

PV generation of Hydrogen for operational rawinsonde usage: design and economic analysis

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Abstract. Operational meteorological rawinsonde balloons are usually filled by using Helium gas, provided by an external company. Alternatively, renewable energies may be used to generate Hydrogen for operational meteorological balloons usage. In this work, a Hydrogen plant to produce gas by electrolysis, with electricity generated by PV cells, is proposed and designed, to be used in an operational rawinsonde.

Taking into account both technical and legal conditions for solar energy exploitation in Spain, two technical configurations were considered and designed: (a) autonomous system, that is, electric power produced by the PV cells is used to feed the whole process of Hydrogen production; and, (b) connected system, that is, electric power produced by the PV cells is supplied to the Spanish Electric Network (REE) and, at the same time, Hydrogen is produced by electrolysis using energy provided by REE. Option (b) can be considered because of the economic benefits set by the Spanish Real Decreto 436/2004, as the energy is provided by REE at a lower price than the energy supplied by the PV cells.

In order to compare both options and the feasibility of the project, an economic analysis is also presented, including: investment evaluation, incomes and expenses analysis. Different sold and consumed power supply prices are considered as well as financial costs, and Helium gas savings. In addition, a feasibility study based on the general criteria of operation and installation, such as payback period, net actual value (NAV) and internal rate of return (ROI) is also presented.

1. Introduction

The development of technologies to enhance renewable energies is a priority target to sustainability. Reasons are different, mainly dealing with the solution of global

problems, such as energy supply and carbon dioxide reduction [1]. According to this, the current trend is to make renewable energies more and more competitive with respect to the traditional ones.

Between renewable energies, solar resource is one of the most attractive since it can be used in either direct or indirect way, providing a wide range of energy generation, including Hydrogen [2]. Photovoltaic Hydrogen represents a renewable source of fuel and electricity; nowadays, production plants are operational all over the world. Moreover, there are installations to generate Hydrogen built in private houses that supply the energy required by the owners [3]. Some installations are also used to practical purposes, such as the filling of meteorological balloons [4].

One of the tasks carried on by MeteoGalicia, the Galician Weather Service (www.meteogalicia.es), is an operational rawinsonde that, twice a day, provides aloft observations of atmospheric parameters. Currently, balloons are filled with Helium provided by a company.

In this work, a plant to produce Hydrogen by water electrolysis, starting from electricity generated by PV panels, is designed. This plant would be placed in the School of Engineering at Santiago de Compostela (NW Spain), where the balloons are daily launched. In order to evaluate the feasibility of this project, two options were considered:

1. electric power produced by the PV cells is used to feed the whole process of production of Hydrogen (autonomous system).
2. electric power produced by the PV cells is supplied to the Spanish Electric Network (REE) (connected system), taking advantage of the economic benefits set by the Spanish Real Decreto 436/2004. At the same time, Hydrogen is produced by electrolysis using energy provided by the REE network, at a lower price than the supplied by the PV cells.

The decision of undertaking a project with this characteristics has to be taken according to different factors. Some projects are carried out because of their social profitability, others for their environmental profitability, and many because of their election yield. But the feasibility of most of the projects uses to be determined by their financial profitability.

For this reason, both technical and economic issues are considered in this analysis. After presenting both technical solutions (including the specific problems related to the Hydrogen production and storage), investment budget, operating costs and exploitation incomes are evaluated. Then, the financial yield of the project is considered.

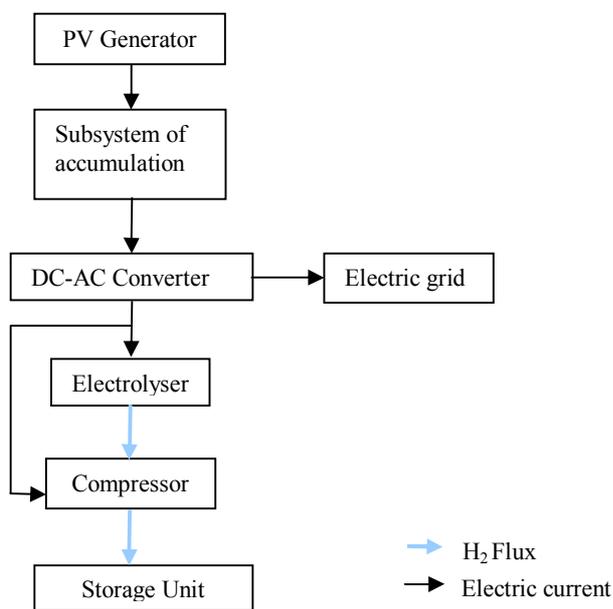


Fig 1-a. Diagram of the autonomous system

A. Photovoltaic Generator

For the technical design of this module, it is of primary importance the determination of the number (N) of PV modules to be connected in serial and in parallel. The modules can be placed over the roofs and other available spaces of the School of Engineering. Selected model was Isofotón IS-150/12, which main features are described on Table I.

TABLE I – Main features of the selected PV modules

Physical Features	
Dimensions [mm]	1590x790x39.5
Weight [kg]	14.4
Electrical Features (1000 W m ⁻² ; 25 C)	
Maximum power [Wp]	150 ± 5%
Maximum power current [A]	8.7
Maximum power voltage [V]	17.3
Short circuit current [A]	9.3
Open circuit voltage [V]	21.6

2. Plant description

Based on the work of Hollmuller [3] and considering the requirements of Hydrogen production and its frequency, the Hydrogen process is based in a home installation, as it is described in Hollmuller [3]. This kind of installations includes two main parts: a PV generator, DC-AC, water supply, and an electrolyser for Hydrogen production; compression and storage units, for Hydrogen storage. Every module is described in detail in this section.

Keeping in mind the two options described in section 1, installations diagrams are shown on Fig. 1-a and Fig. 1-b. Since the design is made for the worst month, in the autonomous system (Fig. 1-a) the exceeding energy produced by the photovoltaic generator is sold to the REE.

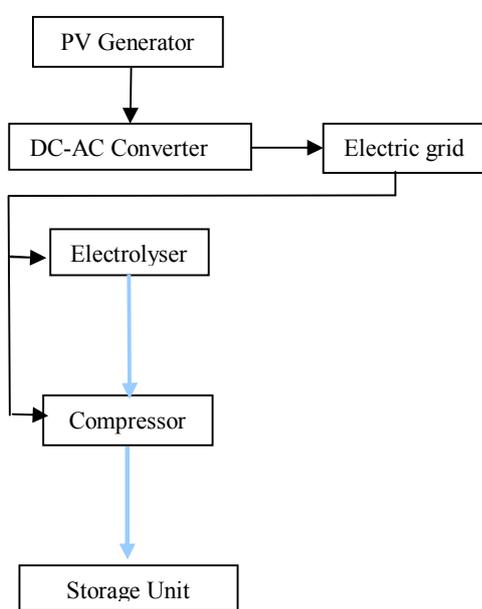


Fig. 1-b. Diagram of the connected system

B. Accumulation subsystem

Since commercial devices used to produce and store Hydrogen work in a AC regime, it is necessary to provide them a constant power value. This is achieved by setting a battery array, load regulators and AC/DC converters.

For this work, Pb-acid tubular batteries from Isofotón were selected. Model 2.AT.4505 from Isofotón was considered appropriate. Table II contains its main features. The state of the batteries is regulated by the controller Xantrex C40, while the DC-AC converter, that connects the system to the grid, is the Xantrex SW4548E.

TABLE II – Main features of the batteries selected in this work

Physical Features	
Dimensions [mm]	576x212x813
Weight [kg]	239
Electrical Features	
Voltage [V]	2
Capacity 10 h @ 25 C [Ah]	3360
Capacity 100 h @ 25 C [Ah]	4505

C. Electrolyser, compression and storage units

Following the work of Hollmuller, it has been taken into account an electrolyser with a flow of 2 Nm³/hour released with a pressure of 2 bar. The module considered for the present work has a working temperature of 50 C, employs KOH as electrolyte and should consume 9.5 kW at full regime. In order to keeping down the costs, the electrolyser should be customised [6].

Hydrogen produced by the electrolyser is then compressed to 29 bar by the compressor Corken-D191. Power consumption is 0.125 kWh/0.59 Nm³. The process takes a few minutes to complete.

Hydrogen is then stored in a stack of metal cylinders filled with a hydrogen absorbing alloy (derivative of TiMn₂). In order to accomplish the needs of H₂ even in days characterized by low levels of irradiation (see following sections), it has been considered appropriate a volume of 90 L. Because of legal security rules, storage unit is enclosed in a isolated room that includes the electrolyser.

3. System design

A. Estimation of the Hydrogen volume requirements

For the current operational rawinsonde, two launches per day are performed with balloons filled with Helium. The gas volume needed to fill one balloon, in order to achieve an aloft rate of 300 ms⁻¹, is determined by a reference weight of 2.5 kg; when the balloon begins to lift the weight, there is gas enough to launch the balloon.

Therefore, the Hydrogen volume that is necessary for a launch can be estimated by means of the Archimedes' Principle:

$$2.5 \cdot g + \rho_{H_2O} \cdot V \cdot g = \rho_{air} \cdot V \cdot g \quad (1)$$

where g is the gravity's acceleration, ρ is the air density (in standard conditions), and V is the volume of the balloon (filled of Hydrogen). From equation (1) a value of 2.31 m³ of Hydrogen volume is obtained; therefore, the daily volume of hydrogen that has to be generated is $V=4.62$ m³. Considering the efficiency of the electrolyser, the value of V may be rounded to 5 m³.

B. Daily mean irradiation and determination of the worst month

As this process is planned to be installed at the School of Engineering in Santiago de Compostela, solar irradiation measurements at this location were considered. Observations of horizontal surface irradiation collected by the EOAS jointly automatic weather station [5], located near the School, were collected. Measurements provided by a Ph-Schenk class A pyranometer, from June 2005 to June 2006, are reported in Table III. Besides the monthly daily means of irradiance, it also includes the derived [7] mean values of monthly mean optimal inclination, and the corresponding values of irradiation.

The PV system is designed to accomplish the energy demand along the worst month of the year, as the month where the ratio between the daily mean irradiation and the energy demand is the lowest one. It can be noticed that the worst month is March 2006, mainly due to the high number of rainy days recorded at this period. Anyway, a longer data set in the location (not yet available) would allow a better design of the PV equipment.

TABLE III – Mean values of irradiation in Santiago (June 2005 – June 2006)

Month	Daily Irradiation monthly averaged over horizontal surface (kWh/m ²)	Mean optimal slope (degrees)	Daily Irradiation monthly averaged optimal slope (kWh/m ²)
Jan	2.11	63.75	4.77
Feb	2.70	56.27	4.86
Mar	2.64	45.36	3.75
Abr	5.07	33.47	6.08
May	6.01	24.13	6.58
Jun	5.18	19.81	5.50
Jul	6.06	21.71	6.52
Aug	6.10	29.46	7.01
Sep	4.715	40.73	6.22
Oct	3.99	52.58	6.57
Nov	2.16	61.83	4.58
Dic	1.82	65.95	4.47

C. Design of the autonomous system

1) *Determination of the daily electric energy to supply.* As it was shown in section 2, every module requires AC. On Table IV are reported the receiving devices, together with the estimated daily consumption of energy. The average total energy demanded by the whole system is given by equation (2),

$$E_{dem} = (100 + F_S) \cdot \frac{E_{AC}}{\eta_{DC-AC}} \quad (2)$$

where η_{DC-AC} is the efficiency of the converter, assumed to be 90%, and E_{AC} is the total energy demanded by all the devices that work in alternate current. F_S represents the security factor that accounts for possible energy losses in the connections. F_S has been estimated to be 15% [8]. According to equation (2), $E_{dem}=31.94$ kWh per day.

TABLE IV – Daily mean energy requested by the devices that work in AC

Device	Power (kW)	Hours of functioning	Daily energy request (kWh)
Electrolyser	9.5	2,5	23.75
Compressor	3.2	-	1.25 [3]
Total consumption (kWh)			25

2) *Determination of the number of PV modules and its connection.* In this project will be installed PV modules Isofotón IS-150/12, which features are described in Table I. The efficiency of each module is $\eta_{mod}=11.9\%$, given by the ratio between the peak power and the nominal irradiance captured by the panel.

Considering the optimal irradiation G_{opt} in the worst month (Table III), the average daily energy supplied by the PV generator, will be,

$$E_p = \eta_{mod} \cdot G_{opt} \cdot S \cdot N \quad (3)$$

where S is the area of each PV module and N is the number of panels of the generator.

As the real conditions of work of the PV generator may not match with the nominal ones, a correction factor, C_f , must be applied, that depends on the site and its climatologic conditions. A typical value of C_f for the North of Spain is 1.3 [9]. Of course, generated energy has to be equal to the demanded energy estimated before.

Thus, the total number of PV modules has to be $N=76$, connected 4 in serial and 19 in parallel.

3) *Design of the accumulation subsystem.* In this work it has been chosen Pb-acid batteries, with a maximum depth of discharge $P_{D,max}=0.7$ and a maximum depth of daily discharge $P_{D,daily}=0.2$. From the climatologic data contained in the database of meteogalicia, it has been established that the number of days of autonomy of the batteries system has to be $N_D=7$. The capacity needed by the accumulation system, C'_T , is given by (4):

$$C'_T = 1.1(N_D \cdot E_{elec,max}) / (P_{D,max} \cdot V_{T,acc}) \quad (4)$$

where $E_{elec,max}$ is the mean daily energy needed by the system during the worst month and $V_{T,acc}$ represents the operational voltage of the subsystem. The value of $C'_T=7319.6$ Ah justifies the choice of the batteries described in Table II. Consequently, the number of accumulators connected in series and parallel will be, respectively, $N_{S,acc}=24$ and $N_{P,acc}=2$, providing a total number $N_{acc}=48$.

4) *Design of the regulation subsystem.* Regardless of the specific features of a particular regulator, it must be specified the nominal values of the following parameters: the nominal voltage V_{reg} , the nominal intensities of the switch between PV modules and batteries ($I_{reg,gen-acc}$) and between batteries and the devices connected ($I_{acc,dev}$). These parameters, for the present work, have the following values:

$$\begin{aligned} V_{reg} &= 48V \\ I_{reg,gen-acc} &= 220.9 A \\ I_{acc,dev} &= 142.01 A \end{aligned}$$

5) *Shadow calculation.* The presence of shadows plays an important role in determining the area of the PV

generator. Shadows should be avoided to eliminate losses by dispersion and the so-called “warm point” problem. The effect of shadows of the PV panels has been evaluated for the winter solstice, as it is shown on Fig. 2. The value of the shadow has been increased, multiplying it by 1.25. Consequently, the area occupied by the photovoltaic generator is $A=296.6 \text{ m}^2$.

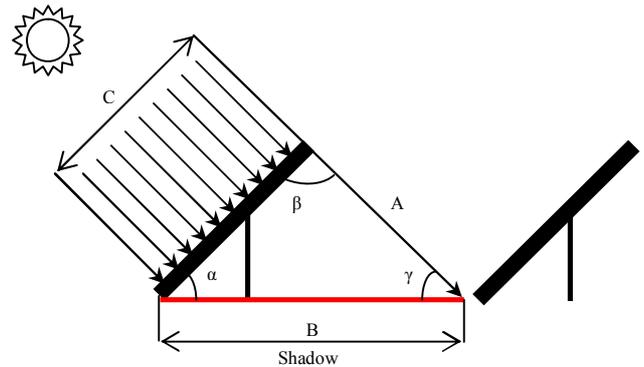


Fig.2. Estimation of the shadows of PV panels

D. Design of the connected system

This configuration differs from the autonomous system because all the PV electric power is sold to REE, obtaining a reimbursement. On the other hand, the energy needed by the devices to produce Hydrogen is taken from REE. This procedure gives a profit, set by the Spanish Real Decreto 436/2004 [11], that may write off the original investment.

Following Fig. 1-b, and assuming a converter efficiency of 90%, the energy demanded to assure the production of Hydrogen is $E_{dem}=31.9$ kWh/day. Thus, the number of PV modules that constitute the generator is $N=76$, connected in serial (4) and parallel (19).

4. Economical Analysis

In this section an economic study of both proposed installations, autonomous system and connected system, is shown. From the results of this analysis, a decision about the feasibility of both systems (which are technically similar) can be obtained, in order to select the best solution. In addition, a general evaluation about the legal conditions of both PV autonomous and connected systems in Spain can be achieved.

A. Autonomous system

1) *Investment.* As this economic study is treated from the point of view of a design selection, estimations of the costs values of the different equipments were considered (Table V), in order to obtain a coarse estimation of the global investment.

2) *Investment funding.* According to the IDAE [11] subsidy plan (started on July 2006), up to 100% of the initial costs of autonomous photovoltaic installations can be financed, including: photovoltaic collector, storage batteries, converters, regulators, wiring and the

associated civil engineering. This means the 77.5% of the total investment, with the conditions shown on Table VI.

TABLE V - Costs Investment for the autonomous system.

Device	Cost (Euros)	% of total investment
PV panels	43300	36.0
Electric wiring	3000	0.5
Battery array	44000	36.6
Metallic structure and upright	2500	2.08
AC/DC converter	2850	2.4
Electrolytic unit	6000	5
Storage system	21000	17.46
Total	120250	100

TABLE VI - Financial conditions of the autonomous system investment (IDAE)

Own funds	22.5%
Financed capital	77.5%
Loan deadline	11 years
Interest rate	Euribor + 0.30

3) *Exploitation costs.* In this section, operation costs are considered. For the autonomous system, the costs of the water supply are calculated taking into account the water (tap) requirements of the electrolyser, which is 25550 l/year.

Besides, maintenance cost is considered, as usual (10 % of the investment). In addition, because of the low cost of the PV panels' maintenance, their cost is excluded from the maintenance estimation.

4) *Operating incomes.* For the autonomous system, incomes can be evaluated by the Helium saving. Thus, taking into account the expenses in the last year due to the Helium purchase, an annual saving of 1876 €/year is obtained. For annual saving the update, an IPC of 3.9% is considered. Apart from this, the installation has the possibility of sell the excess of the produced energy to the REE network. According to a monthly study for the energy production, an estimation for the annual excess of energy is 6200 kWh. The sale price is 0,44 €/kWh, and for the following years an IPC of 3.9% is considered.

5) *Cash flow calculation.* In this case the profit is calculated by means of the yearly cash-flows. The gross cash-flow is determined with the Helium saving, which will be considered as an income, and the electricity sale minus the exploitation costs, and also the financial costs applied to the 77.5% of the total investment, with an interest rate of 3,93%. At the same time, the taxes are supposed at the 35% of net margin.

6) *Analysis of the economic feasibility.* In this section some economic criteria that show the profitability of the project will be presented [12]. From the analysis of the incomes and expenses the profit value for the first years of operation is negative, as a consequence of the high exploitation costs. The payback period needed to recover

the initial outlay is evaluated from the cash-flows, giving as result a number of years higher than the expected lifetime of the project. From this point of view the operation of the autonomous system will not be able to recover the initial investment, thus the project is not profitable. Therefore to continue with an analysis in depth is not necessary.

B. Connected system

1) *Investment.* In this case the batteries are not necessary. So the initial outlay for connected systems, as in general, tends to be lower than in autonomous ones.

TABLE VII - Investment costs of connected system.

Device	Cost (Euros)	% of total investment
PV panels	43320	59
Electric wiring	3000	0.8
Metallic structure and upright	2500	3.4
AC/DC converter	2850	8.1
Electrolytic unit	6000	8.2
Storage system	21000	24.5
Total	73420	100

2) *Investment funding.* There are not grants for the investment of PV installations which supply electric power to the REE, therefore an investment funding plan is proposed on table VIII.

TABLE VIII - Financial conditions of the connected system investment (market)

Installation investment	
Owner funds	30%
Financed capital	70%
Loan deadline	11 years
Interest rate	7.23

3) *Exploitation costs.* In the case of the connected system, the costs of supplies come from both the use of water to produce Hydrogen in the electrolytic unit (as in the autonomous case) and the supplied electric energy provided by REE.

The annual cost of the supplied energy is calculated taking into account that the foreseeable purchase price for 2007 is 0.05 €/kWh, that will be increased every year ahead of the IPC, initially a 1% is assumed until a 1.5% in 25 years.

In addition, the maintenance cost must be considered, as usual (10% of the investment). Again, because of the low cost maintenance of the PV panels, this module is not included in the maintenance.

Apart from the financial cost calculated with an interest rate of 7.23%, straight line depreciation is considered during 20 years.

4) *Operating incomes.* In this case, incomes can be evaluated by both the Helium saving and the sale of the

electric energy produced by the PV system to the REE. Helium annual profit is the same as in the autonomous system, so electric energy sale profit can be added directly.

According to the Spanish Real Decreto 436/2004 [10], which establishes for Spain the methodology for the updating and systematization of the legal and economic regime of electric power production activity in special regime, the sale price of the produced kWh is 0,44038 €/kWh, and for the following years an IPC of 3.9% is considered.

5) *Cash flow calculation.* The gross cash-flow is determined with the combination of the Helium saving and electricity sale, which will be considered as an income, minus the exploitation costs and also the financial costs applied to the 50% of the total investment, with an interest rate of 7.23%.

Net cash-flow is calculated taking the taxes away from the gross cash-flow. At the same time the taxes are estimated at the 35% of the subtraction between the incomes and expenses of the exploitation. Results of the annual balance are presented in table IX, considering an expected lifetime of the project of 20 years.

TABLE IX - Cash-flows for the connected system.

Year	1	2	3	4	5	6	7	8	9	10
Incomes	7019.64	7293.40	7577.85	7873.38	8180.45	8499.48	8830.96	9175.37	9533.21	990500
Expenses:	1516.95	1539.73	1563.39	1587.98	1613.52	1640.07	1667.64	1696.30	1726.07	1757.00
Operating	1857.89	1857.89	2171.56	1930.28	1688.99	1447.71	1206.42	965.14	723.85	482.57
Financial										
Total	3374.84	3397.62	3734.95	3518.26	3302.52	3087.77	2874.07	2661.44	2449.92	2239.57
Net margin	5502.69	5753.68	6014.46	6285.41	6566.92	6859.42	7163.32	7479.07	7807.14	8148,01
GrossCF	3644.80	3895.79	3842.89	4355.13	4877.93	5411.71	5956.89	6513.93	7083.29	7665.44
Net CF	1718.5	3032.73	2940.72	3412.32	3892.89	4382.80	4882.40	5392.07	5912.22	6443.24
Year	11	12	13	14	15	16	17	18	19	20
Incomes	10291.30	10692.66	11109.67	11542.95	11993.13	12460.86	12946.83	13451.76	13976.38	14521.46
Expenses	1789.14	1822.53	1857.22	1893.27	1930.72	1969.63	2010.06	2052.07	295.72	2141.06
Operating	241.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial										
Total	2030.42	1822.53	1857.22	1893.27	1930.72	1969.63	2010.06	2052.07	2095.72	2141.06
Net margin	8502.16	8870.13	9252.45	9649.68	10062.41	10491.23	10936.77	11399.69	11880.66	12380.39
GrossCF	8260.88	8870.13	9252.45	9649.68	10062.41	10491.23	10936.77	11399.69	11880.66	12380.39
Net CF	6985.55	75396.1	7864.58	8202.23	8553.05	8917.54	9296.25	9689.73	10098.56	10523.33

6) *Analysis of the economic feasibility.* In this section some economic criteria that show the profitability of the project will be presented. First of all, the payback period needed to recover the initial outlay is evaluated from the cash-flows, giving between 9 and 10 years.

Second, the net actual value (NAV), as the overall updated inlets and outlets of the capital, is calculated by equation (4),

$$NAV = -A + \sum_{i=0}^n q_i \cdot (1+k)^{-i} \quad (4)$$

where A is the initial investment, q_i is the cash-flow at the end of the year i , and k is the updating rate, that takes the value of 10%.

The resulting NAV has to be positive for a profitable project. Considering 20 years of operation, a NAV of 6877 € is obtained for the connected system.

On the other hand, a project is considered profitable when the internal rate of return (ROI) is higher than the normal interest rate in the capital market. It is calculated finding the value r in equation (4) for NAV equal to zero.

As it is shown on Figure 3, according to the ROI the connected installation is profitable, so it represents a

lower risk for the investment than the autonomous installation. Moreover, the time needed to recover the initial outlay is shorter and the NAV is positive, so the investment in the connected case produces profit in the same year of operation.

TABLE X - Economic feasibility results, connected system.

Criteria	Value	Analysis
Payback	9 -10 years	Favorable
NAV	6877 Euros	Favorable
ROI	0.118	Favorable

5. Conclusions

A technical and economical evaluation of two options for a sustainable filling with Hydrogen of operational rawinsonde balloons, using PV energy and a electrolytic module, are presented. The first one is an autonomous system, which applies the PV energy directly to the Hydrogen production; the second one is a connected system, that provides the PV power to REE and collect

the electricity for Hydrogen production from the electric company.

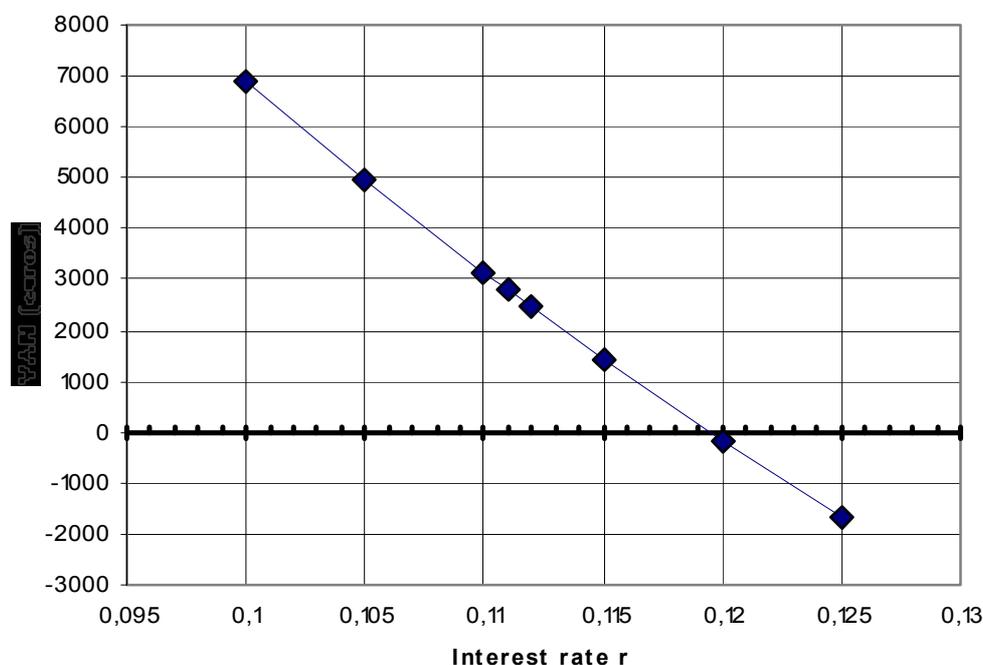


Figure 3. ROI for the connected system.

Technically, both solutions are feasible to be installed at the School of Engineering at Santiago de Compostela (where an operational rawinsonde is currently installed running with Helium). However, economically only the connected system is favorable, because of its lower investment and the price advantages of the PV production supplied to REE.

Therefore, from the feasibility study of both installations, the connected system is presented as the best option. One of the reasons is the large difference between the initial outlays of both installations in our case of study, due to the necessity of an electric storage system that allows the autonomy for the autonomous system. At the same time, the high investment derived in high maintenance costs and therefore, in a high exploitation values.

On the other hand, the connected system shows a good economic behavior from the point of view of the usual economic criteria. As the investment in this case is higher than in the general connected systems because of the equipment for hydrogen production, the payback period is a little longer as it is usual. The positive value for the VAN indicates that the investment in the project produces higher excesses than if this initial outlay was invested with an interest of 10%.

The autonomous system takes advantage of the grants from IDAE, in order to reduce the capital risk. However, the best economic results are obtained by the connected system, taking advantage of the Spanish Real Decreto 436/2004, with a higher profit derived from the difference between the PV price supplied to REE and the normal electric supply price paid to the electric company. Therefore, in this case the autonomous system suffer the

disadvantage of the Spanish legal conditions of electric production and supplying, respect to the PV production.

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