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An Overview of Micro-Hydropower Technologies and Design Characteristics of Waterwheel Systems

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Abstract

In recent years, the global warming and efficient usage of energy sources are become most attractive issues. Furthermore, renewable energy technologies play an important role in addressing global energy and environmental challenges. Among the renewable energy technologies, hydropower is considered to be the most advanced and mature, providing some level of electricity generation in more than 160 countries worldwide. Micro-hydropower plant is in the category of small-scale hydropower projects, and it provides an affordable, reliable, economically viable, socially acceptable and environmentally energy alternative for rural area. In this article, micro-hydropower technologies, design and performance characteristics, power losses, mechanical powers and efficiencies for the waterwheel systems such as breastshot, overshot and undershot are reviewed in detail and compared each other. In addition, the development of worldwide hydropower capacity is discussed, and the top countries in terms of total installed capacity are reported and investigated.

Keywords: Micro-hydropower, Waterwheels systems, Breastshot, Overshot, Undershot.

Mikro-Hidroelektrik Teknolojileri ve Su Çarkı Sistemlerinin Tasarım Özelliklerine Genel Bir Bakış

Özet

Son yıllarda, küresel ısınma ve enerji kaynaklarının verimli kullanılması en cazip konular haline gelmiştir. Ayrıca, yenilenebilir enerji teknolojileri, küresel enerji ve çevre sorunları açısından önemli bir rol oynamaktadır. Yenilenebilir enerji teknolojileri arasında, hidroelektrik dünya çapında 160'tan fazla ülkede elektrik üretimini belli bir düzeyde sağlayarak, en gelişmiş ve olgun olarak kabul edilmektedir. Mikro hidroelektrik santrali küçük ölçekli hidroelektrik projelerin kategorisindedir ve kırsal alan için uygun fiyatlı, güvenilir, sosyal açıdan kabul edilebilir, ekonomik ve çevre açısından duyarlı bir enerji alternatifi olarak sunulmaktadır. Bu makalede, gövde çarpmalı, üstten çarpmalı ve alttan çarpmalı gibi su çarkı sistemleri için mikro hidroelektrik teknolojilerinin tasarım ve performans özellikleri, güç kayıpları,

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mekanik güçler ve verimliliği ayrıntılı olarak gözden geçirilmiş ve birbirleriyle karşılaştırılmıştır. Buna ek olarak, tüm dünyada hidroelektrik kapasitesinin gelişmesi tartışılmış ve toplam kurulu güç açısından başta gelen ülkeler detaylı olarak incelenmiştir.

Anahtar Kelimeler: Mikro-hidroelektrik, Su çarkı sistemleri, Gövde çarpmalı, Üstten çarpmalı, Alttan çarpmalı.

1. INTRODUCTION

Fossil fuel resources are rapidly dwindling and over the last decade energy demand has doubled [1]. Without decisive action, energy related greenhouse gas emissions may become doubled by 2050, and increased oil demand will heighten concerns over the security of supplies. For this reason, an energy revolution is needed to achieve a 50% reduction of global CO_2 emissions relative to current levels by 2050. In this revolution, energy efficiency, sustainable and low-carbon energy technologies play a crucial role. In addition, renewable energy technologies (biomass, wind, solar, hydro and geo- thermal) play an important role in addressing global energy and environmental challenges [2,3]. They are offering clean and reliable energy to reduce greenhouse gas emission that lead to global warming while saving money and creating jobs. Furthermore, they provide a cost-effective source of electricity in rural areas where distances are large, populations are small, and demand for energy is low [4].

Hydropower is a good example of renewable energy [5], and it is the single largest share of renewable electricity worldwide. In rural areas and particularly in mountainous regions, which are usually economically passive and not easily accessible, small power plants up to 10 MW appear as a cost effective energy production technology [6]. In addition, it is the most advanced and mature renewable energy technology and provides some level of electricity generation in more than 160 countries worldwide [7]. Today, hydropower plays a key role in the green energy production, avoiding the combustion of 4.4 million barrels of oil equivalent daily, only 33% of potential hydro resources has been developed and the remaining technical potential is estimated to be very high (14,576 TWh/year).

Hydropower does not only remain a backbone of the power sector, but is also one of the most ambitious emission reduction paths for low-carbon and sustainable energy system [8]. It plays an important role in the global renewable energy supply. Hydropower potential on large scale has been exploited in almost every part of the world. However, large hydropower plants suffers from several problems like long gestation period, ecological changes, loss due to long transmission lines, submergence of valuable forest and underground mineral resources etc. Due to all these factors, large hydropower plants are becoming unfavourable in the current era. On the other hand, small/micro/mini/pico hydropower projects are free from these aspects. The mini hydro energy source is available in almost every country of the world [9]. Small hydropower is a kind of renewable energy with no pollution, mature in development, reliable and flexible in operation, easy to maintain and financially competitive. In addition, it has gained the highest attraction due to its environment friendly operation, and it can be the best economical option for rural electrification in developing countries. With these advantages, small hydropower plant becomes a favorable energy source for rural and mountainous areas to get access to electricity [9]. The very low head water technology is an innovation in renewable-energy technology in view of the fact that it uses a completely different approach to equip low-head sites such as locks, canals, old mills or existing weirs. It has become more widely implemented over the past few years due to minimal environmental impact. Although this technology represents one of the best current options for decentralized power generation, development has been hindered by significant implementation costs, of which civil work generally constitutes 40–50% of the total initial cost [10]. Alternative approaches and new designs in implementations of the very low head water technology with conventional hydraulic, electrical equipment's and controllers would reduce the overall cost of mini hydro system and would help in making it a cost effective technology. Furthermore, these innovations will also help developing countries to provide electricity to rural areas or remote regions where interconnection of transmission line from the electrical grid is uneconomical [9].

Today, there are many regions with very low head below 2,5 m in the irrigation canals, old mill sites, or weirs in the river. Many of these hydropower regions still remain unexploited. But, the need for harnessing these regions for electrical power production has been ever increasing because of the growing interest towards renewable energy. Therefore, there exists a great potential of producing hydropower from those regions using appropriate technology [11]. Research shows that waterwheel technologies are technically and economically favourable alternatives for low head sites with an efficiency of 75-85% over a wide range of flow. Slow speed of rotation and large sized cells of the water wheel can reduce the risk to aquatic life as well as allow better sediment transport and tolerance to floating debris [11].

2. HYDROPOWER IN THE WORLD

Energy shares of global electricity production are presented in Figure 1. As seen from the figure that renewable energy sources have accounted for an ever-growing share of electric capacity added worldwide each year. While renewable energy capacity continues to rise at a rapid rate from year to year, renewable electricity's share of global production is increasing at a slower pace. During the years 2010 through 2014, installed capacity as well as output of most renewable energy technologies grew at rapid rates, particularly in the power sector. Over this period, solar photovoltaics (PV) experienced the fastest capacity growth rates of any energy technology, while wind saw the most power capacity added of any renewable technology. On the other hand, hydropower is being used increasingly to balance systems with high shares of variable renewables. By the end of 2014, renewable energy sources supplied an estimated 22,8% of global electricity, with 16,6% of total electricity provided by hydropower [12].

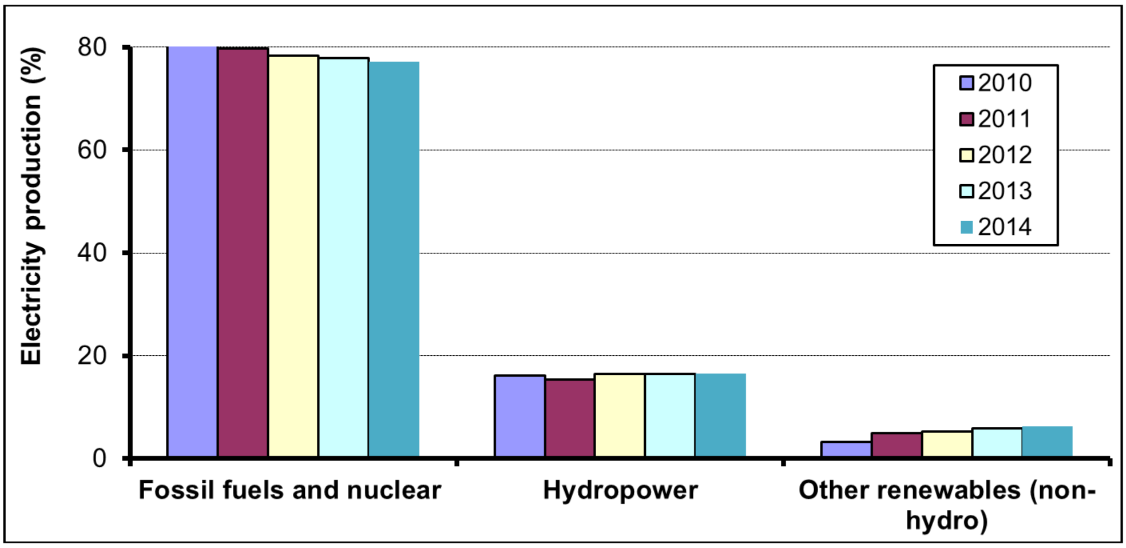

Figure 1. Energy shares of global electricity production

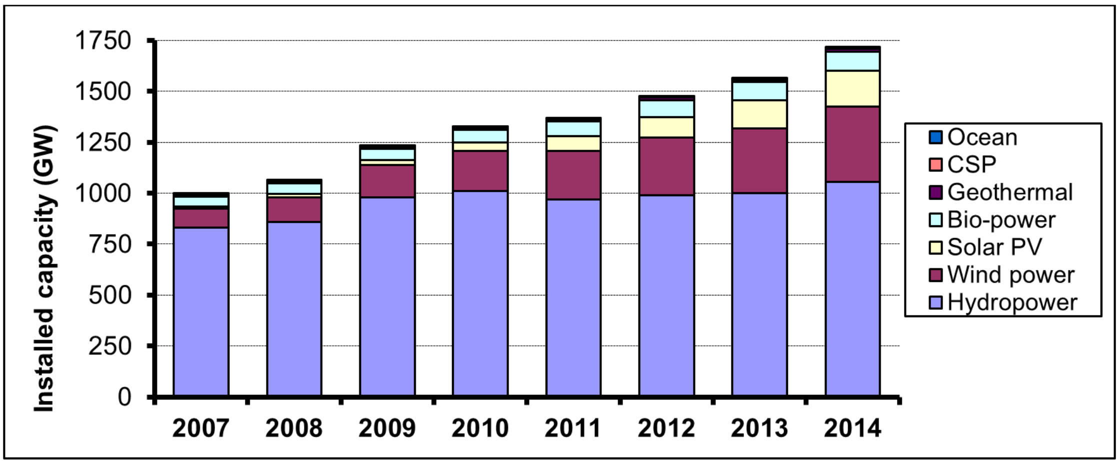

Figure 2. The cumulative installed renewable electric power capacity in the world between 2007 and 2014.

Hydropower has been utilized for more than a hundred years, and it is the most widely used renewable energy source worldwide [9]. The cumulative installed renewable electric power capacity in the world between 2007 and 2014 is presented in Figure 2. During this period, installed capacity of many renewable electric power technologies grew very rapidly. In 2007, there was 1,000 GW of renewable electric power capacity installed in the world. On the other hand, total renewable electric power capacity worldwide had reached to 1,712 GW in 2014. As seen from Figure 2, hydropower rose to an estimated 1,055 GW.

Top 6 countries in hydropower global capacity and additions are given in Table 1. As seen, an estimated 37 GW of new hydropower capacity was commissioned in 2014, increasing total global capacity by 3.6% to approximately 1,055 GW. Global hydropower production, which varies each year with hydrological conditions, was estimated at 3,900 TWh in 2014. The top countries for hydropower capacity remained China (280 GW), Brazil (89 GW), the United States (79 GW), Canada (77 GW) and Russia (48 GW), India (45 GW) [12]. The lion’s share of all new capacity in 2014 was installed by China, with significant additions by Brazil, Canada, Turkey, India, and Russia. China commissioned a record 22 GW, for a total of 280 GW of hydropower capacity at year’s end. Brazil added 3,3 GW in 2014, including 138 MW of small-scale hydro (<30 MW) capacity, for a year-end total of at least 89 GW. Third for new installations was Canada, which completed 1,7 GW of new hydropower capacity in 2014, raising its total generating stock to 77,4 GW. Turkey added 1,35 GW of hydropower capacity in 2014, for a total of 23,6 GW. Hydropower generated 40,1 TWh during the year, representing a 32% decline from 2013, and the result of drought in recent years. India added about 1,2 GW of capacity in 2014, 228 MW of which was classified as small-scale hydro (<25 MW per facility), bringing the country’s total capacity to 44,9 GW. Annual generation was estimated at 144 TWh. In Russia, net capacity additions in 2014 were 1,1 GW, increasing installed capacity to 47,7 GW. Even as capacity rose, hydropower generation (164 TWh) declined 4,4% from the previous year [12].

3. HYDROPOWER SYSTEMS

Hydropower plants are very different in terms of size and type of generating unit, size and type of plant, the height of the water fall (head), their functions (electricity generation, capacity or multi-purpose) and sizes. They are extremely site specific and tailor-made to local conditions. For example, a classification by hydraulic head refers to the difference between the upstream and the downstream water levels. The classifications of low head (less than 30 m) and high head (above 300 m) technologies vary widely from country to country, and there are no generally accepted scales. Head determines the water pressure on the turbines. Together, head and discharge are the most important parameters for deciding the type of hydraulic turbine to be used [13].

Table 1. Top 6 countries in hydropower global capacity and additions [12]

Country	**Net Added 2013 GW**	**Total End-2013 GW**
Top Countries by Total Capacity		
China	22	280
Brazil	3,3	89
US	0,0	79
Canada	1,7	77
Russia	1,1	48
India	1,2	45
Top Countries by Net Additions		
China	22	280
Brazil	3,3	89
Canada	1,7	77
Turkey	1,4	24
India	1,2	45
Russia	1,1	48
World Total	**37**	**1055**

Hydropower plants can also be classified in three functional categories such as storage, run-of-river and pumped storage plants [13]. In storage plants, dam impounds water in a reservoir that feeds the turbine and generator, which is usually located within the dam itself. Run-of-river plants use the natural flow of a river, where a weir can enhance the continuity of the flow [14]. They are considered to be more environment friendly mainly due to small/no reservoir impoundment and quite less displacement of natives as compared to their reservoir based counterparts. Both storage and run-of-river schemes can be diversion plants, where water is channelled from a river, lake or dammed reservoir to a remote powerhouse, containing the turbine and generator. Pumped storage incorporates two reservoirs. At times of low demand, generally at night, electricity helps pump water from the lower to the upper basin. This water is then released to create power at a time when demand, and therefore price, is high. Although not strictly a renewable energy (because of its reliance on electricity), pumped storage is very good for improving overall energy efficiency [14].

Table 2. Hydropower systems according to their installation power production capacity [14]

Category	**Output/unit**	**Storage**	**Power use (load)**
Small	< 10 MW	run-of-river	base load
Medium	10-100 MW	run-of-river	base load
Medium	100-300 MW	dam and reservoir	base and peak
Large	> 300 MW	dam and reservoir	base and peak

Hydropower systems are classified as small-scale, medium and large according to their installation power production capacity. Table 2 gives hydropower systems according to their installation power production capacity [14]. Small-scale hydropower is a kind of hydropower systems, and it is one of the most economical and environmentally friendly technologies to be considered for rural electrification projects. It can be a very good complement to a solar power system, as it produces electricity for 24 h a day as long as the running water is available. It is a much more concentrated energy resource than either wind or solar power. Different categorisation of small-scale hydropower systems in terms of installed capacity is given in Table 3. As seen from the table, the size of a small hydro-power project is about 10 MW or less. However, the definition and categorization of small-scale hydropower varies from country to country and may vary from time to time. There is no consensus on the upper limit for the definition of small-scale hydropower systems [15].

Table 3. Different categorisation of small-scale hydropower systems in terms of installed capacity [15]

Small-scale hydropower categorisation	Installed capacity
Picohydro	Less than 5 kW
	Less than 10 kW
Microhydro	Below 20 kW
	Greater than 5 kW but less than 100 kW
	Up to 100 kW
	Between 10 kW and 200 kW
	Below 500 kW
Mini hydro	Greater than 500 kW but less that 2 MW
Small hydro	Less than 10 MW
	100 to 10 MW
	2,5 MW to 25 MW

4. MICRO-HYDROPOWER SYSTEMS

Micro-hydropower plant is in the category of small-scale hydropower projects. Micro-hydropower provides an affordable, reliable, economically viable, socially acceptable and environmentally sound energy alternative for rural area [16]. Fundamental components of a typical micro-hydropower system are mainly civil works components (headwork, intake, headrace canal, fore bay, penstock/pipe and tailrace) and powerhouse components (turbines, generators, drive systems and controllers). In case of power house components turbine or waterwheel is the most essential part. The turbine is connected either directly to the generator or is connected by means of gears or belts and pulleys, depending on the speed required for the generator.

There is no consensus on the upper limit for the definition of micro-hydropower plants. However, the installed capacity of 100 kW seems to be the common upper limit referred in the definition [15]. In micro-hydropower plants, the most common sources of potential are specific location(s) on the course of the river from that have head and flow suitable for the scale of the micro-hydropower projects. Therefore, location of the river and identifying the potential sites is one of the important exercises in micro-hydropower development [15].

Generally, micro-hydropower systems can be generated energy using turbines and waterwheels. Turbine is one of the key and costly elements of micro-hydropower systems depending on the particular requirements of any given site. It converts hydraulic power into mechanical power, and it is made up of a rotating and stationary elements. Energy conversion process takes place in the runner that is made up of an assembly of blades on a disc. The select of turbine for hydropower plant depends upon the head and discharge from the available site [9]. In addition to these, turbine technical efficiency is one of the factors to look for when selecting a turbine for the particular micro-hydropower site. Turbine efficiency is evaluated as the ratio of extracted mechanical power to input hydraulic power at the turbine inlet. The turbine efficiency depends mainly on four factors, namely: flow leakage, disc friction, bearing friction and hydraulic loss. Efficiency levels for micro-hydropower systems range from 60% to around 85% while large-scale hydro-power projects, have efficiency levels of over 90% [15]. There are several examples of turbines used in micro-hydropower projects. They are classified according to their principles of operation. Depending on site characteristics, such as available head and flow rate, and on the selected running speed of the generator, different turbine types with different operating range and performance characteristics, they can be divided into impulse, reaction and archimedes screw turbines [15].

In reaction turbines, both pressure and velocity energies are extracted from the flowing water and then converted into shaft- power by the runner. Common examples of reaction turbines used in micro-hydropower plants are Kaplan, Francis, Propeller and Pump-as-turbine. In impulse turbines, hydraulic energy is first converted into kinetic energy in form of free water jet by nozzles. The water jet impacts the runner blades and due to change of momentum of the jet, a force is created on the runner blades that makes the turbine rotate. Common examples of impulse turbines applied in micro-hydropower plants include Turgo, Pelton and Crossflow [15]. In an archimedes screw, water falls through the screw and turns it. The turning screw turns the gearbox and the generator so that electricity can be generated. Archimedes screw is excellent for hydroelectric systems with low heads (2-10 m) and large flow, and it is manufactured as bespoke installation [17].

Environmental effects of run-of-river type hydroelectric power plants have many dimensions associated with both construction and operational phases. The issues that are expected to occur during the construction phase include air pollution, dust emissions, noise, landslide, erosion and excavation debris. The topics related to the amount and the timing of water to be released back to the river, efficiency of fish passages, sediment passages, access roads and energy transmission lines are the main considerations of the operational phase. Aquatic life may be adversely affected in the diversion reach if sufficient amount of water is not kept in the river for sustaining a healthy aquatic habitat. Moreover, chemical composition and physical characteristics of the water (pH, temperature, suspended solids, etc.) might change and migration of fish may also be disturbed. In addition to such ecological, environmental and aesthetic impacts, run-of-river plants have major social effects on the local people. Local people usually use rivers for their social and economic needs such as fishing, irrigation, recreation, swimming, transportation, etc. [18].

5. WATERWHEELS SYSTEMS

Waterwheel is one of the oldest hydraulic machines known to humankind, and it was introduced more than 2000 years ago as a source of mechanical power to grind cereals and to pump water [19]. It is a simple machine generally made of wood or steel with blades fixed at regular interval around their circumference. The blades are pushed by the water tangentially around the wheel. The thrust produced by the water on the blades produces torque on the shaft and as a result the wheel revolves [20]. If waterwheels are well designed, they can reach a high and constant efficiency for a wide range of external conditions, but, turning at slow rotation speeds (6-10 rpm), they need high gearbox for generating alternate electricity [21].

Water wheels are a sustainable and economic technology, since their construction is simpler over turbines, their environmental impact is lower, the payback periods are faster and practically there is no public resistance to their installation. They may also improve the local economy by promoting tourism and cultural activities, in addition to crop grinding and electrical production [19]. Waterwheels may not be a strategical solution for large scale renewable energy generation, but they may be a suitable method for decentralized electricity generation and for a smart land use. Wide variety of waterwheel models has been evolved throughout the history [21]. Especially, three distinct types of waterwheels evolved the breastshot, the overshot and the undershot wheel. Operational ranges of these waterwheel types are given in Table 4. Especially, in Ref. [19, 21-23] a detailed work has been conducted on a breastshot, overshot and undershot waterwheels, presenting a modern theoretical model and experimental results.

Table 4. Waterwheels operational ranges [19]

Type	Head (m)	Flow (m3/s.m)	Power (kW/m)	Efficiency (%)
Early undershot	0,5-2,5	0,5-1,2	0,7-5,0	35-40
Breastshot	1,5-4,0	0,35-0,65	4,0-20	60-70
Overshot	2,5-10	0,1-0,65	2,0-18	70-90

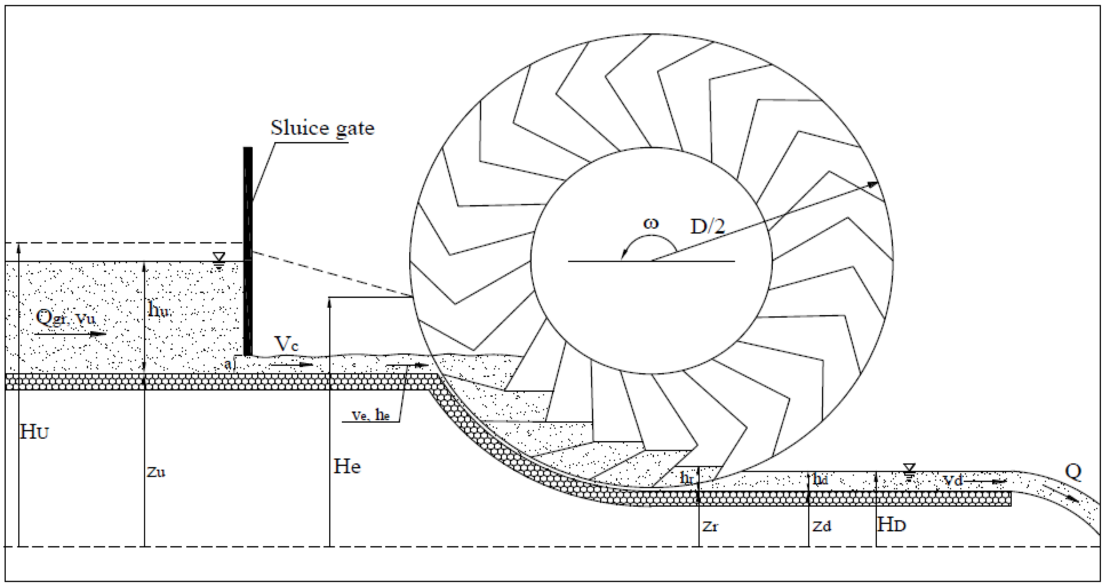

Figure 3. Breastshot waterwheel technology [21]

5.1. Breastshot Waterwheels

Among the three types the breastshot waterwheel is the most suitable for the application of low-head micro-hydro system. However, breastshot waterwheels are generally less efficient than overshot wheels and more efficient then undershot ones. They are applicable to the smaller head difference of 1.5-4 m [20]. As seen from Figure 3, water level on the breastshot waterwheel is maintained approximately at the level of wheel axle. Weight of the water enclosed in the blade cell is the main driving force on this type of waterwheel [20]. Breastshot waterwheels are used for sites with abundant flow rates and medium heads. Since the water enters at about the same height of the rotation axle, both the kinetic energy and the potential energy of the stream are exploited.

In the recent years, only a little design and performance information has been known about breastshot wheels. One of the most advanced design method was developed by Quaranta and Revelli [21]. In their study, a theoretical approach is adopted to estimate the different kinds of power losses occurring inside a breastshot waterwheel in order to estimate its mechanical output power. The theoretical results are then validated with experimental results on a physical steel model. To achieve this, the wheel is installed inside an open channel, where a sluice gate increases the water depth in the conveying channel and accelerates the water flow in the headrace. According to Quaranta and Revelli [21], the gross and net heads available for the wheel are expressed by:

$$H_{gr} = (H_U - H_D) = \left[\left(z_u + h_u + \frac{v_u^2}{2g}\right) - \left(z_d + h_d + \frac{v_d^2}{2g}\right)\right] \quad (1)$$

$$H_{net} = (H_e - H_D) = \left[\left(z_e + h_e + \frac{v_e^2}{2g}\right) - \left(z_d + h_d + \frac{v_d^2}{2g}\right)\right] \quad (2)$$

where H_U is the energy head before the sluice, H_e the flow energy head just before the wheel and H_D the downstream one (that at the tailrace). The generic head H_x is the sum of the bed channel elevation z_x, the water depth hx and kinetic term $v_x^2/2g$, where g=9.81 m/s^2 is the acceleration of gravity. The input power for the wheel and the input power for the laboratory hydroelectric plant are found by:

$$P_{gr} = \rho g . Q_{gr} . H_{gr} \quad (3)$$

$$P_{net} = \rho g . Q . H_{net} \quad (4)$$

where Q_{gr} is the total flow rate, $Q=Q_{gr}-Q_U$ and Q_U is the discharge lost before the wheel, through leakages and slits. The mechanical output power Pout at the wheel axle is still lower than P_{gr} and P_{net}, because different power losses occur in the wheel and headrace between the sluice gate and the wheel. Quaranta and Revelli [21] stated that six main kinds of power losses may occur in the wheel and headrace: (1) impact losses include the impact of the entry water on the blades (L_{imp}) and the impact of the blades on the tailrace (L_t), (2) leakage losses are water losses through the slits between the buckets and the channel (L_Q), (3) friction losses are due to mechanical friction at the shaft supports (L_g) and to drag effect of the water (contained in the buckets) on the channel bed (L_{bed}), (4) hydraulic losses may occur when the residual power of the water in the last bucket is lost in the tailrace (L_h) and (5-6) there are the hydraulic (L_c) and leakage (L_{Qu}) losses in the headrace between the sluice gate and the wheel.

P_{out} can be calculated by:

$$P_{out} = P_{gr} - \sum \text{Losses} = P_{gr} - (L_c + L_{Qu} + L_{imp} + L_Q + L_g + L_{bed} + L_t + L_h) \quad (5)$$

The wheel efficiency is defined as:

$$\eta_w = \frac{P_{out}}{P_{net}} = 1 - \frac{(L_{imp} + L_Q + L_g + L_{bed} + L_t + L_h)}{P_{net}} \quad (6)$$

The conveying channel efficiency is expressed as:

$$\eta_c = \frac{P_{net}}{P_{gr}} = 1 - \frac{(L_c + L_{Qu})}{P_{gr}} \quad (7)$$

The global efficiency of the installed hydroelectric plant is defined as:

$$\eta = \eta_c . \eta_w = \frac{P_{out}}{P_{gr}} = 1 - \frac{(L_c + L_{Qu} + L_{imp} + L_Q + L_g + L_{bed} + L_t + L_h)}{P_{gr}} \quad (8)$$

The experimental power can be determined by:

$$P_{exp} = C . w \quad (9)$$

where C and w are torque and angular velocity, respectively.

From the experimental and theoretical analyses studied by Quaranta and Revelli [21], as seen in Figure 4, the average error between the theoretical and experimental analyses is obtained as 9%, and various concluding remarks can be summarized as follows:

- The maximum power losses occur in the impact loss (L_{imp}) on the blades and hydraulic (L_c) loss in the headrace.
- Friction loss (L_{bed}) due to drag effect of the water on the channel bed is always negligible, because it is two orders lower than other terms (even if it increases with angular velocity and flow rate).
- Figure 5 presents the magnitude of the power losses respect to the input power. The biggest dimensionless power losses are L_Q/P_{net}=0,32

(which occurs at low flowrates, when the dimension of the slits is comparable with the water depth in the headrace and in the buckets), and L_{imp}/P_{net}=0,43 (for the highest entry velocity).

- When L_h<0 it means that the water at the tailrace has more energy than the water in the last bucket and the mechanical output power increases, since the hydraulic loss in the headrace becomes a recovery of energy.
- The efficiency increases with the flowrate and, after a maximum value, it remains quite constant, or it slightly decreases.
- The torque increases with the flowrate and with the decrease in angular velocity.
- The mechanical output power increases with the flowrate. It reaches its maximum value for $w \cong (0,6 \div 0,7) v_e$ and then decreases.
- The maximum efficiency of the wheel is obtained as 96% for Q=0,09 m^3/s.
- A correct future blade and inlet design may allow to reduce the impact loss on the blades and hydraulic loss in the headrace.

5.2. Overshot Waterwheels

Overshot waterwheels are driven by the potential energy created by the accumulated water in the buckets of the wheel. As seen from Figure 6, water flows at the top of the wheel and fills into the buckets attached on the periphery of the wheel [20]. During rotation, the water acts on the blades by its weight, up to the lowest point of the wheel, where the buckets completely empty. Overshot waterwheels are suitable in sites with heads of 2,5-10 m and small flowrates (unit width flowrates Q <0,1 – 0,2 m^2/s) and they can reach constant efficiency of about 80-90% for a wide range of flowrates [20].

Although a large number of overshot water wheels were in operation in the last century, only few series of tests were performed. Most of the test results were never published in hydraulic engineering textbooks or journals and they are only available in not widely known reports and articles. However, Quaranta and Revelli [19] developed a theoretical model in order to calculate the different kinds of power losses occurring inside an overshot water wheel. In their study, the theoretical results are validated on experimental ones. According to Quaranta and Revelli [19], the total input power depends on the hydraulic and geometric boundary conditions and it is calculated as:

$$P = \gamma . Q . \Delta H = \gamma . Q . \left(\Delta H_g + \frac{v_u^2 - v_d^2}{2g} \right) \quad (10)$$

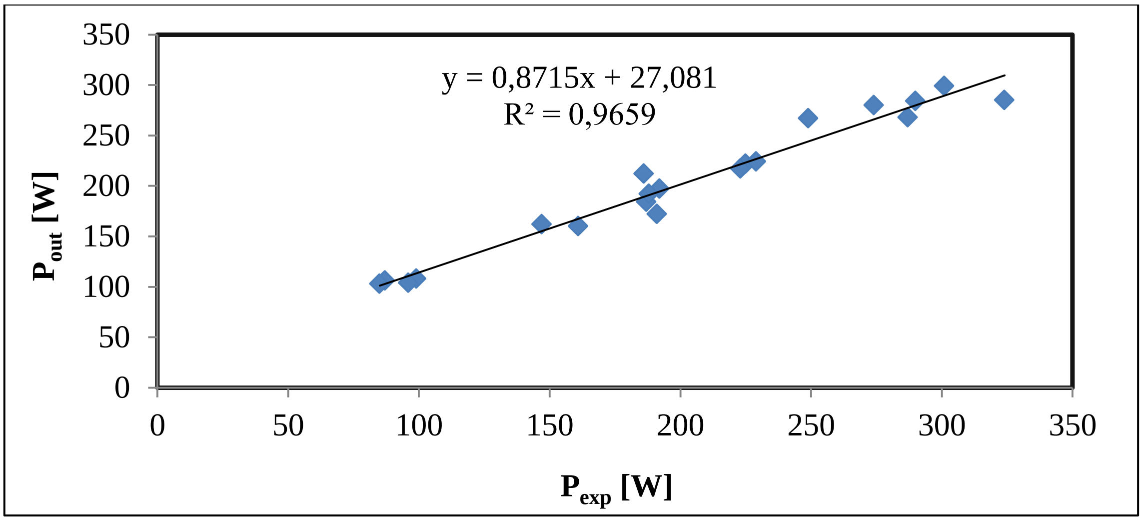

Figure 4. The experimental and theoretical power output results

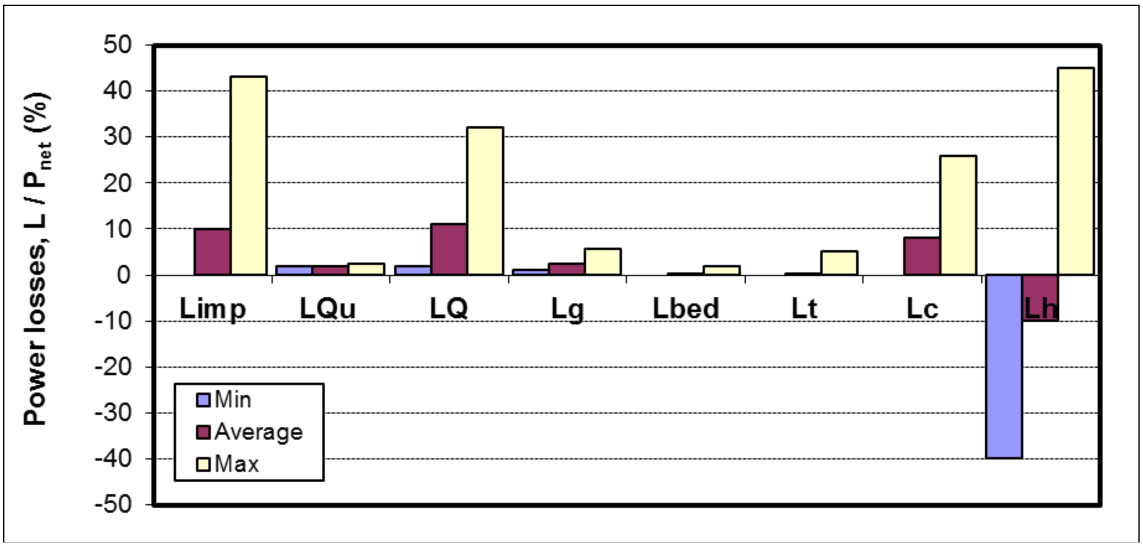

Figure 5. The magnitude of the power losses respect to the input power

where Q is the incoming flowrate, γ =9810 N/m^3 the water specific weight, ΔHg the geometric distance between the free surfaces, v_u^2 and v_d^2 the upstream and downstream water velocity, respectively, and g = 9,81 m/s^2 the gravity acceleration.

The mechanical output power in overshot waterwheel is defined as:

$$P_{out} = P - \sum Losses = P - \left(L_{imp} + L_t + L_g + L_{Qu} + L_{Qr}\right) \quad (11)$$

where L_{imp} is the power loss occurring in the impact, L_t the impact loss generated when the blades impact against the tailrace (if the blades are submerged in the tailrace), L_g the mechanical friction loss at the shaft supports, L_{Qu} the volumetric loss at the top of the wheel and L_{Qr} the volumetric loss during rotation. The efficiency is calculated as:

$$\eta = \frac{P_{out}}{P} = 1 - \frac{\sum Losses}{P} \quad (12)$$

From experimental analysis studied by Quaranta and Revelli [19], it is showed that theoretical power results is very good agreement with experimental ones for assuming L_{Qu}= 0 and for small flowrates (Q <0,04 m^3/s). In their study, various concluding remarks can be summarized as follows:

- Two different limit rotational speeds are identified: the runaway velocity w_r, in correspondence to which the output power tends to become null (w_r≅4,2÷4,3 rad/s) and the critical velocity w_{cr}, where the output power begins to decrease brusquely (w_{cr} ≅2,7 rad/s).
- The power losses, as a percentage of the input power, are presented in Figure 7. As seen, the volumetric loss at the top of the wheel is the most important loss for $w>w_{cr}$, while the volumetric loss during rotation, the mechanical friction loss at the shaft supports and the power loss occurring in the impact have a maximum values of 32%, 7% and 12%, respectively.
- The mechanical friction loss at the shaft supports is the smallest one and all the power losses depend strictly on the rotational speed.
- As the rotational speed increases the parameters L_{Qu} and L_g also increase, and the parameters L_{Qr} and L_{imp} take their maximum values at the value of $w=w_{cr}$=2,7 rad/s.
- The increase in the discharge Q makes all the power losses enhance.

- The tailrace loss is considered to be L_t=0, since the wheel is uplift on the tailrace.
- The output power decreases with the increase in the rotation speed of the wheel. For higher flowrate and tangential velocity, most of the water cannot fill into the buckets, it slips around the external part of the blades and the volumetric loss at the top of the wheel increases.
- The efficiency (80%) remains constant up to angular wheel speed of 2,7 rad/s. Then, the efficiency tends to decrease as a consequence of the increase in L_{Qu} mainly.
- The new recovery systems and the blades geometry should be investigated in order to reduce the power losses and to increase the performance of the wheel.
- The maximum efficiency is 85% for Q=0,05 m^3/s and then it decreases, due to the increase in the volumetric losses, mainly those at the top of the wheel.

5.3. Undershot Waterwheels

In undershot waterwheels, the stream impacts the blades at the bottom of the wheel. Undershot waterwheels are suitable in sites with small heads and high flow rates. They operate with very small head differences of less than 2 m head [20]. In the early undershot wheels the most of the stream kinetic energy was lost in the impact against the flat blades, making the efficiency quite low (30%). Then, efficiency was improved with increasing up to 70%. Few model experiments have been described on undershot waterwheels nowadays. A literature review shows that the most advanced design method was carried out by Denny [22] and Senior et al. [23].

***Conventional Undershot Design**

Denny [22] presented a simple model of conventional undershot waterwheels, as seen in Figure 8. According to the Denny's study, the mass of water that presses against each vane per unit time can be calculated as:

$$\dot{m} = \rho A(v - v') \tag{13}$$

where A is the vane area. v and $v'$are the mean water speed before transferring momentum to the waterwheel and the mean water speed afterwards, respectively. v' is can be found as:

$$v' = wR = cv \quad (0 < c < 1) \tag{14}$$

The force exerted by the water against the vanes is expressed as:

$$F = \frac{d}{dt}[m(v - v')] = \rho A v^2(1 - c)^2 \tag{15}$$

The output power of the waterheel, resulting from this force, is

$$P_{out} = Fv' \tag{16}$$

This is the applied force multiplied by the distance moved by the vanes per unit time. Thus,

$$P_{out} = \rho A v^3 c(1 - c)^2 \tag{17}$$

The input power and the waterwheel efficiency are calculated as:

$$P_{in} = \frac{1}{2}\rho A v^3 \tag{18}$$

$$\eta = \frac{P_{out}}{P_{in}} = 2c(1 - c)^2 \tag{19}$$

This peaks for c = 1/3 so that the waterwheel vanes move at a third of the initial water speed in the millrace. Hence the maximum efficiency of the undershot waterwheel is about 30%.

***Poncelet Modification**

Denny [22] states that the efficiency of undershot waterwheel can be significantly improved by the Poncelet modification. In the Poncelet type, a gravitational component of torque is provided, and more of the mill race water momentum is transferred to the wheel, as seen in Figure 9. The analysis is as for conventional undershot design except that now the force exerted by water pressing against the vanes is given by

$$F = \rho A v^2(1 - c) \tag{20}$$

since here the speed difference of the water, resulting from interaction with the vane, is approximately v, and not $v - v'$. Calculating input and output powers as before leads to the following expression for Poncelet waterwheel efficiency:

$$\eta = 2c(1 - c) \quad (21)$$

As seen, efficiency peaks for c=1/2 at η=50%. This is a significant improvement.

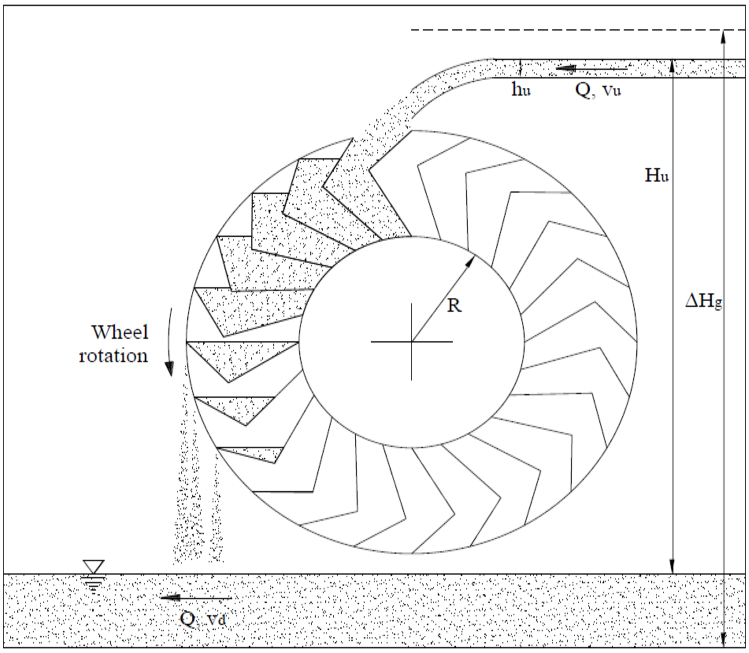

Figure 6. Overshot waterwheel technology [20]

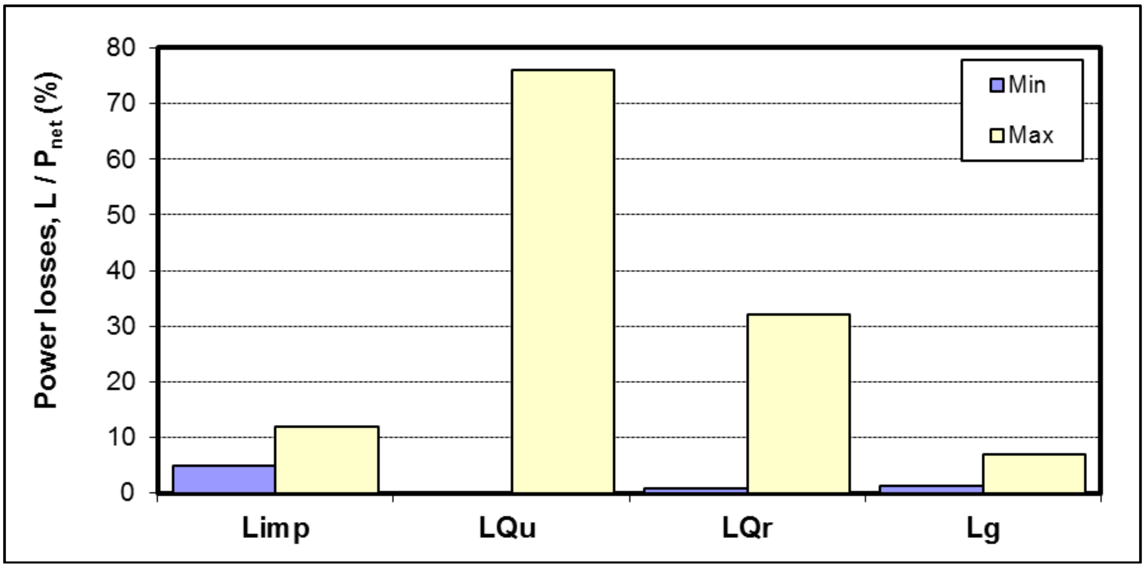

Figure 7. The power losses as a percentage of the input power

***Hydrostatic Pressure Wheel (HPW)**

The theoretical and experimental analyses of the hydrostatic pressure wheel for head differences between 0,2 and 1 m were presented by Senior et al. [23]. According to this, the available hydraulic power is calculated for the wheel of unit width as:

$$P_{hyd} = \rho g v_1 h_1 (h_1 - h_2) \quad (22)$$

where v_1 is the upstream flow velocity, h_1 is upstream water depth and h_2 is downstream water depth, as seen Figure 10. The resultant hydrostatic force can be defined as:

$$F = F_1 - F_2 = \rho g \frac{h_1^2 - h_2^2}{2} \quad (23)$$

Assuming an infinite wheel radius, the mechanical power at the blade is found as:

$$P = F v_1 = \rho g \frac{h_1^2 - h_2^2}{2} v_1 \quad (24)$$

Efficiency without losses is calculated as:

$$\eta = \frac{P}{P_{hyd}} = \frac{1}{2}\left(1 + \frac{h_2}{h_1}\right) \qquad if\ 0 \leq \frac{h_2}{h_1} \leq 1 \quad (25)$$

For a wheel of finite radius, the mechanical power and efficiency are defined as:

$$P = F_1 v_1 \frac{R - \frac{h_1}{3}}{R - \frac{h_1}{2}} - F_2 v_1 \frac{R - \frac{h_2}{3}}{R - \frac{h_1}{2}} \quad (26)$$

$$\eta = \frac{F_1 v_1 \frac{R - \frac{h_1}{3}}{R - \frac{h_1}{2}} - F_2 v_1 \frac{R - \frac{h_2}{3}}{R - \frac{h_1}{2}}}{v_1 d_1 (h_1 - h_2)} \quad (27)$$

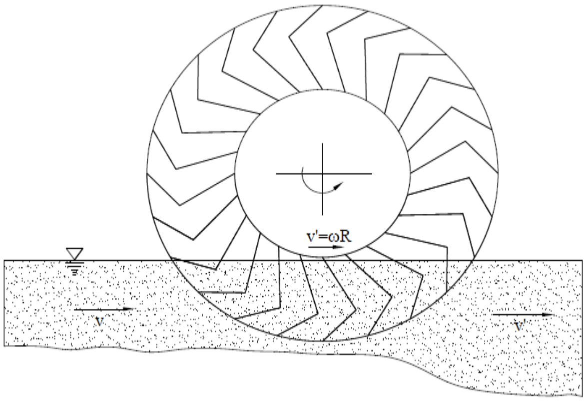

Figure 8. Conventional undershot waterwheel technology [22]

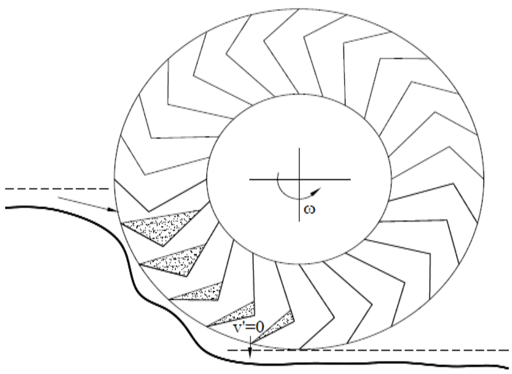

Figure 9. Poncelet type waterwheel technology [22]

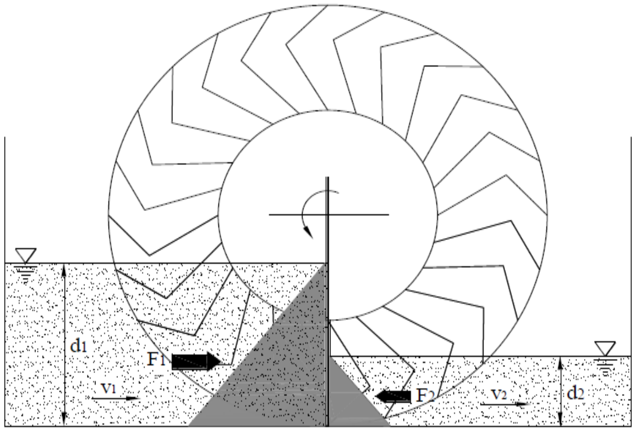

Figure 10. Hydrostatic pressure wheel technology [23]

Figure 11 shows the efficiencies for $R/h_1=\infty$, and $R/h_1=2$. Note that the maximum theoretical efficiencies for a finite radius exceed these for an infinite radius by up to 6,5% if h_2/h_1 = 0,5. However, turbulent energy and leakage losses occur in the wheel. The reduction in the theoretical efficiency η_{th} due to leakage discharge Q_L is expressed for a given Q as:

$$\eta = \eta_{th}\left(1-\frac{Q_L}{Q}\right) \tag{28}$$

The leakage discharge was in the range of 6.7–13% at the maximum efficiency/power output [23]. In hydrostatic pressure wheel, the turbulence energy loss is created by the blade entry, with trailing vortices forming at the blade tip. The machine resistance of width b, with a wetted blade area A, was expressed with C_D as a force counteracting the hydrostatic force thereby reducing the actual power as:

$$P_a = \rho g(F_1 v_1 - F_2 v_2)b - \frac{\rho}{2}C_D A v_b^3 \tag{29}$$

Figure 12 shows efficiency with leakage and with leakage and turbulence adjusted. As seen, the turbulent losses increase for higher wheel speeds.

***Hydrostatic Pressure Machine**

The theoretical and experimental analyses of the hydrostatic machine wheel for head differences between 1 and 2,5 m were presented by Senior et al. [23]. According to this, the available hydraulic power is calculated for the wheel of unit width as:

$$P_{hyd} = \rho g v_1 h_1 (h_1 - h_2) \tag{30}$$

The resultant hydrostatic force can be defined as:

$$F = F_1 - F_2 = h_2(p_1 - p_2) = \rho g d_2(h_1 - \Delta h - h_2) \tag{31}$$

$$\Delta h = \frac{v_2^2}{2g} - \frac{v_1^2}{2g} = \frac{v_1^2}{2g}\left(\frac{h_1^2}{h_2^2} - 1\right) \tag{32}$$

where $v_2 = v_1(h_1/h_2)$ is the downstream flow velocity, p_1 and p_2 are hydrostatic pressures, as seen Figure 13. The mechanical power and efficiency of the ideal machine can be defined as:

$$P = v_2(F_1 - F_2) = \rho g h_2 v_2\left[h_1 - h_2 - \frac{v_1^2}{2g}\left(\frac{h_1^2}{h_2^2} - 1\right)\right] \tag{33}$$

$$\eta = \frac{d_1 - d_2 - \frac{v_1^2}{2g}\left(\frac{h_1^2}{h_2^2} - 1\right)}{h_1 - h_2} \tag{34}$$

However, turbulent energy and leakage losses occur in the wheel. With the effect of turbulent loss, the maximum power output is reduced further to 69% of P_{max}, for Q/Q_{max} = 0,41 [23]. The blades leave gaps between a curved bottom section and the channel side walls. Because of the head difference, leakage discharge Q_L leads to leakage losses. Unlike hydrostatic pressure wheel, leakage for hydrostatic pressure machine is not constant, but a function of the effective head difference. The reduction in the theoretical efficiency η_{th} due to reduced leakage discharge Q'_L is expressed as:

$$\eta = \eta_{th}\left(1 - \frac{Q'_L}{Q_{max}}\right) \quad (35)$$

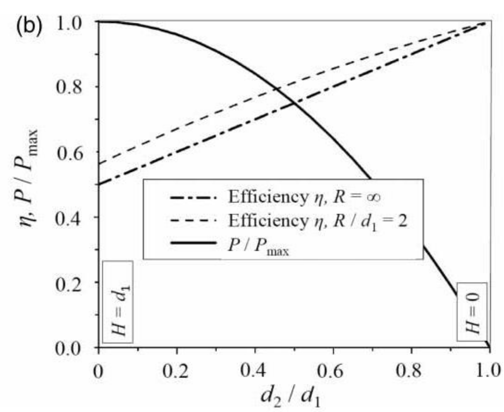

Figure 11. Hydrostatic pressure wheel efficiencies for R/h_1=∞ [23]

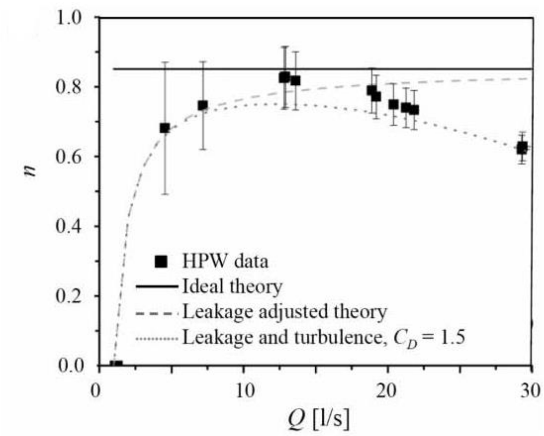

Figure 12. Hydrostatic pressure wheel efficiencies with leakage and with leakage and turbulence adjusted [23]

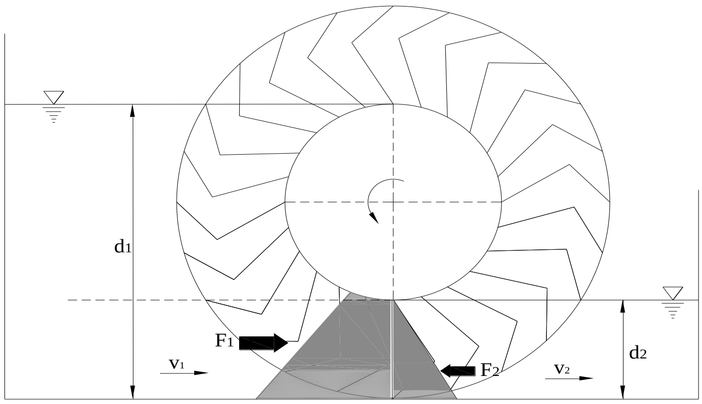

Figure 13. Hydrostatic pressure machine [23]

where Q'_L is reduced leakage discharge which takes into account that the hydrostatic pressure, which drives leakage discharge. Q'_L can be calculated as:

$$Q'_L = Q_L(1 - \Delta h/H) \quad (36)$$

Q_{max} is maximum discharge and it is determined using the maximum upstream flow velocity v_{max} for $P=0$, i.e. $h_1 - h_2 - \Delta h = 0$, namely;

$$v_{max} = \sqrt{2g\frac{h_1 - h_2}{h_1^2/h_2^2 - 1}} \quad (37)$$

$$Q_{max} = v_{max} h_1 \quad (38)$$

Effects of turbulent energy and leakage losses on the wheel are illustrated in Figure 14. As a result, hydrostatic pressure wheel and machine are particularly useful for small hydropower sites where the ratio of water depths upstream and downstream is higher than 0,5 m, with head differences between 0,2 and 1 m, and with power outputs of 1,5 to some 25 kW/m. Otherwise, efficiency becomes too low or the wheel too large [23].

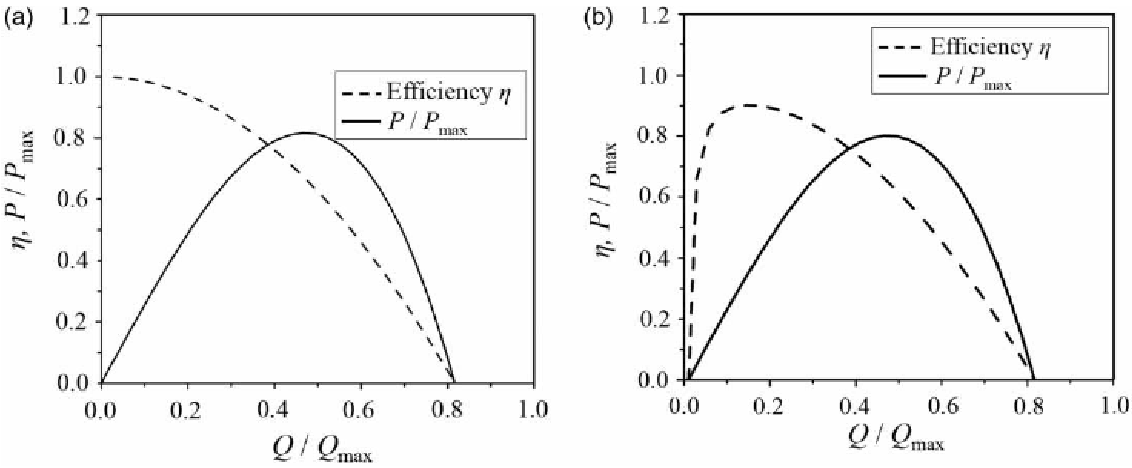

Figure 14. Effects of turbulent energy and leakage losses on the wheel [23]

6. CONCLUSION

The contribution of renewable energies to the world's total energy demand has increased particularly during the last two decades, and they will continue gaining market share. Among all renewable energy sources, hydropower is the single largest share of renewable electricity worldwide, and it is the most advanced and mature renewable energy technology and provides some level of electricity generation in more than 160 countries worldwide. Micro-hydropower, very low head and run-of-the-river hydroelectric technologies have become more widely implemented over the past few years due to minimal environmental impacts, ease in operation, cheaper and easier installations, its simplicity in design and no requirement of heavy construction in comparison to large hydro-power schemes. However, run-of-river type hydroelectric power plants may have ecological, social, environmental and aesthetic impacts. The use of waterwheel technologies in the run-of-river type hydroelectric power plants can be a sustainable and economic system, since their construction is simpler over turbines, their environmental impact is lower, the payback periods are faster and practically there is no public resistance to their installation. They can also provide electricity to rural areas or remote regions where interconnection of transmission line from the electrical grid is uneconomical.

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