OXYGEN FROM ELECTROLYSIS FOR MEDICAL USE: AN ECONOMICALLY FEASIBLE ROUTE

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Overview

Today, worldwide hydrogen production (around 70 Mt/year, in 2018) is almost exclusively (96%) derived from fossil fuels, with water electrolysis accounting for a residual share (4%) [1]. But, the conventional processes used for hydrogen generation – mainly, steam methane reforming (SMR) – are responsible for about 5% of the global carbon dioxide emissions [2]. By contrast, water electrolysis powered by renewable energy sources (solar, wind, etc.) is a mature and environmentally friendly technology for large-scale hydrogen production, whose main bottleneck for a widespread diffusion is still related to economic concerns [3]. In fact, according to the literature [4, 5], the production cost of hydrogen from electrolysis is at least 5–6 €/kg, which is not competitive compared with hydrogen production by SMR (ca. 1.5–2.3 €/kg [6]).

In our previous investigations [7, 8], we performed some evaluations of a system based on alkaline water electrolysis (180 kW) coupled with a photovoltaic plant (200 kW), looking at the oxygen valorisation for reducing hydrogen production costs. These studies allowed us to demonstrate the economic profitability of the system when the extra revenues generated from the selling of the co-produced oxygen (usually vented into the atmosphere) are considered. Recently [9], we completely reversed the usual concept, and considered a photovoltaic-powered electrolysis plant whose main purpose was to satisfy the oxygen requirements of a hypothetical enterprise, while the obtained hydrogen could be sold to external users to achieve additional revenues. The obtained results evidenced that the proposed plant was economically attractive if compared to the case when the same enterprise buys the compressed oxygen from local gas distributors/resellers. In particular, by assuming a hydrogen selling price of 10 €/kg (a reference price for hydrogen as a fuel, at the pump), the economical sustainability (recovery of the investment within 20 years) is achieved if the market price of oxygen is at least 3 €/kg, whatever the size of the electrolyser (in the range from 100 kW to 10 MW).

Nowadays, the energy-health nexus is a key theme whose importance and priority cannot be neglected or postponed anymore. The availability and quality of energy supply affect the quality of primary healthcare, and some studies [10] evidenced that sustainable decentralized renewable energy technologies could bridge the gap for access to healthcare in medical centres located in remote areas. In addition, due to the current COVID-19 pandemic, the demand for oxygen increased – e.g., in parts of Italy, oxygen consumption has tripled [11] – and this has exacerbated the shortage of medical oxygen in many developing countries [12].

Based on these considerations, in this work we consider an electrolysis plant devoted to gaseous oxygen generation for a typical medium-size hospital (200–250 beds capacity) and, assuming that the hydrogen produced from the plant is sold at 3 €/kg (a price competitive with hydrogen from fossil fuels), we perform some calculations to estimate what should be the (market) price of oxygen to achieve economic profitability within 15 years through the oxygen self-production from the proposed system.

Methods

The core of the examined system consists of an alkaline electrolyser powered by a renewable energy plant (photovoltaic); besides, compressor and storage units are also included in the economic analysis. The plant is assumed to supply oxygen to a hypothetical hospital located in the South of Italy. On this basis, and considering an efficiency typical for an alkaline electrolyser (70%), we estimated that the size of the electrolyser should be in the order of 1 MW (coupled to a 1.25 MW PV plant). In fact, such size allows to produce about 160,000 Nm^3/year of gaseous oxygen; an amount able to satisfy a 200–250 beds hospital [9].

The method applied to verify the economic profitability of the plant is based on the calculation of the net present value (NPV), following the approach proposed by Kuckshinrichs et al. [13], and adopted in our previous works [7–9]. In particular, investment costs (CAPEX), operative and maintenance costs (OPEX), and taxes have been included in the economic evaluation. Positive cash flows are those associated with the selling of hydrogen and the avoided costs for non-purchased (self-produced) oxygen. Assuming a discounted payback period of 15 years, the corresponding oxygen price is determined, and the economic feasibility of the plant is then evaluated.

Additional details on the mathematical approach can be found in [7–9], here we want just to recall the equations used to calculate the specific costs of electrolyser and PV plant.

$$Electrolyser\ specific\ cost\ [\text{€/kW}] = 1{,}200\ (P_{EL})^{-0.2} \qquad (1)$$

$$\textit{PV plant specific cost}\ [€/\mathrm{kW}] = \begin{cases} 1{,}800 & \text{if } P_{PV} < 20\ kW \\ 1{,}500 & \text{if } 20\ kW < P_{PV} < 200\ kW \\ 1{,}300 & \text{if } 200\ kW < P_{PV} < 1\ MW \\ 700 & \text{if } P_{PV} > 1\ MW \end{cases} \quad (2)$$

where P_{EL} is the electrolyser nominal power (in MW) and P_{PV} is the peak power of the photovoltaic plant (kW, or MW).

To better analyse the economic feasibility of our proposed solution for oxygen production in the medical sector (hospitals, clinics, medical centres), we introduced in this contribution the two following additional equations.

$$\textit{Annual consumption of oxygen}\ [\mathrm{Nm^3/year}] = 8.3(\textit{Number of hospital beds})^{1.814} \quad (3)$$

$$\textit{Electrolyser size}\ [\mathrm{MW}] = \frac{\textit{Annual consumption of oxygen}\ [\mathrm{Nm^3/year}]}{160{,}570} \quad (4).$$

In particular, Equation (3) is based on the work of Gómez-Chaparro et al. [14], which monitored gas consumptions in 12 Spanish hospitals in the period 2008–2016, and found a correlation between the number of hospital beds and the average annual consumption of oxygen. We used this relationship to estimate the consumption of oxygen as a function of the hospital size. Then, we derived the size of the electrolyser able to provide this amount of oxygen by using Equation (4), where – has already mentioned – the value 160,570 $\mathrm{Nm^3}$/year is the annual oxygen production corresponding to an alkaline electrolyser of 1 MW capacity powered by a PV plant located in the South of Italy [9].

Results

By considering the 1 MW electrolyser plant, and assuming a hydrogen selling price of 3 €/kg, the results derived from the economic evaluation indicate that an oxygen (market) price of about 3.3 €/kg warrants a null NPV after 15 years (Fig. 1, brown curve). This represents the so-called discounted payback period or break-even point (BEP), i.e. the number of years to recover (break-even) the initial investment; the project is expected to generate a profit only after this period.

Since the surface area needed for a PV plant is typically 7–8 $\mathrm{m^2}$/kW, the above-mentioned system (1.25 MW PV) requires a large area of about 1 hectare. Therefore, we also performed a calculation assuming an electrolyser of 500 kW coupled with a 625 kW PV plant, determining that in such a case the oxygen price to warrant a break-even after 15 years is 4.4 €/kg (Fig. 1, blue curve). This condition could be a feasible choice for smaller hospitals (< 150 beds [14]) having an oxygen consumption in the order of 80,000 $\mathrm{Nm^3}$/year or, in the case of larger ones could warrant a share (e.g., according to our estimations, about 30% of the oxygen needs for a 300 beds hospital) of their oxygen requirements.

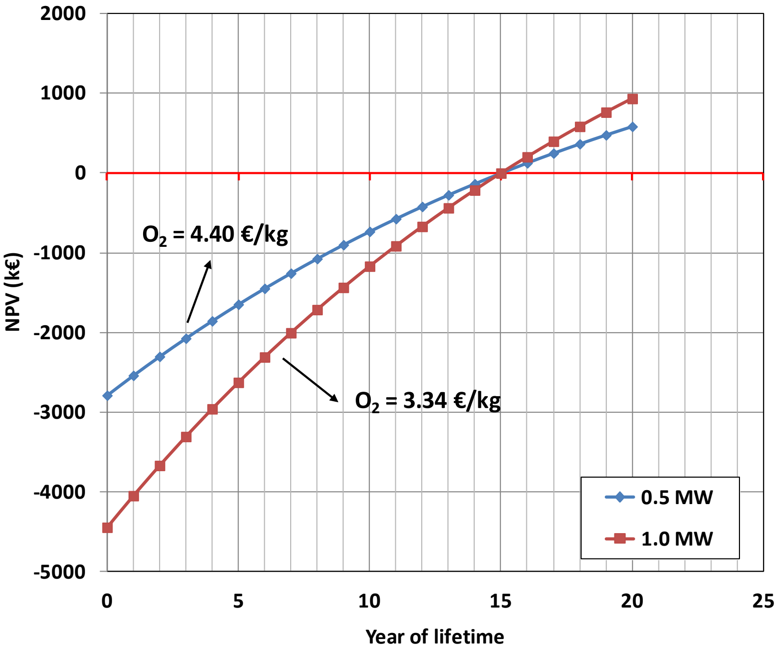

Figure 1: Net present value (NPV) evolution, for the 500 kW (blue curve) and 1 MW (brown) electrolysers, calculated assuming a BEP of 15 years.

Based on the previous equations (3) and (4) we estimated the annual consumption of oxygen (blue curve, in Fig. 2) as a function of the hospital size (for hospitals up to 500 beds), and determined the electrolyser size able to warrant this consumption (brown curve, in Fig. 2). It is evident that our assumption (i.e., 1 MW electrolyser for a 200–250 beds hospital) is confirmed; while, larger hospitals in the order of 500 beds need electrolysers having a capacity of about 4 MW. Then, based on the size of the electrolyser, through the proposed economic evaluation [7–9] we determined the oxygen (market) price to obtain a break-even point after 15 years (green curve, in Fig. 2).

The result is that for small hospitals (< 100 beds) the economic convenience of the studied system can be achieved only for a purchase price of oxygen higher than 5 €/kg. While, as a consequence of the economy of scale, the profitability can be obtained at lower oxygen prices – e.g., in the order of 4 €/kg for a 200 beds hospitals – when the size of the hospital is larger. In particular, an oxygen market price of about 3 €/kg represents the threshold limit value for hospitals with 300 beds or more.

The curve relative to the oxygen price for BEP of 15 years is not continuous. This is due to the fact that we assumed a step function for the specific price of the PV plant (see Eq.(2)): e.g., when the number of hospital beds is around 200, there is a “jump” in the curve because the specific price of PV plant passes from 1,300 to 700 €/kW.

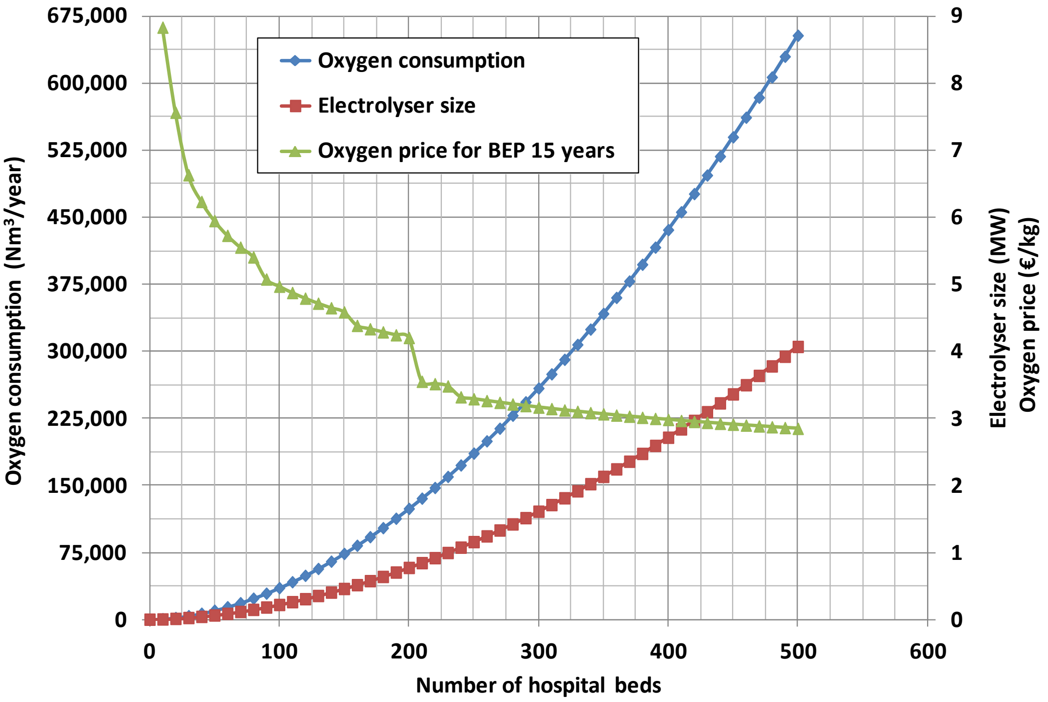

Figure 2: Average annual oxygen consumption (blue curve), electrolyser size (brown) and oxygen “market” price for BEP of 15 years (green), as a function of the number of hospital beds.

Table 1: Oxygen prices set by AIFA [15].

	Ex-factory prices		**Retail prices**	
	€/Nm^3	**€/kg**	**€/Nm^3**	**€/kg**
Cryogenic gas	4.20	2.94	6.55	4.59
Compressed gas at 200 bar	6.20	4.34	9.67	6.77
Compressed gas at 300 bar	9.30	6.51	14.51	10.16

Table 1 summarizes the gaseous oxygen prices set by AIFA [15], the Italian Medicines Agency. The ex-factory prices range from about 2.9 €/kg (cryogenic oxygen) to 6.5 €/kg (compressed oxygen at 300 bar). While the pharmacy retail prices are higher: from about 4.6 €/kg (cryogenic) to 10.2 €/kg (compressed at 300 bar). Therefore, a price of 3–4 €/kg is surely competitive for medical oxygen, and allow us to conclude that the use of medical

oxygen from on-site electrolysis plant should be considered as an economically feasible route for hospitals and medical centres with 200 beds or more. Besides, since in literature market prices of gaseous oxygen up to 7 €/kg are reported [16], the economic profitability of the proposed solution could also be warranted for smaller hospitals.
In our case, we assumed a compression section at 200 bar [7–9]; therefore, by referring to the ex-factory price set by AIFA for this condition (4.34 €/kg), it is remarkable to notice that – maintaining a selling price of 3 €/kg for gaseous hydrogen – it is possible to obtain economic profitability (BEP of 15 years) for hospitals having at least 170 beds (see Fig. 2). While, just to make a comparison with the traditional cryogenic technology, for which the AIFA ex-factory price is 2.94 €/kg, the profitability could be achieved only for larger hospitals (> 430 beds). Otherwise, considering for instance a 200–250 beds hospital, we estimated that the selling price of hydrogen should be in the order of 6 €/kg to achieve economic profitability.

Figure 3 shows the behaviour of the cash flows (costs and revenues) calculated, after 20 years, for six hospitals of different size (50, 100, 200, 300, 400 and 500 beds). Since a break-even point of 15 years has been assumed, as well as in the previous simulations, a profit is obtained at the end of 20 years, as demonstrated by the net present value (red curve) depicted in the graph. In particular, this profit increases when the size of the hospital increases, passing from about 90 k€ for a 50 beds hospital, to around 1,430 k€ for a 300 beds hospital, and reaching a value of about 3,300 k€ for a 500 beds hospital. This is mainly due to the "avoided" cost associated with the gaseous oxygen (yellow bars, in Fig. 3), which is self-produced by the plant and not purchased from the market. This term represents the highest cash flow associated with the system, and it allows to recover more than 85% of the global costs (CAPEX, OPEX and taxes).

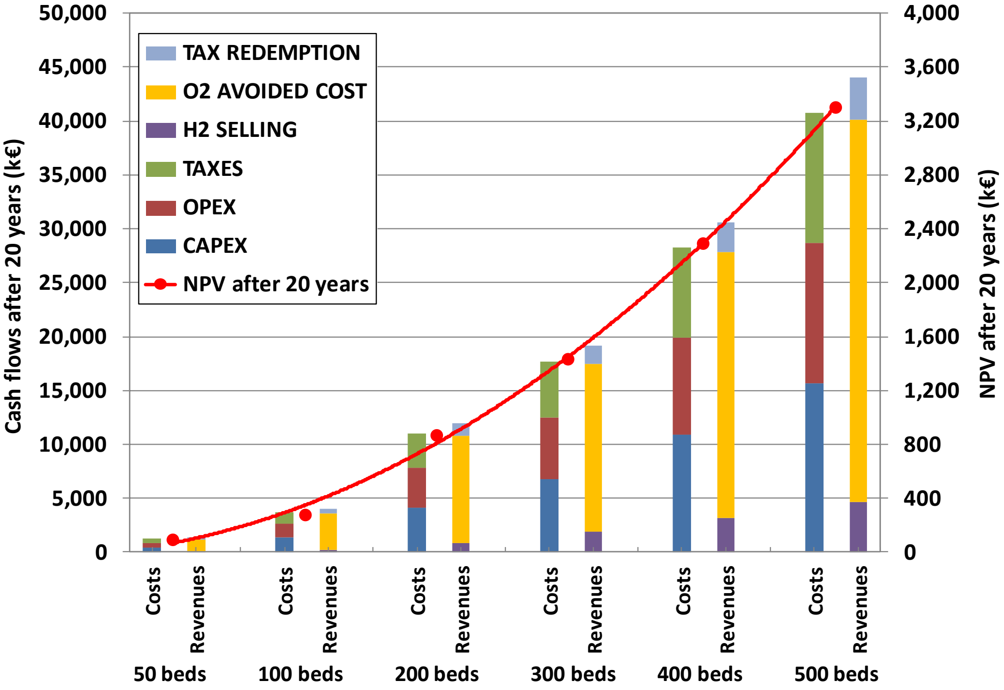

Figure 3: Cash flows calculated as a function of the number of hospital beds (at six fixed values) and corresponding net present values (NPV) after 20 years.

Conclusions

An economic analysis has been carried out to evaluate the attractiveness, for a medical centre that needs gaseous oxygen for healthcare, to produce it by a proprietary plant based on water electrolysis. The obtained results evidenced that the on-site production of this gas could be an interesting alternative compared to purchasing from the local gas resellers, if the market price of oxygen is higher than 3–4 €/kg, a value in line with today's Italian prices established by AIFA for ex-factory oxygen [15]. Besides, since in literature market prices of gaseous oxygen up to 7 €/kg are reported [16], we can conclude that the use of medical oxygen from on-site electrolysis plant should be considered as an economically feasible route for hospitals and medical centres. In this respect, even if it is based on a different technology (oxygen concentrators with molecular sieves), it is remarkable the case of Venaria Reale hospital (Piedmont), where a saving in the cost of oxygen in the order of 80% has been obtained through oxygen self-production [17].

In our case, the self-produced oxygen has a fourfold advantage: (i) it is economically convenient; (ii) it is obtained by a carbon-free technology; (iii) the hospital is (partially or fully) independent from external gas suppliers; (iv) oxygen production depends only on sun energy and not on electric grid availability, while hydrogen could be used for emergency energy backup and other purposes, if necessary.

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