Energy Supply
Run-of-the-river Hydroelectricity

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ABSTRACT

In this study, we evaluated the potential of a run-of-the-river hydro power plant located on an isolated island with an area of 500 km^2. For this, a computer program was created to process the rainfall data and calculate the river flow and the annual energy production for each one of the four options for installed power considered (0.5, 1.0, 1.5, and 2.0 MW). Considering a project lifetime of 40 years, the study concluded that the more advantageous investment is the 1.5 MW powerplant, using a Francis turbine. For these conditions, the total investment cost is about 4 605 034 €, the annual production expectation is 6 927 MWh and LCOE is 0.049 €/kWh.

I. INTRODUCTION

Despite being clean and renewable, hydro energy is highly criticised due to its extensive environmental impacts. Its mechanisms consist of using the potential gravitational energy of a water fall. The water's kinetic energy inflicts movement on the turbine blades. Then, this mechanical energy is converted into electrical energy by a generator. The amount of energy generated by hydro power plants depends on the height of the fall (also known as the head), river flow, and turbine type.

In this study, we evaluated the potential of a run-of-the-river (which has smaller environmental impacts than a dam, and is more appropriate at the scale of a relatively small island) hydro power plant located on an isolated island with an area of 500 km^2. All calculations were made based on rainfall data and considering a project lifetime of 40 years.

II. MODEL USED, AND ASSUMPTIONS

Firstly, we assumed the existence of three water "reservoirs", each with a different quantity of water:

- M, denoting the amount of water in the river itself;
- N_1, water flowing on the surface;
- N_2, underground water, infiltrated in the soil.

We had to assume initial values for these reservoirs, which introduces uncertainty. To minimise this, we ran the simulation for two consecutive years, tweaking initial values until the two showed similar profiles. We then used data from the second year only.

We assumed rainwater, after falling, flows into the river (from each of the reservoirs N_1 and N_2) in a fashion similar to radioactive decay, as such:

$$\frac{dN}{dt} = -\lambda N \tag{1}$$

We considered two kinds of rainfall: direct, which does not infiltrate in the soil, and has a time constant of one day; and indirect, which infiltrates in the soil, and whose time constant is three months. This means that half of direct rainfall on a given day will have flowed into N_1 one day later, and half of indirect rainfall will have flowed into N_2 three months later.

We know from the radioactive decay model that this time constant is given by:

$$T_{1/2} = \frac{ln2}{\lambda} \tag{2}$$

This will allow us to determine λ for each of the N_1 and N_2 reservoirs.

We then defined the time derivative of M as:

$$\frac{dM}{dt} = -\frac{dN_1}{dt} - \frac{dN_2}{dt} - Q - C = \lambda_1 N_1 + \lambda_2 N_2 - Q - C \tag{3}$$

In which Q is the discharge rate of the river (representing the water which flows into the sea and thus leaves the reservoir), and C is water for human consumption which was considered but does not represent a significant fraction. Regardless, C was calculated by gathering data on water consumption in Portugal[1], and extrapolating to our island, adjusting for population size.

We also chose to assume that the discharge rate is directly proportional to the total amount of water in the river:

$$Q = kM \tag{4}$$

In which k is a constant, which we defined as 5% — the fraction of total river water which flows into the sea in 1h. This would certainly be too much for a large river, but perhaps not for a small island.

From our discharge rate Q, we assume that a fraction cannot be used - the "ecological discharge rate", f_{eco}. We set this value at 20%. Thus, power available to the turbine is given by:

$$P = (1 - f_{eco})\rho_w g Q h \tag{5}$$

With ρ_w being water density [kg/m^3], g gravitational acceleration [m s^{-2}], and h the head [m], which is 50m for this specific site.

All this considered, we obtain the flow duration curve shown in Figure 1, and the graph in Figure 2, representing available power throughout the year.

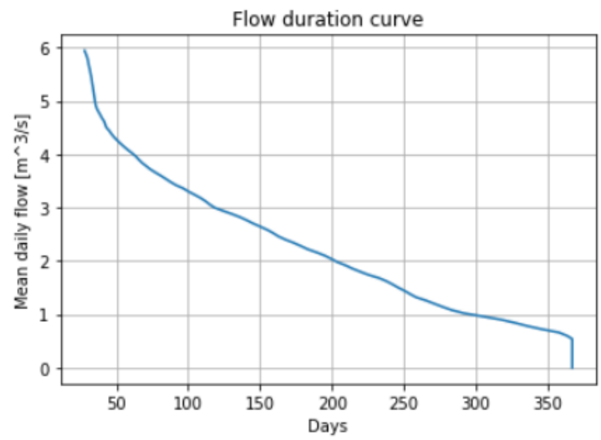

Figure 1

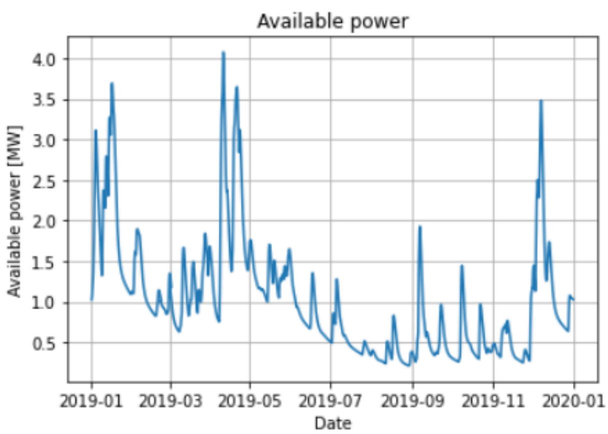

Figure 2

III. POSSIBILITIES FOR INSTALLED POWER

Considering the data shown above, we studied four possibilities for installed power: 0.5 MW, 1 MW, 1.5 MW and 2.0 MW. We considered a conversion efficiency of $\eta = 88\%$, and that the power generated at any given hour equals:

$$E_{generated,hourly} = \min(P_{installed}, P_{available}) \times \eta \times 1 \text{ h} \tag{6}$$

Annual energy generation is the sum of generated hourly energy throughout the year. Results are shown on table I.

Installed power (MW)	0.5	1.0	1.5	2.0
Annual production (MWh)	3 557	5 775	6 927	7 424

Table I

IV. COST OF THE HYDROELECTRIC POWERPLANT

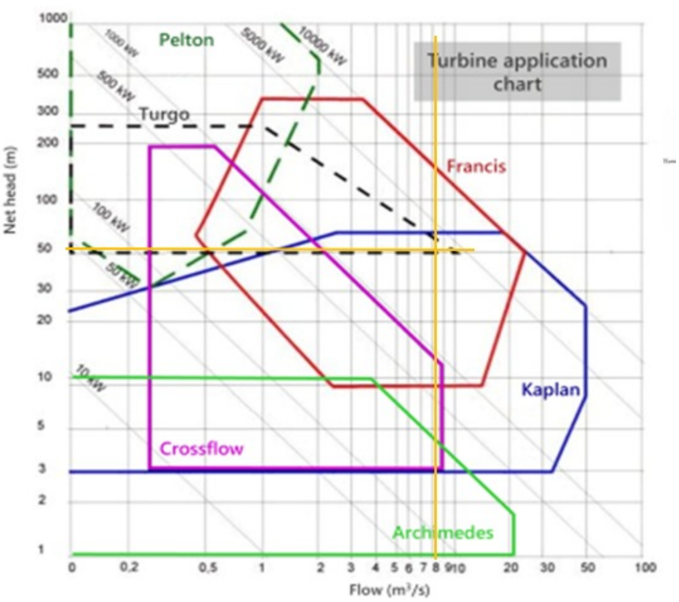

Figure 3

In Figure 3, yellow lines have been drawn to help visualise the intersection between our values for the flow and net head, and thus conclude that it is within the domain of a Francis-type turbine, corresponding to a factor $K_p = 4\ 500\ 000$. To calculate the costs associated with the hydroelectric power plant, it was necessary to use the following expression:

$$c_t = K_p \times P^{0.7} \times H_{power}^{-0.35} (€) \tag{7}$$

Where:

- c_t = total cost (€)
- K_p = factor equal to 5 000 000 or to 4 500 000 for Pelton and Francis turbines, respectively
- P = installed capacity (MW)
- H_{power} = net head (m)

Civil construction costs are 25% of this value while equipment costs are 75% of the total cost.
For the costs of the weir, channel and conduit, approximate values of an example with similar characteristics were used. For the weir, there was a cost for civil construction and a cost for equipment which is 15% of the cost of civil construction. For the canal, a cost of civil construction was obtained. Grid connection costs were calculated assuming a distance of 500 m from the plant to the grid and using the values of 70 €/ m plus the cost of the substation, which costs 40 000 €.
Finally, calculations were made for the cost of creating access to the hydroelectric facilities, for studies and another for supervising the site during its construction. These costs are respectively 20%, 3% and 5% of civil construction costs.
All the costs mentioned above were calculated for different powers, as can be seen in Table IV in the annexes.

V. NPV

In order to find the LCOE, we must calculate NPV for each year, and adjust the price of electricity until payback is guaranteed after 40 years of operation.

$$NPV = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+d)^t} \tag{8}$$

Where:

- B_t = Benefits in year t
- C_t = Costs in year t
- d = discount rate

On year 0, we have no benefits (B_t), and our costs (C_t) are the investment costs. For every other year, C_t consists of Maintenance Costs and B_t is the Annual Revenue in Electricity. The latter depends on the price of electricity, and this is the value we will adjust until we get a 0 or a positive NPV. The discount rate is 5%. Table II shows the obtained values.

Power (MW)	0.5	1.0	1.5	2.0
Maintenance Costs (€)	49 422.19	59 630.27	68 528.14	76 682.70
Annual Revenue (€)	266 775	306 075	339 423	371 200
Total Investment Costs (€)	3 716 615	4 195 872	4 605 034	4 974 427

Table II

The electricity prices were adjusted for each case so that for installed powers of 0.5 and 1 MW, payback happens on the last year - year 40. This means the payback time is exactly 40 years. In the case of an installed power of 1.5 and 2.0 MW, payback happens on the 38th year.

Table III shows the LCOE for each case, as well as other values (which were calculated knowing that the island has 500 km^2 and 50 000 inhabitants.

Power (MW)	0.5	1.0	1.5	2.0
Annual Production (MWh)	3 557	5 775	6 927	7 424
LCOE (€/MWh)	75	53	49	50
kWh/year/person	71.14	115.5	138.54	148.48
kWh/year/m^2	0.0071	0.0116	0.0139	0.0148

Table III

As we can see, it is more advantageous to invest in the 1.5 MW power plant, because we have more energy production capability at a lower monetary value. However, it is also noteworthy to see that the difference in LCOE between the 1.5 and 2.0 MW cases is extremely small, which means that if we need a larger installed power on the island, the 2.0 MW option is also quite a good choice. At larger installed powers, however, the capacity factor would begin to decrease much more, which means that the rise in energy production would not make up for the rising costs, rendering the project more costly.

VI. TYPICAL WEEKS

We chose three "typical" weeks to represent an average summer, winter and midseason week. Weeks chosen were:

- Winter: January 28th - February 3rd
- Midseason: May 8th - May 14th
- Summer: July 12th - July 18th

And respective weekly energy productions are shown in figure 4. An installed power of 1.5 MW was considered for this, as it was shown previously to be the most profitable of the three options studied.

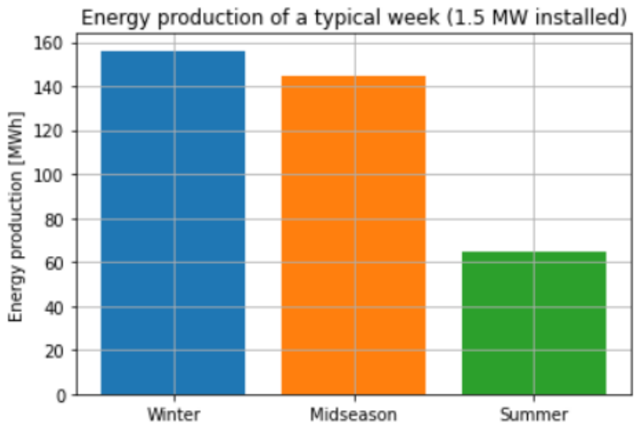

Figure 4

VII. IMPACTS

The construction stage of run-of-the-river hydro power plants is marked by heavy environmental impacts, which are caused mainly by the construction of roads for the transportation of building materials and workers, construction of a temporary dike to interrupt the river flow, rubble deposit from works and noise resulting from heavy machinery operation. These factors, in addition to destroying habitats, lead to water and soil contamination and GHG emissions, such as CO_2 and methane.

From the economic point of view, the construction of a hydro power plant promotes a significant increase in the number of jobs in the region.

The exploration stage of run-of-the-river hydro power plants brings additional ecological issues. The hydrological disturbances, such as the change in natural flow rate and the deviation of the river course, may disorient the fauna, hindering the dispersal and recolonisation of the animals after extreme events and increasing the probability of long-term biological extinctions. Moreover, the reduction of the flow rate can interrupt the migratory routes of fish species with subsequent impact on the spawning of these animals.

In terms of social impacts, the exploration of a run-of-the-river plant comes with the obvious benefit of diversifying power supply (particularly if there are no other hydro plants in the region) and increasing the installed capacity of the power grid, despite being sometimes highly variable and thus not offering guarantee of power.

VIII. CONCLUSION

Out of the three options that were studied, the optimal one is clearly an installed power of 1.5 MW, as it is the one which provides the lowest LCOE for a situation of payback in 40 years. For this situation, the lowest values of harnessed power throughout the year happen at the end of summer and during autumn, as a result of low precipitation during summer (this makes sense considering the large time constant of three months for indirect rainfall), and correspond to about 0.2 MW. One may conclude, then, that only this value is guaranteed from our run-of-the-river plant — even less in the case of an unusually dry year, as hydro in general and run-of-the-river plants in particular are extremely susceptible to variations in precipitation. Therefore this power plant, if built, will not be helpful in maintaining security of supply of electricity throughout the year — this estimated minimum power corresponds to only about 13% of installed power and is, once more, not actually a hard minimum limit for supplied power. The plant is profitable, and provides a decent amount of electrical energy throughout the year, but must always be complemented with other options — energy supply must be as diverse as possible to ensure security of supply.

IX. ANNEXES

Power (MW)	0.5	1.0	1.5	2.0
Construction of the power plant (30%) (M€)	0.179	0.291	0.387	0.473
Power plant Equipment (70%) (M€)	0.538	0.874	1.161	1.420
Civil construction of the weir (M€)	0.500	0.500	0.500	0.500
Weir Equipment (15% da cc) (M€)	0.075	0.075	0.075	0.075
Canal construction (M€)	0.945	0.945	0.945	0.945
Civil construction pipeline (M€)	0.015	0.015	0.015	0.015
Conduct equipment (M€)	0.930	0.930	0.930	0.930
Grid connection (70€/m)+40000 (500m) (M€)	0.075	0.075	0.075	0.075
Hits (20% cc) (M€)	0.328	0.350	0.369	0.387
Study and design (3% da cc) (M€)	0.049	0.053	0.055	0.058
Site supervision (5% da cc) (M€)	0.082	0.088	0.092	0.097
Total investment (M€)	3.717	4.196	4.605	4.974

Table IV

[1] PORDATA, “Abastecimento público de água: total e para o sector doméstico,” .