ENERGY MIX IN THE PRODUCTION OF HYDROGEN

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Abstract. *This paper presents a study related to the production of electricity through a mini-hydro plant (MHP) and a photovoltaic (PV) system particularly sized for a location in Tomar (Portugal). A system based on this energy mix is adopted in order to produce hydrogen (H_2) and oxygen (O_2) at high pressure for energy storage purposes. The main features of the different equipments chosen in this study are also presented in the paper.*

1. Introduction

Generally mini-hydro plants (MHP) are built near the place of energy end use, which may cause an overproduction problem that can be solved using energy storage systems. The storage of electrical energy obtained from MHP can be achieved through the production of hydrogen using electrolysis. This hydrogen stored can be subsequently used either in the chemical industry or in the production of electricity using a fuel cell.

Hydrogen is not a primary energy source but has the characteristic (advantage) of being stored over time, thus overcoming the power supply fluctuations associated with the intermittency of primary renewable energies. Hydrogen is the simplest substance that can be found in abundance in our planet, and is non-polluting.

Hydrogen is one of the elements that contain a great amount of energy. It contains more energy per unit mass than any other known fuel, 119.93kJ per gram [1]. More specifically, the amount of energy released during the reaction of the hydrogen is about two and a half times the power of combustion of a hydrocarbon (gasoline, diesel, methane, propane, and others) [2, 3, 4, 5]. Thus, to meet power consumption, the required mass of hydrogen is only approximately a third of the mass of a hydrocarbon (Table 1). When cooled to a temperature of -253°C, i.e. to 20°C above absolute zero, it will be in the liquid state, which due to its low molecular weight occupies a space that is equivalent to 1/700 of the space that it would occupy in its gaseous state.

Table 1. Calorific value of different fuels [1].

Fuel	***Higher calorific values*** (at 25°C and 1 atm) (kJ/g)	***Lower calorific value*** (at 25°C and 1 atm) (kJ/g)
Hydrogen	141.86	119.93
Methane	55.53	50.02
Propane	50.36	45.6
Gasoline	47.5	44.5
Diesel	44.8	42.5
Methanol	19.96	18.05

Hydrogen has a great energy potential that can be exploited as an alternative energy vector, complementing the primary renewable energy sources that are currently used. When burned with pure oxygen, the resulting products are heat and water.

The electrolysis is a process that separates the elements of a chemical compound by applying an electric current. The process of electrolysis is an oxidation-reduction reaction opposite to the one that occurs in a cell, thus this is a physical-chemical phenomenon that is not spontaneous.

Commercial production of hydrogen through this process has efficiency between 70 and 75% [6], this can be improved by adding salts to the electrolyte to increase the conductivity, as well as by the use of steam electrolysis, by replacing partially the electricity by heat energy. Since the amount of energy required for hydrogen production is high (4.5 to 5 $\text{kWh}/m^3\, H_2$), its cost is also high, and electricity accounts for two thirds thereof. Therefore the production of hydrogen by this method is not economically favorable except if the electricity is obtained from renewable sources, such as mini-hydro plants (MHP) and/or photovoltaic (PV) as presented in this paper.

2. Proposed Approach

One of the functions of the MHP in the proposed approach is to feed the hydrogen storage unit.

2.1. Hydrogen Storage

Nowadays, the most common hydrogen storage systems are the high pressure systems, with hydrogen in the gaseous state. Most of these systems use cylinders (or "bottles") (similar to those used for natural gas) to store hydrogen in the gaseous state. The normal storage pressure is usually between 150 and 400 bar, but higher pressures are also possible. The electrical energy used on hydrogen compression at 350 bar, corresponds to 5% of the total energy of the stored hydrogen, this value varies with the current capacity and efficiency of the compressors used [6].

2.1.1. Selection of the hydrogen generator

When choosing a H_2 generator, it is necessary to take into account several factors such as its efficiency, its production capacity, technology and the initial investment for the purchase.

The main advantage of the Proton Exchange Membrane (PEM) generator is having a H_2 "*cleaner*" production. In fact the PEM generator does not require to, regularly, replace the solution with the electrolyte as it happens in the classic generators. However, the membrane needs replacement but with less periodicity and lighter ecological impact. Nevertheless, the acquisition cost of a PEM generator can be three to four times as much as a classic generator. These factors were decisive for the generator choice in this project [7, 8].

Thus, the chosen generator is the G16d model *ErreDue* which produces H_2 and O_2, and as auxiliary to the system are chosen two boosters: a "*Baurer*" for H_2 and a RIX for O_2, with a power of 11kW and 5.5kW, respectively.

Therefore, the hydrogen storage unit uses the G16d generator that produces its maximum power at a flow of 10.66 Nm^3/h of H_2 and 5.33 Nm^3/h of O_2, both at a 4 bar pressure. Therefore, a booster (compressor) is necessary to raise the pressure to 200 bar and fill the 50 liters cylinders. Due to physical and chemical differences between these two gases, a specific booster is required for each. Due to the different capacity of the compression of H_2 and O_2, i.e. due to the different physical characteristics of the gases, at a pressure of 200 bar a cylinder of 50 liters contains 8.9 Nm^3 of H_2 and 10.6 Nm^3 of O_2 [6]. It should be noted that the O_2 produced also has a great commercial potential, since the cylinders of 50 liters of this gas have market in both the chemical industry and in the health sector.

The G16d generator uses the traditional technology with an electrolyte solution between the two positive and negative electrodes, with a consumption of 59.5kWh and 9 liters of water per hour for the maximum production capacity. This generator has a water purifier included, allowing to get H_2 with purity of 99.995 % and O_2 with 99.5 % [9].

2.2. Characteristics of the MHP

The MHP is placed in the *Nabão* river, near the city of Tomar (Portugal). After studying the annual's daily average flow of the river at the site of implantation of MHP, the curve shown in Fig. 1, was obtained.

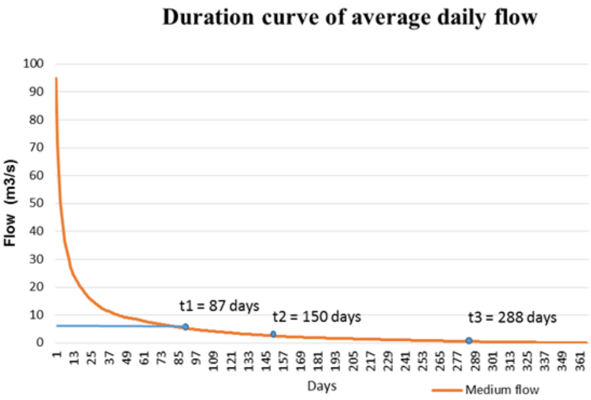
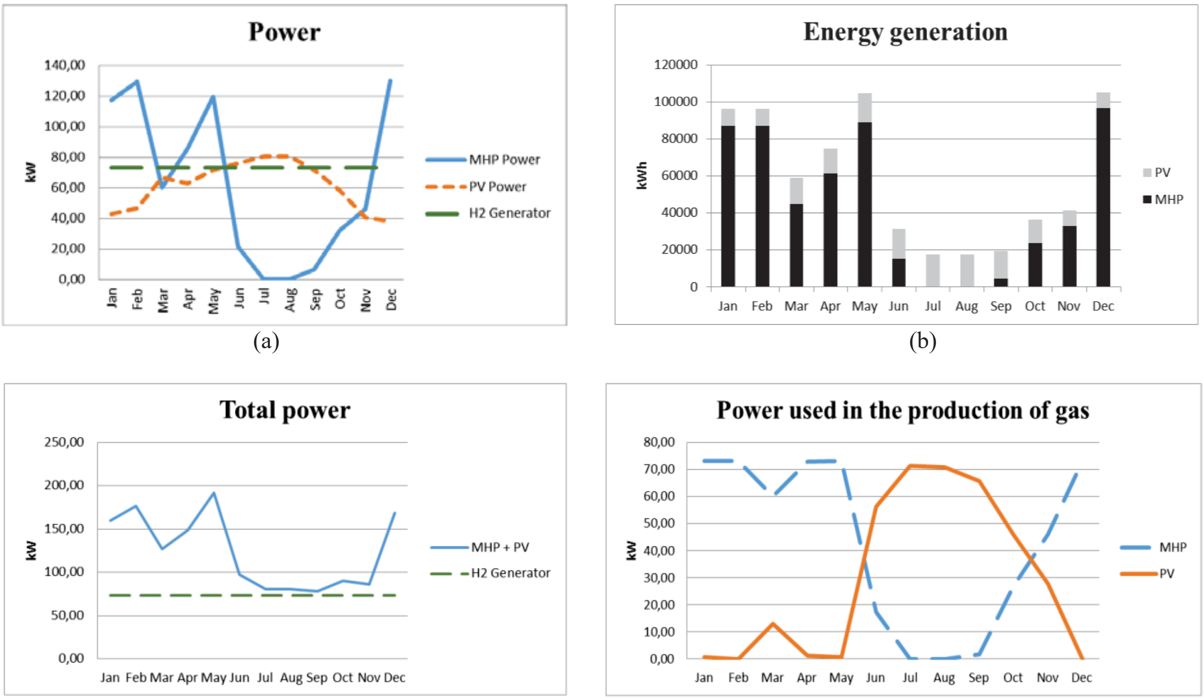


Fig. 1. Duration curve of average daily flow

The nominal flow (Q_n) corresponds to the average flow rate of 5.4 m^3/s, this flow has been used for choosing the generator. As can be seen in Fig. 1 (the straight line to t1), the rated flow is present on 87 days a year (t1) which corresponds to 24 % of the year, therefore the flow rate is greater than or equal to the rated flow of 5.4 m^3/s. The head of fall (H_b) considered is 3.6m. Equation 1 gives the electrical power supplied by MHP [10, 11].

$$P = \gamma \times Q \times \left[H_b - \left(h_{hidr} + h_{flood}\right)\right] \times \eta_t \times \eta_g \times \eta_{trans} \times (1 - p_{elec}) \; [W] \tag{1}$$



(a) (b)

(c) (d)

Fig. 2. Power and Energy generation curves. (a) Power of MHP and PV; (b) Energy of MHP and PV; (c) Total Power output, and (d) Power used in the production of gas.

Where $\gamma = 9810\ \mathrm{N}/m^3$ is the unit weight of water; Q (m^3/s) is the turbine water flow rate; $h_{hidr}(m)$ and $h_{flood}(m)$ are the height losses, losses in the hydraulic circuit and losses due to floods that lower H_b, respectively; $\eta_t(\%)$, $\eta_G(\%)$ and η_{trans} are the efficiency of the turbine, the generator and the transformer, respectively; and $p_{elec}(\%)$ represents the various electrical losses.

The study considers the turbines and generators efficiencies, the calculation of the pressure drop in the penstock to the turbine and losses during floods. These parameters were taken into account in determining the turbines power, and computing the electrical power produced along the standard hydrological year, shown in Fig. 1. A spreadsheet was used to perform these calculations. The power calculated from the detailed model has a value of 150 kW.

The most appropriate group of turbines to be installed in the mini-hydro plant is the group composed of two turbines *Hydrohrom Kaplan* turbine model HH780SSK with a $Q_{max} = 2\ x\ 2.5\ m^3s^{-1}$. The turbines are *Kaplan S-Shape* with simple regulation and are equipped with adjustable propellers, and the nominal power of each turbine is 70 kW. The nominal power of each generator is 65 kW, in a total of 130 kW for the group of generators [12].

The option of two groups instead of one is economically more advantageous than installing only one group, because the two turbines, having half the Q_n can operate longer and thus producing more electricity, offsetting the increased investment. The estimated annual energy production is around 542 MWh.

2.3. Integrating a PV System

In order to maximize the use of renewable energy available on site, a photovoltaic generator (PV) was included in this study, to operate in parallel with the MHP generator. As can be seen in Fig. 2(a), the time of year (summer months) when the water production is minimal is when the PV production is at its best (in July reaches its maximum). So, it is possible to maintain the production of H_2 and O_2 close to the rated power (about 73kW) of the *boosters* and the generator in the months of June to October and thus increase the system productivity and subsequently improve the project profitability [13, 14, 15].

By the analysis of Fig. 2(c) it can be seen that it is possible to maintain the H_2 generator operating at rated power even in the summer months. However, it should be noted, that in the summer months when the available power supply is only the PV source, H_2 and O_2 can only be produced during the daytime, taking advantage of about 7 solar peak hours (SPH). This short period of operation is a disadvantage regarding the MHP that works day and night harnessing the available river flow.

Analyzing Fig. 3, that represents the amount of surplus energy in the production of gases that is injected into the grid, it can be verified that 183MWh was produced by the MHP and 86MWh by the PV source. In the winter and spring months, due to excess production of MHP, a large part of PV production is injected into the grid. In the summer months the amount of energy injected is reduced, and in this period the gas generator consumes most of the power available from the PV (see Fig. 2(d)).

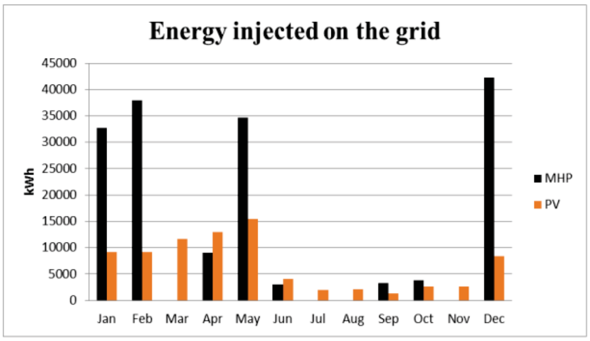


Fig. 3. Energy injected on the grid

The PV generator designed for this purpose has a peak power of 100kWp consisting of 400 modules REC 250PE of 250Wp placed in a fixed structure on the ground with 30° slope and an azimuth of 180°, south. The nominal power of the 6 inverters *Fronius Symo* 15.0-3-M of 15kW is 90kW. On average, this generator produces around 158MWh/year, i.e. about 29.2 % of the energy that the turbine group HH780SSK produces, contributing in the overall MHP+PV system with 22.5% of the energy produced.

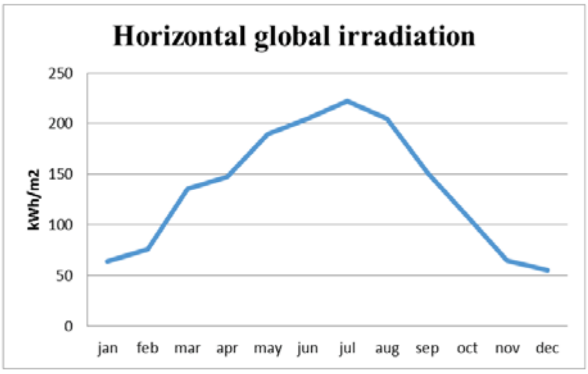


Fig. 4. Horizontal global irradiation on site

On site implementation of this project has a Horizontal Global Irradiation of 1623 kWh/m^2, whose irradiation curve is shown in Fig. 4. Thus, the site conditions allow the PV generator to supply the energy needed to maintain the gas production rate during the summer.

3. Economic Profitability of the Project

The production of H_2 with the implementation of PV increases from 50554 to 62568 Nm^3/year, and the production of O_2 increases from 25277 to 31277 N$m^3/year$ (Fig. 5 and Fig. 6). This represents an increase of 23.76 % in the production of these gases.

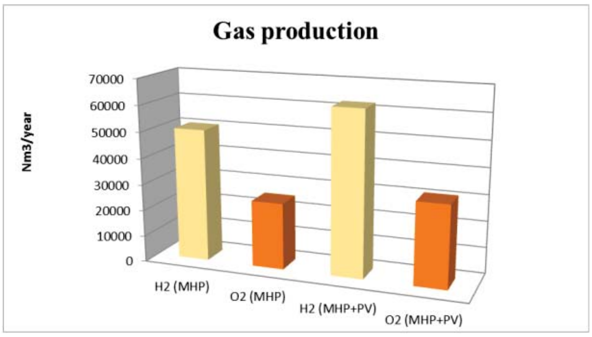


Fig. 5. Annual gas production

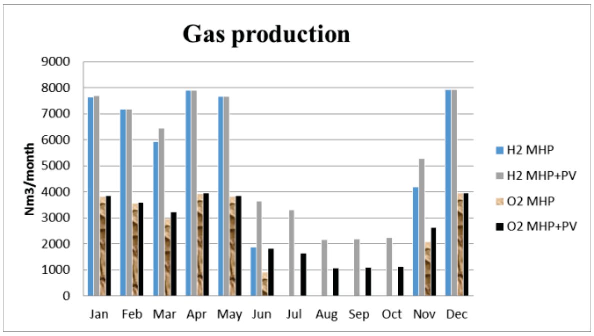


Fig. 6. Month gas production

The economic profitability of the project is improved with the introduction of PV, as presented below.

Case 1. In the initial design of gas production using only the MHP, the initial investment is €988150, including the acquisition of the gas generator (€116000), boosters (€166300), turbine (€319000), cylinders/tanks (€116850) and their installation (€270000). In this case the annual income is €230252 from the gases sale and €16772 from selling electrical energy surplus to the grid (Table 2).

Table 2. Annual income of the project (*in Euros*).

	Incomes					
	Case 1		**Case 2**			
	H2	**O2**	**H2**	**O2**	**Energy injected**	
	MHP	***MHP***	***MHP+PV***	***MHP+PV***	***MHP***	***PV***
Jan	13,608.22	20,841.19	13,298.81	20,271.40	3,174.00	471.95
Feb	12,993.57	19,520.59	12,970.28	18,842.95	3,518.52	389.61
Mar	11,115.83	16,867.97	11,435.57	17,830.62	0.00	504.73
Apr	13,977.20	21,511.51	13,637.35	20,211.11	801.49	342.73
May	13,648.80	20,914.92	12,948.48	20,260.30	3,171.51	656.55
Jun	4,932.71	5,080.69	7,675.83	10,065.87	1,385.49	239.63
Jul	0.00	0.00	6,746.45	9,171.61	0.00	95.80
Aug	0.00	0.00	5,016.16	5,976.95	0.00	105.85
Sep	0.00	0.00	5,050.32	6,039.19	401.82	136.06
Oct	0.00	0.00	5,137.90	6,200.92	419.84	257.78
Nov	8,518.11	11,432.48	9,707.45	14,639.35	0.00	171.42
Dec	13,676.56	21,612.08	13,676.56	20,968.98	3,899.90	396.74
	€92,471.00	€137,781.45	€117,302.00	€170,479.27	**€16,772.57**	**€3,768.18**
Total:	**€230,252.45**		**€287,781.27**			

Case 2. In the case of MHP plus PV the initial investment is increased by €110000 (PV investment), corresponding to a total investment of €1098150. In this case the yield in the first year is €287781 from the gases sale plus €20540 from selling electrical energy (MHP+PV) to the grid (Table 2).

In the study of the economic viability of this project, presented in Table 3, it turns out that the return on capital invested is faster with the introduction of the photovoltaic system. In *Case 1* (MHP) the payback is achieved in 5 years and 9 months, the Return On Investment (ROI) corresponds to 2.51 and the Internal Rate of Return (IRR) is 16.98%. For *Case 2* (MHP+PV) the payback is 4 years and 5 months, the ROI corresponds to 2.93 and the IRR is 19.33%.

Table 3. Economic viability of the project.

	Case 1 (MHP)	**Case 2 (MHP+PV)**
Initial investment	€988,150.00	€1,098,150.00
Payback	5 years 9 months	4 years 5 months
Cash flow (25 years)	€2,477,217.00	€3,215,733.00
ROI	2.51	2.93
IRR	16.89%	19,33%

4. Conclusions

The power to be installed at the MHP is 130kW and at the PV system is 90kW, which means that the producible electrical energy corresponds to 700 MWh/year. The MHP contributes with 77.5% of global production and the PV system with 22.5%.

From July to September (around 77 days) there is a very low or no flow water in the *Nabão* river, so it is not profitable to keep the turbines operating. To generate electricity in this less favorable period, a combination of a MHP with a PV system can be used.

With this energy *mix* MHP+PV, it is estimated a production and storage of H_2 around 62568 Nm^3/year and 31277 Nm^3/year of O_2, that represents an increase of 23.76%.

This increased gas production allows the return on investment to be reduced to 4 years and 5 months, therefore it is profitable to use two renewable sources that complement production and storage of energy in the form of H_2. This H_2 can be used in numerous applications, either to produce electrical power through fuel cells in electric vehicles, or in the industry in general. The use of these sources allows the electrical energy obtained to be truly "*green*".

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