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Modularisation Analysis for Scaling Hydrogen Production: High-Power Single-Electrolyser vs. Multiple-Smaller-Electrolyser Plants

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Abstract

The deployment of electrolysis-based hydrogen technology requires identifying the advantages and disadvantages of scaling hydrogen production plants and determining the limits of the scaling-up process. Until now, experience has been demonstrated with electrolysers of tens and hundreds of kilowatts, but electrolysers in the tens of megawatts range are still closer to being prototypes than commercial products. Additionally, challenges such as maintenance, reliability, long-term operation, and investment recovery time arise in parallel as the scale increases. This raises the question of what is more suitable: installing a single high-power electrolyser or a modular plant composed of multiple smaller electrolysers? This paper addresses that question from both a technical and an economic perspective. Accordingly, it presents a study identifying the degree of modularisation that optimises the technical and economic performance of a large-scale hydrogen production plant. The results show that configurations with a higher degree of modularisation (based on multiple smaller electrolysers) exhibit a better technical performance and lower degradation. However, configurations with a lower degree of modularisation are more competitive in terms of costs. When combining technical and economic criteria, the results show that solutions based on a medium–low degree of modularisation are the most suitable. The advantages are lower replacement costs and uninterrupted hydrogen production. This study also recommends embracing modularisation to prevent a dependence on a single high-power electrolyser.

Keywords: electrolysis-based hydrogen production; modularisation analysis; techno-economic study

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1. Introduction

The challenges posed by energy decarbonisation make it essential to integrate green energy carriers (e.g., hydrogen produced by electrolysis technologies) to compensate for the intermittency of renewable energies [1]. To achieve this goal, the large-scale deployment of hydrogen production, storage, and final use technologies is necessary [2–7], as demonstrated by the large-scale projects already underway around the world (HyDeal Ambition, ENERGIX, EnergiePark Mainz, Hydrogen Pilot Storage, North H_2, AquaVentus, etc.) [8,9]. However, the implementation of these projects faces serious barriers, such as the high costs of hydrogen production, the absence of a well-established supply and demand market, regulatory uncertainty [10,11], and the challenge of overcoming the high costs associated with these technologies. In this regard, previous studies have addressed the issue of hydrogen production costs. In [12], a 10 MW polymer exchange membrane (PEM) electrolyser operates under a dynamic operating regime (i.e., with variable current densities, as opposed to a constant operating regime) to minimise hydrogen production costs. In [13], the cost reduction of 20 MW alkaline and 9.75 MW PEM electrolysers for an advanced stack design, based on a larger active area (2.6 and 0.5 m^2, respectively), is analysed. This allows for higher current densities with fewer materials, positively affecting the overall cost. Other studies (e.g., [14]) estimate the influence of capital expenditure (CAPEX) for 180 MW photovoltaic (PV) systems, a 171 MW alkaline electrolyser, and an 11-tonne hydrogen storage tank, as well as the influence of the price of electricity on the levelised cost of hydrogen (LCOH). On the other hand, research carried out in [15,16] studies the influence of geolocation on the cost of green hydrogen production, while [17] estimates the optimal size (57% of the nominal power of a PV field and 89% of the nominal power of a wind field) of an electrolyser that minimises the cost of hydrogen production in a green hydrogen plant. In addition, in [18], cost reductions per unit of power for alkaline and PEM electrolysers are estimated based on the size (considering power ranges between 10 kW and 1 GW) of the electrolyser for the years 2015 and 2030. Moreover, in [19], the reduction in LCOH for a 12 MW alkaline electrolyser is estimated based on the ratio between installed renewable power and electrolyser power.

However, no research has specifically focused on technical and economic studies comparing the performance of a hydrogen production plant built from a single high-power electrolyser with one built from multiple smaller electrolysers. In fact, the few studies [20,21] that refer to multi-stack electrolyser systems focus on analysing the performance of the system, rather than its economic behaviour. Indeed, large-scale green hydrogen production plants using a single high-power electrolyser can be found in China: 150 MW alkaline electrolyser [22]; in Finland: 1 GW PEM electrolyser [23]; in Egypt: 100 MW PEM electrolyser [24]; and in Spain: 1 MW PEM electrolyser in the north of the country [25].

But is a single high-power electrolyser technically and economically feasible for large-scale green hydrogen production plants or is it preferable to modularise the plant with multiple smaller electrolysers? To answer that question, this paper presents a technical–economic study comparing both configurations. This study analyses the influence of modularisation and energy management systems (EMSs) in a green hydrogen production plant. Additionally, this study compares the economic impact, taking into account the acquisition costs, operation and maintenance (O&M) costs, and replacement costs associated with modular configurations and the implementation of one EMS or another. Regarding the scientific literature, this paper studies the optimal degree of modularisation of a hydrogen production plant, distinguishing between alkaline (ALK) and PEM technologies, which reduces the CAPEX of a green hydrogen plant (understood as the number of electrolysers that reduce the total costs associated with the plant), as well as the economic impact of the EMS implemented on the green hydrogen production plant.

Table 1 summarises the main contributions of the authors' proposal in relation to the scientific literature and highlights the main novelties of this paper.

Table 1. Comparison between the authors' proposal and the scientific literature analysed.

Reference	Modularisation Study	Modularity Impact on CAPEX Reduction	Modular Green Hydrogen Production Plant Economic Study	Economic Impact Based on EMS	Discerning ALK and PEM Technologies
[12,14–16]	No	No	No	No	No
[13]	No	Yes	No	No	No
[17]	No *	No	No	No	No
[20,21]	Yes	No	No	No	No
Authors' proposal	Yes	Yes	Yes	Yes	Yes

* The optimal size of electrolysis plants is studied, but not the optimal degree of modularisation.

2. Materials and Methods

To carry out this research, the economic impact of a hydrogen production plant, depending on the nominal power of each electrolyser it contains, must first be addressed. In this study, an electrolyser is considered to consist of the electrolyser stack and its corresponding balance of plant (BoP), excluding hydrogen compression and storage systems from the analysis. The system analysed is assumed to be connected exclusively to a photovoltaic field, with no connection to the electricity grid. Equation (1) (derived from [18]) allows the unit cost of a hydrogen production plant to be calculated.

$$C = \left(k_0 + \frac{k}{Q} Q^{\alpha}\right) \cdot \left(\frac{Y}{Y_0}\right)^{\beta} \tag{1}$$

where

C: unit cost of the hydrogen production plant (€/kW);
k_0, k: fitting constants;
Q: nominal capacity of the electrolyser module (kW);
Y: plant installation year;
Y_0: reference year (2020);
α: scaling factor (dimensionless, indicating cost reduction based on power capacity);
β: learning factor (dimensionless, indicating cost reduction over time).

In turn, the parameters of Equation (1) depend on the electrolysis technology considered, alkaline or PEM (Table 2).

Table 2. Parameters influencing the unit cost of the electrolyser [18].

Parameter	ALK	PEM
k	9917.09	8083.93
k_0	257.30	500.73
α	0.649	0.622
β	−27.33	−158.9

Figure 1 shows the relationship between the unit cost of the electrolyser (€/kW) and its nominal power, differentiated by technology.

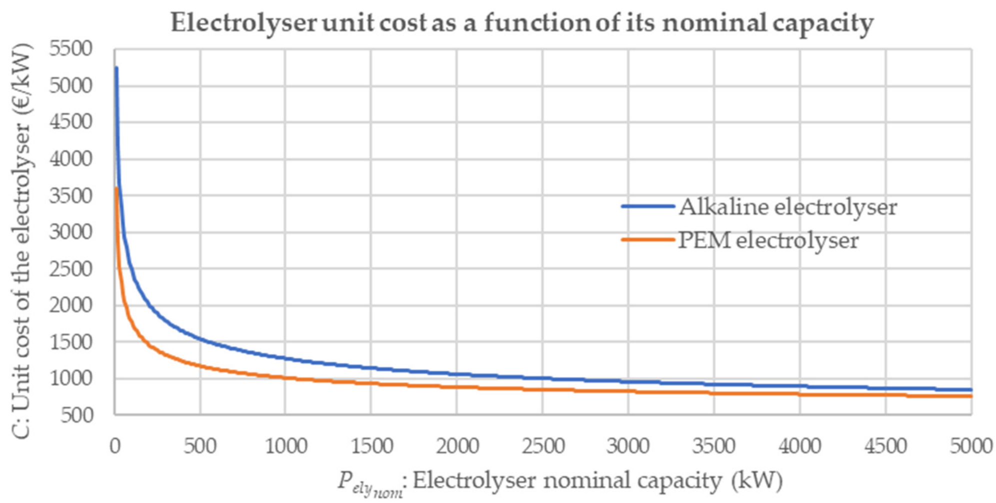


Figure 1. Electrolyser unit cost based on its nominal power.

This graph, obtained from Equation (1), shows the unit costs of electrolysis technologies in line with the data provided in [26] (especially if the reference year in Equation (1), i.e., 2020, is taken as the year of study), allowing certain trends to be observed. As can be seen, up to a nominal power of 1000 kW, the unit cost decreases almost exponentially. Above 1000 kW, the rate of decrease slows considerably. On this basis, 1 MW is considered to be the critical threshold for evaluating modularisation in hydrogen production plants. Five 1 MW configurations will then be considered: configuration 1 consists of a single high-power electrolyser, configuration 2 has two 500 kW electrolysers, configuration 3 consists of four 250 kW electrolysers, configuration 4 has ten 100 kW electrolysers, and configuration 5 has twenty 20 kW electrolysers (Table 3).

Table 3. Modular configurations to be studied.

	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5
Number of Electrolysers	×1—1 MW EL1	×2—500 kW EL1-EL2	×4—250 kW EL1-EL4	×10—100 kW EL1-EL10	×20—20 kW EL1-EL20

For operation, two alternatives for the EMS will be considered:

- EMS 1 is based on available power criteria. It analyses the available power to determine whether the electrolyser or electrolysers should be started up. That is, for example, in configuration 2 (×2—500 kW), if the available power is lower than 500 kW, electrolyser EL1 is ON, and EL2 is OFF. However, if the available power is greater than 500 kW, both EL1 and EL2 are ON.
- EMS 2 is based on operating hours' balance. It distributes the operating hours of each electrolyser equally. In other words, given that the hydrogen production plant is supplied by a photovoltaic field located in Huelva, in southwestern Spain, the average daily duration of solar irradiation is 12 h. Therefore, EMS 2 puts EL1 ON from hour 1 to hour 6, and EL2 ON from hour 7 to hour 12.

The next section details the configurations studied and the EMS alternatives for modularisation analysis.

3. Configuration Design: Developed Architectures

This section describes the configurations listed in Table 3 and the EMSs implemented in each of them.

3.1. Configuration 1: Modularisation Level 1

This configuration consists of building a 1 MW hydrogen production plant using a single electrolyser connected to a PV field via the appropriate power electronics (Figure 2). The operating mode is very simple: whenever there is PV production, P_{PV}, it is transferred to the electrolyser, P_{Ely}, via the power electronics, taking into account losses $\eta_{DC/DC} = 3\%$. At this stage of conceptual design, it is common to assume very low losses and focus on the performance of the main component (electrolyser and balance of plant), avoiding additional complexities that do not significantly alter the comparison between configurations or the overall magnitude of consumption. Additionally, the purpose is to compare modular alternatives or manage energy on a large scale, as their relative impact is marginal and does not affect the trends in the results or preliminary decision-making.

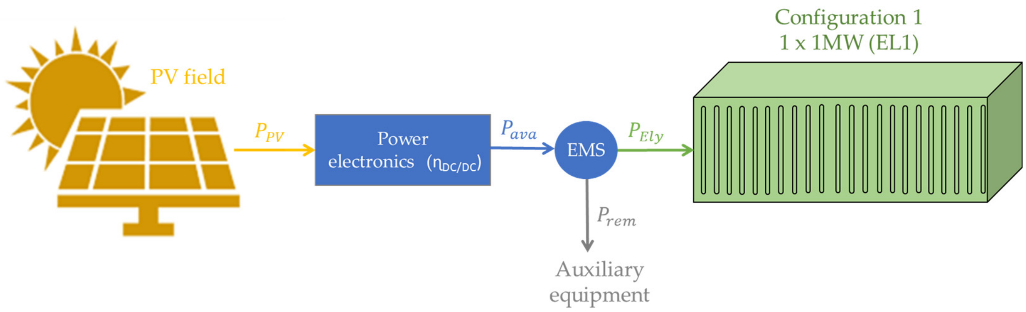


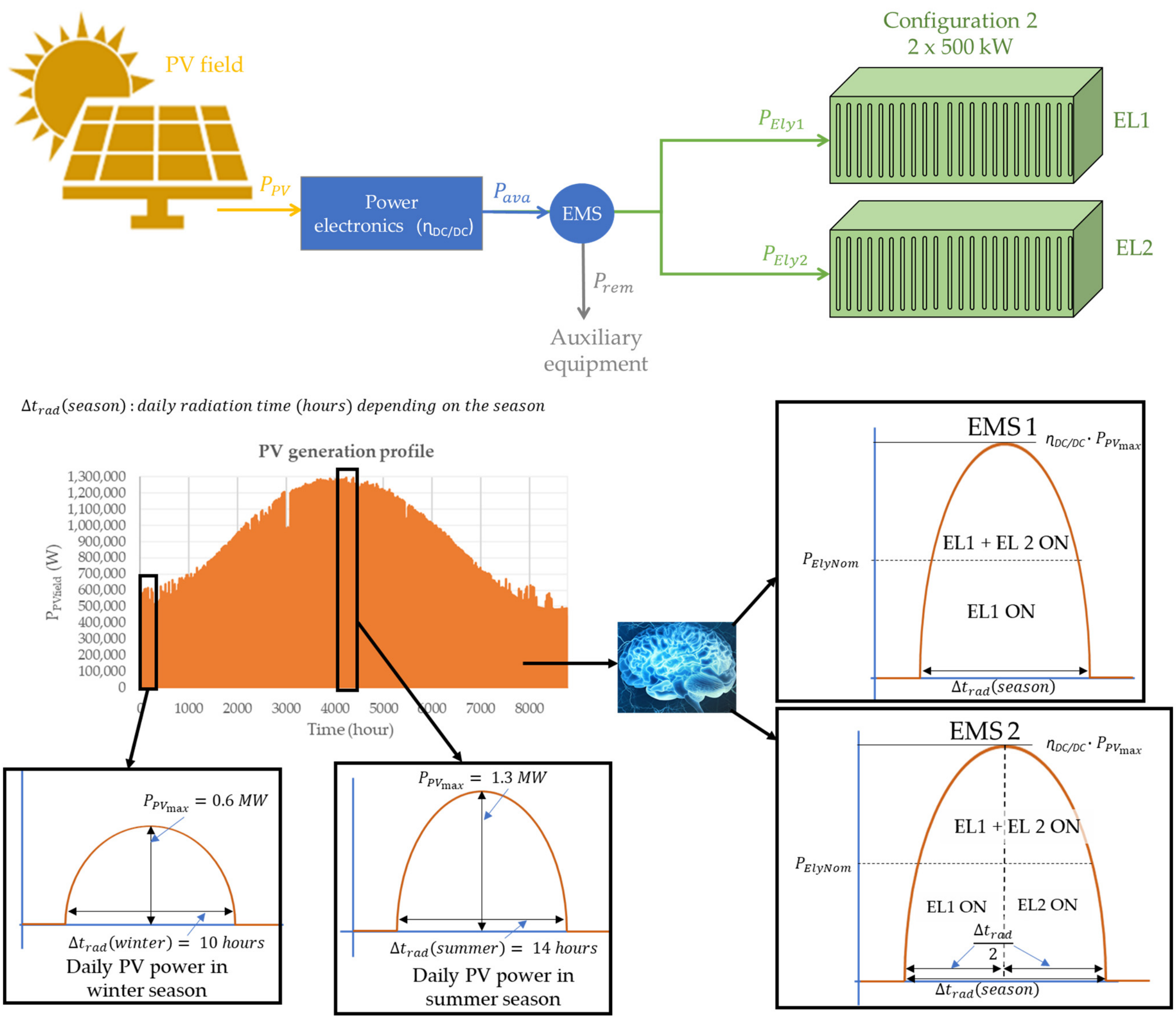
Figure 2. Configuration 1: ×1—1 MW-electrolyser plant.

If PV production exceeds the nominal power of the electrolyser ($P_{ElyNom} = P_{H2plant} = 1$ MW), the available power, $P_{ava} = \eta_{DC/DC} \cdot P_{PV}$, will be supplied to the electrolyser until it reaches the nominal operating point $P_{Ely} = P_{ElyNom}$. The remaining power, $P_{rem} = P_{ava} - P_{ElyNom}$, will then be diverted to auxiliary equipment. In terms of minimum load rates, alkaline and PEM electrolysis technologies have minimum load rates of 20% and 5%, respectively [27]. This means that the EMS starts up the electrolyser when $P_{ava} \geq$ 20% or 5% of $P_{Ely_{Nom}}$, respectively.

3.2. Configuration 2: Modularisation Level 2

In configuration 2, the 1 MW hydrogen production plant consists of two 500 kW electrolysers ($P_{ElyNom} = 500$ kW) (Figure 3a). Then, under the EMS1 strategy (Figure 3b), if $P_{ava} \leq P_{ElyNom}$, EMS 1 only operates EL1, and it keeps EL2 switched off. When $P_{ElyNom} < P_{ava} \leq P_{H2plant}$, EMS 1 operates electrolysers EL1 and EL2.

On the other hand, EMS 2 (Figure 3c) aims to balance the number of operating hours of each electrolyser. To do this, EMS 2 takes into account the hours of irradiation. Taking into account the geographical location of the authors' institution (University of Huelva, southwest Spain), the average daily sunshine hours is 12 h (ranging from 10 h in winter to 14 h in summer), according to preliminary studies carried out by the authors [28,29]. If the available power is $P_{ava} \leq P_{ElyNom}$, EMS 2 operates EL1 during hours 1 to 6, and EL2 during hours 7 to 12 (considering hour 1 as the moment when PV production begins). When $P_{ElyNom} < P_{ava} \leq P_{H2plant}$, EMS 2 operates both EL1 and EL2 electrolysers.



(**a**)

EMS 1. Electrolyser in operation. Criteria: available power.

Available power	Electrolyser in operation
$P_{ava} \leq P_{ElyNom}$	EL1 ON
$P_{ElyNom} < P_{ava} \leq P_{H2plant}$	EL1 + EL2 ON

(**b**)

EMS 2. Electrolyser in operation. Criteria: operating hours balance.

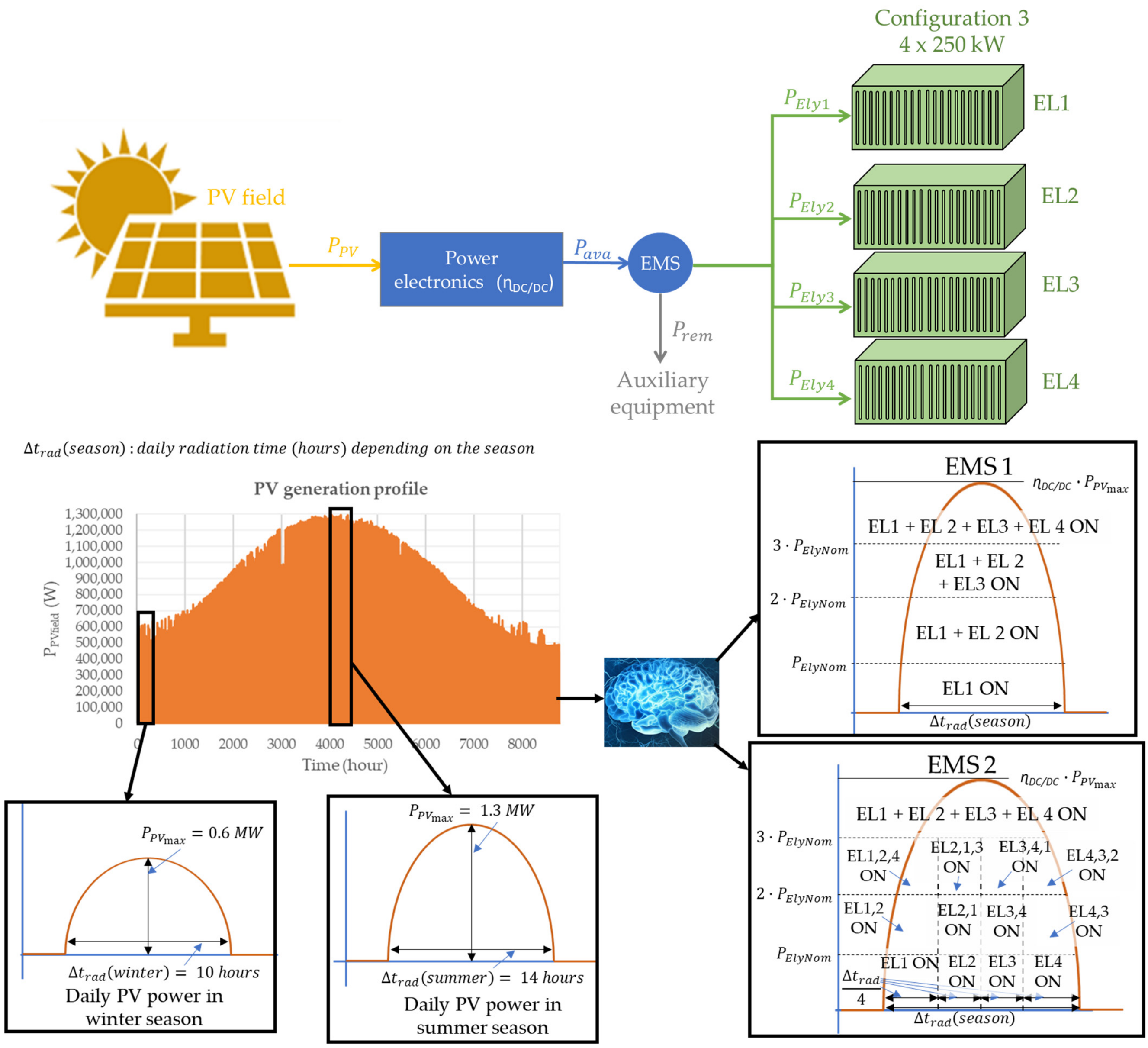
	Daily irradiance hour (h)	
Available power	**1–6**	**7–12**
$P_{ava} \leq P_{ElyNom}$	EL1 ON	EL2 ON
$P_{ElyNom} < P_{ava} \leq P_{H2plant}$	EL1 + EL2 ON	EL1 + EL2 ON

(**c**)

Figure 3. (**a**) Configuration 2: ×2—500 kW electrolyser plant; (**b**) EMS 1 based on available power; (**c**) EMS 2 based on operating hours balance.

3.3. Configuration 3: Modularisation Level 4

Configuration 3 (Figure 4a) consists of a hydrogen production plant with a total power of 1 MW, comprising four 250 kW electrolysers, P_{ElyNom} = 250 kW. As in configuration 2, a distinction must be made between EMS 1 and EMS 2. EMS 1 is based on the nominal power, and then, if $P_{ava} \leq P_{ElyNom}$, EMS 1 starts up electrolyser EL1. When $P_{ElyNom} < P_{ava} \leq 2 \cdot P_{Ely_{Nom}}$, electrolysers EL1 and EL2 are started up, while if $2 \cdot P_{ElyNom} < P_{ava} \leq 3 \cdot P_{Ely_{Nom}}$, EL1, EL2, and EL3 are activated. If $P_{ava} > 3 \cdot P_{Ely_{Nom}}$, all four electrolysers are activated (Figure 4b).



(**a**)

EMS 1. Electrolyser in operation. Criteria: available power.

Available power	Electrolyser in operation
$P_{ava} \le P_{ElyNom}$	EL1 ON
$P_{ElyNom} < P_{ava} \le 2 \cdot P_{ElyNom}$	EL1 + EL2 ON
$2 \cdot P_{ElyNom} < P_{ava} \le 3 \cdot P_{ElyNom}$	EL1 + EL2 + EL3 ON
$3 \cdot P_{ElyNom} < P_{ava} \le P_{H2plant}$	EL1 + EL2 + EL3 + EL4 ON

(**b**)

EMS 2. Electrolyser in operation. Criteria: operating hours balance.

	Daily irradiance hour (h)			
Available power	1 – 3	4 – 6	7 – 9	10 – 12
$P_{ava} \le P_{ElyNom}$	EL1 ON	EL2 ON	EL3 ON	EL4 ON
$P_{ElyNom} < P_{ava} \le 2 \cdot P_{ElyNom}$	EL1 + EL2 ON		EL3 + EL4 ON	
$2 \cdot P_{ElyNom} < P_{ava} \le 3 \cdot P_{ElyNom}$	EL1 + EL2 + EL4 ON	EL 2 + EL1 + EL3 ON	EL3 + EL4 + EL1 ON	EL4 + EL3 + EL2 ON
$3 \cdot P_{ElyNom} < P_{ava} \le P_{H2plant}$	EL1 + EL2 + EL3 + EL4 ON			

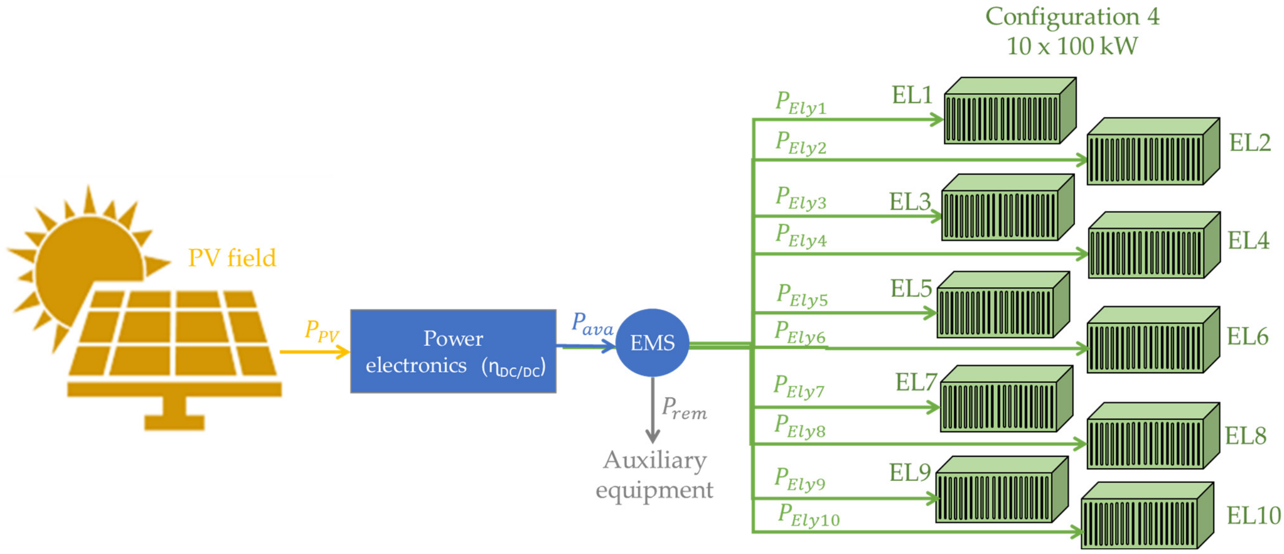
(**c**)

Figure 4. (**a**) Configuration 3: 1 MW four-module electrolyser plant: (**b**) EMS 1 based on available power; (**c**) EMS 2 based on operating hours' balance.

On the other hand, EMS 2 (Figure 4c) decides which electrolyser should be put into operation based on the equitable distribution of daily irradiation time.

3.4. Configuration 4: Modularisation Level 10

Configuration 4 consists of ten 100 kW electrolysers (Figure 5a). As in the previous configurations, the EMS1 strategy based on the nominal power of the electrolyser will give priority to the use of EL1 over EL2, EL2 over EL3, and so on up to EL10 (Figure 5b).



(**a**)

EMS 1. Electrolyser in operation. Criteria: available power.

Available power	Electrolyser in operation
$P_{ava} \leq P_{ElyNom}$	EL1 ON
$P_{ElyNom} < P_{ava} \leq 2 \cdot P_{ElyNom}$	EL1 - EL2 ON
$2 \cdot P_{ElyNom} < P_{ava} \leq 3 \cdot P_{ElyNom}$	EL1 - EL3 ON
$3 \cdot P_{ElyNom} < P_{ava} \leq 4 \cdot P_{ElyNom}$	EL1 - EL4 ON
$4 \cdot P_{ElyNom} < P_{ava} \leq 5 \cdot P_{ElyNom}$	EL1 - EL5 ON
$5 \cdot P_{ElyNom} < P_{ava} \leq 6 \cdot P_{ElyNom}$	EL1 - EL6 ON
$6 \cdot P_{ElyNom} < P_{ava} \leq 7 \cdot P_{ElyNom}$	EL1 - EL7 ON
$7 \cdot P_{ElyNom} < P_{ava} \leq 8 \cdot P_{ElyNom}$	EL1 - EL8 ON
$8 \cdot P_{ElyNom} < P_{ava} \leq 9 \cdot P_{ElyNom}$	EL1 - EL9 ON
$9 \cdot P_{ElyNom} < P_{ava} \leq P_{H_2plant}$	EL1 - EL10 ON

(**b**)

EMS 2. Electrolyser in operation. Criteria: operating hours balance.

	Daily irradiance hours (h)											
Available power	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$P_{ava} \leq P_{ElyNom}$	EL1 ON	EL2 ON	EL3 ON	EL4 ON	EL5 ON	EL6 ON	EL7 ON	EL8 ON	EL9 ON	EL10 ON	EL8 ON	EL8 ON
$P_{ElyNom} < P_{ava} \leq 2 \cdot P_{ElyNom}$	EL1 - EL2 ON		EL3- E L4 ON		EL5 - EL6 ON		EL7 - EL8 ON		EL9 - EL10 ON		EL3 , EL8 ON	EL7, EL8 ON
$2 \cdot P_{ElyNom} < P_{ava} \leq 3 \cdot P_{ElyNom}$	EL1 - EL3 ON	EL1, EL2, EL4 ON	EL3 - EL5 ON	EL3, EL4, EL6 ON	EL5 - EL7 ON	EL5, EL6, EL8 ON	EL7 - EL9 ON	EL7, EL8, EL10 ON	EL1, EL9, EL10 ON	EL2, EL9,EL10 ON	EL3, EL7, EL8 ON	EL6 - EL8 ON
$3 \cdot P_{ElyNom} < P_{ava} \leq 4 \cdot P_{ElyNom}$	EL1 - EL4 ON		EL3 - EL6 ON		EL5 - EL8 ON		EL7 - EL10 ON		EL1, EL2, EL9, EL10 ON		EL3, EL7-EL9 ON	EL6 - EL9 ON
$4 \cdot P_{ElyNom} < P_{ava} \leq 5 \cdot P_{ElyNom}$	EL1-EL5 ON	EL1-EL4,EL6 ON	EL3-EL7 ON	EL3-EL6, EL8 ON	EL5-EL9 ON	EL5-EL8,EL10 ON	EL1,EL7-EL10 ON	EL2, EL7-EL10 ON	EL1-EL3,EL9, EL10 ON	EL1, EL2, EL4, EL9, EL10 ON	EL3, EL6 - EL9 ON	
$5 \cdot P_{ElyNom} < P_{ava} \leq 6 \cdot P_{ElyNom}$	EL1-EL6 ON		EL3-EL8 ON		EL5-EL10 ON		EL1,EL2,EL7-EL10 ON		EL1-EL4,EL9,EL10 ON		EL3,EL5-EL9 ON	EL3,EL6-EL10 ON
$6 \cdot P_{ElyNom} < P_{ava} \leq 7 \cdot P_{ElyNom}$	EL1-EL7 ON	EL1-EL6,EL8 ON	EL3-EL9 ON	EL3 - EL8, EL10 ON	EL1, EL5 - EL10 ON	EL2, EL5-EL10 ON	EL1-EL3, EL7-EL10 ON	EL1, EL2, EL4, EL7-EL10 ON	EL1 - EL5,EL9, EL10 ON	EL1- EL4, EL6, EL9, EL10 ON	EL3, EL5 - EL10 ON	
$7 \cdot P_{ElyNom} < P_{ava} \leq 8 \cdot P_{ElyNom}$	EL1-EL8 ON		EL3-EL10 ON		EL1,EL2, EL5-EL10 ON		EL1-EL4, EL7-EL10 ON		EL1-EL6,EL9,EL10 ON		EL3-EL10 ON	
$8 \cdot P_{ElyNom} < P_{ava} \leq 9 \cdot P_{ElyNom}$	EL1-EL9 ON	EL1-EL8, EL10 ON	EL1, EL3-EL10 ON	EL2-EL10 ON	EL1-EL3, EL5-EL10 ON	EL1-EL2, EL4-EL10 ON	EL1-EL5, EL7-EL10 ON	EL1, EL4, EL6-EL10 ON	EL1 -EL7, EL9,EL10 ON	EL1 – EL6, EL8-EL10 ON	EL1, EL3-EL10 ON	EL2-EL10 ON
$9 \cdot P_{ElyNom} < P_{ava} \leq P_{H_2plant}$	EL1-EL10 ON											

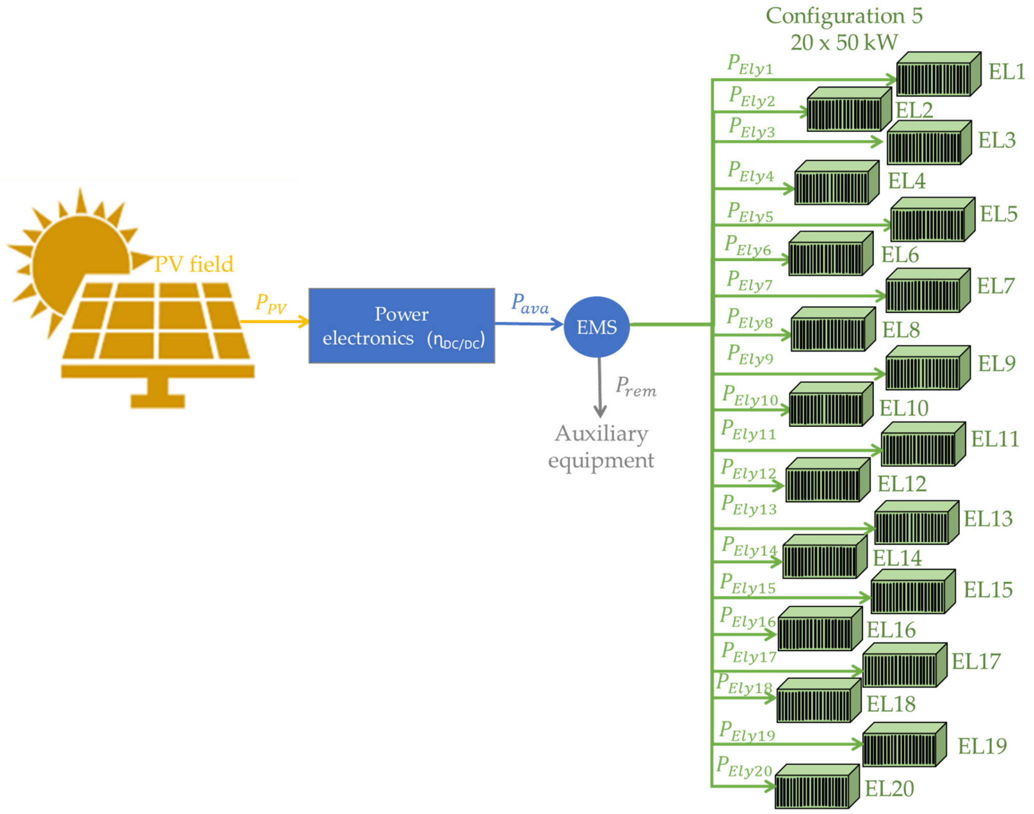
(**c**)

Figure 5. (**a**) Configuration 4: 1 MW ten-module electrolyser plant: (**b**) EMS based on PV power; (**c**) EMS based on operation time sharing.

In contrast, EMS2 takes into account the number of hours of daily irradiation (between 10 and 14 h for winter and summer, respectively) at the location of this study in order to establish the priority of use of one or the other electrolyser (Figure 5c).

3.5. Configuration 5: Modularisation Level 20

Finally, configuration 5, shown in Table 3, consists of a 1 MW hydrogen production plant comprising twenty 50 kW electrolysers (Figure 6a). As in the previous configurations, the electrolysers operate in an order of priority determined by the selected EMS. Thus, as in the previous configurations, EMS1 gives priority to EL1 over EL2, EL2 over EL3, and so on up to EL20 (Figure 6b).



(**a**)

EMS 1. Electrolyser in operation. Criteria: available power.

Available power	Electrolyser in operation
$P_{ava} \leq P_{ElyNom}$	EL1 ON
$P_{ElyNom} < P_{ava} \leq 2 \cdot P_{ElyNom}$	EL1 - EL2 ON
$2 \cdot P_{ElyNom} < P_{ava} \leq 3 \cdot P_{ElyNom}$	EL1 - EL3 ON
$3 \cdot P_{ElyNom} < P_{ava} \leq 4 \cdot P_{ElyNom}$	EL1 - EL4 ON
$4 \cdot P_{ElyNom} < P_{ava} \leq 5 \cdot P_{ElyNom}$	EL1 - EL5 ON
$5 \cdot P_{ElyNom} < P_{ava} \leq 6 \cdot P_{ElyNom}$	EL1 - EL6 ON
$6 \cdot P_{ElyNom} < P_{ava} \leq 7 \cdot P_{ElyNom}$	EL1 - EL7 ON
$7 \cdot P_{ElyNom} < P_{ava} \leq 8 \cdot P_{ElyNom}$	EL1 - EL8 ON
$8 \cdot P_{ElyNom} < P_{ava} \leq 9 \cdot P_{ElyNom}$	EL1 - EL9 ON
$9 \cdot P_{ElyNom} < P_{ava} \leq 10 \cdot P_{ElyNom}$	EL1 -EL10 ON
$10 \cdot P_{ElyNom} < P_{ava} \leq 11 \cdot P_{ElyNom}$	EL1 - EL11 ON
$11 \cdot P_{ElyNom} < P_{ava} \leq 12 \cdot P_{ElyNom}$	EL1 - EL12 ON
$12 \cdot P_{ElyNom} < P_{ava} \leq 13 \cdot P_{ElyNom}$	EL1 - EL13 ON
$13 \cdot P_{ElyNom} < P_{ava} \leq 14 \cdot P_{ElyNom}$	EL1 - EL14 ON
$14 \cdot P_{ElyNom} < P_{ava} \leq 15 \cdot P_{ElyNom}$	EL1 - EL15 ON
$15 \cdot P_{ElyNom} < P_{ava} \leq 16 \cdot P_{ElyNom}$	EL1 - EL6 ON
$16 \cdot P_{ElyNom} < P_{ava} \leq 17 \cdot P_{ElyNom}$	EL1 - EL17 ON
$17 \cdot P_{ElyNom} < P_{ava} \leq 18 \cdot P_{ElyNom}$	EL1 - EL18 ON
$18 \cdot P_{ElyNom} < P_{ava} \leq 19 \cdot P_{ElyNom}$	EL1 - EL19 ON
$19 \cdot P_{ElyNom} < P_{ava} \leq P_{H_2plant}$	EL1 - EL20 ON

(**b**)

EMS 2. Electrolyser in operation. Criteria: operating hours balance.

	Daily irradiance hours (h)											
Available power	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
$P_{ava} \leq P_{ElyNom}$	EL1 ON	EL12 ON	EL9 ON	EL14 ON	EL7 ON	EL16 ON	EL5 ON	EL18 ON	EL3 ON	EL20 ON	EL5 ON	EL5 ON
$P_{ElyNom} < P_{ava} \leq 2 \cdot P_{ElyNom}$	EL11 ON	EL10 ON	EL13 ON	EL8 ON	EL15 ON	EL6 ON	EL17 ON	EL4 ON	EL19 ON	EL2 ON	EL6 ON	EL6 ON
$2 \cdot P_{ElyNom} < P_{ava} \leq 3 \cdot P_{ElyNom}$	EL2 ON	EL13 ON	EL10 ON	EL15 ON	EL8 ON	EL17 ON	EL6 ON	EL19 ON	EL4 ON	EL11 ON	EL4 ON	EL4 ON
$3 \cdot P_{ElyNom} < P_{ava} \leq 4 \cdot P_{ElyNom}$	EL12 ON	EL1 ON	EL14 ON	EL9 ON	EL16 ON	EL7 ON	EL18 ON	EL5 ON	EL20 ON	EL3 ON	EL3 ON	EL3 ON
$4 \cdot P_{ElyNom} < P_{ava} \leq 5 \cdot P_{ElyNom}$	EL3 ON	EL14 ON	EL1 ON	EL16 ON	EL9 ON	EL18 ON	EL7 ON	EL20 ON	EL5 ON	EL12 ON	EL7 ON	EL7 ON
$5 \cdot P_{ElyNom} < P_{ava} \leq 6 \cdot P_{ElyNom}$	EL13 ON	EL2 ON	EL15 ON	EL10 ON	EL17 ON	EL8 ON	EL19 ON	EL6 ON	EL11 ON	EL4 ON	EL19 ON	EL19 ON
$6 \cdot P_{ElyNom} < P_{ava} \leq 7 \cdot P_{ElyNom}$	EL4 ON	EL15 ON	EL2 ON	EL17 ON	EL10 ON	EL19 ON	EL8 ON	EL11 ON	EL6 ON	EL13 ON	EL17 ON	EL17 ON
$7 \cdot P_{ElyNom} < P_{ava} \leq 8 \cdot P_{ElyNom}$	EL14 ON	EL3 ON	EL16 ON	EL1 ON	EL18 ON	EL9 ON	EL20 ON	EL7 ON	EL12 ON	EL5 ON	EL18 ON	EL18 ON
$8 \cdot P_{ElyNom} < P_{ava} \leq 9 \cdot P_{ElyNom}$	EL5 ON	EL16 ON	EL3 ON	EL18 ON	EL1 ON	EL20 ON	EL9 ON	EL12 ON	EL7 ON	EL14 ON	EL16 ON	EL16 ON
$9 \cdot P_{ElyNom} < P_{ava} \leq 10 \cdot P_{ElyNom}$	EL15 ON	EL4 ON	EL17 ON	EL2 ON	EL19 ON	EL10 ON	EL11 ON	EL8 ON	EL13 ON	EL6 ON	EL20 ON	EL15 ON
$10 \cdot P_{ElyNom} < P_{ava} \leq 11 \cdot P_{ElyNom}$	EL6 ON	EL17 ON	EL4 ON	EL19 ON	EL2 ON	EL11 ON	EL10 ON	EL13 ON	EL8 ON	EL15 ON	EL15 ON	EL20 ON
$11 \cdot P_{ElyNom} < P_{ava} \leq 12 \cdot P_{ElyNom}$	EL16 ON	EL5 ON	EL18 ON	EL3 ON	EL20 ON	EL1 ON	EL12 ON	EL9 ON	EL14 ON	EL7 ON	EL13 ON	EL13 ON
$12 \cdot P_{ElyNom} < P_{ava} \leq 13 \cdot P_{ElyNom}$	EL7 ON	EL18 ON	EL5 ON	EL20 ON	EL3 ON	EL12 ON	EL1 ON	EL14 ON	EL9 ON	EL16 ON	EL14 ON	EL14 ON
$13 \cdot P_{ElyNom} < P_{ava} \leq 14 \cdot P_{ElyNom}$	EL17 ON	EL6 ON	EL19 ON	EL4 ON	EL11 ON	EL2 ON	EL13 ON	EL10 ON	EL15 ON	EL8 ON	EL8 ON	EL11 ON
$14 \cdot P_{ElyNom} < P_{ava} \leq 15 \cdot P_{ElyNom}$	EL8 ON	EL19 ON	EL6 ON	EL11 ON	EL4 ON	EL13 ON	EL2 ON	EL15 ON	EL10 ON	EL17 ON	EL11 ON	EL8 ON
$15 \cdot P_{ElyNom} < P_{ava} \leq 16 \cdot P_{ElyNom}$	EL18 ON	EL7 ON	EL20 ON	EL5 ON	EL12 ON	EL3 ON	EL14 ON	EL1 ON	EL16 ON	EL9 ON	EL12 ON	EL12 ON
$16 \cdot P_{ElyNom} < P_{ava} \leq 17 \cdot P_{ElyNom}$	EL9 ON	EL20 ON	EL7 ON	EL12 ON	EL5 ON	EL14 ON	EL3 ON	EL16 ON	EL1 ON	EL18 ON	EL2 ON	EL2 ON
$17 \cdot P_{ElyNom} < P_{ava} \leq 18 \cdot P_{ElyNom}$	EL19 ON	EL8 ON	EL11 ON	EL6 ON	EL13 ON	EL4 ON	EL15 ON	EL2 ON	EL17 ON	EL10 ON	EL9 ON	EL9 ON
$18 \cdot P_{ElyNom} < P_{ava} \leq 19 \cdot P_{ElyNom}$	EL10 ON	EL11 ON	EL8 ON	EL13 ON	EL6 ON	EL15 ON	EL4 ON	EL17 ON	EL2 ON	EL19 ON	EL10 ON	EL10 ON
$19 \cdot P_{ElyNom} < P_{ava} \leq P_{H_2plant}$	EL20 ON	EL9 ON	EL12 ON	EL7 ON	EL14 ON	EL5 ON	EL16 ON	EL3 ON	EL18 ON	EL1 ON	EL1 ON	EL1 ON

(**c**)

Figure 6. (**a**) Configuration 5: 1 MW twenty-module electrolyser plant; (**b**) EMS based on PV power; (**c**) EMS based on operation time sharing.

On the other hand, EMS2 takes into account the daily irradiation hours at the study location to establish the priority of use of one or another electrolyser (Figure 6c).

4. Techno-Economic Study: Analysis Seeking Optimal Modularisation

Once the configurations and possible EMSs governing the hydrogen production plant have been designed, the economic study can be carried out. To do this, investment costs, replacement costs, and operating and maintenance costs will be taken into account. Therefore, first of all, the number of operating hours for each electrolyser must be determined based on the plant configuration and the EMS to which it is subject in the geographical location under study [30]. As justified, the influence of power electronics on the power injected into the electrolyser assembly is ruled out, since current commercial models of power converters are very robust and capable of operating at efficiencies between 95% and 98% across their entire operating range (see [31]), i.e., their impact is negligible on the overall operation of the green hydrogen production plant. Consequently, in this study, the total losses associated with power electronics and parasitic effects are set at 3%.

To do this, the PV generation profile of the location under study, Huelva, in southwestern Spain, must be taken into account. Thus, for a PV field with sufficient installed capacity to guarantee a maximum photovoltaic power $\boldsymbol{P_{PVmax}} \geq \boldsymbol{P_{H2plant}} = \mathbf{1\ MW}$, taking into account solar irradiation, the resulting annual PV power profile is obtained (Figure 7).

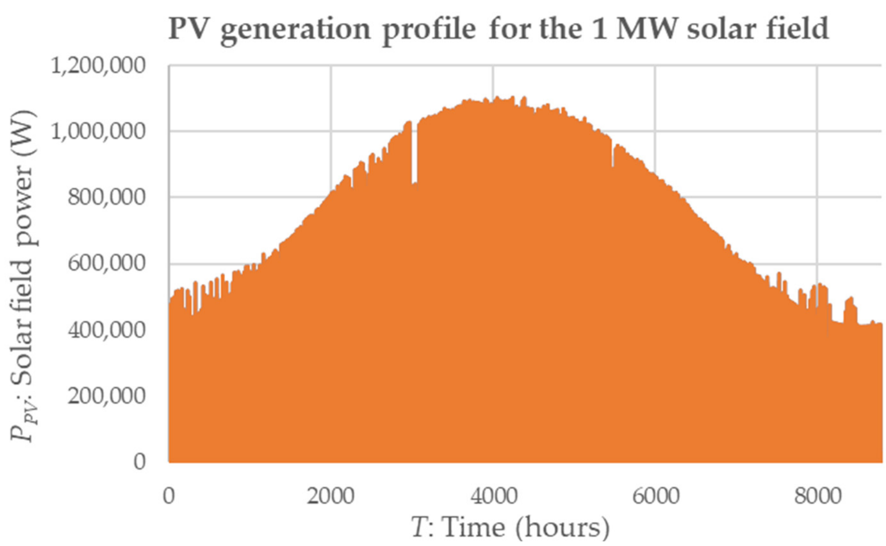


Figure 7. Annual PV generation profile for 1 MW solar field.

Next, once the hydrogen production plant is operational at the site indicated for each configuration defined above, it is possible to obtain the operating hours for each electrolyser, depending on the EMS (EMS1 or EMS2) governing the hydrogen production plant and the electrolysis technology integrated into that plant (Tables 4 and 5). For this study, the minimum load rate of electrolysis technologies (20% for alkaline technology and 5% for PEM technology [27]) has been taken into account.

As can be seen in Tables 4 and 5, with EMS 2, the distribution of operating hours among electrolysers becomes more homogeneous. However, as the number of electrolyser modules exceeds 10, no significant reduction in the number of operating hours is observed.

Therefore, knowing the number of operating hours of each electrolyser, it is possible to determine how the configuration implemented in the hydrogen production plant and the EMS that governs it influence the lifetime of each electrolyser and the associated replacement frequency. To this end, it should be borne in mind that a higher replacement frequency entails higher costs, so the optimal configuration and strategy will aim to minimise the number of replacements.

Table 4. Annual working hours of each electrolyser for alkaline technology plant according to configuration and EMS deployed.

	Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
	EMS 1	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**
Electrolyser 1	3975 h	3975 h	4370 h	3580 h	4370 h	3171 h	4370 h	2655 h	4370 h	2629 h
Electrolyser 2			1960 h	2750 h	3363 h	2752 h	4370 h	2639 h	4370 h	2411 h
Electrolyser 3					2228 h	2708 h	3804 h	2538 h	4370 h	2584 h
Electrolyser 4					1056 h	2391 h	3331 h	2438 h	4370 h	2390 h
Electrolyser 5							3001 h	2579 h	3883 h	2186 h
Electrolyser 6							2389 h	2567 h	3421 h	2392 h
Electrolyser 7							1841 h	2690 h	3352 h	2665 h
Electrolyser 8							1369 h	2581 h	3290 h	2553 h
Electrolyser 9							976 h	2264 h	3108 h	2593 h
Electrolyser 10							592 h	2628 h	2781 h	2615 h
Electrolyser 11									2453 h	2705 h
Electrolyser 12									2179 h	2594 h
Electrolyser 13									1904 h	2532 h
Electrolyser 14									1648 h	2549 h
Electrolyser 15									1423 h	2471 h
Electrolyser 16									1214 h	2639 h
Electrolyser 17									1019 h	2580 h
Electrolyser 18									786 h	2608 h
Electrolyser 19									619 h	2646 h
Electrolyser 20									451 h	2669 h

Table 5. Annual working hours of each electrolyser for a PEM technology plant according to configuration and EMS deployed.

	Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
	EMS 1	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**	**EMS 1**	**EMS 2**
Electrolyser 1	4370 h	4370 h	4370 h	3763 h	4370 h	3300 h	4370 h	2710 h	4370 h	2665 h
Electrolyser 2			2359 h	2966 h	3420 h	2868 h	4370 h	2698 h	4370 h	2441 h
Electrolyser 3					2430 h	2777 h	3939 h	2602 h	4370 h	2611 h
Electrolyser 4					1206 h	2486 h	3358 h	2593 h	4370 h	2437 h
Electrolyser 5							3141 h	2683 h	3963 h	2214 h
Electrolyser 6							2489 h	2610 h	3435 h	2395 h
Electrolyser 7							1932 h	2715 h	3360 h	2676 h
Electrolyser 8							1450 h	2623 h	3292 h	2572 h
Electrolyser 9							1040 h	2333 h	3155 h	2617 h
Electrolyser 10							636 h	2670 h	2824 h	2638 h
Electrolyser 11									2507 h	2728 h
Electrolyser 12									2216 h	2610 h
Electrolyser 13									1947 h	2556 h
Electrolyser 14									1683 h	2633 h
Electrolyser 15									1456 h	2496 h
Electrolyser 16									1240 h	2661 h
Electrolyser 17									1046 h	2616 h
Electrolyser 18									818 h	2624 h
Electrolyser 19									645 h	2654 h
Electrolyser 20									476 h	2699 h

Therefore, it is necessary to establish the lifetime of the electrolysers. To do so, it is necessary to refer to the scientific literature, which offers different data on the lifespan of electrolysers, differentiating between alkaline technology and PEM technology. Thus, in [32,33], the degradation of an electrolyser is considered to be based on its number of operating hours (but not on the effect of shutdowns on electrolyser degradation), while [34] studies the degradation rate of a PEM electrolyser in a dynamic operating regime and in a steady-state operating regime (but also does not take into account the effect of a shutdown on degradation). On the other hand, the authors from [35,36] mention the effect of alternating periods of inactivity with periods of operation; however, the degradation associated with this phenomenon is not quantified. According to the available literature, electrolysers are assumed to have a service life that depends solely on the number of hours of operation. Table 6 summarises the data on the service life of the two electrolysis technologies studied in terms of their operating hours. The service life of the photovoltaic field (which will determine the service life of the hydrogen production plant) is considered to be 25 years [37,38].

Table 6. Lifetime of electrolyser technologies.

Electrolyser	Alkaline Electrolyser	PEM Electrolyser
Lifespan (hours)	<90,000 [39,40] 55,000–96,000 [36] 60,000 [41] 10,000 [42]	<20,000 [39] 60,000 [35] <60,000 [40] 60,000–100,000 [36] 20,000–60,000 [43] 50,000–80,000 [41]

As shown in Table 6, there is a considerable disparity in the scientific literature regarding the lifespan that can be expected for both electrolyser technologies. Therefore, four significant lifespan ranges are considered (low lifespan: 10,000 h; medium–low lifespan: 40,000 h; medium–high lifespan: 70,000 h; and high lifespan: 100,000 h), in order to conduct a more comprehensive and exhaustive study.

Next, based on Table 6 and with the operating hours calculated in Tables 4 and 5, for ALK and PEM technology, it is possible to determine the replacement frequency in each configuration based on the EMS governing the hydrogen production plant. The data in Tables 7 and 8 include a 10% reduction in replacement time from the theoretical value to account for degradation due to start-ups/shutdowns and possible BoP failures.

Using the data obtained from Tables 7 and 8, it is possible to obtain the number of replacements for each electrolyser, based on the configuration, the EMS implemented, and the electrolysis technology used in the hydrogen production plant, thanks to Equation (2).

$$N_{rep} = \frac{T_{H_2plant}}{T_{ely}} \quad (2)$$

where

N_{rep}: number of replacements of each electrolyser.

T_{H_2plant}: lifespan of the hydrogen production plant (25 years).

T_{ely}: electrolyser replacement time (years).

The results obtained show that configurations with a higher degree of modularisation suffer less degradation. The electrolysers that make up these configurations are replaced at longer intervals.

Therefore, based on the data obtained in Tables 7 and 8, the economic study can be addressed. To do so, Equation (1) (and the values applicable to each technology, shown in Table 2) will be taken into account. According to Equation (1), the unit cost (per unit of power) decreases as the nominal power of the electrolyser modules increases. Thus, for a 1 MW hydrogen production plant (such as the one designed in this work), the initial acquisition costs depend only on the selected configuration (Table 9).

Based on the above, it is possible to establish the relationship between hydrogen production and initial cost vs. normalised power. Next, taking into account the nominal power of the electrolyser, P_{ElyNom}, and the power of the hydrogen plant, $P_{H2plant}$, Figure 8a shows the hydrogen production curve vs. normalised power $\left(P_{ElyNom}/P_{H2plant}\right)$, and Figure 8b shows the initial cost curve vs. normalised power, differentiated by technology.

Table 7. Replacement frequency (years) for each electrolyser based on configuration and EMS. Alkaline technology.

Electrolyser Lifespan	Electrolyser	Replacement Frequency (Years)									
		Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
		EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2
10,000 h	1	2.27		2.06	2.51	2.06	2.84	2.06	3.38	2.06	3.42
	2			4.59	3.28	2.67	3.27	2.06	3.40	2.06	3.74
	3					4.04	3.32	2.37	3.55	2.06	3.48
	4					8.51	3.76	2.70	3.69	2.06	3.76
	5							3.00	3.49	2.32	4.11
	6							3.76	3.51	2.63	3.76
	7							4.89	3.35	2.68	3.38
	8							6.57	3.48	2.74	3.53
	9							9.23	3.98	2.90	3.47
	10							15.20	3.43	3.24	3.44
	11									3.67	3.33
	12									4.13	3.47
	13									4.73	3.56
	14									5.45	3.53
	15									6.33	3.65
	16									7.42	3.41
	17									8.83	3.49
	18									11.45	3.45
	19									14.54	3.40
	20									19.95	3.38
40,000 h	1	9.05		8.24	10.05	8.24	11.35	8.24	13.56	8.24	13.69
	2			18.37	13.10	10.70	13.08	8.24	13.64	8.24	14.93
	3					16.16	13.29	9.47	14.18	8.24	13.93
	4					>25	15.05	10.80	14.77	8.24	15.07
	5							12.00	13.96	9.27	16.47
	6							15.07	14.02	10.52	15.05
	7							19.56	13.38	10.74	13.51
	8							>25	13.95	10.94	14.10
	9							>25	15.90	11.58	13.89
	10							>25	13.70	12.94	13.77
	11									14.68	13.31
	12									16.52	13.88
	13									18.90	14.22
	14									21.84	14.12
	15									>25	14.56
	16									>25	13.64
	17									>25	13.95
	18									>25	13.80
	19									>25	13.61
	20									>25	13.49

Table 7. *Cont.*

Electrolyser Lifespan	Electrolyser	Replacement Frequency (Years)									
		Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
		EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2
70,000 h	1	15.85		14.42	17.60	14.42	19.86	14.42	>25	16.02	>25
	2			>25	>25	20.81	>25	14.42	>25	14.42	>25
	3					>25	>25	16.56	>25	14.42	>25
	4					>25	>25	18.91	>25	14.42	>25
	5							23.32	>25	16.23	>25
	6							>25	>25	18.41	>25
	7							>25	>25	18.79	>25
	8							>25	>25	19.15	>25
	9							>25	>25	20.27	>25
	10							>25	>25	>25	>25
	11									>25	>25
	12									>25	>25
	13									>25	>25
	14									>25	>25
	15									>25	>25
	16									>25	>25
	17									>25	>25
	18									>25	>25
	19									>25	>25
	20									>25	>25
100,000 h	1	>25		20.59	>25	20.59	>25	20.59	>25	20.59	>25
	2			>25	>25	>25	>25	22.88	>25	20.59	>25
	3					>25	>25	>25	>25	20.59	>25
	4					>25	>25	>25	>25	20.59	>25
	5							>25	>25	>25	>25
	6							>25	>25	>25	>25
	7							>25	>25	>25	>25
	8							>25	>25	>25	>25
	9							>25	>25	>25	>25
	10							>25	>25	>25	>25
	11									>25	>25
	12									>25	>25
	13									>25	>25
	14									>25	>25
	15									>25	>25
	16									>25	>25
	17									>25	>25
	18									>25	>25
	19									>25	>25
	20									>25	>25

Note: In this study, for each configuration and each EMS, identical degradation behaviour is assumed for all electrolysers.

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Table 8. Replacement frequency (years) for each electrolyser based on configuration and EMS. PEM technology.

Electrolyser Lifespan	Electrolyser	Replacement Frequency (Years)									
		Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
		EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2
10,000 h	1	2.06		2.06	2.39	2.06	2.73	2.06	3.32	2.06	3.38
	2			3.82	3.03	2.63	3.14	2.06	3.34	2.06	3.69
	3					3.71	3.24	2.29	3.46	2.06	3.45
	4					7.46	3.62	2.68	3.47	2.06	3.69
	5							2.86	3.36	2.27	4.07
	6							3.62	3.45	2.62	3.76
	7							4.66	3.31	2.68	3.37
	8							6.21	3.43	2.74	3.50
	9							8.66	3.86	2.85	3.44
	10							14.15	3.38	3.19	3.41
	11									3.59	3.30
	12									4.06	3.45
	13									4.63	3.52
	14									5.35	3.41
	15									6.18	3.61
	16									7.25	3.38
	17									8.60	3.44
	18									11.00	3.43
	19									13.95	3.39
	20									18.90	3.34
40,000 h	1	8.24		8.24	9.57	8.24	10.91	8.24	13.28	8.24	13.51
	2			15.26	12.14	10.53	12.56	8.24	13.35	8.24	14.75
	3					14.81	12.96	9.14	13.83	8.24	13.79
	4					>25	14.48	10.72	13.89	8.24	14.77
	5							11.46	13.42	9.08	16.26
	6							14.46	13.80	10.48	15.03
	7							18.63	13.26	10.71	13.46
	8							>25	13.73	10.94	14.00
	9							>25	15.43	11.41	13.75
	10							>25	13.48	12.74	13.64
	11									14.36	13.19
	12									16.25	13.80
	13									18.49	14.09
	14									21.39	13.67
	15									>25	14.42
	16									>25	13.53
	17									>25	13.76
	18									>25	13.72
	19									>25	13.56
	20									>25	13.34
70,000 h	1	14.42		14.42	16.74	14.42	19.09	16.02	14.42	14.42	>25
	2			>25	21.24	18.42	21.97	16.02	14.42	14.42	>25
	3					>25	>25	17.77	15.99	14.42	>25
	4					>25	>25	20.85	18.77	14.42	>25
	5							22.29	20.06	15.89	>25
	6							>25	>25	18.34	>25
	7							>25	>25	18.75	>25
	8							>25	>25	19.13	>25
	9							>25	>25	19.97	>25
	10							>25	>25	22.31	>25

Table 8. *Cont.*

Electrolyser Lifespan	Electrolyser	Replacement Frequency (Years)									
		Configuration 1		Configuration 2		Configuration 3		Configuration 4		Configuration 5	
		EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2
70,000 h	11									>25	>25
	12									>25	>25
	13									>25	>25
	14									>25	>25
	15									>25	>25
	16									>25	>25
	17									>25	>25
	18									>25	>25
	19									>25	>25
	20									>25	>25
100,000 h	1	20.59		20.59	>25	20.59	>25	20.59	>25	20.59	>25
	2			>25	>25	>25	>25	20.59	>25	20.59	>25
	3					>25	>25	>25	>25	20.59	>25
	4					>25	>25	>25	>25	20.59	>25
	5							>25	>25	>25	>25
	6							>25	>25	>25	>25
	7							>25	>25	>25	>25
	8							>25	>25	>25	>25
	9							>25	>25	>25	>25
	10							>25	>25	>25	>25
	11									>25	>25
	12									>25	>25
	13									>25	>25
	14									>25	>25
	15									>25	>25
	16									>25	>25
	17									>25	>25
	18									>25	>25
	19									>25	>25
	20									>25	>25

Note: In this study, for each configuration and each EMS, identical degradation behaviour is assumed for all electrolysers.

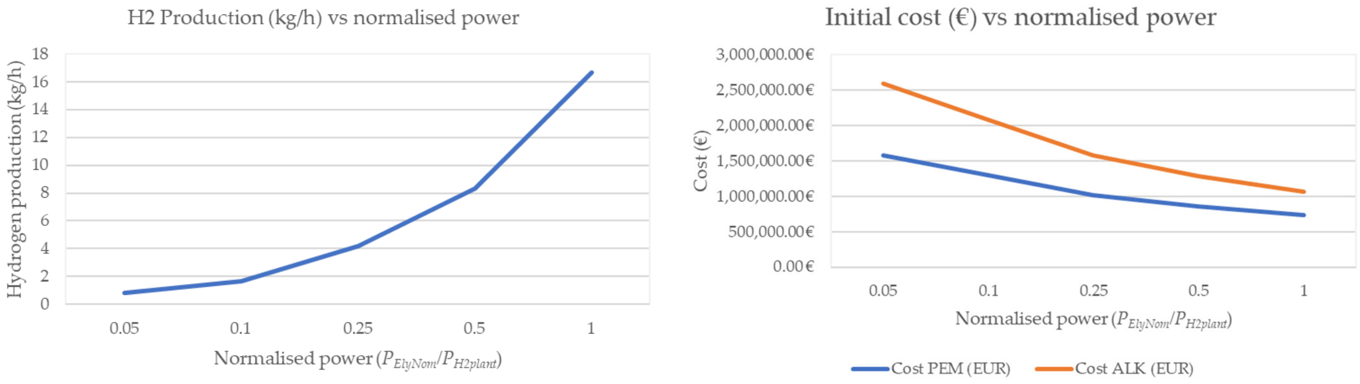
Table 9. Initial acquisition costs (EUR) of the electrolyser plant for the configurations implemented.

Electrolysis Technology	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5
PEM technology	738,945	859,025	1,015,075	1,295,296	1,582,025
Alkaline technology	1,060,918	1,286,901	1,575,129	2,081,436	2,588,514

Initial acquisition costs have been obtained from $C_{initial\ acq.\ cost} = 1000\ \text{kW} \cdot \left(k_0 + \frac{k}{Q} Q^{\alpha}\right) \cdot \left(\frac{Y}{Y_0}\right)^{\beta}$, where $Q = 1000$ kW for configuration 1; $Q = 500$ kW for configuration 2; $Q = 250$ kW for configuration 3; $Q = 100$ kW for configuration 4; $Q = 50$ kW for configuration 5.

Once the hydrogen production plant is up and running, the electrolysers begin to suffer greater or lesser degradation, depending on the EMS implemented, which will consequently affect replacement times (as shown above in Tables 7 and 8). Greater degradation leads to a higher number of replacements (which will entail higher associated costs), which will be greater when the lifetime of the electrolysers is shorter.

Thus, taking into account the initial acquisition costs of the electrolysers (Table 9), and replacement costs in a hydrogen production plant (for which the timing of replacements will be taken into account, thanks to Tables 7 and 8; and the costs associated with each replacement in the year in which they occur, using Equation (1)), the total acquisition costs of the hydrogen production plant are obtained (Table 10).



(**a**) (**b**)

Figure 8. (**a**) Hydrogen production vs. normalised power. (**b**) Initial cost vs. normalised power.

Table 10. Total acquisition costs during the lifespan of the plant for the different configurations and EMSs implemented in terms of technology.

Electrolysis Technology		Configuration 1	Configuration 2		Configuration 3		Configuration 4		Configuration 5	
	Lifetime (Hours)	EMS 1 Costs (€)	EMS 1 Costs (€)	EMS 2 Costs (€)	EMS 1 Costs (€)	EMS 2 Costs (€)	EMS 1 Costs (€)	EMS 2 Costs (€)	EMS 1 Costs (€)	EMS 2 Costs (€)
PEM	10,000	3,997,853	3,824,289	3,789,161	3,893,251	3,812,789	4,555,977	4,578,695	5,503,463	5,474,112
	40,000	1,285,285	1,309,534	1,300,850	1,430,719	1,408,605	1,767,435	1,712,473	2,137,577	2,070,613
	70,000	950,536	982,013	1,041,429	1,140,976	1,103,359	1,454,225	1,295,296	1,768,493	1,582,026
	100,000	871,662	936,167	859,026	1,060,652	1,015,075	1,341,824	1,295,296	1,638,853	1,582,026
ALK	10,000	9,192,813	8,958,133	8,973,370	9,930,697	9,622,525	12,313,797	12,290,409	14,892,292	15,181,992
	40,000	2,799,219	2,854,008	2,853,733	3,175,295	2,880,160	3,792,709	3,778,217	4,710,098	4,697,276
	70,000	1,905,137	1,805,823	1,785,405	2,193,729	1,868,220	2,890,455	2,081,436	3,499,482	2,588,515
	100,000	1,060,919	1,765,819	1,286,901	1,868,220	1,575,130	2,391,277	2,081,436	2,973,839	2,588,515

Total acquisition costs have been obtained from $C_{total\ acq.\ cost} = C_{initial\ acq.\ cost} + \sum_{i=1}^{N} P_{elec} \cdot \left(k_0 + \frac{k}{Q} Q^{\alpha}\right) \cdot \left(\frac{Y_i}{Y_0}\right)^{\beta}$, where P_{elec} is the electrolyser module nominal power; $Q = 1000$ kW for configuration 1; $Q = 500$ kW for configuration 2; $Q = 250$ kW for configuration 3; $Q = 100$ kW for configuration 4; $Q = 50$ kW for configuration 5; N is the number of replacements for the different configurations and EMSs implemented; and Y_i is the year when the replacement occurs.

Apart from acquisition costs, the electrolyser also incurs O&M costs (including feedstock costs for water, as well as routine monitoring, checking operations, periodic maintenance, or corrective actions), which amount to 2.5% of the acquisition cost of the module per year [44]. The PV field is isolated from the general electricity grid; therefore, no electricity is purchased, no electricity tariff is applied, and no PV CAPEX is attributed to the hydrogen plant, as PV modelling is outside the scope of the techno-economic assessment.

On the other hand, as acquisition costs decrease over time (Equation (1)), O&M costs also decrease over time (as electrolysers are replaced). Therefore, the O&M costs of the electrolysis plant will depend on both the configuration and the EMS. Table 11 shows the O&M costs of the different hydrogen production plants under study (based on electrolysis technologies, configuration, EMS, and electrolyser lifetime).

Table 11. O&M costs of the electrolysers for the different configurations and EMSs implemented in terms of the electrolyser technology and electrolyser lifespan.

Electrolysis Technology		Configuration 1	Configuration 2		Configuration 3		Configuration 4		Configuration 5	
	Lifetime (Hours)	EMS 1 (€)	EMS 1 (€)	EMS 2 (€)	EMS 1 (€)	EMS 2 (€)	EMS 1 (€)	EMS 2 (€)	EMS 1 (€)	EMS 2 (€)
PEM	10,000	221,438	263,818	263,200	327,188	318,022	435,149	408,251	538,610	500,487
	40,000	280,134	357,133	353,931	473,694	443,864	626,867	579,257	775,778	717,284
	70,000	343,186	467,923	453,719	568,607	608,602	728,154	809,560	897,788	988,766
	100,000	416,374	510,463	536,891	618,808	634,422	793,620	809,560	969,298	988,766
ALK	10,000	573,008	703,261	704,054	865,341	865,315	1,147,790	1,142,585	1,430,271	1,422,748
	40,000	598,428	749,160	748,588	928,551	928,382	1,235,688	1,225,243	1,538,522	1,526,249
	70,000	619,734	776,294	782,571	958,096	976,904	1,270,433	1,300,898	1,581,132	1,617,822
	100,000	663,074	791,973	804,313	976,904	984,456	1,292,914	1,300,898	1,607,893	1,617,822

O&M costs have been obtained from $C_{O\&M} = \frac{2.5\%}{year} \cdot \left(\sum_{i=1}^{N} c_{acq.el.{}_i} \cdot T_i \right)$, where $c_{acq.el.{}_i}$ is the acquisition cost (as initial investment or as a replacement) of the electrolyser module and T_i is the module lifetime (years).

Based on Tables 10 and 11, the PEM technology can be stated to be more economically competitive than alkaline technology. Furthermore, in terms of modularity, configurations with a higher degree of modularisation (configurations 4 and 5) have higher acquisition and maintenance costs, regardless of the electrolysis technology implemented and the lifetime of the electrolyser. For both PEM and alkaline technologies, configuration 2 is the most competitive when technological development fails to extend the service life of electrolysers beyond 10,000 hours, regardless of the EMS implemented. When the service life is extended, configuration 1 yields a better economic impact. For these reasons, configurations 1 and 2 are the most competitive from an economic standpoint. Figure 9 shows the total costs (acquisition + O&M) of the configurations and electrolysis technologies under study.

To more accurately determine how the total costs of the plant would evolve for lifetimes intermediate to those proposed for the electrolysers (10,000, 40,000, 70,000, and 100,000 h), Figure 10 shows a sensitivity analysis of the total costs associated with the H2 plant, considering the electrolyser lifetime, configuration, and EMS implemented.

As shown, configurations with the lowest degree of modularity (1 and 2) are the most economically competitive. However, the choice of the optimal option, from an economic perspective, depends on the electrolysis technology deployed, as well as the lifetime of the electrolysers. For PEM electrolysis technology, at medium and long lifespans (greater than 40,000 h), configuration 1 (a single electrolyser module) is undoubtedly the most economically competitive. Conversely, at an early stage of technological maturity (electrolysers with 10,000 h lifespan), it may be advantageous to introduce a certain degree of modularity in the hydrogen production plant. In this case, configuration 2 (2 × 500 kW) is expected to prevail economically; additionally, EMS 2 is even more cost-effective than EMS 1 within configuration 2 under these circumstances.

In contrast, for alkaline technology, configurations 1 and 2 exhibit similar associated costs. Differences are observed only at a high lifespan of 100,000 h, where configuration 1 shows the lowest costs (regardless of the EMS implemented in configuration 2).

In addition to studying the costs related to acquisition, operation, and maintenance, it is necessary to analyse losses due to reduced hydrogen production resulting from the electrolyser reaching the end of its lifetime (EoL) and requiring replacement. To this end, it is assumed that, in an industrial hydrogen production plant (where measures are in place to resume operations as soon as possible, such as having spare equipment available), a period of one week (7 days, i.e., 168 h) elapses between electrolyser failure and full restoration of operation (base case). During this period, hydrogen production is reduced, leading to lost revenue (as a certain amount of power, equal to the electrolyser power, generated by PV field is not used for hydrogen production).

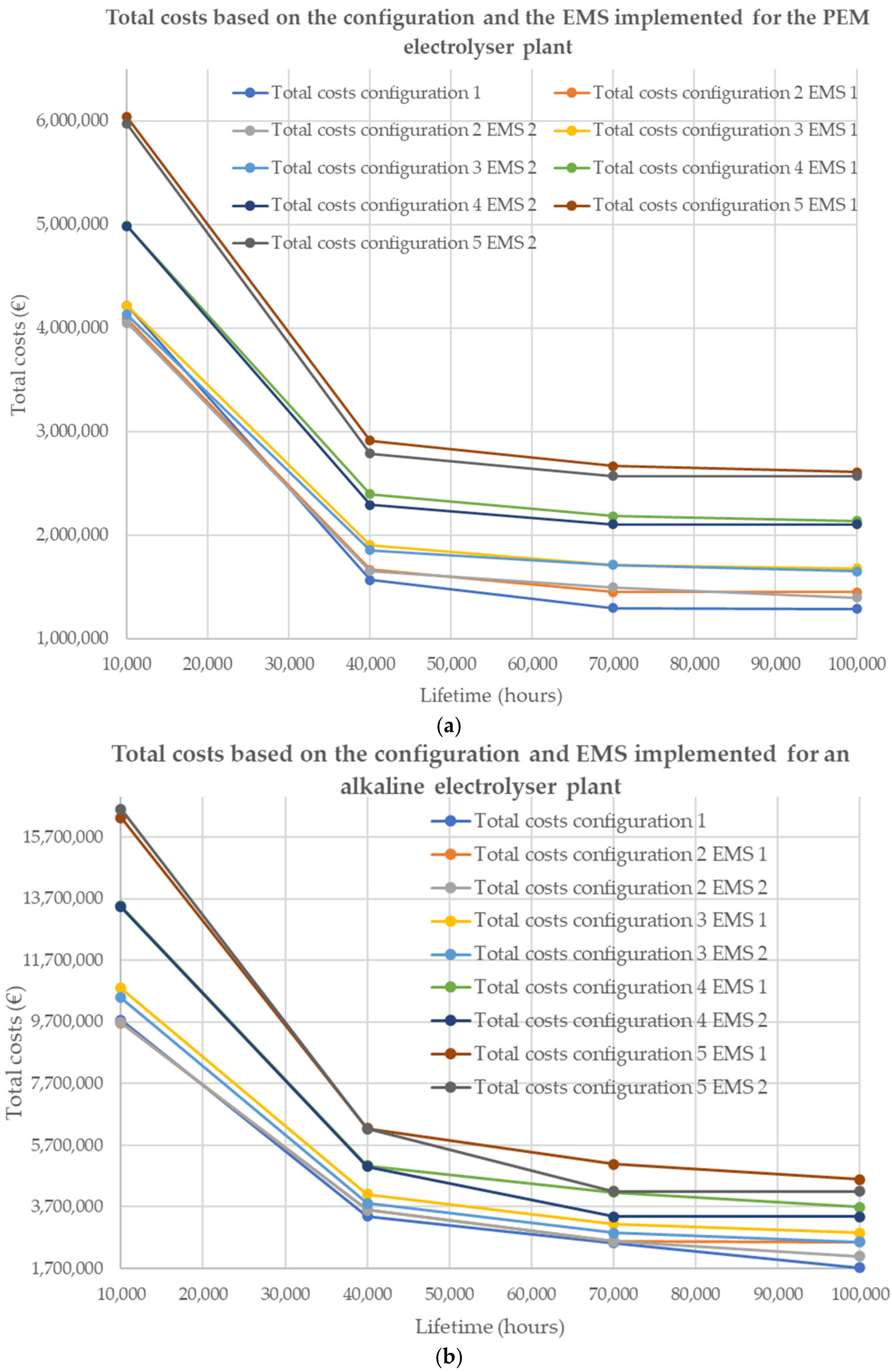
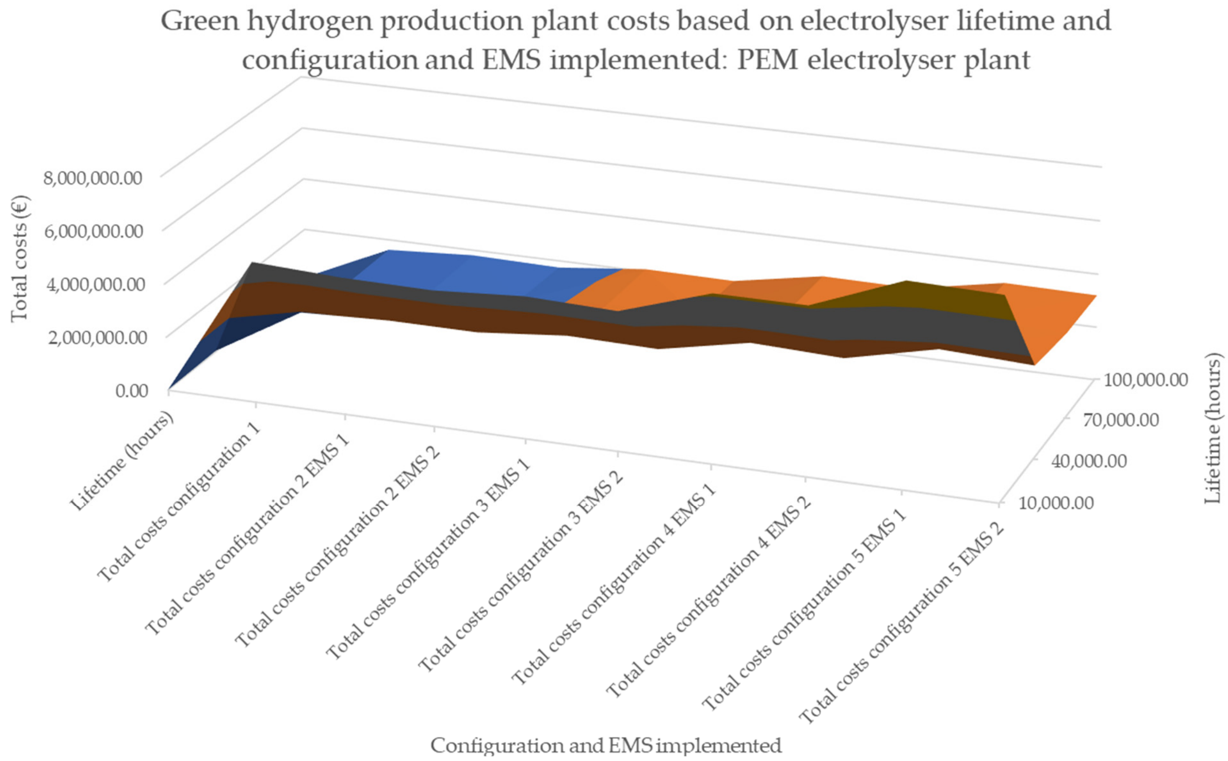
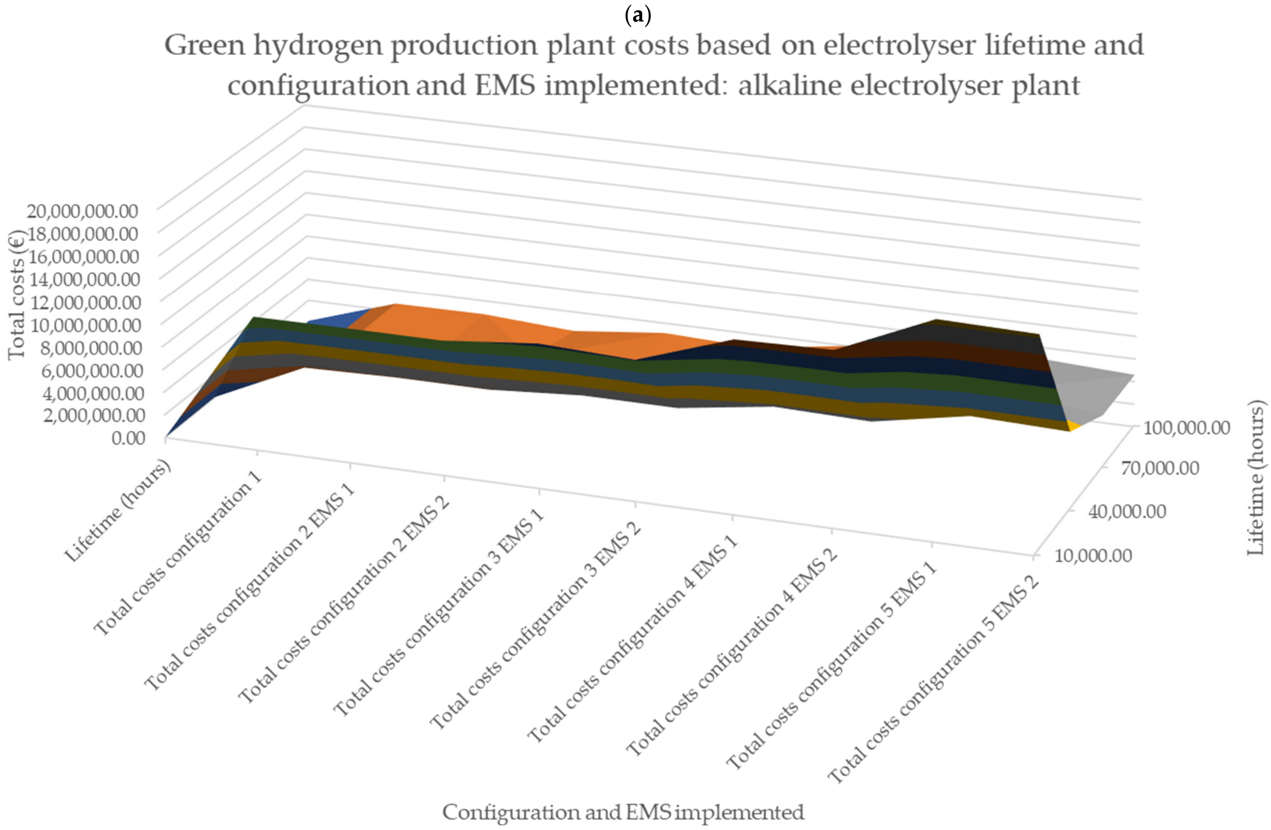


Figure 9. Total costs regarding modularity and EMS: (**a**) PEM technology, (**b**) alkaline technology.



(**a**)



(**b**)

Figure 10. Total costs of green hydrogen production plants based on (**a**) PEM and (**b**) alkaline electrolysis, depending on the electrolyser's lifetime and the configuration and EMS implemented.

Given that the typical selling price of green hydrogen ranges from 4 to 6 €/kg [45], a reference value of 5 €/kg is adopted for each kilogram of hydrogen not produced (base case). For PEM and alkaline technologies, the electrical energy consumption of the system is reported to be 50–83 kWh/kg and 50–78 kWh/kg [41], respectively; therefore, 60 kWh/kg is considered the base case. However, to capture a broader range of potential economic losses, three scenarios are analysed: in the first case, electrical efficiencies of between 50 and 83 kWh/kg are considered for alkaline technology and 50–78 kWh/kg for PEM technology (keeping the rest of the parameters at their base case values); in the second case, a variation of between 3 and 21 days for electrolyser replacement will be considered (other parameters fixed at their base case values); and in the last case, a variation in the price of hydrogen between 2 and 6 €/kg will be considered (other parameters fixed at their base case values).

Thus, the economic losses due to non-operation for the different configurations and EMSs can be estimated using Equation (3) and are presented in Table 12 for the three cases described above.

$$C_{losses}(€) = c_{H2} \cdot \sum_{i=1}^{T} \frac{N_{rep} \cdot P_{PV} \cdot \frac{P_{ElyNom_i}}{P_{H2plant}} \cdot t_i}{E_{ely}} \quad (3)$$

where

$C_{losses}(€)$: economic losses of the configuration studied;

c_{H2}: unitary cost of green hydrogen (2–6 €/kg or 5 €/kg in base case);

P_{PV}: PV field power (kW);

P_{ElyNom_i}: individual module's electrolyser power (kW);

T: electrolyser replacement time (3–21 days, i.e., 72–504 h, or 7 days, i.e., 168 h in base case);

t_i : unit time (1 h);

E_{ely}: energy needed by the electrolyser to produce hydrogen (50–83 kWh/kg for alkaline electrolysis or 50–78 kWh/kg for PEM electrolysis, or 60 kWh/kg in base case).

Table 12. Economic losses for different configurations and EMSs because of the non-operation of electrolysers.

Configuration	1	2		3		4		5	
		EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2	EMS 1	EMS 2
Economic losses alkaline electrolysis (50–83 kWh/kg) (€)	27,825–46,189 Δ = 18,904	22,659–37,613 Δ = 14,954		19,221–32,085 Δ = 12,864		16,816–30,789 Δ = 13,973		18,183–30,184 Δ = 12,001	
Economic losses alkaline electrolysis (3–21 days' replacement time) (€)	16,496–115,474 Δ = 98,978	13,433–94,033 Δ = 80,600		11,395–80,213 Δ = 68,818		10,468–76,974 Δ = 66,506		10,780–75,460 Δ = 64,680	
Economic losses alkaline electrolysis (2–6 €/kg H_2) (€)	15,396–46,189 Δ = 30,793	12,538–37,613 Δ = 25,075		10,635–32,085 Δ = 21,450		9770–30,789 Δ = 21,019		10,061–30,184 Δ = 20,123	
Economic losses PEM electrolysis (50–78 kWh/kg) (€)	28,634–47,534 Δ = 18,900	22,890–37,997 Δ = 15,107		20,036–33,274 Δ = 13,238		18,269–31,367 Δ = 13,098		18,326–30,422 Δ = 12,096	
Economic losses PEM electrolysis (3–21 days' replacement time) (€)	16,976–118,835 Δ = 101,859	13,570–94,992 Δ = 81,422		11,879–83,184 Δ = 71,305		10,831–78,416 Δ = 67,585		10,865–76,054 Δ = 65,189	
Economic losses PEM electrolysis (2–6 €/kg H_2) (€)	15,845–47,534 Δ = 31,689	12,665–37,997 Δ = 25,332		11,087–33,274 Δ = 22,187		10,109–31,367 Δ = 21,258		10,141–30,422 Δ = 20,281	

As shown, the differences in economic losses associated with the different configurations and implemented EMSs are very small compared with the total acquisition and O&M costs. Since the differences in economic losses among the configurations and EMSs are well below EUR 100,000, they can be considered negligible in terms of their economic impact on the hydrogen production plant.

To summarise the economic suitability of the configurations, the CAPEX-only LCOH is presented in Table 14, as a function of the configuration and EMS implemented. This LCOH is calculated as the ratio of the total acquisition costs (from Table 10) to the total hydrogen production over the plant lifetime (shown in Table 13).

Table 13. Hydrogen production during its lifetime based on configuration and EMS implemented.

		Configuration 1	Configuration 2		Configuration 3		Configuration 4		Configuration 5	
Electrolysis Technology	**Lifetime (Hours)**	**EMS 1 H_2 Production (kg)**	**EMS 1 H_2 Production (kg)**	**EMS 2 H_2 Production (kg)**	**EMS 1 H_2 Production (kg)**	**EMS 2 H_2 Production (kg)**	**EMS 1 H_2 Production (kg)**	**EMS 2 H_2 Production (kg)**	**EMS 1 H_2 Production (kg)**	**EMS 2 H_2 Production (kg)**
PEM	10,000	1,035,558	1,034,737	1,034,737	1,035,146	1,035,558	1,035,368	1,035,558	1,035,558	1,035,558
	40,000	1,035,558	1,034,737	1,034,737	1,035,146	1,035,558	1,035,368	1,035,558	1,035,558	1,035,558
	70,000	1,035,558	1,034,737	1,034,737	1,035,146	1,035,558	1,035,368	1,035,558	1,035,558	1,035,558
	100,000	1,035,558	1,034,737	1,034,737	1,035,146	1,035,558	1,035,368	1,035,558	1,035,558	1,035,558
ALK	10,000	1,006,273	1,024,289	1,024,289	1,029,777	1,035,558	1,031,954	1,013,568	1,035,558	1,035,558
	40,000	1,006,273	1,024,289	1,024,289	1,029,777	1,035,558	1,031,954	1,013,568	1,035,558	1,035,558
	70,000	1,006,273	1,024,289	1,024,289	1,029,777	1,035,558	1,031,954	1,013,568	1,035,558	1,035,558
	100,000	1,006,273	1,024,289	1,024,289	1,029,777	1,035,558	1,031,954	1,013,568	1,035,558	1,035,558

Total H_2 production is obtained from $Prod_{H_2} = T_{H_2\ plant} \cdot Prod_{H_2\ annual}$, where $Prod_{H_2}$ is the hydrogen production during the hydrogen electrolyser plant lifetime (kg), while $Prod_{H_2\ annual}$ is the annual hydrogen production in the plant (kg).

Table 14. CAPEX-only LCOH surrogate in hydrogen production plant during its lifetime based on configuration and EMS implemented.

		Configuration 1	Configuration 2		Configuration 3		Configuration 4		Configuration 5	
Electrolysis Technology	**Lifetime (Hours)**	**EMS 1 LCOH (€/kg)**	**EMS 1 LCOH (€/kg)**	**EMS 2 LCOH (€/kg)**	**EMS 1 LCOH (€/kg)**	**EMS 2 LCOH (€/kg)**	**EMS 1 LCOH (€/kg)**	**EMS 2 LCOH (€/kg)**	**EMS 1 LCOH (€/kg)**	**EMS 2 LCOH (€/kg)**
PEM	10,000	4.07	3.95	4.08	3.99	4.82	4.82	5.83	5.77	5.77
	40,000	1.51	1.61	1.84	1.79	2.31	2.21	2.81	2.69	2.69
	70,000	1.25	1.40	1.65	1.65	2.11	2.03	2.57	2.48	2.48
	100,000	1.24	1.40	1.62	1.59	2.06	2.03	2.52	2.48	2.48
ALK	10,000	9.70	9.43	9.45	10.48	10.13	13.04	13.25	15.76	16.03
	40,000	3.38	3.52	3.52	3.99	3.68	4.87	4.94	6.03	6.01
	70,000	2.51	2.52	2.51	3.06	2.75	4.03	3.34	4.91	4.06
	100,000	1.71	2.50	2.04	2.76	2.47	3.57	3.34	4.42	4.06

LCOH is obtained from $\boldsymbol{LCOH} = \frac{C_{totalacq.cost}}{Prod_{H_2}}$, where $\boldsymbol{LCOH}$ is the levelised cost of hydrogen (€/kg).

Having analysed all the variables affecting the techno-economic aspects associated with the modularity of green hydrogen production plants, it is now possible to identify the most suitable configuration for implementation. These recommendations will clearly depend on the application in which the green hydrogen production plant is integrated.

Thus, for applications where economic factors are paramount (e.g., industrial applications), configurations with a lower degree of modularity (configurations 1 and 2) are the most suitable. However, when configuration 1 is more cost-effective than configuration 2, the difference is at most around 300,000 EUR (between the most cost-effective EMSs of configuration 2 and configuration 1), which occurs in an alkaline-based hydrogen production plant with a 100,000 h electrolyser lifetime.

Given that this difference is relatively small compared with the total acquisition cost of a single 1 MW electrolyser module, and considering the risk of operational failures that could render an electrolyser inoperative before the end of its estimated lifetime, it may be more convenient to implement configuration 2 rather than configuration 1 (i.e., solutions with a certain degree of modularisation). In this way, if one electrolyser needs to be replaced due to a failure, hydrogen production can still be maintained and, furthermore, the replacement cost will be significantly lower.

However, in applications where technical factors are paramount (i.e., prioritising the useful life of equipment, as in military applications, where economic profitability is not a priority), the most suitable configurations are those with the highest degree of modularity (configurations 4 and 5, with longer replacement times; see Tables 7 and 8).

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5. Conclusions

This paper has analysed the impact of modularity on hydrogen production plants based on electrolysers, using a 1 MW_e green hydrogen production plant as a case study. The analysis considers both technical and economic factors.

For a green hydrogen production plant, conducting a techno-economic analysis requires identifying the EMS and degree of modularity that make the plant most economically competitive. From a technical perspective, a higher degree of modularity reduces degradation, but the unit cost of a single electrolyser (per unit of power) increases significantly (as economies of scale make larger electrolysers more cost-effective). Although high-modularity configurations require fewer replacements, they are associated with higher costs. Consequently, the most economically competitive configurations are 1 (single-module plant) and 2 (two-module plant).

Regarding configurations 1 and 2, there is no clear winner, as the outcome depends on the electrolysis technology, the EMS, and the electrolyser lifespan. However, even when configuration 1 is more profitable than the most profitable EMS of configuration 2, the difference is at most 300,000 EUR. Furthermore, in the event of replacement, the economic risk is higher for configuration 1 (which includes a single electrolyser module) than for configuration 2 (which consists of two 500 kW electrolyser modules), since replacing an electrolyser with twice the power would entail significantly higher costs.

For these reasons, the authors recommend implementing a configuration with a certain degree of modularity in a green hydrogen production plant, rather than a single-module plant), in order to avoid potentially high economic risks. Furthermore, as shown in this paper, to reduce the costs associated with electrolysers in a green hydrogen production plant, it is more important to increase the electrolysers' lifespan (thereby avoiding a high number of replacements) than to reduce the cost of the electrolyser module.

Accordingly, another recommendation is the need to invest heavily in research and development to both reduce the unit cost of electrolysers and, more importantly, increase their lifetime. However, configurations with a higher degree of modularity may be even more advisable than those with lower modularity in applications where technical factors (i.e., extending electrolyser lifespan) are more important than economic factors. An example of such applications could be military installations.

However, the conclusions drawn from this work assume that electrolyser degradation occurs as a function of operating hours. For this reason, the scope of these conclusions is subject to certain limitations; in particular, the techno-economic behaviour of the hydrogen production plant may also be influenced by phenomena such as degradation caused by start–stop operation of the electrolyser modules.

This paper represents a starting point for the study of electrolyser modularity in large-scale green hydrogen production plants. Future research should address additional topics, such as the influence of alternative EMSs, or extend the current CAPEX-only LCOH analysis to a comprehensive assessment that includes electricity and O&M costs, as well as other configurations with different installed electrolysis capacities. In addition, future studies shall integrate sensitivity analysis and probability theory to determine the replacement time for electrolysers once they break down or the influence of starts and stops in the electrolyser lifetime on the techno-economic performance of the green hydrogen plant. Finally, this line of research opens the door to studies aimed at quantifying the CAPEX uncertainty associated with each configuration and each strategy, thereby enabling stakeholders to make informed decisions based on these results.

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Abbreviations

The following abbreviations are used in this manuscript:

BoP	Balance of plant
C	Unit cost of the hydrogen production plant (€/kW)
CAPEX	Capital expenditure
c_{H_2}	Selling unitary cost of green hydrogen (5 €/kg)
C_{losses}	Economic losses (€)
E_{ely}	Energy needed by the electrolyser to produce 1 kg hydrogen (50–83 kWh/kg)
EMS	Energy management strategy
EoL	End of life
k_0	Fitting constant
$\boldsymbol{k}$	Fitting constant
$LCOH$	Levelized cost of hydrogen (€/kg)
MSELS	Multi-stack electrolyser system
MSFC	Multi-stack fuel cell
N_{rep}	Number of replacements
O&M	Operation and maintenance
P_{ava}	Available power (kW)
P_{ElyNom_i}	Individual module's electrolyser power (kW)
PEM	Polymer exchange membrane
P_{H_2plant}	Nominal electrical power of the hydrogen production plant (1 MW)
P_{PV}	PV field power (W)
$Prod_{H_2}$	Hydrogen production during hydrogen electrolyser plant lifetime (kg)
$Prod_{H_2\ annual}$	Annual hydrogen production in the plant (kg)
PV	Photovoltaic
Q	Nominal capacity of the electrolyser module (kW)
T_{H_2plant}	Lifespan of the hydrogen production plant (25 years)
t_i	Unit of time (1 h)
T_{ely}	Electrolyser replacement time (years)
Y	Installation year of the hydrogen production plant
Y_0	Reference year (2020)
α	Scaling factor
β	Learning factor

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