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ON THE ECONOMICAL CONVENIENCE OF OPTIMIZED, PICO-HYDRAULIC RUN-THE-RIVER, POWER PARKS

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ABSTRACT

When at the end of the 19th century the Edison Company had its board of directors in Milan (Italy), a splendid marble panel showed a collection of fountains, each one representing a hydroelectric plant. If water came out from the orifice the power plant was working and gold was flowing into the bank account of the Edison Company. The electric power came from the "potential energy" of "dammed" water driving a "water turbine" and a "generator". In this traditional hydraulic power machines, an electromechanical control system, at an accurately tuned constant speed, feeds the electric power into the network. The very expensive and complicated system should deliver the energy within the tolerances set by the Edison Company. Now, with electronic, the control system is not more a problem, especially for powers up to 100 kW, where low-cost mass-produced integrated circuits deliver the energy within the prescribed tolerances. These devices cost less than 10 USD. For this reason it is easier to produce many micro or pico power "plants" than few but very expensive, dammed, high-power large plants. Many and well distributed micro/pico plants that can work without maintenance for several years (typically 20 years) using the energy wasted in rivers. This is possible due to mass production of micro/pico plants with extremely reduced installation costs. Electricity can be delivered as close as a km away to the location where it is being used with little overload to the distribution network. Hydro produces a more continuous supply of electrical energy in comparison to other small-scale renewable technologies (wind or sun). The power peak is during the wintertime when large quantities of electricity are required. Pico-hydro can function as a "run-of-river" or "free-flow" system, meaning that the water, passing through the generator, is directed back into the stream with relatively little impact on the surrounding ecology. The manufacturing of a micro hydro-power system can cost as little as € 1, 000, depending on the site electricity requirements and location. Maintenance fees are relatively small in comparison to other technologies. If your site produces a large amount of excess energy, some power companies will buy back your electricity overflow. You also have the ability to supplement your level of micro power with intake from the power grid. The environmental impact of small-scale hydro is minimal; however the low-level environmental effects must be taken into consideration before construction begins. Stream water will be diverted away from a portion of the stream, and proper caution must be exercised to ensure there will be no damaging impact on the local ecology or civil infrastructure. A large number of small, pico hydroelectric plants can recover the amount of energy wasted in rivers. A possible geometry of a run-the-river power park and the economic convenience of the solution is demonstrated in this paper.

Keywords: pico-hydro power parks.

INTRODUCTION

Privates and small-companies stand to reap significant benefits from the ability to capture constant grid-compatible power from continuously flowing water. Run-of-the river turbines present a viable and sensible alternative to current energy production based on fossil or nuclear fuel. Rivers flow continuously in one direction, so energy production can be ongoing, theoretically delivering a constant and plentiful supply of electricity. While there are several competing turbine technology options in development, most of them use wind-derived turbine designs that are not water friendly. This paper uses a specially designed waterwheel with a hatch control to harness renewable energy from free flowing rivers, providing a powerful source of constant, grid-compatible power. The water turbine technology proposed in this paper is strictly commercial, making it simple and economical for mass production, efficient to operate, and scalable. It has a waterwheel with fixed pitched blades. It uses commercial inverters to avoid the necessity of a constant speed generator. The turbine assembly is mounted on a floating platform and it is protected against floating river debris. The small dimensions of the system do not restrict river traffic and fish can swim freely, this reduces construction costs, saves time and resources, and eliminates land use. In flood or drought conditions, the waterwheel floats and continues to generate clean usable power since it does not necessitate rotating at a constant speed. A river farm equipped with a cluster of turbines can generate as much electricity as a wind farm, with reduced construction costs. There are many different types of plant, but all referable to the same physical principle which consists in the conversion of potential energy of a mass flow of water, which flows through a vertical drop, into mechanical energy and then into electrical energy. The classic hydroelectric plant just described is the most widely used for the production of electrical energy as it is the most economically advantageous and the most efficient for the production of energy. These types of plants can be used also for rivers. In this case, the flow should be deviated to a vertical propeller turbine. This type of plant is efficient but it is expensive and environmental unfriendly. In recent decades, however, there has been a considerable and growing interest to the production of electricity by exploiting the free flow of a watercourse with several small turbines. Engineers and

VOL. 10, NO. 7, JULY 2015 ISSN 1990-6145
ARPN Journal of Agricultural and Biological Science

Inventors have tried to use the conventional hydraulic turbines even in this situation without success. These, in fact, are not suitable in this context because they are too expensive for such a use and because the conventional turbines in the free flow should "capture" as much water as possible to be economical. Moreover, referring to the Bernoulli equation (1),

$$gz+\frac{p}{\rho}+\frac{v^2}{2}=const \tag{1}$$

traditional hydro-turbines are constructed to convert height into pressure, velocity and work. The situation is different regard to run the river turbines. In these cases, the component p/ρ is negligible and the kinetic term $v^2/2$ becomes the dominant factor.

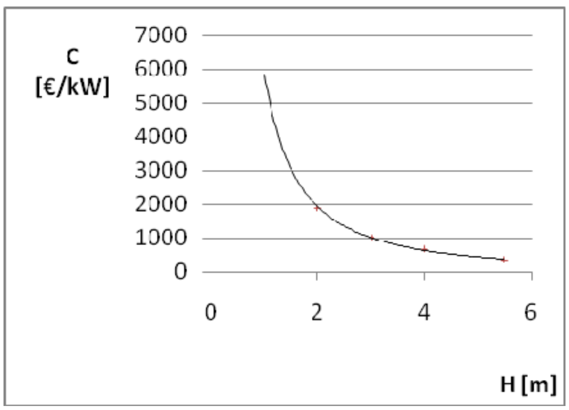

Figure-1. Unit cost of Kaplan turbine vs. hydraulic head.

The use of pico-hydro power plants, to provide a source of constant, grid-compatible power, was unthinkable until a few decades ago. In fact, there was no off-the-shelf technology for the conversion of the run-the-river variable speed energy into constant frequency alternate current. Now, this control system is not more a problem, especially for powers up to 100 kW, where low cost, massively produced integrated circuits deliver the energy well within the prescribed tolerances. These devices may cost less than 10 USD. For this reason, it is easier to produce many micro or pico-power “plants” than a few very expensive, dammed, high-power large plants. Mass produced micro/pico-plants can work without maintenance for several years (typically 20 years) using the energy of “run-of-river” or “free-flow” system. Then power can be delivered closer to the final user with little overload to the distribution network. Hydro produces a more continuous supply of electrical energy in comparison to other small-scale renewable technologies (wind or sun).Microhydro can function as a “run-of-river” or “free-flow” system, meaning that the water passing through the generator is directed back into the stream with relatively little impact on the surrounding eco-system. Building a micro hydro-power farm can cost as little as €1, 000, depending on site requirements and location. Maintenance fees are relatively small in comparison to other technologies.

Hydropower potential

The global hydropower potential is estimated at more than 16, 400 TWh per year. This potential is unevenly distributed. There are five countries with the highest potential account for about two-thirds of this potential. Figure-2 shows the hydropower production and potential for the world regions. Figure-3 depicts the same information for a few countries.

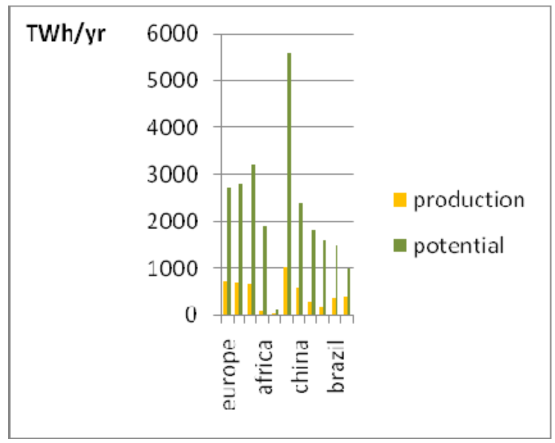

Figure-2. Actual and potential hydropower production (by world regions) [1].

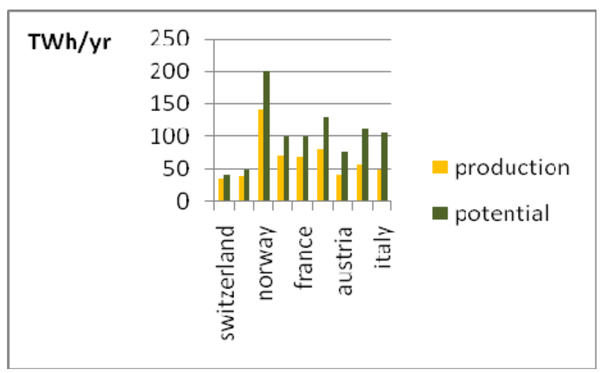

Figure-3. Actual and potential hydropower production (by countries) [1].

Globally, around 19% of the potential is currently used. Numerous countries have a huge amount of wasted hydropower potential. Although climate changes may vary of the potential for hydropower at a country level, these variations are expected to cancel out on the global scale, leaving the overall potential virtually unaffected. Actually, countries that have actively developed hydropower use a nimble 60% of their potential. Numerous other countries have a huge amount of wasted hydropower potential. It is then fundamental to maximize the production of energy throw the sun-water cycle.

VOL. 10, NO. 7, JULY 2015 ISSN 1990-6145
ARPN Journal of Agricultural and Biological Science

Current situation in Italy

In 2010 Italy was the world's 14th largest producer of hydroelectric energy, for about 20% of the national electricity production. Hydroelectric plants in the northern part of Italy contributed for almost 60% of the total energy production. In that year, Italy totaled about 3,000 hydroelectric plants, of which 302 had a greater capacity than 10 MW. Until the 1950s almost all the electric energy produced in the country came from this source. In fact, almost all the current capacity was installed in the first half of the twentieth century as it can be seen in Figure-4. Electric energy production in Italy remained almost the same since the 1950s. Hydroelectricity remained the main source at least until the sixties.

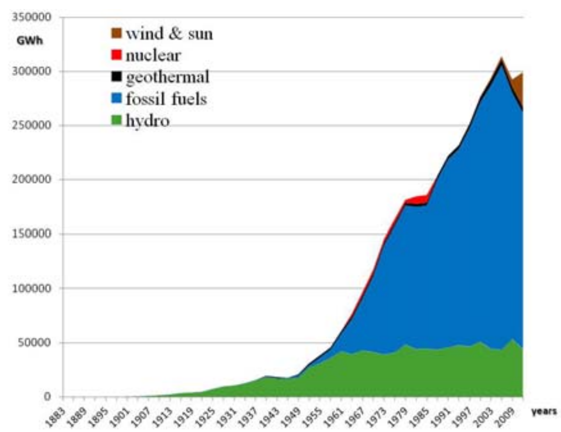

Figure-4. Electric energy production in Italy from 1883 to 2010: hydroelectricity (blue color) remained almost the same since the 1950s [2].

All the most favorable places for traditional hydroelectric plants have already been taken. Only pico-hydroelectric energy is still to be exploited. A major source may be run-the-river generators.

The starting point

This study starts from an average speed of a water of 1.5 m/s. Another requirement is ease of transportation with constraints on size and weight of the water turbine. By the way, small units are easier to mass produce than large ones. The specific energy available is then very low (1):

$$E = \frac{1}{2}v^2 = 1.125 \qquad \text{[J/kg]} \qquad (1)$$

With an active area of the turbine of A=1m^2 the available energy is then (2):

$$P = E\,\dot{m} = \frac{1}{2}\rho A v^3 = 1687 \qquad \text{[W]} \qquad (2)$$

The pico-hydroelectric run-the-river generator

A fully submersed pico-turbine would require a submersed generator with all the connected problems for manufacturing costs and maintenance. For this reason a floating turbine was chosen. The turbine that was finally chosen is similar to the one was used for the old mills, with the typical curved blade shape of Figure-5.

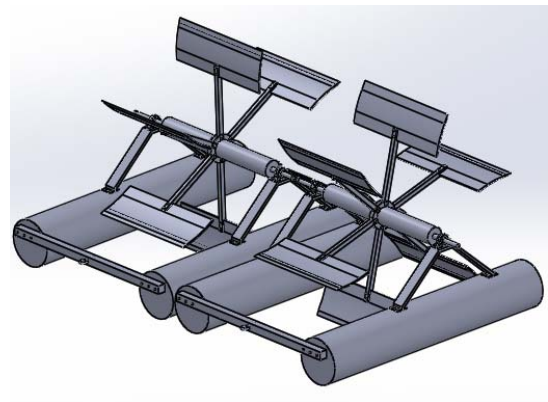

Figure-5. An array of two run-the-river turbines.

After various studies it was found that the best form of the blade is that of Figure-2, convex in the central part and straight in its ends. The wheel diameter is 2 m and the length of the floats is 2.4 m. The width of the single unit is 1.5 m. The camber in the central part allows collecting and converting a larger amount of energy compared to a plane geometry; the curved shape also reduces the hydraulic drag during the in-water movement of the blade. In the case of Figure-2, with a blade area of about 0.3 m^2 and an estimated efficiency of 20%, the mechanical power obtainable is around 100W at 11.4rpm: the CFD simulation confirms this estimation (see Figure-6). In this way it is possible to evaluate the output torque on the turbine shaft.

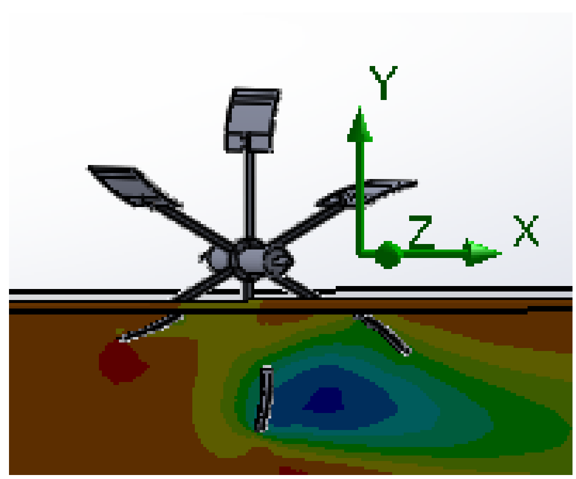

Figure-6. CFD evaluation of the turbine.

ARPN Journal of Agricultural and Biological Science

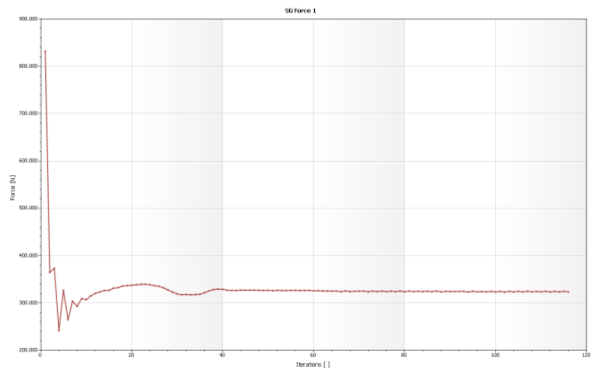

Figure-7. Output force from the turbine.

The generator

It is then preferable to use an array of turbines connected together to generate power. This is the reason why Figure-5 shows two turbines with the shafts connected by a flexible joint. The electric power obtainable from a turbine array of ten units is about 860W@11.4rpm.

For the conversion of mechanical energy into electrical energy, a car alternator seems to be the most cost-effective choice (Figure-6).

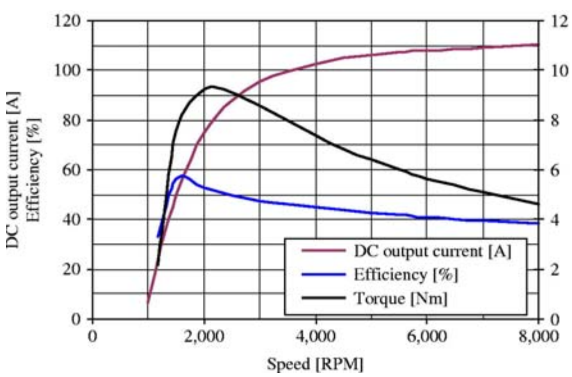

Figure-8. Automotive generator characteristic curves.

The chosen automotive generator has the following "nominal" features: 120A, 14 V, max power 1,680W. With this alternator it is possible to obtain the required output torque at a shaft speed of about 1,500rpm (maximum efficiency).

Since the working speed of this generator is higher than the one of the turbine it is necessary to design a speed multiplier.

The speed multiplier

A commercial automotive speed multiplier from starter motors can be directly assembled to the alternator. This unit has a transmission ratio of 10 (Figure-9). The required speed from the generator multiplier unit is then 1, 500 rpm.

Figure-9. Commercial automotive speed multiplier.

It was necessary to design a further speed multiplier to multiply the speed from the 11.4 rpm of the turbine up to the 1, 500 rpm required by the alternator.

A lantern type angular gearing taken from the old windmill technology obtains this second multiplication (see Figure-10).

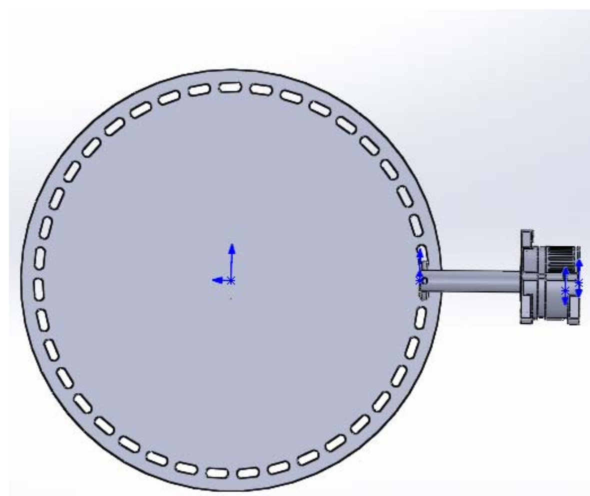

Figure-10. The "lantern" type angular gearing.

Finally, an inverter feeds the electric power into the power-grid.

Cost analysis

Table-1 summarizes the manufacturing costs for the 10 turbines array.

VOL. 10, NO. 7, JULY 2015 ISSN 1990-6145
ARPN Journal of Agricultural and Biological Science

Table-1. Manufacturing costs.

Item	Cost
Generator + inverter + gear multiplier	67 €
Bearings	30 €
Elastic joints (Rotex type)	27 €
M8 bolts	10.5 €
M16 bolts	3.5 €
Other components	247 €
Assembly	129 €
Total	514 €

The total cost is then 514 €. A reasonable selling price is about 2000€. The installation will cost about 500€, for a total of the installed item of about I_0=2500€. The energy from this run the river generator is 870W; since the cost of energy is about 0.14 €/kWh, the annual profit is CNF=1070€.

The theoretical pay back period TR is then (3)

$$TR = \frac{I_0}{CNF} \approx 2.5 \qquad \text{[years]} \tag{3}$$

If the interest rate is *i* and the variation in energy cost is *h*, the Net Present Value (NPT) is then (4)

$$NPT = CFN \sum \frac{(1+h)^j}{(1+i)^j} - Io = CFN\left[1-(\frac{1+h}{1+i})^n\right]\frac{1+h}{i-h} - Io \tag{4}$$

It is then possible to evaluate the actual pay back period TR_a by evaluating the value of *n* that makes $NPT = 0$ (5):

$$\left[1-\left(\frac{1+h}{1+i}\right)^n\right]\frac{1+h}{i-h} = \frac{Io}{CFN} = TR \tag{5}$$

then

$$TR_a = \frac{\ln\left(1 - TR\frac{i-h}{1+h}\right)}{\ln\left(\frac{1+h}{1+i}\right)} \tag{6}$$

Figure-11 shows the TR_a for different i and h percentage values.

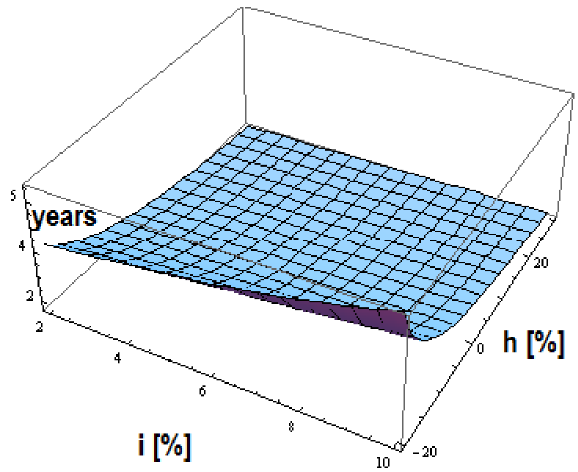

Figure-11. Actual Pay Back Period [years] for different interest rates *i* [%] and energy cost variation *h* [%].

Therefore, as shown in Figure-11, the investment is convenient, even including into the interest rate the cleaning of the power plant from debris and with falling oil (energy) prices.

CONCLUSIONS

With modern technologies for the mass production of pico-hydro-generators it is very convenient to recover the energy that comes from the rivers. In particular, off the shelf technology for "run the river" or "free-flow" systems completely eliminates the necessity of reservoirs. This is due to microelectronics that makes it possible to eliminate the constant speed system for the turbine. Very high quality electric energy can be inputted into the distribution grid even with highly fluctuating turbine speed. The minimum or null environmental impact of run-the-river pico-electric generation, the much reduced maintenance and the technical feasibility of pico-hydraulic generation makes this solution highly advisable.

Symbols

Symbol	Description	Unit
g	Gravity acceleration	m/s^2
z,H	Piezometric height	m
ρ	Water density	kg/m^3
v	Water velocity	m/s
C	Cost per kW	€
E	Specific energy	J/kg
m'	Mass flow	kg/s
A	Active turbine area	m^2
P	Power	W
TR	Theoretical pay back period	years
I0	Total installed cost	€
CNF	Annual profit	€

NPT	Net Present Value	€
i	Interest rate	-
h	Variation in energy cost	-
TR_a	Actual pay back period	years
n	Number of years for TR_a	-

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