Analysis of Seawater Electrolysis Technologies for Green Hydrogen Production

Marcelo Azevedo, Fátima Nunes Serralha, Rui Pedro Borges

Abstract**—**The main goal of this study is to understand the technical and economic feasibility of installing and operating a seawater desalination plant to supply water to a GW-scale water electrolysis process. That hydrogen production facility should be powered by dedicated renewable energy sources such as wind and solar photovoltaic. The announcement of significant investments in hydrogen production in the Sines region makes it relevant to perform a detailed analysis of the operation of this type of system that will present challenges with regards to the electricity and water supply. Water, in particular freshwater, is a scarce resource in the south of Portugal and the installation of an industry that uses large amounts of water as feedstock can place considerable pressure on existing reserves. Given the proximity of the region to the Atlantic Ocean, it is appropriate to evaluate the installation of a desalination plant and analyze the overall impact of that option on hydrogen production.

The levelized cost of desalinated water is estimated and compared to the cost of grid water. It has been found that the levelized cost of desalinated water is lower than the price of potable water supplied to the local industries by the Sines municipal water service (Águas de Santo André).

The impact on the levelized cost of hydrogen is analyzed. It is shown that the installation and operation of the desalination unit increases the levelized cost of hydrogen by less than 1%.

Seawater desalination is shown to be a technically viable alternative for producing the water feedstock for a GW-scale electrolysis facility that could alleviate pressure on local freshwater sources.

Keywords**—**Hydrogen, Electrolysis, Water, Desalination

I. INTRODUCTION

With the rising concerns about climate change there has been much effort in the investigation and development of sustainable energy production, to reduce the damage caused by energy generated from non-renewable sources. Ideally these new sustainable technologies reduce greenhouse gas (GHG) emissions caused by burning fossil fuels, which contribute to the increase of global temperature, and other pollutants that damage the environment, such as fine particles and carbon monoxide. The Paris Agreement has concluded that until year 2100 the effort should be put into reducing greenhouse gas emissions, to contain the global temperature increase within 1.5ºC above pre-industrial levels [1].

The European Commission stance towards the reduction of GHG emissions has been very strong over the last years. A new strategy that aims to cut down emissions, the European Green Deal [2], has been proposed for the European Union (EU) countries, using innovative, environmentally friendly technologies that will work on decarbonizing the energy sector.

In the EU there has been an increase in the use of renewable energies for energy production since 2005. In the EU, Portugal greatly uses renewable energies, making up a total use of 34.0% by 2020.

The current National Hydrogen Strategy (Estratégia Nacional para o Hydrogénio, ENH2) [3] intends to promote a gradual use of hydrogen in the Portuguese energy and economic systems by introducing the necessary requirements for the regulations, security, technology, and financing of the projects. The key initiatives of this strategy are the creation of a main project for green hydrogen production in Sines, the decarbonization of the heavy transport sector, the decarbonization of the national industry, the creation of a collaborative hydrogen laboratory, and the application to IPCEI (Important Projects of Common European Interest) Hydrogen.

To achieve such goals, a green hydrogen production industry must be established. The most ambitious project to date is the Sines Industrial Project. In Sines, a city in south of Portugal (coastal Alentejo), there was a thermoelectric coal plant that ended operation in the beginning of 2021. In response to that a hydrogen production plant based on water electrolysis will be built, with a total capacity of 1GW, sustained by Renewable energy sources (RES). This project is set to be completed by 2030 [3].

The water electrolysis process requires a relatively large amount of freshwater to produce industrial quantities of hydrogen. While sea water can be used for the water electrolysis it can quickly corrode the equipment, due to its dissolved salts. Therefore, to avoid using freshwater, a desalination process can be used to obtain fresh water for the water electrolysis. This is a viable option considering the proximity of Sines to the sea and the relative simplicity of introducing a desalination unit to an electrolysis unit. The

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proposed desalination unit should run on RES, much like the electrolyzers. As such it is necessary to ensure there is a source of water available, which can either come from the sea, from the public water supply or as a waste from industrial processes.

There are several mature desalination technologies widely used in large scale, such as distillation and reverse osmosis. The removal of impurities ensures that the electrodes won't be damaged by contact with the water. There are disadvantages over using these technologies, mainly the economic impact they may cause due to the equipment investment cost and because electricity is required for the desalination technologies (electric power is necessary for heating in the case of distillation, or to compress the water if reverse osmosis is used). However, these technologies have been improved and the electricity consumption has been reduced while the desalination processes have shown greater efficiencies [4].

From an economical point of view, it has been shown that the electricity demand to desalinate water are very low when compared to the actual process of electrolysis [5] and the cost of producing 1kg of desalinated water is much lower than the cost of producing 1kg of hydrogen.

The direct use of sea water for electrolysis has advantages, however there is limited research [6]. Brine electrolysis is possible and seems to be promising since it eliminates the need to desalinate sea water or use water from the public water supply, and doesn't produce undesirable by-products from desalination technologies, such as waste brine.

There are two types of desalination technologies, which can be divided as thermal methods and membrane methods. The desalination technologies have several phases, common to each method: the water is sourced, and then supplied to a pretreatment section and then to the desalination system, and finally the water is subjected to a post-treatment to improve quality. The brine that is a by-product of the desalination process is disposed, usually to the sea. New technologies have been developed and so there are currently very efficient desalination methods, both thermal-based and membrane- based. Examples of thermal methods are Multi-stage Flash Distillation (MSFD), Multiple-effect Distillation (MED) and Solar Distillation. Examples of membrane methods are Reverse Osmosis (RO) and Electrodialysis (ED).

Thermal-based desalination methods rely on the evaporation of water, producing water vapor, which is then condensed. The heat for the evaporation of water is usually generated from a thermal process such as fuel combustion or waste heat. The most efficient thermal technology is MSFD [7]. Membrane-based desalination methods rely on the filtration of water using semipermeable membranes, which are permeable to water molecules but not dissolved salts. The sea water is pressurized in some methods, such as RO to force the water through the membrane. The most efficient membrane technology is RO [7]. The electrical energy required for MSFD and RO is similar; however, MSFD also requires thermal energy which increases the electricity needed, unless the MSFD unit is coupled in a CHP system. This means that between the two technologies MSFD may require the most energy. However, MSFD can produce water in higher quantities, compared to RO. These technologies are compared in table 1.

TABLE I
COMPARISON BETWEEN MSFD AND RO TECHNOLOGIES

Technol.	Average capacity [m^3/day]	Electricity Consump. [kWh/m^3]	Thermal energy Consump. [KJ/kg]	Water pressure [atm]	Water cost [€/m^3]
MSFD	23000-528000 [8]	4-6	190-390	0.01-140,41	0.48-1.49 [9]
RO	1000-320000 [9]	3-5.5	-	54-67 [10]	0.06-1.46 [9]

Since MSFD and RO are currently the most efficient desalination methods, these technologies will be used in this study.

II. METHODOLOGY

A. *Energy Modelling and Calculations*

Energy PLAN is one of such energy modeling tools, free for download, and it was used in this study to simulate the operation of a hydrogen production plant, the associated desalination system and to estimate the quantities of water produced by the electrolyzers, the amount of energy required for the desalination process.

B. *Hydrogen Production Scenarios and Desalination Unit*

In that work the operation of the hydrogen plant is simulated by considering different weather conditions and plant configurations. The electrolyzer electric input power ranges from 1 GW to 3 GW and the energy is supplied by either solar PV panels, wind turbines, or a combination of both, whose capacity can range from 1 GW to 3 GW. The system can either consume or inject electricity on the national electricity grid, depending on the operation mode. The feedstock water was supplied by the local grid and the focus of the study was on its contribution to the levelized cost of hydrogen.

Different weather conditions have also been considered, to better analyze the RES performance. Since there is data regarding the performance of solar PV and wind energy from 2011 to 2019, it was possible to conclude that 2012 is a sunny year, with higher solar PV energy production, and 2016 is a windy year, with higher wind energy production.

Two main inputs are vital for the functioning of the hydrogen production plant: energy and water. The energy can either be sourced from the grid or it can be produced, or in certain cases it may come from those two sources, and the water can either be sourced from the public water supply or from desalination. If desalination is used, it is necessary to provide energy for the process. In periods of severe drought, the desalinated water could be injected to the public water supply, if hydrogen production is halted.

In this study it was considered three operating modes: B, C and E.

Operating mode B – Hydrogen production in s self-sufficiency with a single RES

In this mode, the energy required for the electrolyzers is provided only by either solar PV or wind power and is not expected to withdraw electricity from the national grid to feed the electrolyzers. Therefore, there is hydrogen production if energy is being generated by the RES, and part of the energy will also supply the desalination unit. In case there is excess electricity, it will be injected to the national grid. In these cases, to avoid overcharging, the electrolyzers will work at a maximum of 50% above their nominal capacity, for shorts periods of time [11]. In case there is not enough electricity production, the electrolyzers and desalination units will not work.

Operating mode C – Hydrogen production in a self-sufficiency regime with a combination of RES

In this mode, the energy required for the electrolyzers is provided only by a combination of RES, solar PV and wind power. This mode has the same specifications as mode B however the combination of RES makes the system less prone to intermittence, since the wind turbines are expected to work during the night when the solar panels aren't producing energy.

Operating mode E – Hydrogen production in a self-sufficiency regime with a combination of RES and a minimum electrolyzer load of 20% of nominal capacity

In this mode the electrolyzers work at a minimum load value of 20% of their nominal capacity. This means that the system will import energy from the national grid if the electricity production falls below the minimum required for the electrolyzer load. The energy is produced by either solar PV and wind power. The desalination unit is powered either by the RES or the national grid, depending on the amount of energy that is generated. Like the other modes, the electrolyzers are restricted to work at a maximum load of 50% above their nominal capacity.

The dissociation of the water molecule in the electrolyzer is not fully efficient and that should be taken in consideration for estimating the amounts of water necessary for the operation. By analyzing the characteristics of a few commercial electrolyzers we determined that, on average (and only for the electrolyzers that were analyzed), the water consumption is double the stoichiometric amount necessary to produce a given quantity of H_2, that is, the water dissociation efficiency is 50%.

C. Technical analysis

Each combination was simulated with different specifications to obtain data on the desalination. Such information allowed an accurate comparison of values to determine the energy implications of using desalination. The minimum, maximum and average hourly values of water that the electrolyzers require were also calculated. Such information was necessary in order to understand what is the desalination plant capacity for each combination.

A nomenclature was used to specify each of the combinations, according to its operating mode, weather condition, electrolyzer power and RES power. Figure 1 shows one example the nomenclature for the combination.

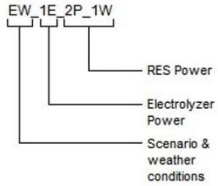

Fig. 1 – Example of nomenclature of a combination.

In this combination we have operating mode E in a windy year (w), having an electrolyzer power of 1 GW (1E) and a RES power of 2 GW photovoltaic (2P) and 1 GW of wind power (1W). The nomenclature is shorter for combinations which only use one RES, such as Bs_2E_3P (operation mode B in a sunny year with 2000 MW electrolyzer power and 3000 MW solar photovoltaic). Of the 144 combinations that were designed inicialy [11], 4 were chosen.

TABLE II
COMBINATIONS USED THE PRODUCT ANNUAL H2 PRODUCTION X INVESTMENT PRODUCTIVITY AND THEIR SPECIFICATIONS

Discount		Combination	Electrol. power (GW)	Wind power (GW)	Solar PV power (GW)	Exchanges with national grid
Electr	RES					
3%	3%	Bs2E3P	2	0	3	N
		Cs1E2P1W	1	1	2	N
		Ew1E2P1W	1	1	2	Ye
6%	6%	Cw1E2P1W	1	1	2	N

The values for the discount rate, interest rate, specific Operation and Maintenance (O&M) and equipment lifetime were based on articles covering the economic evaluation of seawater desalination [12]. For the electrolyzer and RES technologies the values were adapted from the EU Reference Scenario. Table 3 shows the CAPEX and OPEX values of the electrolyzer and RES, in €$_{2015}$ and table 4 the variable costs.

TABLE III
CAPEX AND OPEX OF THE VARIOUS TECHNOLOGIES CONSIDERED IN THIS STUDY [13].

	CAPEX	OPEX	Period
PEM electrolyser	0.540 M€2015/MW	3.2% of CAPEX/year	50000 hours
Solar PV	0.380 M€2015/MW	2.3% of CAPEX/year	25 years
Wind	1.000 M€2015/MW	1.2% of CAPEX/year	25 years
RO desalination	0.45 M€2015	2% of CAPEX/year	20 years
MSFD desalination	0.45 M€2015	2% of CAPEX/year	20 years

TABLE IV:
VARIABLE COSTS (€)

Variable costs (€)	
Electricity price	30,79 €/MWh
Access tariff for injection in transmission network	0,49 €/MWh
Average tariff on access to electricity network	22,70 €/MWh
Water (drinking quality)	1.89 €/m3
Water grid access tariff	19777 €/year

III. Results

A. Technical analysis

The technical results will show the viability of the desalination and storage unit of each scenario and combination. From the analysis of this hourly profile, it is possible to extract the maximum hourly production during the year. Table 5 shows the estimates of hydrogen production of each combination. The performance of the desalination unit is analyzed, according to each combination and taking into consideration the fact that the water dissociation efficiency of the electrolyzer is 50%.

TABLE V
ESTIMATES OF ANNUAL OF HYDROGEN PRODUCTION AND MAXIMUM PRODUCTION ANNUAL WATER CONSUMPTION OF EACH COMBINATION

Combination	Annual hydrogen production (kt/a)	Maximum hourly production (kt/h)	Annual water consumption (m3/y)
Bs2E3P	116.899	0.056	10.5×10^5
Cs1E2P1W	93.217	0.033	8.3×10^5
Cw1E2P1W	96.366	0.033	8.6×10^5
Ew1E2P1W	95.992	0.033	8.6×10^5

Having the water requirements of each combination, two different operation modes of the desalination unit were established. The first operation mode defined to be a continuous operation mode of the desalination unit, where the water supply needs of the electrolyzer are instantaneously supplied by the desalination unit, using energy either from the RES or the national grid. For the second operation mode we start by considering the electricity consumption of the electrolyzer plant without the desalination unit. We then impose the constraint that the same amount of electricity will have to be used to feed both the electrolyzer and the desalination unit, implying a reduction in hydrogen production.

The electricity consumption of the desalination plant for each combination was calculated. This value can be obtained by considering the hourly water demand and the efficiency of the desalination plant, which is set to be an average of 5 kwh/m^3, as Table 1 shows. Table 6 shows the annual electricity consumption of the desalination plant for each combination in comparison to the annual electricity consumption of the electrolyzer.

Because of the low desalination unit electricity consumption, there is a relatively large difference of energy consumption when compared to the electricity that the electrolyzer requires. Therefore, the energy requirements for the desalination are substantially lower than the electrolyzer, over 1000 times lower in some cases.

TABLE VI
ELECTRICITY CONSUMPTION OF THE DESALINATION PLANT FOR EACH COMBINATION IN COMPARISON TO THE ELECTRICITY CONSUMPTION OF THE ELECTROLYZER, IN GWH/YEAR

Combination	Electricity consumption of desalination plant, Gwh/year	Electricity consumption of electrolyzer, Gwh/year
Bs2E3P	10.190	5337.862
Cs1E2P1W	8.800	4256.501
Cw1E2P1W	8.866	4400.277
Ew1E2P1W	11.217	4383.206

Figure 2 shows the hourly values of the electricity exports and the electricity consumption of the desalination unit in a week of the Bs2E3P and Cs1E2P1W combinations, as example.

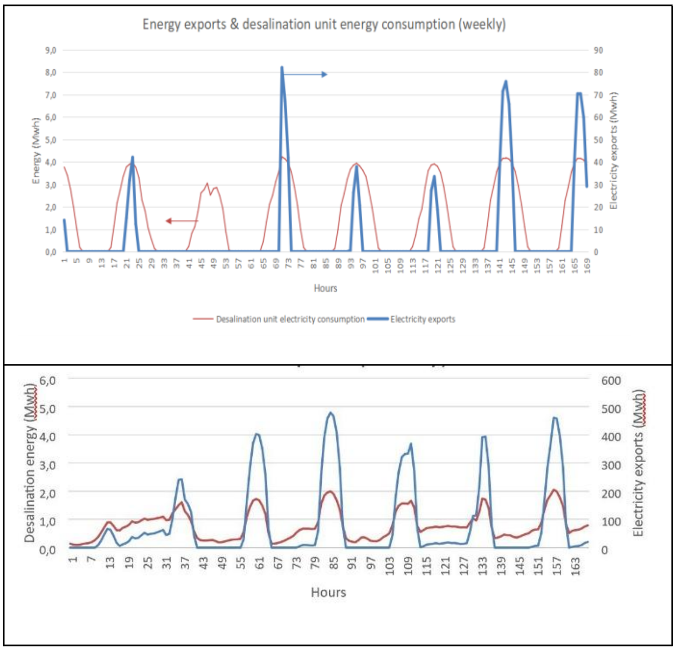

Fig 2 – Electricity exports and electricity consumption of the desalination unit throughout a week, of the combination Bs2E3P and Cs1E2P1W, respectively.

The lack of energy for desalination in certain periods has made it necessary to calculate how much electricity the desalination unit will withdraw from the national grid. This was done by calculating the total electricity the desalination unit uses in periods where the energy exports are 0, which are during the darker hours, that usually account for 9 hours in one day. Table 7 shows the electricity the desalination unit uses from the grid.

The second operation mode is set to work at a reduced hydrogen production to avoid energy consumption from the energy grid by the desalination unit. In this mode, the total electricity consumed by the electrolyzer is now shared between the electrolyzer and desalination unit and consequently, the hydrogen production is reduced.

TABLE VII
ELECTRICITY CONSUMPTION OF THE DESALINATION PLANT, THE AMOUNT OF ELECTRICITY USED FROM THE GRID AND ITS PERCENTAGE FOR EACHCOMBINATION, IN GWH/YEAR

Combination	Electricity consumption of desalination plant, Gwh/year	Electricity consumption from grid, Gwh/year	% from grid
Bs2E3P	10.190	5.582	54.779
Cs1E2P1W	8.800	0.760	8.636
Cw1E2P1W	8.866	1.560	17.595
Ew1E2P1W	11.217	0.800	7.132

Although the hydrogen production is changed, the values are not significantly reduced, because of the low energy requirements of the desalination unit. Table 8 shows the estimates of reduced hydrogen production of each combination.

TABLE VIII
ESTIMATES OF HYDROGEN PRODUCTION, ELECTROLYSE ELECTRICITY, WATER AND DESALINIZADOR ELECTRICTY REQUIREMENTS FOR THE SECOND OERATION MODE OF EACH COMBINATION

Combin.	H2 product. (kt/y)	Electrol electric (Gwh/y)	Water needs (m3)	desalinize electricity (Gwh/y)
Bs2E3P	116.79	5332.77	2.102×10^6	10.170
Cs1E2P1W	93.12	4252.11	1.676×10^6	8.781
Cw1E2P1W	96.27	4395.85	1.732×10^6	8.848
Ew1E2P1W	95.87	4367.60	1.725×10^6	11.188

B. Economic analysis

The CAPEX value of each combination was calculated by considering the desalination price for the size of the desalination unit (a value of 1.72 €/m^3 was assumed, taking into consideration the price range of medium sized RO plants of 0.262-1.72 €/m^3) [12], the construction cost [14] and the desalination plant capacity. This value is necessary for further calculations. The construction costs were estimated from the capital cost of other desalination plants study [15].

Table 9 shows the capacity and CAPEX for desalination of each combination, considering a desalination plant cost of 1.72 €/m^3.

TABLE IX
DESALINATION PLANT CAPACITY, CAPEX AND CONSTRUCTION COSTS VALUES FOR EACH COMBINATION

Combination	Capacity (m^3/y)	CAPEX (€)	Construction costs (€)
Bs2E3P	8968112.64	15425154	8638872
Cs1E2P1W	5241412.80	9015230	5026012
Cw1E2P1W	5363861.76	9225842	5143429
Ew1E2P1W	5270400.00	9065088	5053808

The CRF of the combinations was calculated by assuming an interest rate of 3% for the desalination unit over the course of 20 years, which is 0.067. This value is necessary for calculating the LCOW.

The annualized investment cost was calculated for each combination. The values are different from each combination due to the CAPEX values. Table 10 shows the annualized investment costs of each combination.

TABLE X: ANNUALIZED INVESTMENT COSTS OF EACH COMBINATION

Combination	Annualized investment costs (€)
Bs2E3P	1036813
Cs1E2P1W	605965
Cw1E2P1W	620122
Ew1E2P1W	609316

Unlike the CAPEX and annualized values, the LCOW value of each combination varies depending on the operation mode. The energy costs of each combination of the first operation mode were calculated by multiplying the electricity that the combination uses (Table 8) by the electricity price and tariff access price (Table 3). These values are considered variable costs. The energy costs of the second operation mode are zero. Figure 3 shows the LCOW values for each combination of the first operation mode.

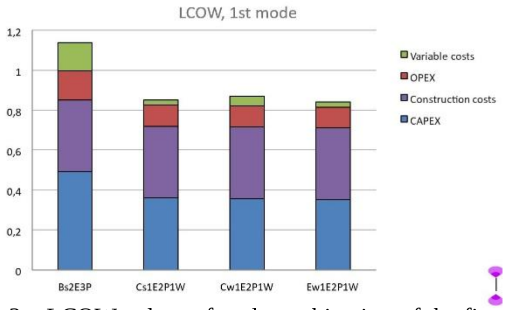

Fig. 3 – LCOW values of each combination of the first operation mode, in €/m^3.

Figure 4 shows the LCOW values for each combination of the second operation mode.

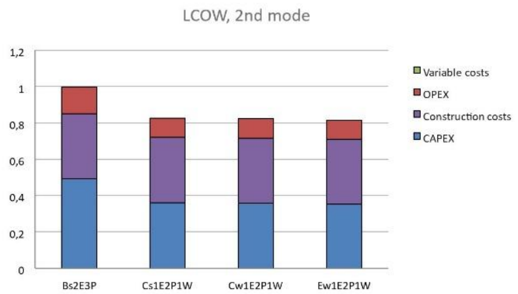

Fig. 4 – LCOW values of each combination of the second operation mode, in €/m^3.

The maximum LCOW value is roughly 1.14 €/m^3, which belongs to Bs2E3P on the first operation mode. The remaining LCOW values are mostly close to 0.85 €/m^3 on either operation modes. The LCOW values obtained for the two operation modes are significantly lower than the value of 2.0571 €/m^3 charged for potable water by the local water utility (Águas de Santo André) to industrial customers that consume more than 150 m^3 per month [16]. The value charged for industrial water is 0.4223 €/m^3. So, the cost of desalinated water is within the range of utility water prices. Furthermore, desalination would make use of a much more abundant resource (sea water) than the fresh water supplies in the region. This is an expected result, as the desalination unit benefits from the energy produced by the RES, decreasing costs.

It is important to understand the economic impact the desalination plant has; namely how much it changes the LCOH (Levelized Cost of Hydrogen). The LCOH value is obtained by dividing the total annual costs of the plant by the quantity of hydrogen produced [16]. While the hydrogen production stays the same, only changing slightly on the second operation mode, the total annual costs increase with the addition of a desalination plant.

Table 11 shows the LCOH value before the addition of the desalination plant, the calculated annual costs and the adjusted LCOH value.

TABLE XI
LCOH VALUES AND ANNUAL COSTS

Combination	Annual cost (M€) [11]	LCOH (€/kg) [16]	Adjusted annual cost (M€)	Adjusted LCOH (€/kg)	% increase in LCOH
BS2E3P	174.03	1.487	175.066	1.497	0.672
CS1E2P1W	152.29	1.637	152.895	1.644	0.428
Cw1E2P1 W	155.78	1.675	156.400	1.681	0.358
EW1E2P1 W	162.86	1.679	163.469	1.702	1.370

The LCOH value does not change significantly, due to the low annual cost of the desalination plant. The LCOW and LCOH values differ since the LCOH includes the investment costs of the RES.

IV. Conclusion

It was concluded that regardless of the operation mode, the desalination unit has a very low energy consumption profile, especially when compared to the electrolyzer, as the energy consumption of the desalination unit is about 500 times lower than the electrolyzer for all the configurations.

One important contribution for the viability of such desalination plant is the fact that it uses energy, partially or in its entirety, from the renewable energy park that is modelled for the electrolyzer of each configuration. While a desalination plant of such dimensions would not require a large-scale renewable energy park such construction, even if small-scale, would make the project less sustainable.

For the first operation mode, the LCOW is in the range of 0.840-1.140 €/m^3. The first operation mode must consider variable costs which consist of energy withdrawals from the grid, which increases costs.

For the second operation mode, the LCOW is in the range of 0.816-0.998 €/m^3. The LCOW of the second operation mode is generally lower than the LCOW of the first operation mode because in the present case there is no use of grid electricity and therefore the variable costs are lower.

The LCOW values obtained for the two operation modes are significantly lower than the value of 2.0571 €/m^3 charged for potable water by the local water utility to industrial customers that consume more than 150 m^3 per month. The value charged for industrial water is 0.4223 €/m^3. So, the cost of desalinated water is within the range of utility water prices. Furthermore, desalination would make use of a much more abundant resource (seawater) than the freshwater supplies in the region.

The other factor to consider is how the desalination unit would add to the cost of production of hydrogen. Since the LCOH is calculated from the annualized costs, the adjusted LCOH is obtained by including the desalination annualized costs to the H_2 production plant annual costs. Overall, the installation of the desalinator increases the LCOH by less than 1%. The study has demonstrated that the addition of a desalination unit to the H_2 production plant would be viable.

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