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An Economic Case Study of Hydrogen Energy Storage

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Abstract

The use of hydrogen as an energy vector has been considered as one promising way to attend society decarbonization. Hydrogen can be used as a chemical to store electricity and as a fuel to electric fuel cell mobility. This work makes hydrogen production potential economical evaluation of 5 real solar photovoltaic installations intended primarily for self-consumption. The surplus electrical energy can be used to produce hydrogen, which will be used later as a form of energy, potentially in an application. That provides greater economic value. Hydrogen serves as an important career to the storage of energy and can be more interesting and competitive than a battery-based solution. The results show that the use of hydrogen is only economically viable for medium-sized installations, greater than 300MW and for the production of hydrogen for mobility.

Keywords: Hydrogen vector; Energy economic analysis

Introduction

Currently, humanity is confronting a major environmental problem that demands scientific and innovative solutions: the rise in the average temperature of the planet. This problem has resulted due to the rise of carbon dioxide emissions in the last 200 years due to the massive use of fossil fuels, and therefore it is imperative to develop new sources and ways for energy and fuel production that can be sustainable and simultaneously with neutral emissions of carbon dioxide. The previous problem requires persistent work in scientific research focused on the implementation of innovative solutions that can be sustainable for the environment, economy, and society. Nowadays, hydrogen is an important intermediate in the chemical industry and refineries. Renewable hydrogen is seen as an important secondary energy carrier of the future and could be used directly as fuel and feedstock for further syntheses as well as for the generation and storage of electricity. Generally, hydrogen production processes can be classified into three categories: electrochemical, biological, and thermochemical methods [1]. All of these methods can be realized on a renewable base. In the case of electrochemical methods, electricity must be generated by sustainable energy sources. Biological processes are a promising alternative approach for production of hydrogen from low cost, renewable, and environment-friendly resources [2]. In this process microorganisms convert organic substrates and water molecules into hydrogen by catalytic activity of two main enzymes as hydrogenase and nitrogenase [3]. Bio-hydrogen can be produced through different processes including photo-fermentation, dark-fermentation, CO gas-fermentation, and photolysis. Among these processes, dark fermentation and photo-fermentation are considered as the most promising processes [4]. Dinesh et al. [5] performed an economic analysis of bio hydrogen production from food waste using dark fermentation method and reach a low hydrogen production cost of 3.20$/kg. However, as production rate of the fermentation processes is very low, required size of reactor would be high and hence installation cost is high. This is the key challenge of fermentation processes is the low production capacity per unit of capital investment [6]. Thermochemical hydrogen production process produces hydrogen from synthesis gas which is obtained from different processes. This technology mainly constitutes pyrolysis and gasification of biomass processes where a gas mixture mainly comprising hydrogen, carbon monoxide, methane, and carbon dioxide is obtained [7]. This gas mixture needs to be further processed to hydrogen gas by steam reactions and water gas shift reaction [8]. However, the use of thermochemical methods for hydrogen production is very expensive. Gholkar et al. [9] performed a techno-economic assessment of hydrogen and methane production from thermochemical conversion of microalgae and conclude that the process is only viable if the market price of hydrogen is as high as $10/kg. Sara et al. [10] performed a techno-economic analysis of hydrogen production from fluidized bed gasification of lignocellulosic biomass on a small-scale system and found out even a greater hydrogen production cost of 12.75€/kg. In terms of electrochemical hydrogen production processes, electrolysis processes are those with the highest degree of maturity and highest yields [8]. The electrolysis of water consists of the decomposition of water into oxygen and hydrogen by the effect of the passage of a continuous electric current through the water in a device called an electrolyzer. Hydrogen and oxygen are produced from water through redox reactions. The electrolyzer is a device that combines oxidation and reduction reactions to produce hydrogen and oxygen from water. A typical electrolysis process can use three different types of electrolytes: liquid electrolyte, solid polymeric electrolyte in the form of a Proton-Conducting Membrane (PEM), or oxygen ion-conducting membrane [1]. Grimm et al. [11] performed a techno-economic analysis of two solar assisted hydrogen production technologies: A photoelectrochemical system and its major competitor, a photovoltaic system connected to a conventional water electrolyzer. The production cost of hydrogen resulted in 6.22$/kg for the photovoltaic-electrolyzer system and in 8.43$/kg for the photoelectrochemical system. Pinaud et al. [12] found a production cost of hydrogen even it higher in 10.40$/kg for the photoelectrochemical system. Since alkaline electrolysis is the most mature electrolysis technology and also most widely used [13]. An alkaline solution, which normally consists of 20-40% Potassium Hydroxide (KOH), is used as an electrolyte to increase the

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ionic conductivity of cells [14]. The main disadvantage of alkaline electrolysis is that the liquid alkaline solutions used are corrosive. In recent years, major developments have focused on reducing operating costs associated with electricity consumption, thereby improving efficiency. However, the current density has been increased, thereby reducing investment costs [15]. New materials are also being tested to replace the asbestos used in the diaphragm. These include membranes based on polymers of antimony impregnated with polymers, porous composites consisting of a matrix of polysulfone and ZrO_2, known as Zirfon, and separators based on polyphenol sulfide. With regard to PEM electrolyzers, the main difference compared to alkaline electrolyzers is the use of electrolytes. PEM electrolysis employs a solid polymeric membrane as an electrolyte instead of the corrosive liquid electrolyte used in the alkaline electrolysis process. However, high-purity deionized water is required for this electrolysis process [16]. At the anode, water is oxidized to produce oxygen, electrons, and protons. Protons pass through the membrane to the cathode side while the electrons pass to the cathode side through an external circuit. At the cathode, protons are reduced to generate hydrogen. The PEM electrolyzer is more suitable for working with variable energy sources such as renewable energies. This is due to the transport of protons across the membrane which is facilitated by floating energy sources. Currently, the main drawback of PEM electrolyzers is the high cost of production, so the development of these types of demonstration projects on a pilot-scale contributes positively to the growth of these technologies that allow the energy storage and the production of fuels and raw materials with practically environmental null impact. The aim of this work is to evaluate the potential for hydrogen production in 5 real solar photovoltaic installations intended primarily for self-consumption. Currently, all energy that exceeds the facility's own consumption is either injected into the public utility grid, with a very low economic value or is simply wasted. The alternative that this study proposes is that this surplus electrical energy can be used to produce hydrogen, which will be used later as a form of energy, potentially in an application that provides greater economic value. Hydrogen thus serves an important function of storing electrical energy and can be more interesting and competitive than a battery-based solution. Its later use will be made essentially as thermal fuel, but it can also be used to produce electricity again through fuel cells either to produce electrical energy to inject into the grid or in hydrogen-electric mobility. This function is sometimes described as an energy vector, since it is not a primary source of energy, but it allows the transformation to other forms of energy in other applications.

Methodology

Five practical cases of units in Portugal that have renewable production systems for photovoltaic electricity were studied, namely.

Case A: Services Operational Center Facilities in Évora.

Case B: Pharmaceutics facilities in Lumiar/Lisbon.

Case C: Services Operational Center Facilities in Porto Salvo/ Oeiras.

Case D: Services Operational Center Facilities in Queluz/Sintra

Case E: Car Stand Facilities in Abrunheira/Sintra.

The choice of locations for the case studies fell on the technical

Table 1: Summary of global values obtained during 2017.

	Case				
	A	**B**	**C**	**D**	**E**
Energy [kWh/year]					
Total Installation consumption	153.141	198.409	94.677	170.663	210.942
power produced by the plant	90.642	123.242	51.935	32.467	102.644
Energy for self-consumption	23.487	86.802	16.742	26.559	75.422
Rations					
Energy Produced/ Energy Consumed	59%	62%	55%	19%	49%
Self-consumption energy/ energy produced	25.90%	70.40%	32.20%	81.80%	73.50%
Surplus/Energy Produced	74.10%	29.60%	67.80%	18.20%	26.50%
H_2 Production					
Surplus Energy (kWh)	67.156	36.44	35.193	5.908	27.223
Specific energy consumption (kWh/Nm^3)	4.5-7.5	25%	25%	25%	25%
H_2 Production Potential (Nm^3)	16.789	9.11	8.798	1.477	6.806

conditions in terms of electricity consumption, power level, and consumption profiles, as well as the characteristics of the location and the available area of exposure to solar radiation. In addition to the technical framework, the choice of locations was linked to the existing hydrogen consumption potential, in order to be used as an energy vector, as well as its location within or close to industrial parks. In all cases, the Energy Audit carried out proposed and designed photovoltaic installations for Self-consumption. In some cases, it was necessary to resize the photovoltaic solar installation in order to guarantee a surplus of energy necessary for the production of hydrogen. Table 1 shows the global values obtained during 2017 and Figure 1 shows the curves of energy consumption, electricity produced by the photovoltaic system and hydrogen production in a typical summer week. Most of the installations presents most of its electricity consumption at night, so during the day the production of electrical energy by means of photovoltaics ends up generating excess electrical energy that can be stored. Case A is an operational center of a large company, located in Évora. Since this type is a typical industrial park facility, we chose to include it in this study. The installation presents most of its electricity consumption at night, so during the day, the production of electrical energy by means of photovoltaics ends up generating surplus electrical energy that can be stored. Case B is an installation corresponds to an office building of an industrial company and is located in a technological park in Lisbon. The company's laboratories are located in the contiguous building. Thus, it appears interesting to include the analysis of this installation in the present study. As it is an office, most of its electricity consumption occurs during the day, so that during the day, the production of electric energy by means of photovoltaics does not generate a significant surplus of electricity unless the production installation is slightly over-sized. This surplus of electrical energy is used to produce electrolytic hydrogen in the sense that it can be stored. In relation do Case C, the facility corresponds to a logistics center (offices, warehouses and workshops) of a large company and is located on a campus in Porto Salvo, municipality of Oeiras. Most of its electricity consumption occurs at night, so during the day, the production of

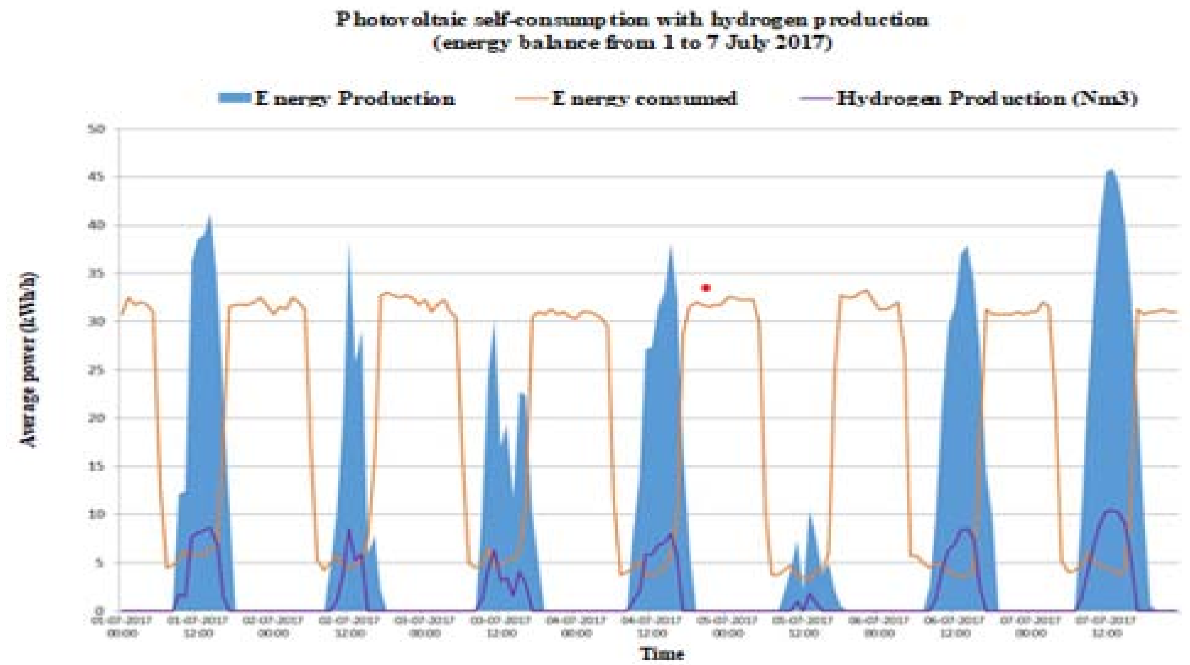

Figure 1a:

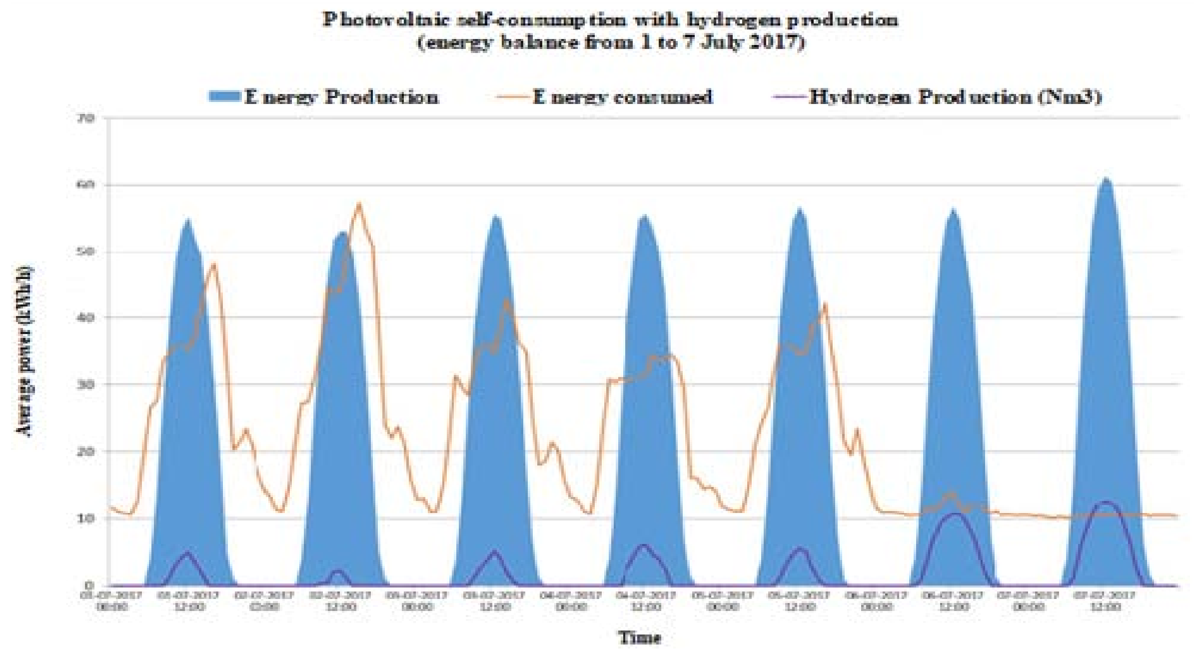

Figure 1b:

electric energy through photovoltaics ends up generating surpluses. Case D is an operational center of a service company, which is located in Queluz, in the municipality of Sintra. This type of facility is typical of industrial parks, so it is also included in this study. This installation presents most of its electricity consumption at night, so during the day, the production of electrical energy by means of photovoltaics ends up generating surpluses. This surplus of electrical energy is sent to the electrolysis device for hydrogen production and storage.

Finally, Case E is a facility corresponds to a large logistics center (offices, warehouses, sales stand, training centers and workshops) of a large automobile and heavy vehicle and bus company. It is located on a campus in Abrunheira, municipality of Oeiras. The installation presents the majority of its electric energy consumption during the day, so that during the day, the production of electrical energy by means of photovoltaics does not generate significant surpluses unless the production installation is slightly over-sized.

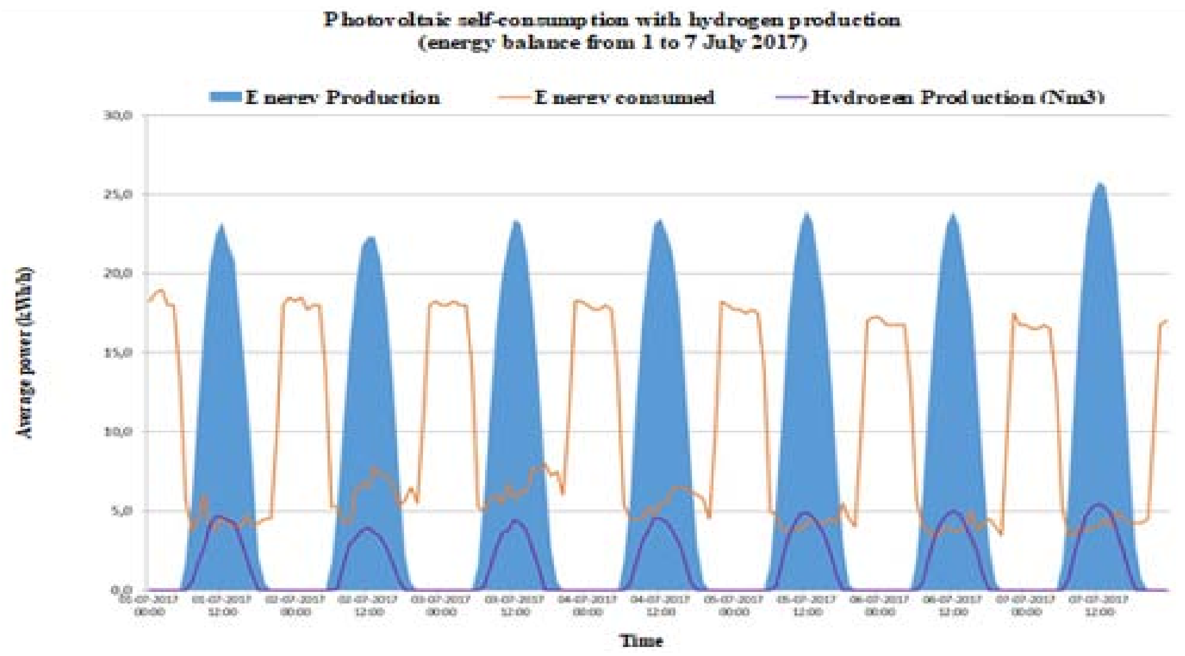

Figure 1c:

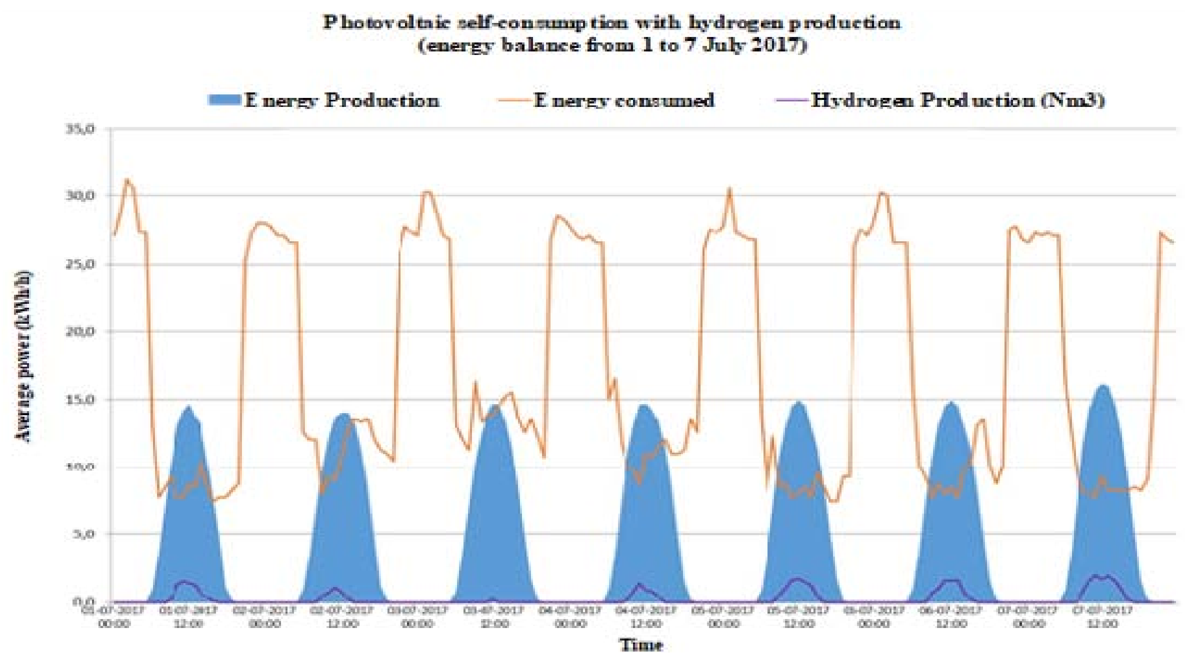

Figure 1d:

Economic Analysis

The economic evaluation of the system was carried out based on the estimated forecast cash-flows and calculation of the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PP) for the various case studies presented and for six scenarios as follows.

Scenario A: Use of excess energy for self-consumption with energy storage via electrolytic hydrogen production; energy production would be carried out based on fuel cells and would be injected into the unit's internal network during periods when energy is needed; for the purposes of economic evaluation, it was considered that the energy injected into the internal network would have a profit equivalent to the cost that the company pays for that energy; in this situation, electrolyzers and PEM fuel cells would be used and hydrogen storage under pressure.

Scenario B: This situation is identical to situation A, but considering that there is a possibility of having a scale factor of 10 times higher. That is, assuming that in the industrial park there would

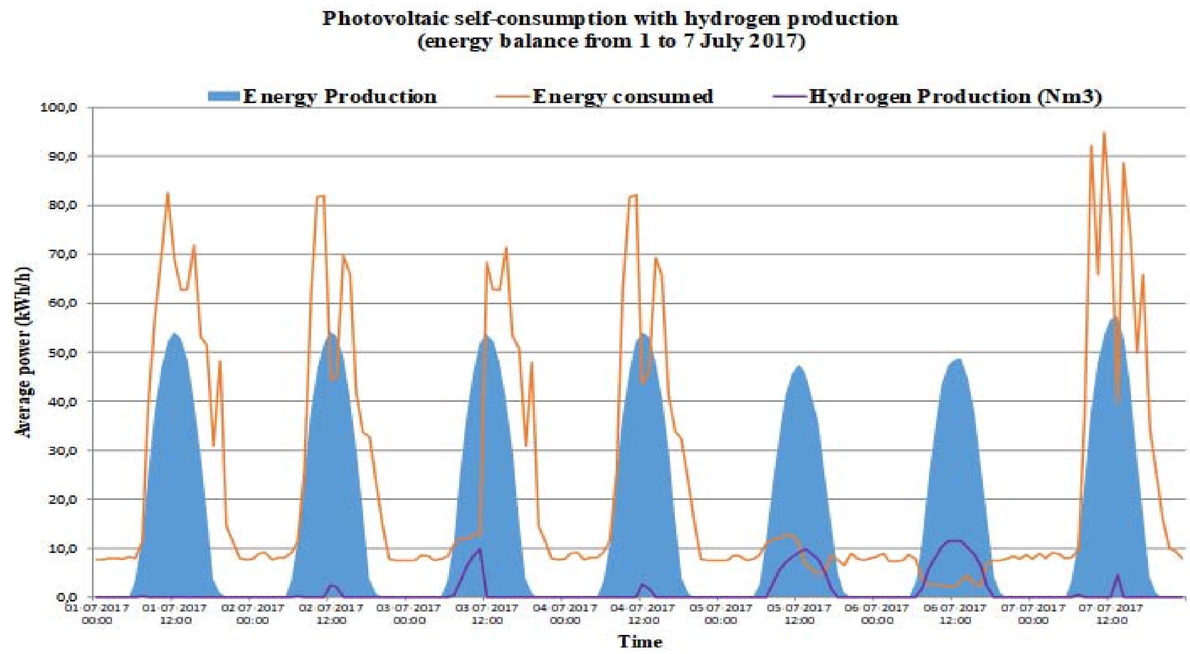

Figure 1e: Energy consumption, photovoltaic electric energy and hydrogen production in a typical summer week: a) Case A; b) Case B; c) Case C; d) Case D and e) Case E.

be 10 entities with identical energy profiles and that could work together with clear benefits in terms of investment and operation costs.

Scenario C: A second scenario involves the use of excess energy from the unit to produce hydrogen with a high degree of purity for sale in hydrogen supply stations (Hydrogen Refueling Stations - HRS) for application in hydrogen electric vehicles or industrial applications; the use of light and heavy hydrogen electric vehicles has been increasing with different demonstration projects already at relatively high scales, both in Japan, the United States, as well as in the European Union, with Portugal at an early stage of this process considering that the existence of HRS's is fundamental for the development of the energy vector under analysis.

Scenario D: This situation is identical to situation C, but considering that there is a possibility of having a scale factor of 10 times higher. That is, assuming that in the industrial park there would be 10 entities with identical energy profiles and that could work together with clear benefits in terms of investment and operation costs.

Scenario E: In this situation, we will evaluate the prospect of an effective reduction in the price of technology in the next 10 years, taking into account the developments that have been taking place, and in the medium term it may allow for a favorable economic evaluation of chemical energy storage solutions via hydrogen. This scenario uses equipment cost forecasts presented in different studies, in particular the one developed by FCH-JU [17]. This scenario should be compare with scenario A.

Scenario F: Possibility of using different electrolysis technologies, namely, PEM technology or Alkaline technology, since both are mature and have different costs and longevity; alkaline electrolyzers are more economical, but have less longevity than PEM. This economic assessment is carried out taking into account the marketable values of hydrogen and electricity presented in Table 2. The price of electricity was determined based on the market price in Portugal considering a bi-hourly situation. As for the price of hydrogen, it was estimated based on the principle of the competitiveness of the price of hydrogen compared to the current price of diesel. Considering a vehicle that has an average consumption of around 5.5 liters of diesel/100km and the current price of diesel on the order of 1.5€L, as well as the average consumption of a hydrogen vehicle in the order of 1kg of hydrogen per 100 km, a competitive price for the current sale of hydrogen will be in the order of 8€/kg.

Table 2: Marketable energy prices.

Energy	
Hydrogen (€/kg)	4.5
Hydrogen (€/Nm^3)	0.4
Electricity (€/kWh)	0.18

Equipment

Table 3 shows the values considered in terms of equipment for the different scenarios addressed. The investment values considered, operating costs and lifetime of the cells took into account market values and references taken from the literature [18,19].

Operative parameters

The Table 4 shows the operating parameters used in this study. It was considered that the electrolyzer would have a power that would guarantee an 80% utilization of the maximum available peak and that it would have an efficiency of 70% [19]. The energy storage capacity was set for one week in order to allow normal fluctuations in production and consumption. In terms of electric energy production

Table 3: Replacement Cost.

	Scenario					
	A	B	C	D	E	F
Cell type	PEM					Alkaline
Year	2020		2020		2030	2020
Power	Elec.	Elec.	H_2	H_2	Elec.	H_2
Power	36	360	36	360	36	36
Electrolyzer						
Electrolyzer cost + Compressor [€/kW]	1200	600	1200	600	804	1000
Lifetime (hours)	32000	32000	32000	32000	48000	60000
Maintenance and operation [% investiment]	1%	1%	1%	1%	1%	1%
Replacement cost [€/kW]	400	250	400	250	200	300
Storage tank						
Tank cost [€/kg]	470	400	470	400	315	470
Lifetime [years]	25	25	25	25	25	25
Maintenance and operation [% investiment]	2.0	2.0	2.0	2.0	2.0	2.0
Fuel Cell						
Fuel cell cost [€/kW]	1600	800				
Fuel cell lifetime [years]	15	15				
Maintenance and operation [% investiment]	1.0	1.0				
Replacement cost [% investiment]	50	50				

Table 4: Global operative parameters.

Parameter	
Electrolyzer	
Peak utilization (%)	80%
Electrolyzer efficiency (%)	70%
Cell voltage (V)	1.5
Tank	
Storage capacity (days)	7
Fuel cell	
Fuel cell efficiency (%)	60%

Table 5: Storage system characteristics.

Parameter	Case Study				
	A	B	C	D	E
Maximum storage power (kW)	45	57	25	10	54
Average power in production (kW)	22	18	11	4	21
Electrolyzer power (kW)	36	46	20	8	43
Operating time per year (hours)	3093	1997	3195	1500	1310
Maximum hydrogen production (kg/h)	0.63	0.79	0.35	0.15	0.76
Fuel cell power (kW)	2.68	1.46	1.41	0.24	1.09

based on fuel cells, the use of PEMFC was assumed with a yield of 60% [20]. Considering that we have neither a constant production nor a constant load, and with an interest in being able to store as much energy as possible, observing the experimental data, a 7 days storage capacity allows to have flexibility in the system. Considering the parameters defined in the previous table and the energy data for one year of the various case studies, the following basic characteristics were defined for each of them Table 5.

The power of the fuel cell was determined assuming that the production of electrical energy is processed regularly for about 2/3 of the day, a period in which there is no capacity for energy storage, a similar situation in all case studies. Based on the assumptions defined above, the five installations were studied, with the following NPV and the following IRR. The economic evaluation of each system combination was done by the determination of two economic indicators: the NPV and the payback period. The formula that was adopted for the calculation of *NPV* (€) is defined in equation 1 [21]:

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+i)^n} - C_{IC} \qquad (1)$$

CF_n is the net incremental cash flow per year expressed in € (i.e. the difference between energy profits obtained from the system combination and the operating costs), n the year under focus, t the total lifetime presumed for the combination (assumed to be 15 years in all cases [22], i the discount rate (equal to 10%(23)) and C_{IC} the initial investment applied in the equipment (€). In fact, CF_n is constant for all the life period due to the fact that both energy profits and operating costs are assumed to be the same in every year. Since the first term of equation [1] is a geometric progression with a ratio of $(1+i)^{-1}$, it can be rewritten in the form of equation [2] for a faster calculation of *NPV*:

$$NPV = \frac{CF_1}{(1+i)^1} \times \frac{1-(1+i)^{-t}}{1-(1+i)^{-1}} - C_{IC} \qquad (2)$$

A positive result for *NPV* indicates that the system combination is economically feasible during the life period of the equipment [22]. For all the solutions that presented economic feasibility the *PP* was also determined for each case based on the study of the accumulated cash flows that were foreseen over time. The accumulated cash power is given by equation 3:

$$ACF_n = \begin{cases} CF_n - C_{IC}, \text{ if } n = 1 \\ ACF_{n-1} + CF_n, \text{ if } n \geq 2 \end{cases} \qquad (3)$$

Where all the variables have the same meanings as described before. The first year presenting a positive value for ACF_n corresponds to the wanted *PP* when the initial investment and succeeding costs are completely returned through the energy profits. Table 6 shows the results obtained. The first observation that the results allow to obtain is a confirmation of our assumption that the larger the size of the photovoltaic electric energy-producing unit, the greater the potential for energy storage via hydrogen, and the more economically attractive a storage unit becomes. Larger units effectively reduce investment costs per unit of energy produced [19]. The results also show that small units in terms of photovoltaic production do not allow energy storage in economic terms. Considering the reference value for the sale of hydrogen, that is the current value of diesel, the hydrogen production could be economically viable. On the other hand, the results show that a medium-sized photovoltaic production unit, such as those studied in this work, is only economically viable if we invest in the production of hydrogen as a fuel. Finally, alkaline electrolyzers, although less efficient, allow better economic evaluations to be obtained at this stage than PEM electrolyzers.

Conclusions

An economic analysis of the hydrogen storage in five real solar

Table 6: Summary of the economic analysis.

	Scenario					
	A	**B**	**C**	**D**	**E**	**F**
Cell type	**PEM**					**Alkaline**
Year	2020		2020		2030	2020
Power	Elec.	Elec.	H_2	H_2	Elec.	H_2
Power	36	360	36	360	36	36
Case Study – A						
NPV (€)	-5 499	326 586	49 354	833 682	12 871	57 444
PP (Year)	>15	6	6	3	9	5
IRR (%)	1.20%	18.30%	16.40%	38.20%	8.60%	20.90%
Case Study – B						
NPV (€)	-33 913	6 570	-4 040	270 298	-11 869	6 171
PP (Year)	>15	15	>15	8	>15	13
IRR (%)	-6.80%	3.30%	2.00%	13.70%	-1.50%	4.70%
Case Study – C						
NPV (€)	-4 649	163 786	23 962	427 686	5 462	28 436
PP (Year)	>15	6	7	3	9	5
IRR (%)	0.20%	17.20%	15.00%	36.00%	7.40%	19.40%
Case Study – D						
NPV (€)	-6 854	-5 466	-1 974	37 190	-2 833	-103
PP (Year)	>15	>15	>15	9	>15	>15
IRR (%)	-8.30%	1.50%	0.30%	11.30%	-3.10%	2.80%
Case Study – E						
NPV (€)	-38 598	-58 991	-16 563	130 671	-17 753	-6 825
PP (Year)	>15	>15	>15	10	>15	>15
IRR (%)	-9.80%	-0.20%	-1.60%	8.80%	-4.70%	0.90%

photovoltaic installations intended primarily for self-consumption is made. The results obtained allow us to verify that there is interesting economic potential in the use of hydrogen as a chemical energy storage system. Results show that in economic terms the viability only happens for larger units and when the output is the production of hydrogen for fuel cell mobility. Results also show that alkaline electrolyzers, although less efficient, allow better economic evaluations to be obtained at this stage than PEM electrolyzers.

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