December 5 6 7
ICEUBI2017
University of Beira Interior
Faculty of Engineering Covilhã | Portugal
International Congress on Engineering
A Vision for the Future

Summary of in-stream energy production devices

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Abstract
Renewable energy is more important as the time advances. The need to replace fossil fuels such as coal and oil is a big concern in the European union which has established goals of 20% of share of energy from renewable sources in whole European union. The importance of small energy production devices increases when we think of this goal, so energy can reach every citizen, even in a remote village which is kilometers away from the main power source. In-stream devices are optimal for remote sources, which almost always have a water source in the proximities. In-stream turbines can generate enough power to a common house and because it does not require any sort of head nor dam it is easy to mount. Its efficiency is around 40% for most recent in-stream turbines. The most recent technology in this area, the vortex induced vibration devices are still in development reaching 20-30% efficiency when a single device is working, reaching up to 40% when arrayed in some exact positions.

Keywords
Decentralization of power; hydropower; in-stream energy systems

INTRODUCTION

Alternative energy is an interesting concept when you think about it. In our global society, it simply means energy that is produced from sources other than our primary energy supply: fossil fuels. Coal, oil and natural gas are the three kinds of fossil fuels that we have mostly depended on for our energy needs, from home heating and electricity to fuel for our automobiles and mass transportation.

The problem is fossil fuels are non-renewable. They are limited in supply and will one day be depleted. There is no escaping this conclusion. Fossil fuels formed from plants and animals that lived hundreds of millions of years ago and became buried way underneath the Earth’s surface where their remains collectively transformed into the combustible materials we use for fuel.

Renewable energy can be produced from a wide variety of sources including wind, solar, hydro, tidal, geothermal, and biomass. By using more renewables to meet its energy needs, the European Union (EU) lowers its dependence on imported fossil fuels and makes its energy production more sustainable. It is known that renewable energy in EU grew strongly in recent years and targets have been set so the share of renewables in gross final consumption reaches 20% by the year of 2020. While the EU as a whole is on course to meet its 2020 targets, some Member States will need to make additional efforts to meet their obligations for the share of energy from renewable sources in the gross final consumption of energy as its progress is shown in Figure 1 where it is clear that come countries are still far away from the 2020 goal. However, renewables will continue to play a key role in helping the EU meet its energy needs beyond 2020. For this reason, Member States have already agreed on a new EU renewable energy target of at least 27% by 2030 [1].

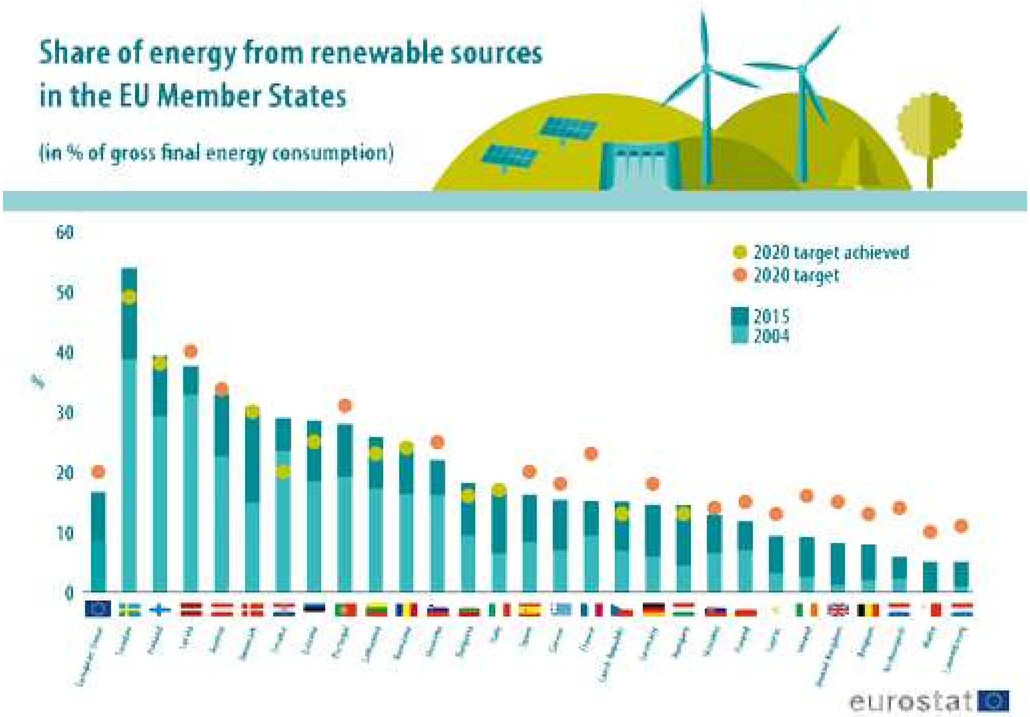

Figure 1. Share of energy from renewable sources, 2004 and 2015, adapted from Eurostat [1]

Decentralization of power in rural areas

Recent research shows that rural regions in Europe may have different characteristics in terms of energy access and use, compared to their intermediate and urban counterparts. Although differences exist between countries and regions, rural communities tend to rely more heavily on carbon intensive fuels that include coal, diesel and heating oil, and some of the more remote regions have no access to main gas supply. Due to a lack of investments in infrastructure, electrical power supply is also not always reliable or efficient. Rural inhabitants may therefore have a more limited choice of energy solutions.

The creations of microgrids with renewable energy sources can be a solution to these remote areas, making them not depend from fuel energy sources which is the observed in most of these areas. Microgrid generation resources can include stationary batteries, fuel cells, solar, wind, or other energy sources such as hydro instream turbines. The multiple dispersed generation sources and ability to isolate the microgrid from a larger network would provide highly reliable electric power. Produced heat from generation sources such as microturbines could be used for local process heating or space heating, allowing flexible tradeoff between the needs for heat and electric power.

Hydropower

Long ago when small villages were created, the people settled near a water source because there was a need of a fresh water source for consumption and irrigation for agriculture. This made most of the small villages that still exist nowadays, to be close to a river or some sort of water source so it makes all sense to utilize water as a source of power as well.

Hydropower (or hydroelectricity power) is the most widely used form of renewable energy, accounting for 16% of global electricity generation and is expected to increase about 3.1% each year for the next 25 years.

Modular and scalable Next generation kinetic energy turbines can be deployed in arrays to serve the needs on a residential, commercial, industrial, municipal or even regional scale. Microhydro kinetic generators neither require dams nor impoundments, as they utilize the kinetic energy of water motion, either waves or flow. No construction is needed on the shoreline or sea bed, which minimizes environmental impacts to habitats and simplifies the permitting process. Such power generation also has minimal environmental impact and non-traditional microhydro applications can be tethered to existing construction such as docks, piers, bridge abutments, or similar structures.

The objective of this research is to make a summary of the most used in-stream energy devices used in river systems, evaluating the energy output that can be generated under certain conditions. An approach of a new, or recent, type of devices is also studied, the vortex induced vibration (VIV) devices. The comparison of both systems' efficiency, regular and VIV systems will be the main point of comparison.

IN-STREAM ENERGY SYSTEMS

In-stream energy systems, as it was already stated, are based in devices that are inserted into the main river, not requiring any sort of dam to accumulate water, relying only on the kinetic energy of water motion. There are two presented types of devices in this study: Turbines, which consist in blade rotation due to the water passing through them, and vortex induced vibration devices, which rely on vibration of the device due to water flow.

TURBINES

River in-stream energy turbines are still in the early development and demonstration phase. They are basically the same as tidal turbines, though there are some small differences. River devices are unidirectional and generally smaller than ocean devices. The most common in-stream turbine types can be observed in Figure 2.

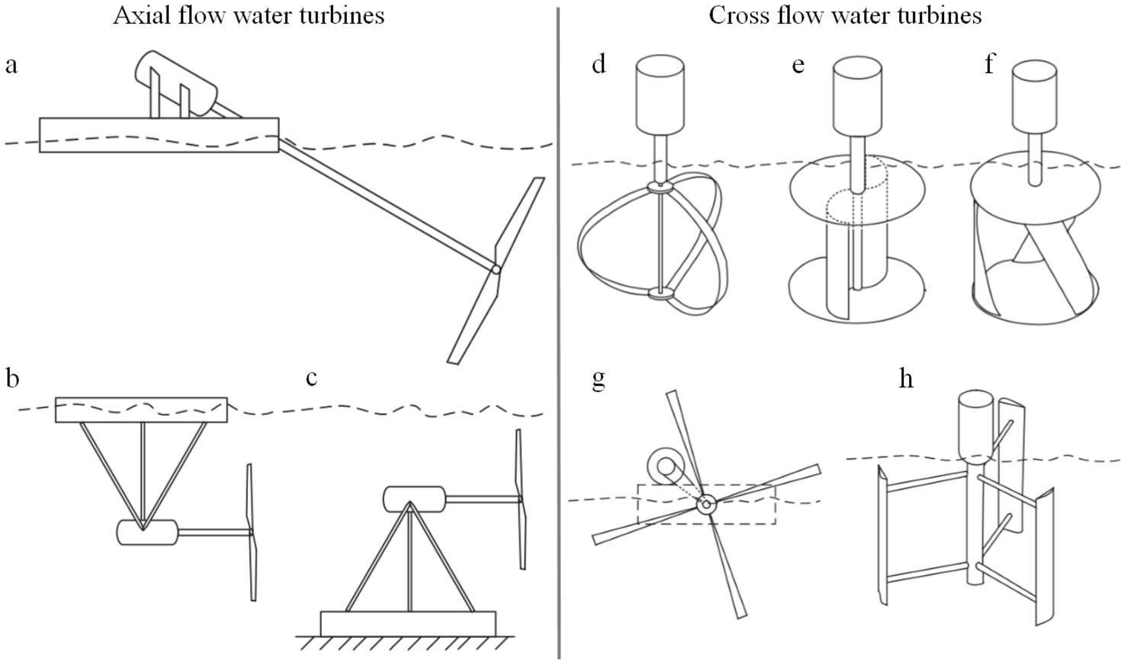

Figure 2. Axial flow water turbines: (a) inclined axis, (b) float mooring; (c) rigid mooring. Cross flow water turbines: (d) Darrieus, (e) Savonius, (f) helical, (g) in-plane, (h) H-Darrieus. Adapted from [2]

Based on the alignment of the rotor axis with respect to water flow, two generic classes could be formed, namely, the axial and cross flow turbines. The axial turbines have axes parallel to the fluid flow and employ propeller type rotors. On the other hand, the cross-flow types encounter water flow orthogonal to the rotor axis and mostly appear as cylindrical rotating structures.

Inclined axis turbines have mostly been studied for small river energy converters. But, horizontal axis turbines are common in tidal energy converters and are very similar to modern day wind turbines from design and structural point of view. Turbines with solid mooring structure require the generator unit to be placed near the river. Horizontal axis rotors with a buoyant mooring mechanism may allow a non-submerged generator to be placed closer to the water surface.

The cross-flow turbines can rotate unidirectionally even with bi-directional fluid flow. These can also be divided into two groups: vertical axis (axis vertical to water plane) and in-plane axis (axis on the horizontal plane of water surface). In-plane axis turbines are better known as floating waterwheels. These are mainly drag based devices and inherently less efficient than their lift based counterparts. The large amount of material usage is another problem for such turbines. Darrieus turbines with in-plane axes may also fall under this category. But such systems are less common and suffer from bearing and power take-off problems.

In the vertical axis domain, Darrieus turbines are the most prominent options. Even though examples of H-Darrieus or Squirrel Cage Darrieus (straight bladed) are rather common, instances of Darrieus turbines (curved blades) being used in hydro applications are non-existent. Savonius turbines are drag type devices, which may consist of straight or skewed blades [2]. There are other types of turbines, such as Gorlov turbine that Professor Alexander Gorlov evolved from the Darrieus turbine design by altering it to have helical blades [3].

As what concerns efficiency of the devices there are theoretical factors that limit the maximum possible efficiency for wind or water turbines that are driven by the stream velocity to around 60%, this has to do with the idea that the turbine cannot slow the water down to zero velocity. There must be some velocity to carry the water away from the turbine. But, real world efficiencies for the machines are much lower.

The bottom line answer appears to be around 35% for a very good turbine, but substantially less for most turbine. The efficiencies often quoted for real world undershot water wheel designs are in the 15 to 20% area for carefully designed ones. The example underwater turbines listed above have efficiencies that range from about 10% up to about 35%, however some companies have reached efficiencies of around 40% [4].

To calculate the harvested power from a fluid with a velocity U, a density ρ, and using a turbine with an area A and a coefficient of power C_P, the equation (1) can be used.

$$P_{fluid} = \frac{1}{2}\rho A U^3 C_p \quad (1)$$

Considering an area of 1m^2, to keep the result as simple as possible, in water at different velocities, the power output of turbines with different coefficients of power is shown in Figure 3.

So, it is clear that for slower flowing streams with small turbine areas, the amount of harvestable power is quite small. On the other hand, if there is a fast-moving stream that has enough width and depth to support a descent size turbine, then the potential power can be significant. Since the power goes up with the cube of velocity, the velocity you have available is very important.

To be successful, flow of river operations need to handle a large amount of flow and that requires a relatively large piece of equipment for the power generated compared to conventional hydro installation that work on water dropping through elevation.

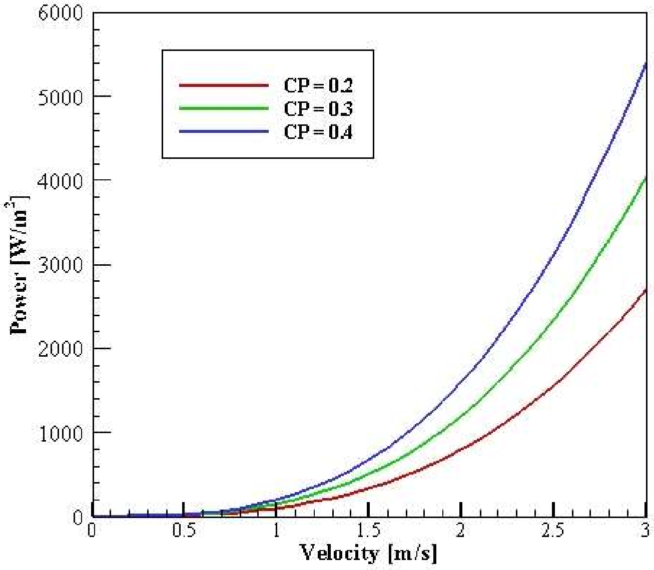

Figure 3. Power output vs. Velocity for different coefficients of power

For the axial flow water turbines, they allow energy harvesting from river currents with minimal environmental impact. Traditional turbines for generating hydropower require dams, as they harness the energy from the head of the water. However, these turbines are placed directly in a flowing river current and require no head to harness the kinetic energy the water already has. Each one is able to generate as much as 5kW of power, is easy to install, and requires minimal maintenance. Also, these turbines are designed to not harm fish and other aquatic life as the water flows through them [4]. An example of a floating turbine and an anchored turbine from the Smart Hydro brand are shown in Figure 4.

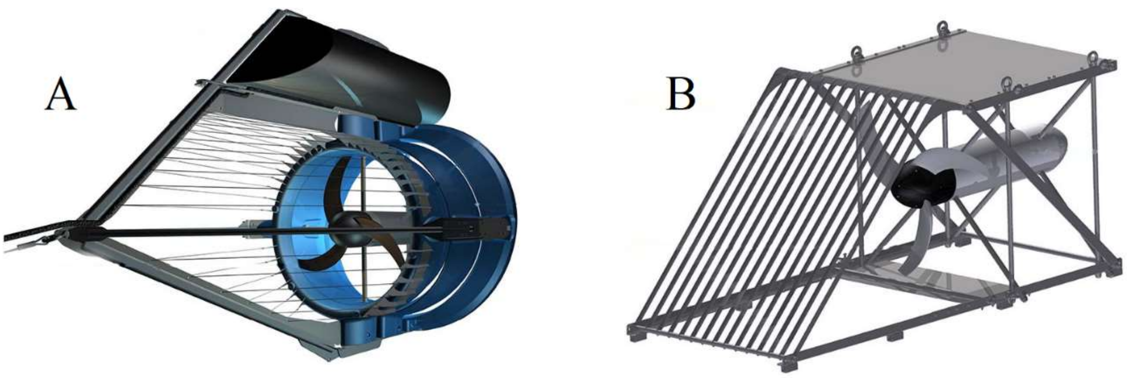

Figure 4. (A) Foat mooring turbine; (B) rigid mooring turbine; Adapted from [4]

For the case of cross-flow turbines, the commonly used are Darrieus, Gorlov, and Savonius turbine. Helical blade and Darrieus straight blade water turbine (also known as H-Darrieus turbines) are commonly suitable for extraction of kinetic energy of flowing water. Helical blades have a smaller rate of pulsation [5] and more favorable starting characteristics than straight blades [6], but the blades are very difficult to be constructed and have to use much stronger materials than the straight blade, given the great forces that any turbine will be under in the water environment. As what concerns the coefficient of power, some authors have reached C_P's of 0.36 [7] for straight bladed Darrieus turbine. Winchester and Quayle [6] reached a lower value of nearly 0.30 for another blade cross-section in a similar study. So as far as Darrieus turbines with straight blades, those are favorable results, having into account that it is easy to manufacture those straight blades. Figure 5 shows a model of a straight bladed Darrieus turbine [8].

Figure 5. Straight bladed Darrieus turbine (or H-Darrieus), from [8]

Moving into the Savonius turbine, it is one of the simplest turbines. Aerodynamically, it is a drag-type device, consisting of two or three scoops. Looking down from above, a two-scoop machine would look like an "S" shape in cross section as it can be seen in Figure 6. Because of the curvature, the scoops experience less drag when moving against the flow than when moving with the flow. The differential drag causes the Savonius turbine to spin. Because of it being a simple turbine, its coefficient of power reflects the simplicity, with 0.15 to around 0.20 being a well-designed turbine. Kailash et al. [9] got this efficiencies for two tests he made, without and with a deflector plate respectively. Elbatran et al. [10] managed to increase the performance to as far as 0.25 of C_p, but they inserted a ducted noozle in the approach to the turbine, so the fluid was redirected there, and in real cases that is not always possible. Although the coefficients of power might seem a bit low, the simplicity of this turbine makes it viable in some cases due to the lack of materials or technology to build better and more sophisticated turbines.

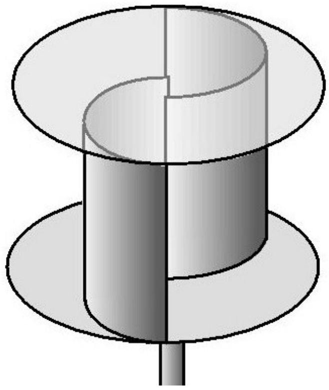

Figure 6. Savonius Turbine [11]

There are some bold designs for vertical axis water turbines such as the ones developed by Shivam Mishra [12]. In the proposed system the half of the wing which gives a negative torque in a vertical axis water turbine comes out of water and hence the negative torque is reduced, which results in better efficiency of the turbine. Figure 7 shows this turbine in a cad model.

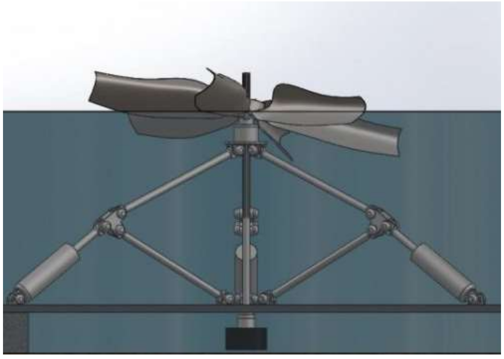

Figure 7. Small scale vertical axis water turbine. By: Shivam Mishra [12]

As it is in its initial state of study, an experimental model it is in the testing phase so no comparisons of the coefficient of power can be made yet. Still, this is a promising design for an in-stream water turbine.

Other authors tried to combine two types of turbines to try to maximize power output. Sahim et al. [13] combined a Savonius turbine with a straight blade Darrieus, including a deflector so the water is redirected towards the turbine. A schematic of this test is shown in Figure 8.

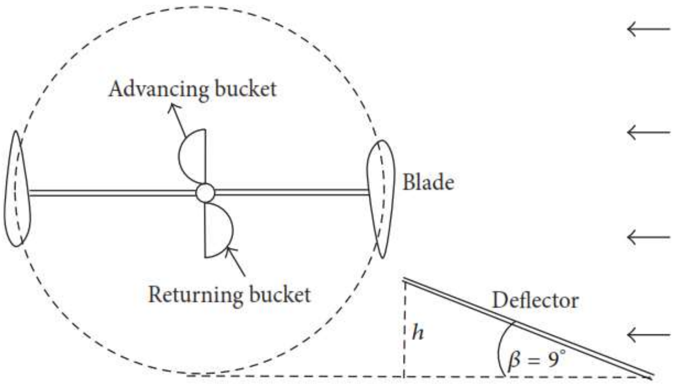

Figure 8. Darrieus-Savonius tuebine. By: Sahim et al. [13]

Although the idea of combining turbines is good, the results shown otherwise, with the efficiency of the system being around 16%, while when the test was made only for the Darrieus turbine, without the Savonius part of it, resulted in a 21% of efficiency, so clearly the combination resulted in loss of efficiency.

Vortex Induced Vibrations

Vortex Induced Vibration (VIV) arises from the interaction of a moving fluid with an elastic structure. Recently, researchers have focused on the application of VIV to produce clean and renewable energy [14–17]. VIV energy can be harnessed to produce hydropower energy in alternative to the more common turbine systems and other technology such as wave or tide used to generate hydropower energy [2].

The equation of motion for an elastically mounted cylinder of mass m can be defined as

$$m\ddot{y} + c\dot{y} + ky = F_y(t) \tag{2}$$

$$F_y(t) = F_{Viscous} + F_{Inviscid} \tag{3}$$

In these equations, y is the direction normal to the flow, $\dot{y}$ and $\ddot{y}$ are velocity and acceleration of cylinder, respectively, c is the viscous damping coefficient, k is the spring stiffness, F_y is the fluid force which is exerted on cylinder perpendicular to the flow direction. The viscous force, $F_{viscous}$, is related to the shear forces on the surface of the cylinder in the normal direction of flow and the inviscid force, $F_{inviscid}$, can be defined in terms of the inviscid added mass $m_a = \rho(\pi/4)D^2L$, defined as the impulse given to the fluid during an incremental change of body velocity, divided by that incremental velocity [15] .Therefore,

$$F_{Inviscid} = -m_a \cdot \ddot{y} \tag{4}$$

$$F_{viscous} = \frac{1}{2} \cdot C_L(t) \cdot \rho \cdot U^2 \cdot D \cdot L \tag{5}$$

where U is the free stream velocity, D is the cylinder diameter, C_L is the time dependent lift coefficient, L is the length of the cylinder and ρ is the density of fluid. Considering the added mass, Equation 2 can be written as

$$(m + m_a)\ddot{y} + c\dot{y} + ky = \frac{2}{\pi D} C_L(t) \cdot m_a \cdot U^2 \tag{6}$$

Assuming linear behavior and a sinusoidal response of the cylinder, the fluctuating transverse amplitude and force coefficient can then be obtained from

$$y = y_{max} \cdot \sin(2\pi \cdot f_s \cdot t) \tag{7}$$

$$C_L(t) = C_L \cdot \sin(2 \cdot \pi \cdot f_s \cdot t + \varphi) \tag{8}$$

where y_{max} and f_s represent the harmonic amplitude and frequency of vortices respectively, C_L is the lift coefficient amplitude, φ is the phase angle of the displacement with respect to the exciting fluid force, which for linear system at resonance is close to $\pi/2$ [14]. In terms of displacement and acting force on the downstream cylinder, for one cycle of oscillation the work done by the fluid force can be calculated as

$$W_{VIV} = \int_0^{T_{CYL}} F_y(t) \cdot \dot{y} \cdot dt \tag{9}$$

Here, T_{CYL} is one complete cycle of oscillation of the cylinder. The force F_y is represented by the right-hand side of equation 6 and thus integrating the right-hand side of equation 9 and averaging over the cycle period, the power due to VIV for a circular cylinder can be obtained as

$$P_{VIV} = \frac{W_{VIV}}{T_{CYL}} \tag{10}$$

$$P_{VIV} = \frac{1}{2} \cdot \rho \cdot U^2 \cdot C_L \cdot f_s \cdot y_{max} \cdot D \cdot L \cdot \sin(\varphi) \tag{11}$$

where y_{max} represents the harmonic amplitude of cylinder and L is the length of the cylinder. Therefore, the efficiency of VIV can be written as

$$\eta_{VIV} = \frac{P_{VIV}}{P_{fluid}} \tag{12}$$

Therefore, the power in the fluid can be calculated as

$$P_{fluid} = \frac{1}{2} \cdot \rho \cdot U^3 \cdot D \cdot L \quad (13)$$

The VIV efficiencies for a single cylinder, according to Bernitsas et al. [14] is somewhere between 20-30% for a well-designed system. But in recent studies, mainly the one performed by Derakhshandeh et al. [18], where he combined two cylinders with this VIV technology, arranged with some distance from each other, he discovered that the second cylinder had an efficiency well above 40%, stating that the first cylinder's vortex helped with the improvement of the second one's energy output, by improving its efficiency by a lot. This is a major breakdown in this technology, which if we remember it is a recent technology, with a lot more to discover, has a lot of potential of improvement.

CONCLUSION

With the need of investments in the clean energy it can be said that this is a reliable source of energy for rural areas. Either the turbines or the more recent system, the VIV system, can reach good values of efficiency, depending of what they are intended for and the available materials for construction. Turbines as they are, leave not much to research apart from the blade cross-sections, which can always have some improvement. But if we think of the VIV system, and how much more it can be researched, because it is a recent system, the values of efficiency can only go higher by placing not only one but various VIV systems, arraying them to work together improving its efficiency.

ACKNOWLEDGMENTS

The authors wish to thank for their financial support the Portuguese Foundation for Science and Technology (FCT) within the Grant ERANETMED/0004/2014, through the ERANETMED initiative of Member States, Associated Countries and Mediterranean Partner Countries (Project ID eranetmed_nexus-14-044) and within the UID/ECI/04082/2013.

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