped with a wooden undershot wheel, combined with a whirlpool, from Nistoresti, Vrancea County (eastern Romania). The fulling-mill from Rucar, Arges County (central-southern Romania), presented in figure 3c, is outstanding because of the dimensions and complexity of the hydraulic system: 3 undershot wheels, of 2.25 m, 2.90 m and 3.45 m diameter, each having its own admission system and whirlpool at its extremity. The hydraulic complex from Sarbi, Maramures County (northern

Romania), presented in figure 3d, includes a fulling-mill and a threshing machine with hydraulic action, built around the interwar period.

The most spectacular *Norse wheels* in Romania are those of the Galesoaia Village watermill, on the Tismana River, Gorj County (southern Romania). That watermill, built in the second half of the 19<sup>th</sup> century, is equipped with 6 wooden horizontal wheels, each with curved buckets at the outer circumference of the hub (figure 4a). The deep river bed, as well as the danger of flooding, determined the raising of the mill on high massive piles, at about 5 m above the water (figure 4b). The waters of the Tismana River were collected in a pond near the mill, to supply the 6 wheels. Each wheel has a penstock for water admission (figure 4c).

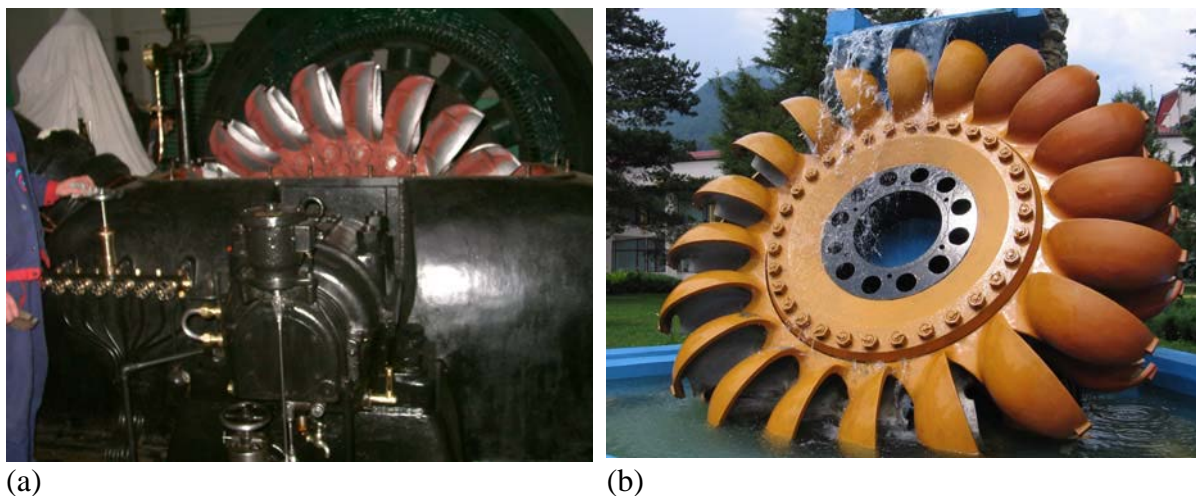
The Norse wheel is the precursor of modern impulse turbines: the wheel from figure 4 is related to the *Turgo turbine*, while the wheel from figure 1b is related to the *Pelton turbine*.

## WATER TURBINES

In the late 19<sup>th</sup> century, *water turbines* (or *hydraulic turbines*) have largely replaced the water wheels. Water turbines have the same operating principle as water wheels. The turbine allows producing electricity in *Hydro-Power Plants* (HPP).

The first HPP in Romania was the Grozavesti plant (attested in 1889), on Dambovitza River in Bucharest, equipped with 4 turbines of 132.35 kW each. In 1896, the Sadu 1 HPP (Sibiu County, in central Romania) was operational with two Francis turbines of 192.2 kW each, followed in 1898 by the Sinaia HPP, on Prahova River (at 123 km North of Bucharest), with 4 Pelton turbines of 265 kW each. At the beginning of the 20<sup>th</sup> century, hydropower production continued to develop in Romania, reaching in 1930 about 30 MW. The Dobresti HPP on Ialomita River (near Sinaia) is operational since 1930, with 4 Pelton turbines of 4 MW each (figure 5a), at a head of 305 m. It is a true technical museum under operation. The main HPPs of Romania were put in operation between 1960 and the early 1990's. In 2005, a considerably wet year, a record in the hydropower generation in Romania was reached, with a production of 20103 GWh (33.7% from the total power production of the country).

There are two main water turbines categories: the *impulse turbine* (e.g. Pelton; Turgo; *cross-flow turbine*), which transforms the kinetic energy of the water, and the *reaction turbine* (e.g. Francis; Dériaz; Kaplan; bulb etc) that transforms both potential and kinetic energy. They are briefly discussed in the following (Georgescu & Georgescu 2007).



**Figure 5.** Pelton wheels from Romanian HPPs: (a) horizontal shaft arrangement (4 MW), at Dobresti HPP; (b) vertical shaft arrangement (170 MW), from Lotru-Ciunget HPP.

⇒ In 1880, Lester Allan Pelton patented the so-called *Pelton turbine*. It is used for low flow rates and very high heads, providing high efficiency (92%). The water admission is performed through up to 6 needle-valves. The maximum power reached is of 423 MW, at Bieudron HPP, in Switzerland (that HPP has also a World record for its 1869 m head). The biggest Romanian HPP equipped with Pelton turbines is the Lotru-Ciunget HPP, on Lotru River (central-southern Romania). It has 3 vertical axis turbines of 170 MW each, with 6 jets, at a head of 809 m. That HPP was operational since 1972, with Pelton wheels with 20 buckets (exposed now outside the HPP – see figure 5b). The HPP has been refurbished between 1996 and 2002 with Pelton wheels with 21 buckets (2.95 m diameter of the runner).

⇒ The *Turgo turbine* was invented in 1920 by Eric Crewdson. Its wheel has long double-curved blades. The operating principle is similar to the Pelton turbine, but with a single inclined jet. The Turgo turbine is used for very low flow rates and low heads (up to 260 m), providing high efficiency (90%). The maximum power is of 4.4 MW.

⇒ In 1917, Donát Bánki invented a *cross-flow turbine* with horizontal axis, where the water crosses twice the runner blades. In 1922, Fritz Ossberger and A.G.M. Michell patented a *Free Jet Turbine*, similar to the *Bánki turbine*. Then, in 1933 they patented an improved-one. Today, the cross-flow turbine with horizontal axis is called both *Bánki* and *Ossberger-Michell*. It is used at very low flow rates and low heads (up to 200 m), providing a good efficiency (86%). The maximum power is of 1.5 MW. It fits to micro HPP, and being a cheap solution, is still implemented in hydropower. Since 2005, two new Bánki turbines, of 770 kW each, run at Zervesti micro HPP, near Caransebes (south-western Romania).

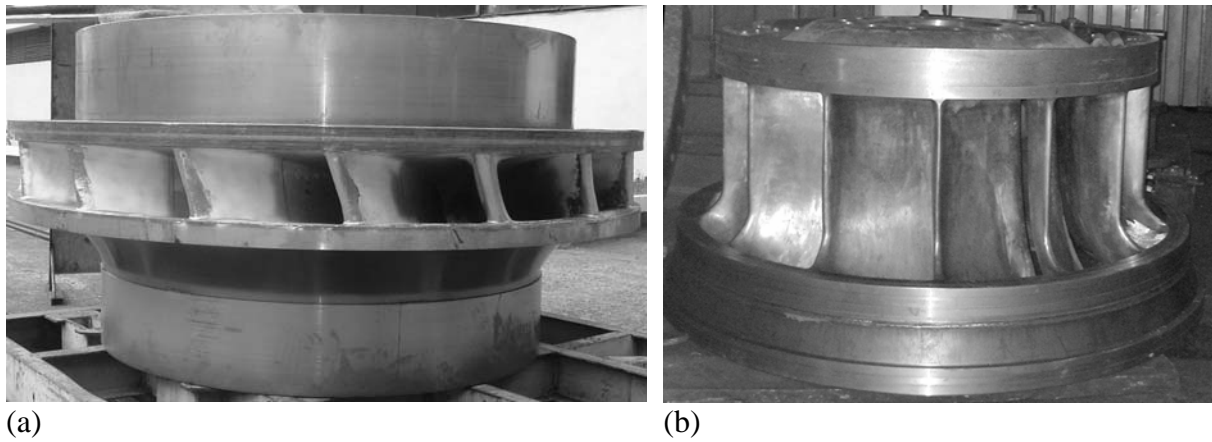
⇒ The first *reaction turbine* has been invented by Johann Andreas von Segner, in 1735-1755 (*Segner wheel*). From 1824 to 1834, Jean-Victor Poncelet improved reaction turbines on advanced hydrodynamic basis (*Poncelet wheel*). Benoît Fourneyron patented in 1834 the first modern reaction turbine, an *outward-flow turbine* (*Fourneyron turbine*). In 1895, such turbines equipped the Niagara Falls HPP. In 1844, Uriah Atherton Boyden improved the Fourneyron concept, and patented the *Boyden turbine*. From 1844 to 1846, four Boyden turbines were installed at Appleton Mills in Lowell, USA. By the mid 19<sup>th</sup> century, the textile industry from New England, USA, replaced the old water wheels with Boyden turbines.

⇒ Following the collaboration between Boyden and James Bicheno Francis, in 1949 a new modern turbine has been patented: an *inward-flow turbine* called *Francis turbine*, which combined elements of the Boyden turbine with a concept of Samuel B. Howd. The Francis turbine is used for low flow rates, and high heads (up to 750 m). The maximum power reached is of 805 MW, at Grand Coulee III HPP, on Columbia River, USA (that HPP has also the World record for efficiency: 95.6%). The Francis turbines are divided into *low specific speed type* (larger and slower runner), and *high specific speed type* (smaller runner diameter and faster operating speed). In figure 6a, we present the runner of one of the 4 Francis turbines, of 55 MW each, from the Vidraru HPP, on Arges River (southern Romania), operational since 1966, at a head of 324 m. In figure 6b, we present the runner of one of the two Francis turbines, of 57.5 MW each, from the Bradisor HPP, on Lotru River, operational since 1982, at a head of 152 m.

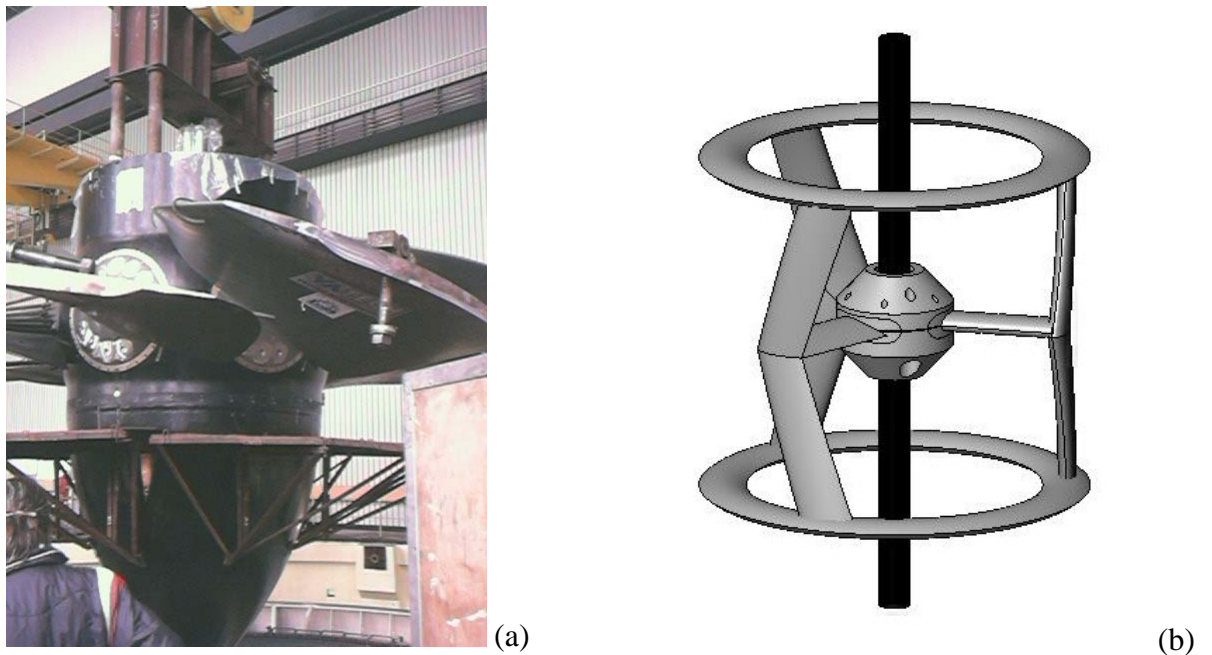
⇒ The *mixed-flow* (or *diagonal*) *Dériaz turbine* has adjustable blades and adjustable wicket gates. It is used for medium flow rates, and low heads (up to 150 m), providing high efficiency (92%). The power can reach 215 MW (e.g. at the Russian Zeisk HPP).

⇒ From 1912 to 1913, Viktor Kaplan obtained 4 patents for some *axial turbines*, one of them with adjustable blades. The *Kaplan turbine*, a *propeller type* turbine, has been patented only in 1920. The classical *Kaplan turbine* has an axial runner with 3 to 8 adjustable blades, adjustable wicket gates, vertical shaft, semi-spiral case intake and draft tube. It is used for high flow rates, and low heads (up to 80 m), providing very high efficiency (94%). The 12 Kaplan turbines installed at the Iron Gates I HPP, a Serbian-Romanian HPP system on

Danube, operational since 1971, are among the biggest in the World (9.5 m diameter of the runner and 191.2 MW per unit at 28.5 m head). In figure 7a we present one of the refurbished Kaplan runners, during the setting up in situ in May 2003, within the Romanian HPP side.



**Figure 6.** Francis runners from Romanian HPPs: (a) low specific speed type (55 MW), at Vidraru HPP; (b) high specific speed type (57.5 MW), at Bradisor HPP



**Figure 7.** Other water turbines: (a) Kaplan runner from Iron Gates I HPP, on Danube; (b) Achard turbine (patent of LEGI Grenoble, France)

⇒ Some *axial turbines* have simple discharge regulation, realised with adjustable wicket gates and fixed blades (so-called *propeller turbines*), or with adjustable blades and fixed guide vanes (also called *semi-Kaplan turbine*). Both have a narrow efficiency curve. The *tube turbine* (or *S-turbine*) consists of a penstock that bends before or after the axial runner (with fixed blades); the generator is placed outside the tube; it is installed in small and micro HPP.

⇒ For high flow rates and very low heads (up to 22 m), the *bulb turbine* is commonly used. The runner with horizontal axis has adjustable blades, and the adjustable wicket gates are of conical type. The turbine and the electric generator form a sealed unit placed directly in the water stream (the generator is inside the bulb). The Serbian-Romanian Iron Gates II



hydropower system on Danube (downstream from the Iron Gates I), operational since 1986, is equipped with 20 bulb turbines of 27 MW each at 10.25 m head (placed in 3 HPPs); the efficiency reaches 94%. Reversible bulb turbines are usually installed in *Tidal Power Plants*.

⇒ The *Water-Current Turbine* (WCT) is a *marine* or *river cross-flow turbine* with vertical axis, which transforms the kinetic energy of the marine currents or rivers. Several concepts are studied (e.g. Darrieus; Gorlov; Achard). Hydropower systems equipped with WCTs need minor civil works. Collections of such turbines (*farms*) can be fixed to a structure on the riverside, on floating pontoons, or on the river bed. Experimental and numerical research is performed in Romania on a new concept of WCT, called *Achard turbine*, in close collaboration with French partners involved in the *HARVEST Project* (Maître et al. 2007). The Achard turbines are flexible enough to be placed in big rivers, as the Danube, and to produce the desired power by summing elementary power provided by small turbine modules. In France, such farms are studied also with regard to marine applications, to extract energy from tidal currents in costal locations. In figure 7b we present the Achard turbine that is studied now in Romania.

## CONCLUSIONS

Within this paper, an overview of the concepts of water wheels and water turbines is realised, the main types being illustrated with pictures from Romania. Water wheels developed in Romania 2000 years ago, and some wooden wheels were operational till the mid of the 20<sup>th</sup> century. Starting from the end of the 19<sup>th</sup> century, water turbines developed in Romania. They were notable among those from other countries, especially at the beginning of the 20<sup>th</sup> century. The turbines from Iron Gates I HPP are among the biggest in the World. To respond to the renewable energy demand, a new turbine concept (the Achard turbine) is studied.

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