

# Study on the Decarbonisation of the Sea-Ferry Stations at Balearic Ports

Deliverable 6.3

Updated December 2024



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## Preface

The aim of **GREEN HYSLAND** is to **deploy a Hydrogen ecosystem on the island of Mallorca**. The initiative is receiving **10 Million Euros of funding** from the European Commission through the **Clean Hydrogen Partnership**. It is a 5-year-project that started on the 1<sup>st</sup> January 2021, and will end on 31<sup>st</sup> December 2025. The consortium is formed by **30 partners from 11 countries**, 9 from the European Union, as well as Chile and Morocco. The project will deliver the **first hydrogen valley of the Mediterranean**, developing a fully functioning hydrogen (H<sub>2</sub>) ecosystem covering all the value chain, from the production to the distribution and consumption of, at least, 330 tonnes per year of green H<sub>2</sub>, traced through a Guarantee of Origin System. This hydrogen will be used in six different applications, as follows:

- The **H<sub>2</sub> pipeline and the injection point** of part of the H<sub>2</sub> produced at the Lloseta plant into the island's natural gas network operated by Redexis.
- The **100 kWe fuel cell** that will supply electricity to the Maritime Terminal of the **Balearic Port**.
- The **50 kWe CHP** system to be located in the **Iberostar Bahía de Palma hotel (4\*)**, which will cover part of the hotel's energy demand.
- The **25 kWe CHP** system to be located at the **Municipal Sports Centre in Lloseta**, which will cover part of the site's energy demand.
- The integration of **5 hydrogen buses to the EMT** city bus fleet of Palma de Mallorca.
- The integration of **H<sub>2</sub> vans** in the Alfill Logistics vehicle fleet as well as the search for rental car companies to incorporate H<sub>2</sub> vehicles in their **rental car fleets**.

The infrastructures which will be developed within the project are:

- The **green H<sub>2</sub> production plant** located on CEMEX land in Lloseta.
- The deployment of a **Hydrogen Refuelling Station (HRS)** at the EMT facilities.
- The development of tube trailers which will transport the H<sub>2</sub> produced in Lloseta's plant to the different applications.

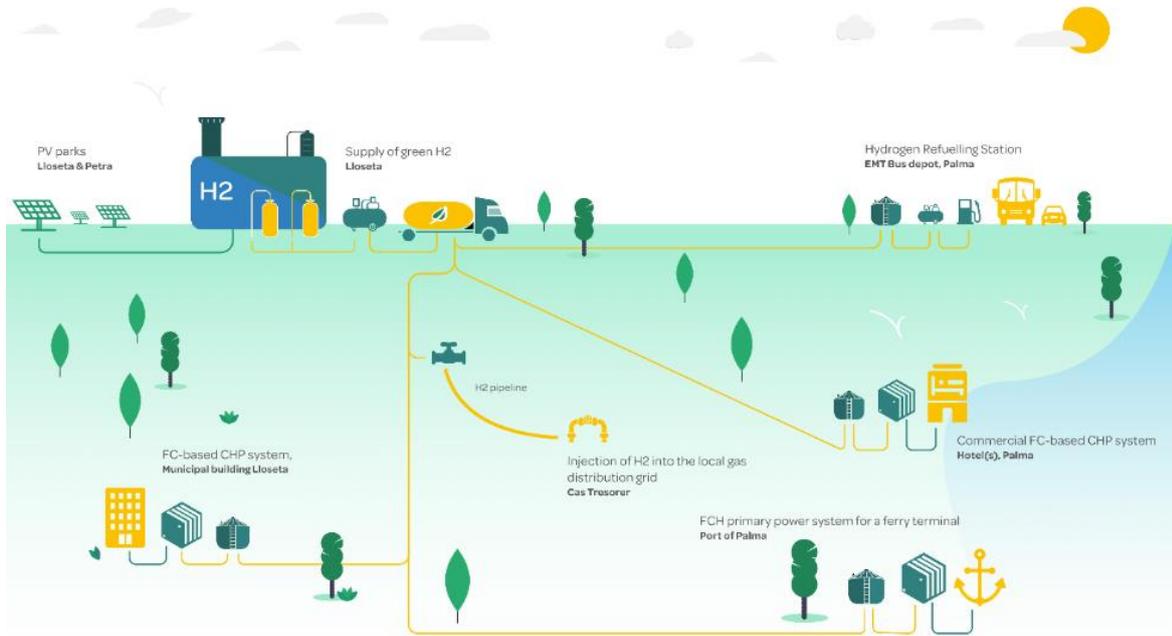
This initiative aims to reduce the CO<sub>2</sub> emissions of Mallorca up to 20,700 tonnes per year by the end of the project.

The project will also deliver a **roadmap towards 2050** that compiles a long-term vision for the **development of a widespread H<sub>2</sub> economy in Mallorca and the Balearic Region**, in line with the **environmental objectives set for 2050**. This long-term roadmap will be an evolution of the current regional roadmap for the deployment of renewable energies and the energy transition, and will involve local and regional stakeholders through public consultations.

In addition, GREEN HYSLAND contemplates the **development of replication experiences** in five other EU islands: Madeira (PT), Tenerife (ES), Aran (IE), Greek Islands and Ameland (NL) as well as Chile and Morocco. Within the project, the impact of deployment of H<sub>2</sub> technologies at regional level (Mallorca and Balearic islands) at technical, economic, energy, environmental, regulatory and socioeconomic levels will be analyzed. Additionally, detailed techno-economic studies for scaling-up renewable H<sub>2</sub>

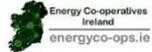
production, interconnecting infrastructure and local H<sub>2</sub> end-uses, both within the island of Mallorca and beyond, will be developed to facilitate and de-risk future sector investment.

The infrastructures for the hydrogen production and distribution, together with the end-users' pilot sites and the logistics required for the green hydrogen distribution will be developed as follows:



No	Participant Name	Short Name	Country Code	Logo
1	ENAGÁS RENOVABLE S.L.	EGR	ES	
2	ACCIONA ENERGIA S.A.	ACCIONA ENER	ES	
3	REDEXIS GAS S.A.	REDEXIS GAS SA	ES	
4	Empresa Municipal de Transports Urbans de Palma de Mallorca S.A.	EMT-PALMA	ES	

5	CALVERA MAQUINARIA E INSTALACIONES S.L.	CALVERA	ES	
6	AJUNTAMENT DE LLOSETA	Lloseta Council	ES	
7	AUTORIDAD PORTUARIA DE BALEARES	PORTS BALEARS	ES	
8	CONSULTORIA TECNICA NAVAL VALENCIANA S.L.	COTENAVAL	ES	
9	BALEARIA EUROLINEAS MARITIMAS S.A.	BALEARIA	ES	
10	INSTITUTO BALEAR DE LA ENERGIA	IBE	ES	
11	UNIVERSITAT DE LES ILLES BALEARS	UIB	ES	
12	FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON	FHa	ES	
13	CENTRO NACIONAL DE EXPERIMENTACION DE TECNOLOGIAS DE HIDROGENO Y PILAS DE COMBUSTIBLE CONSORCIO	CNH2	ES	
14	ASOCIACION ESPANOLA DEL HIDROGENO	AeH2	ES	
15	COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA	FR	

16	ENERCY BV		ENER	NL	
17	HYENERGY TRANSSTORE BV		HTS	NL	
18	STICHTING NEW ENERGY COALITION		NEW ENER.COALIT	NL	
19	HYCOLOGNE GMBH		HyCologne	DE	
20	FEDERATION EUROPEENNE DES AGENCES ET DES REGIONS POUR L'ENERGIE ET L'ENVIRONNEMENT		FEDARENE	BE	
21	NATIONAL UNIVERSITY OF IRELAND GALWAY		NUI GALWAY	IE	
22	THE EUROPEAN MARINE ENERGY CENTRE LIMITED		EMEC	UK	
23	GASNAM - ASOCIACION IBERICA DE GASNATURAL Y RENOVABLE PARA LA MOVILIDAD		GASNAM	ES	
24	UNIVERSIDAD DE LA LAGUNA		ULL	ES	
25	ENERGY CO-OPERATIVES IRELAND LIMITED		En.Coop.Ireland	IE	
26	AGENCIA REGIONAL DA ENERGIA E AMBIENTE REGIAO AUTONOMA MADEIRA		AREAM	PT	

27	GEMEENTE AMELAND	Gem.Ameland	NL	
28	DIKTYO AEIFORIKON NISON TOY AIGAIYOU AE	DAFNI	EL	
29	ASOCIACION CHILENA DE HIDROGENO	H2 CHILE	CL	
30	Association Marocaine pour l'Hydrogène et le Développement Durable	AHMYD	MA	
31	HYENERGY CONSULTANCY LTD	HYE	NL	
32	ENAGÁS S.A.	ENAGAS	ES	
33	Power to Green Hydrogen Mallorca S.L.	P2GH2M	ES	

## Table of contents

### Acronym List

1	Executive Summary.....	1
2	Introduction .....	2
2.1	<b>Study scope and system boundaries .....</b>	<b>3</b>
3	Current situation description .....	9
3.1	<b>General description of the electricity system in the Balearic Islands.....</b>	<b>9</b>
3.2	<b>Operations in sea-ferry stations description .....</b>	<b>12</b>
3.3	<b>Energy Demand in the Sea-Ferry Stations .....</b>	<b>13</b>
3.3.1	Maritime terminal - Estación Marítima 2 (EM2) .....	13
3.3.2	Maritime terminal - Estación Marítima 3 (EM3) .....	16
3.3.1	Maritime terminal - Estación Marítima 4 (EM4) .....	19
3.3.2	Maritime terminal Botafoc- Estación Marítima Botafoc.....	20
3.3.3	Maritime terminal Mahón - Estación Marítima Mahón (Menorca).....	23
3.4	<b>Carbon dioxide emissions estimation in the current situation .....</b>	<b>24</b>
4	Technology assessment: current status and future developments .....	25
4.1	<b>Fuel cells for primary heat and power.....</b>	<b>25</b>
4.2	<b>Fuel Cells Market developments.....</b>	<b>29</b>
5	Hydrogen supply and infrastructure at Balearic Ports: overall requirements	30
5.1	<b>Hydrogen supply (transport to location) .....</b>	<b>30</b>
5.2	<b>Hydrogen storage.....</b>	<b>31</b>
6	Other aspects to consider in the development of the energy system in the maritime terminals.....	33
6.1	<b>Social acceptance .....</b>	<b>33</b>
6.2	<b>Regulatory aspects .....</b>	<b>33</b>
6.3	<b>Safety aspects .....</b>	<b>34</b>
7	Techno-economic assessment .....	37
7.1	<b>Methodology .....</b>	<b>38</b>
7.1.1	Cost-Benefit Analysis (CBA) parameters .....	38
7.1.2	Modelling the hydrogen fuel cell system .....	40

<b>7.2</b>	<b>Main technical and operational input parameters, assumptions and boundaries</b>	<b>44</b>
7.2.1	Electricity demand per building.....	44
7.2.2	Fuel cell technical inputs .....	44
7.2.3	Inverter .....	46
7.2.4	Hydrogen supply and storage.....	46
7.2.5	New PV systems .....	48
7.2.6	Other operational inputs.....	49
7.2.7	Model Boundaries and limitations .....	50
<b>7.3</b>	<b>Economic parameters and lifetime of the various components .....</b>	<b>51</b>
7.3.1	Fuel cell economic inputs .....	51
7.3.2	Hydrogen storage economic inputs .....	52
7.3.3	Inverter.....	53
7.3.4	Civil works.....	53
7.3.5	Hydrogen prices.....	53
7.3.6	Grid electricity costs .....	56
7.3.7	New PV systems Costs.....	57
7.3.8	Other Financial parameters.....	58
<b>7.4</b>	<b>Hydrogen fuel cell-based concepts analysed.....</b>	<b>58</b>
7.4.1	Stand-alone configurations .....	58
7.4.2	Combined system configuration .....	59
<b>8</b>	<b>Results .....</b>	<b>64</b>
<b>8.1</b>	<b>Stand-alone configurations.....</b>	<b>64</b>
8.1.1	Maximum technical output Fuel cell system identification .....	64
8.1.2	Load Following (LF) fuel cell system configuration .....	65
8.1.3	Constant Load (CL) fuel cell system configuration .....	72
8.1.4	Frequency of Hydrogen fuel recharge.....	78
<b>8.2</b>	<b>Combined system configurations.....</b>	<b>80</b>
<b>8.3</b>	<b>Costs Estimates .....</b>	<b>83</b>
8.3.1	Stand-alone configurations costs .....	83
8.3.1	CBA configurations costs .....	85
<b>8.4</b>	<b>Cost for frequency of charge case .....</b>	<b>87</b>
<b>8.5</b>	<b>Sensitivity analysis .....</b>	<b>88</b>
8.5.1	Fuel cell degradation factor.....	90
8.5.2	Sensitivity Power Loss factor .....	91

8.5.3	Fuel cell Capex sensitivity .....	92
8.5.4	Fuel Cell Efficiency sensitivity .....	93
8.5.5	Hydrogen price sensitivity .....	93
<b>8.6</b>	<b>Hydrogen demand Estimations .....</b>	<b>95</b>
<b>8.7</b>	<b>Potential CO<sub>2</sub> emissions avoidance estimations .....</b>	<b>96</b>
9	Risks assessment .....	98
10	Conclusions and recommendations .....	100
11	List of Figures .....	104
12	List of Tables .....	108
13	References .....	110
<b>Appendix A.</b>	<b>Model inputs: Fuel cell stack CAPEX .....</b>	<b>i</b>
<b>Appendix B.</b>	<b>Model inputs: Fuel cell OPEX .....</b>	<b>ii</b>
<b>Appendix C.</b>	<b>LF-FC at 1 day charge: CBA parameters .....</b>	<b>iii</b>
<b>Appendix D.</b>	<b>LF-FC at 1 day charge: energy output and H<sub>2</sub> demand .....</b>	<b>iv</b>
<b>Appendix E.</b>	<b>CL-FC at 1 day charge: CBA parameters .....</b>	<b>v</b>
<b>Appendix F.</b>	<b>CL-FC at 1 day charge: energy output and H<sub>2</sub> demand .....</b>	<b>vi</b>
<b>Appendix G.</b>	<b>Botafoc: results at different frequencies of H<sub>2</sub> charge .....</b>	<b>vii</b>
<b>Appendix H.</b>	<b>Mahón: results at different frequencies of H<sub>2</sub> charge .....</b>	<b>viii</b>
<b>Appendix I.</b>	<b>Stand-alone configurations at 1 day charge: costs summary .....</b>	<b>ix</b>
<b>Appendix J.</b>	<b>Combined configurations: costs summary .....</b>	<b>x</b>

## Acronym list

**AC:** Alternate Current

**AEP:** Annual Electricity Produced

**AFC:** Alkaline Fuel Cell

**BOP:** Balance of Plant

**CAPEX:** Capital expenditure

**CBA:** Cost-Benefit Analysis

**CHP:** Combined Heat and Power

**CL:** Constant-Load

**CMA:** Centred Moving Average

**DC:** Direct Current

**E:** Electricity

**EA:** Energy Autonomy

**EM:** *Estación Marítima* (Maritime Terminal)

**EOL:** End of Lifetime

**ETS:** Emission Trading System

**EU:** European Union

**FC:** Fuel Cell

**GHG:** Greenhouse Gases

**ICE:** Internal Combustion Engine

**LACS:** Lifetime Actualized Cost Savings

**LCOE:** Levelized Cost of Electricity

**LF:** Load-Following

**MA:** Moving Average

**MAPE:** Mean Absolute Percentage Error

**MCFC:** Molten Carbonate Fuel Cell

**MinLCOE:** Minimum LCOE

**MSC:** Model Spatial Constraints

**NIMBY:** Not in My Backyard

**O&M:** Operation and Maintenance

**OPEX:** Operational expenditures

**P:** Power

**PAFC:** Phosphoric Acid Fuel Cell

**PEMFC:** Polymeric Electrolyte Membrane Fuel Cell

**PV:** Photovoltaic panels

**PVGIS:** Photovoltaic Geographical Information System

**RCS:** Regulations, Codes and Standards

**RES:** Renewable Energy Source

**SoA:** State of the Art

**SOFC:** Solid Oxide Fuel Cell

**SWH:** Sanitation Water Heating

**TP:** Tariff Period

**TRL:** Technology Readiness Level

**WP:** Work Package

**$\Delta\text{CO}_2$ :** Carbon dioxide emissions avoided

# 1 Executive Summary

The study focused on the decarbonisation of the activities in the Sea ferry terminals in the Balearic Islands, which is a specialized infrastructure located in a port, dedicated to the operation, boarding, and disembarking of ferries. The techno-economic assessment presented here, conducted within the scope of the GREEN HYSLAND project in collaboration with the port authority Port of Balears has provided valuable insights into the potential integration of renewable energies, hydrogen storage, and fuel cells, for clean and efficient electricity generation and increased energy autonomy of the buildings.

The scope of this study includes five maritime sea-ferry terminals (*Estaciones Marítimas* in Spanish) operated by the Balears Port Authority. The terminals included in the study are: Estación Marítima 2 (EM2) and Estación Marítima 3 (EM3) on the island of Mallorca, the maritime terminal in Botafoc (Ibiza), and the sea terminal in Mahón (Menorca). The study also references the planned hydrogen system for Estación Marítima 4 (EM4), aiming to determine the most suitable type of fuel cells, storage systems, and hydrogen refilling operations for the different sites. Additionally, the study examines the techno-economic feasibility of the integration of the hybrid energy system for EM4 with EM2 and EM3.

With regards to the economic feasibility, the study employed a comprehensive methodology and mathematical model to assess the cost-effectiveness and performance indicators specific to the assessment. Key performance indicators such as Levelized Cost of Electricity (LCOE), Energy Autonomy (EA), lifetime cost savings, and CO<sub>2</sub> emissions reduction were used to evaluate the economic viability, energy self-sufficiency, potential cost reductions, and environmental benefits of the proposed Fuel Cell (FC)-based hybrid energy systems. Various technical solutions were analysed, considering the integration of fuel cells and PV solar systems where applicable.

The energy demand of the buildings was evaluated to determine the optimal sizing and capacity requirements of the hydrogen systems. The conceptual design aimed to achieve at least 80% energy autonomy at the lowest cost possible, resulting in reduced grid electricity consumption and significant emissions reduction.

Based on the analysis of the existing energy supply systems of the sea-ferry terminals, solutions that achieved 80% energy autonomy at reasonable costs were considered well-balanced choices, while the results of the study showed that maximum grid independence and CO<sub>2</sub> emissions avoidance came at significantly higher costs (represented by higher LCOE values). The integration of PV solar systems in the maritime terminals provided economic advantages, reducing operating costs, as well as reducing the need for conventional grid electricity supply. Considering the implementation of the hybrid FC-based energy system at the ports, the study highlighted that achieving the highest energy autonomy does not always correspond to the minimum LCOE, and therefore can have significant economic penalties, mainly due to the current costs of commercially available fuel cells and the costs of green hydrogen supply. A comparison between load-following (LF) and constant load (CL) fuel cell operational modes showed advantages and trade-offs. The analysis also considered the cost implications of fuel cell stack replacements and variations in hydrogen prices.

The study also identified potential social, regulatory, and safety barriers that could affect the realization and operation of these new fuel cell-based energy systems. Mitigation measures were proposed to address these issues. Further analysis was recommended for Botafoc and Mahón maritime terminals, considering factors such as energy demand uncertainties and project definition.

Limitations of the study included the inability to explicitly assess distribution costs, the exclusion of subsidy impacts in cost estimations, and uncertain regulations for hydrogen applications. The study incorporated a risk assessment focused on the operational phase of the project.

The results of the study will be utilized in the development of a hydrogen roadmap for the Balearic Archipelago up to 2050. Overall, the study contributes to the understanding of decarbonisation strategies based on the implementation of fuel cells and green hydrogen supply for maritime ferry terminals, and underscores the importance of integrating renewable energies and green hydrogen for sustainable energy solutions. It suggests the need for further research, addressing the identified limitations and incorporating risk mitigation measures in future studies and project implementation.

## 2 Introduction

The aim of the GREEN HYSLAND project is developing an integrated energy ecosystem in the Balearic Islands based on green hydrogen, namely a Hydrogen Valley. Such ecosystem includes all the steps of the value chain, from hydrogen production through to supply and distribution, and eventually to its final use. Renewable hydrogen will be produced in a dedicated PV-powered electrolysis plant in Lloseta, which is expected to produce at least 300 tons of renewable hydrogen per year, once fully operational.

The produced hydrogen gas will be delivered to the different end-users by mean of a new pipeline and with trucks. Hydrogen will be used to provide heat and power to a sport centre in Lloseta municipality; and also (heat & power) to a hotel located in Palma de Mallorca through Combined Heat and Power (CHP) systems; to (i) meet some of the electrical demand of the Port of Palma (sea-ferry terminals and ships when docked), (ii) to provide fuel to a refuelling station that serves a new fleet of hydrogen buses for public transport, and (iii) it will also be blended into the existing natural gas grid up to a percentage of 4 percent within the duration of the project.

The following deliverable presents a techno-economic assessment on the decarbonisation of the sea-ferry stations at the ports of Mallorca, Ibiza and Menorca, through the integration of renewable energies and green hydrogen supply. The latter is going to be stored and then converted by mean of fuel cells into electricity and heat. Another objective of GREEN HYSLAND project is to deliver a roadmap for the Balearic archipelago towards 2050, in which the use of hydrogen will be scaled-up both in number of applications and in quantities, and its integration with the other renewable technologies should grow as well, with the vision of full decarbonisation of all the islands. This roadmap will be based on different studies, from techno-economic analyses to stakeholder consultations and assessment of RCS (Regulations, Codes and Standards) barrier.

The deliverable presented here is part of the studies that investigate the technical scale-up of end-user applications, to provide input to a Balearic hydrogen roadmap. In particular, this report comprises a decarbonisation study on the integration of renewable energies, green hydrogen storage and hydrogen-fed fuel cells, to supply electricity and heat to the sea-ferry stations at the ports of Mallorca, Ibiza and Menorca.

The study will assess the main benefits and challenges (technical, environmental, and economical) associated to the switch towards hybrid energy systems based on renewable energies and green

hydrogen; this analysis, led by *Energy BV* (ENER) and supported by *Autoridad Portuaria de Baleares* (PORTS BALEARS), *CotenaVal* (COT) and *Hy Energy Consultancy Limited* (HyE) is part of a wider one, whose focus are the different end-user applications in the Balearic Islands, from the industrial sector to the residential and commercial one, to the transportation. For each end-user application, the techno-economic evaluation should investigate their market potential and establish the basic techno-economic parameters for their market entry. More specifically the objectives of this study are:

1. A preliminary selection of the hydrogen technologies
2. A conceptual design of the configuration that will provide energy to the different sea-ferry terminals (fuel cell nominal power, storage capacity, frequency of hydrogen charge, fuel cell operational mode).
3. An estimation of the expected hydrogen demand to satisfy the energy requests of the applications.
4. A preliminary assessment on the technical, environmental, and economical performances of the new proposed system.
5. The decarbonisation study should inspect the main advantages and challenges related to the introduction of renewable and hydrogen technologies to satisfy the energy demand of these maritime terminals.

Moreover, the deployment phase of GREEN HYSLAND includes the installation of a Fuel cell system and hydrogen storage in the maritime terminal “*Estación Marítima 4*” (EM4) located the Port of Palma. The plan for EM4 is to satisfy its electricity demand primarily with an on-grid hybrid energy system that includes a dedicated photovoltaic (PV) plant with a nominal power of 100 kW, placed on its roof. The PV system is going to be the primary energy source, to be complemented by a hydrogen system composed by a 100 kW<sub>el</sub> fuel cell and a dedicated storage of 8,262 litres (able to contain up to 150 kg of gaseous hydrogen at 20°C and 260 bar). The fuel cell system will be used in case the self-consumption from photovoltaic sources will not cover the entire demand of the EM4 building. Eventually, the already existent electricity grid will provide electricity whenever the combination of the two previous sources will not be sufficiently high to meet the building electricity demand (Autoritat Portuària de Balears, 2022).

The GREEN HYSLAND project and the study presented here in particular are aligned with the environmental strategy of *Autoridad Portuaria de Baleares* (Autoritat Portuària de Balears, 2021), in which one of the main strategic objectives is to promote energy generation with renewable sources.

## 2.1 Study scope and system boundaries

This study presented here focuses on the electricity supply to passengers’ sea-ferry stations, also known as passenger’s maritime terminal within the ports in the Balearic Islands. The sea ferry terminals are a specialized port facility that serves as a departure and arrival point for ferry services, which transport passengers, vehicles, and cargo across the Balearic Sea. These passenger’s terminals are designed to accommodate the unique needs of ferry operations and provide necessary infrastructure and services for a smooth and efficient transfer of people and goods. In this study, the term maritime terminal (*Estación Marítima* in Spanish) refers specifically to the passengers building (see *Figure 1*).



Figure 1: View of the sea-ferry passengers terminal buildings EM4 (front) in the Port of Palma de Mallorca (Autorita Portuària de Balears, 2023)

Table 1 shows the specific buildings within the study scope. Figure 2 shows the ports location within the archipelago in the Balearic Sea and Figure 3 to Figure 5 depict the location of the existing and future maritime terminals at their respective port.

Table 1: Sea-Ferry stations considered in the decarbonisation study

Island	Port	Maritime terminal
<b>PALMA DE MALLORCA</b>	<i>Palma</i>	<i>Estación Marítima 2 (EM2)</i>
	<i>Palma</i>	<i>Estación Marítima 3 (EM3)</i>
	<i>Palma</i>	<i>Estación Marítima 4 (EM4)</i> <sup>1</sup>
<b>IBIZA</b>	<i>Ibiza</i>	Botafoc (under construction)
<b>MENORCA</b>	<i>Mahón</i>	Mahón (construction to be started yet)

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<sup>1</sup> Basic information of the design of the Fuel cell system to be deployed in EM4 by Port of Balears will be used in this study as reference, such as: (1) The selection of the hydrogen technologies in EM4 (fuel cell and storage system), as well as the hydrogen refilling operations will be used as reference in the other stations analysed, (2) the main features of EM4 (fuel cell nominal power, storage capacity, frequency of hydrogen charge, expected hydrogen consumption) will be used to calibrate the mathematical model. (3) Including EM4 new energy system into the model developed for this study will allow us to determine any electricity surplus that can be taken into account in this assessment of energy supply to other activities in the Port of Mallorca.

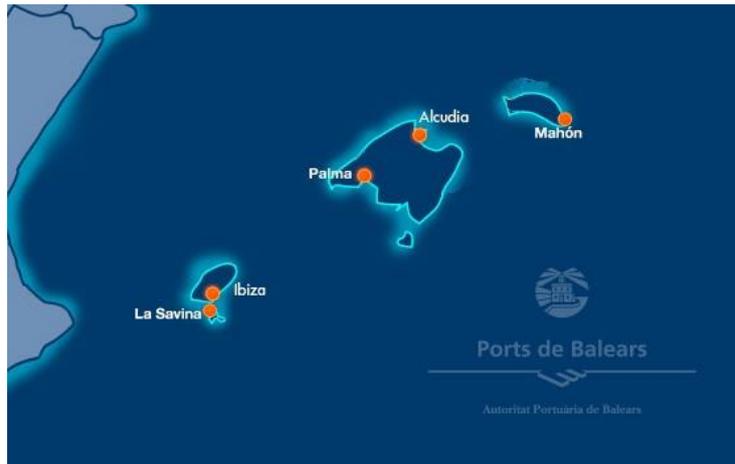


Figure 2: Shows the relative location of the ports included in this report: Palma, Ibiza and Mahón (**AUTORITAT PORTUARIA DE BALEARS, 2022**)

In the *Puerto de Palma*, the maritime terminals of interest (EM2, EM3 and EM4) are very close to each other as shown in the *Figure 3*:



Figure 3: Schematic view of the *Puerto de Palma* (AUTORITAT PORTUARIA DE BALEARS, 2021), with zoom on EM2, EM3 and EM4

The new building in the *Puerto de Eivissa (Ibiza)* expected to start operations by summer 2023; its expected position is shown in *Figure 4*.

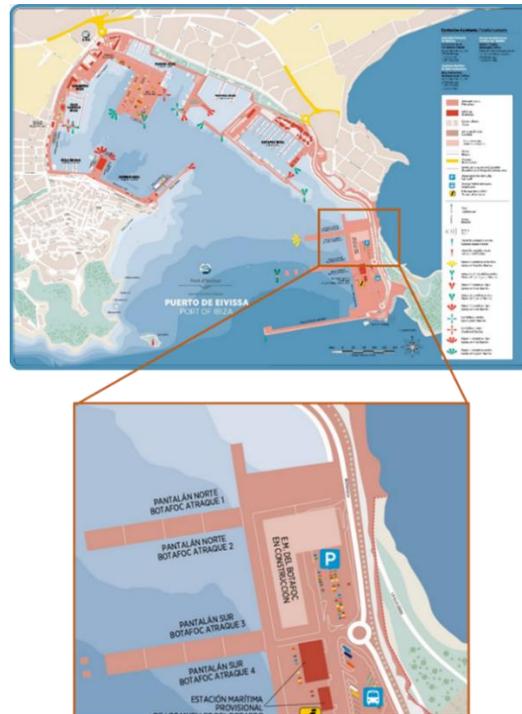


Figure 4: Schematic view of the *Puerto de Eivissa (Ibiza)* (AUTORITAT PORTUARIA DE BALEARS, 2020), with zoom on the maritime terminal of *Botafoc*

The construction works of the new maritime terminal in the *Puerto de Mahón (Menorca)* has not started yet; the building will be realized close to the existing maritime terminal of *Cos Nou* as presented in *Figure 5*.

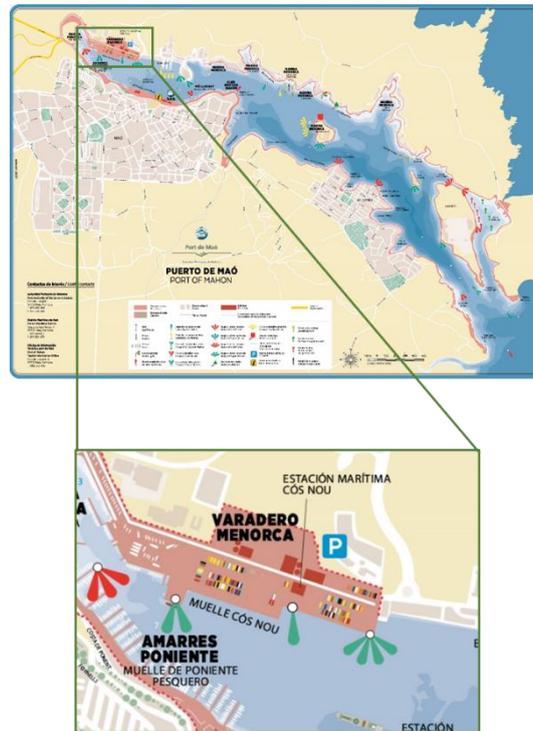


Figure 5: Schematic view of the *Puerto de Mahón* (AUTORITAT PORTUARIA DE BALEARS, 2021), with zoom on the future location of the new maritime terminal

The analysis takes into consideration the system characterized by the hydrogen storage unit and the hydrogen-based fuel cell within the different ports, as well as the renewable energy source available at the building (if applicable), which represents the final stages of the hydrogen value chain. The previous stages, which deal with hydrogen generation, compression and distribution to the port facility, are excluded in the technical analysis. To better understand where this study finds place within the overall scope of the GREEN HYSLAND project, and which are the main characteristics of the hybrid systems considered, *Figure 6* is presented.

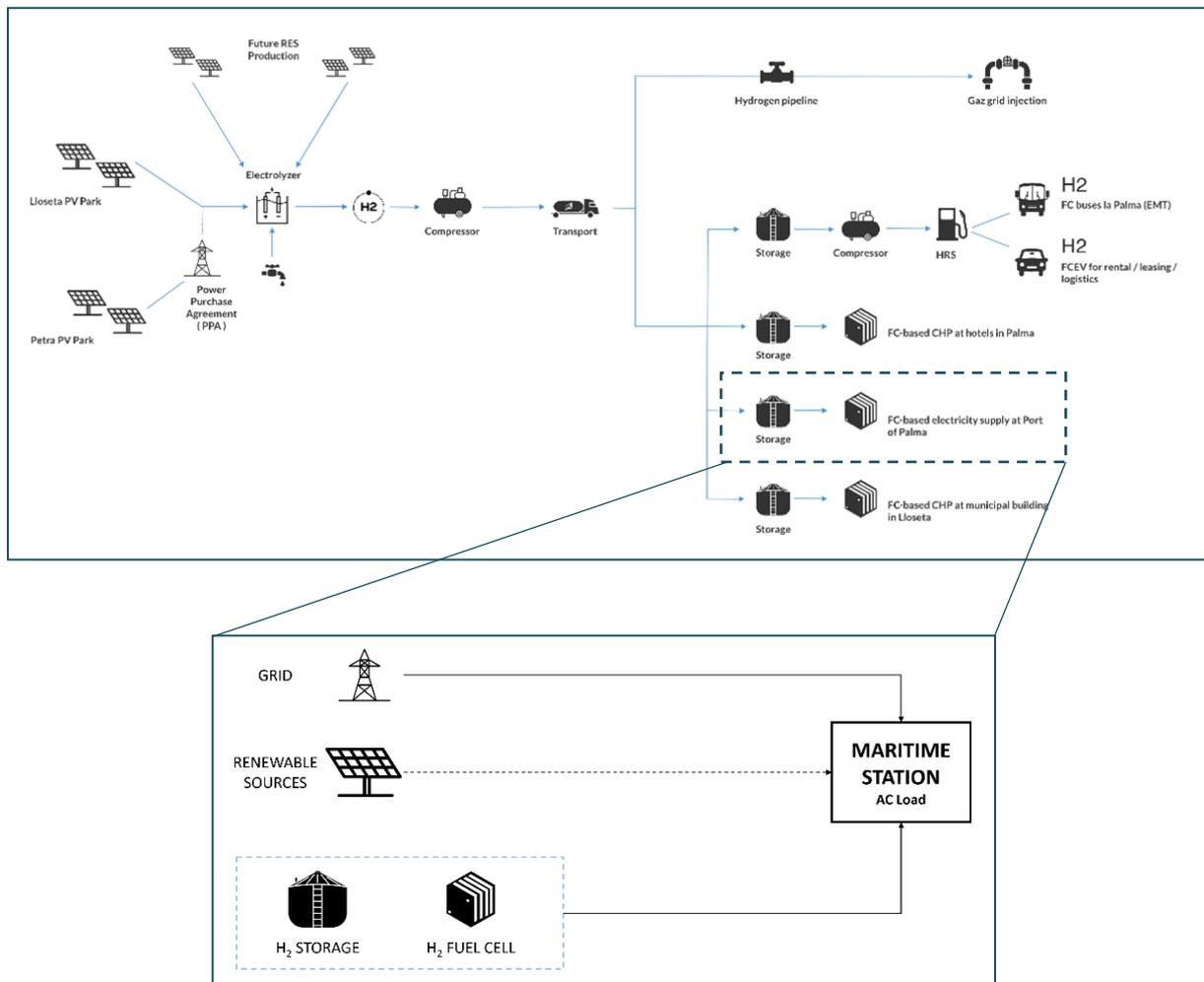


Figure 6: Generic schematic of GREEN HYSLAND project, with focus on the system dedicated to the port buildings for the present study.

In the hybrid energy system considered, the maritime terminal can be supplied with electricity from different sources: the national electricity grid, an eventual dedicated renewable PV-based electricity system, and the system composed by a fuel cell and a dedicated hydrogen storage.

Even though a battery-based system could in principle also be considered for this application (as an alternative to FC-based or complimentary to incumbent grid-based and/or PV-based systems), there is very limited information in the literature assessing the feasibility of power supply to maritime sea ferry terminals with the integration of battery-based systems (BESS). Furthermore, the economic and environmental benefits and ultimately the feasibility of BESS-based (on-grid or coupled to PV) systems for this type of maritime application remains unclear, mainly due to the high capacity of batteries that would be required to meet the operational requirements of the sea-ferry terminals (see Section 3.3), and the necessity to enable either a grid connection or a significant PV capacity to allow for battery charging over significant lengthy periods. On this basis, within the context of the GREEN HYSLAND project, a FC-based system was considered as the most attractive alternative to existing grid-based Cold Ironing systems. A comparison between FC-based and a BESS-based Cold Ironing systems was therefore not deemed justified and was not included within the scope of the analysis presented in the

deliverable, although a more in-depth analysis of BESS-based options (e.g. grid-connected or PV/hybrid) could be the subject of further work.

Under the economic perspective, the annual costs of the two alternatives (new system and reference case) are compared, to evaluate whether the hydrogen-based case can potentially lead to a reduction or a boost in the energy costs for the buildings. The annual costs for the new solution are calculated using the **Levelized Cost of Energy (LCOE)** indicator. The introduction of the hydrogen system will reduce the costs related to the electricity purchase from the electric grid: the associated **economic savings** is considered another important parameter to characterize the economic impact of the new technology, and is therefore included in the economic analysis.

The Lifetime Actualized Cost Savings (LACS) is defined as the potential cost savings over the project's lifetime by considering the annual cost savings, adjusted for inflation and discounted to present value. The objective of the study is to provide a preliminary costs assessment (in the form of a cost-benefit analysis (CBA)) of the implementation of the fuel cell system (FC) at the port, taking into account the reduction in electricity expenses (i.e. electricity that is generated from the fuel cell and therefore not purchased from the grid). The potential cost savings reflected in the LACS are therefore just referred to the costs avoided in the electricity purchase.

For the purposes of the economic assessment and the cost-benefit assessment presented here, total system costs and savings (represented by LCOE and LACS respectively) have been kept separated, based on the assumption that, under current market conditions, it is highly likely that the fuel cell system cost is not entirely incurred by the Balearic Port Authority, but co-funded and/or partly subsidized (e.g.: regional and/or national government would partially contribute to the investment), while all the cost savings will be allocated to the Port Authority.

Aside from direct economic savings, the lower **dependence on the grid** is also assessed with the so-called “Energy Autonomy”, an important indicator used quite often to evaluate the share of self-consumption and grid purchase for a system.

Regarding the environmental performances, the focus will be on the **annual carbon dioxide emissions**, trying to understand whether the new solution is able to reduce the carbon footprint of the port buildings.

## 3 Current situation description

### 3.1 General description of the electricity system in the Balearic Islands

Despite the high potential of electricity generation with renewable sources, numerous small islands around the world, including all those in the Mediterranean Sea, are strongly energy-dependent from fossil fuels (Curto & Trapanese, 2018) (Crainz, et al., 2019). One of the main obstacles that these insular electric systems face is the limited space and the presence of environmental restrictions to preserve the natural landscape, which make the construction of large renewable power plants such as photovoltaic or wind parks more difficult (Curto & Trapanese, 2018) (Crainz, et al., 2019). Generally, insular systems rely on fossil-fuels power plants to satisfy their electricity demand, and because of the seasonal variation of energy demand, mainly due to tourists' presence, these power plants often operate under suboptimal conditions. These factors sometimes lead insular systems to have a higher

emission factor with respect to the mainland system; usually these systems are also characterized by higher costs, linked for example to the transport of the fuel to the power plant, which usually occurs by shipping (Crainz, et al., 2019).

The Balearic Archipelago includes four main islands: Mallorca is the largest island with also the highest request for electricity (75% of the entire demand of the archipelago in 2019), followed by Ibiza, Menorca, and Formentera, respectively (IBESTAT, 2022).



Figure 7 : Electricity interconnections of the Balearic Archipelago (RED ELÉCTRICA ESPAÑOLA, 2022)

As shown in *Figure 7*, the islands of the archipelago are interconnected between each other. The oldest interconnection between two islands involved Ibiza and Formentera, with two distinct cables installed respectively in 1974 and in 1982, while a third cable is planned to be connected in 2023 (Periòdico de Ibiza y Formentera, 2022) (Red Eléctrica de España (REE), 2022); the second oldest interconnection was between Mallorca and Menorca, in 1975 (Sánchez, 2020), while a second cable was completed in 2020, taking 18 months to complete (Red Eléctrica de España (REE), 2020). The two different electric systems (Mallorca-Menorca and Ibiza-Formentera) were finally connected in the year 2016, thanks to the interconnection between Mallorca and Ibiza (Red Eléctrica de España (REE), 2022). Currently, the Balearic Archipelago is connected to the mainland (via submarine cable a.k.a *Enlace* or *Link* ), yet this interconnection is quite recent: the Island of Mallorca was connected to the electric station of Morvedre, Sagunto (Valencia) only in 2012, thanks to the so-called “Proyecto Rómulo” (Red Eléctrica de España (REE), 2022) (Sánchez, 2020).

The interconnection with the Iberian Peninsula brings two main advantages: a higher resilience of the Balearic electric system, which can rely on the supply from the mainland in case one of its plants stopped to work, and a lower use of the local generation plants, more polluting and expensive.

The following graphs show the trend of the electricity demand in the Balearic Islands, and how it is fulfilled, from 2010 to 2021 (IBESTAT, 2022).

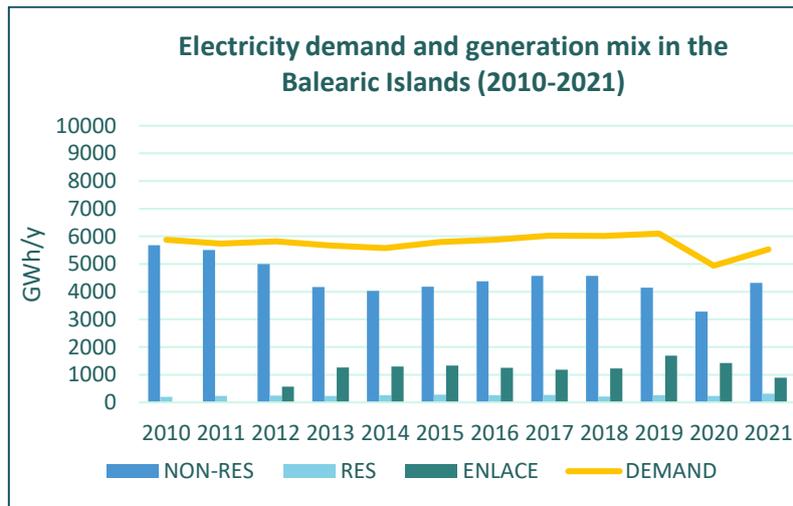


Figure 8: Electricity demand and generation mix in the Balearic Islands between 2010 and 2021 (IBESTAT, 2022)

If, on one side, the electricity demand remained practically constant along the years (except for years 2020 and 2021, because of COVID-19), the generation mix showed important variations starting from 2012, year of the connection of the archipelago with the Iberic peninsula, which made the share of generation from the local non-renewable sources decrease from almost 97% in 2010 to around 68% in 2019, year in which the electricity coming from the mainland reached its maximum share (almost 28%).

Table 2: Electricity generation by source in the Balearic islands in 2019 (IBESTAT, 2022)

	Thermal power plants	Waste	PV + Wind	Biogas & Cogeneration	Peninsular link
<b>% Generation (2019)</b>	64.99 %	4.77 %	1.89 %	0.59 %	27.76 %

Renewable generation from photovoltaic and wind is still limited in the Balearic archipelago, especially considering that in 2021 the electricity generated by photovoltaic and wind comprised 30 % of the total electricity supply in Spain (Red Eléctrica de España (REE), 2023).

The largest thermal power plant is the central of *Es Murterar* in Mallorca. Originally, the central consisted of four coal-fired steam turbines and two gas-and-diesel-fired gas turbines, for a total installed capacity of 585 MW (Siemens Energy, 2021). Although its electricity generation gradually diminished from 3,100 GWh in 2010 to 2,000 GWh in 2019 (IBESTAT, 2022), thanks to the interconnection with the mainland and the increase in RES penetration, its impact on the emissions of the Balearic system is still significant: in 2019, the carbon emissions associated to *Es Murterar* accounted for 65 % of the emissions of the electricity sector in archipelago, and for 29 % of the total emissions of the islands (Sánchez, 2020). In February 2019, the Balearic government released the *Ley de Cambio Climático y Transición Energética* (Presidencia de las Illes Balears, 2019), which also included a plan to progressively shut down the entire power plant. To date – June 2023- two of the four coal-fired steam turbines have been retired (Endesa, 2022) (MallorcaDiario.com, 2019), and reduced the

hours of operation of the other two groups from 1,500 to 500 hours per year (MallorcaDiario.com, 2019) (EnergyNews.es, 2019).

This study aims to demonstrate how the combination of hydrogen fuel cells and other renewable sources to cover the electricity demand of maritime sea-ferry terminals will be effective in reducing the environmental pollution in the archipelago while increasing energy independence, associated to a lower electricity generation from the large thermal power plants and lower dependence on the electricity grid respectively.

### 3.2 Operations in sea-ferry stations description

As previously mentioned, the scope of this study includes three existing buildings in the port of Mallorca, and two projected buildings, one in the Island of Ibiza and another one at the port of Menorca. The existing and future terminals are dedicated to maritime transportation of people and goods. The main functions and characteristics of the buildings are listed in *Table 3*. The term “others” under the “Main appliances” category indicates the energy required by offices devices, like computers and printers, and by the restaurants and cafes present inside the buildings, plus other minor instruments (IDOM, 2021). All the information was provided by *Autoridad Portuaria de Baleares*.

Table 3: Main functions and characteristics of the buildings analysed

Building	Location	Main functions	Main appliances	100% electrified	PV panels	Other RES
<b>EM 2</b>	Mallorca	Ferry passengers boarding + cargo	Climatization, ventilation, lighting, others	YES	NO	NO
<b>EM 3</b>	Mallorca	Ferry passengers boarding + cargo	Climatization, ventilation, lighting, others	YES	NO	NO
<b>EM4</b>	Mallorca	Ferry & cruise passengers boarding	Climatization, ventilation, lighting, others	YES	YES	NO
<b>EM Botafoc</b>	Ibiza	Ferry & Cruise passengers boarding + cargo	Climatization, ventilation, lighting, others	YES	YES	Solar thermal panels
<b>EM Mahón</b>	Menorca	Ferry & Cruise passengers boarding + cargo	Climatization, ventilation, lighting, others	YES	NO	NO

The two new maritime terminals in Ibiza and Menorca are designed to face a higher volume of passengers than the three existing buildings in Mallorca and therefore a higher energy consumption might be expected for these two stations.

At the time of writing this report, there are no specific plans for the installation of photovoltaic panels on the roof of the EM2 and EM3 terminals in Mallorca and the one in *Mahón*, at least in the near future; The maritime terminal EM4 has a dedicated 100 kW roof-mounted PV system (IDOM, 2021). The PV in *Botafoc* will be realized on a parking area next to the maritime terminal, and will have a nominal power of 49 kW (EM; AJ3; MCVALNERA, 2018).

Further details will be presented looking at each building separately, to have a better perspective of the situation.

### 3.3 Energy Demand in the Sea-Ferry Stations

A comprehensive understanding of the maritime terminals energy demand is a fundamental step in designing a hydrogen fuel cell system that optimizes energy production, promotes sustainability, and meets the unique requirements of the building in question. Accurate knowledge of the building's energy requirements allows for the optimal sizing and configuration of the fuel cell system, ensuring efficient and reliable power supply. In this study, for each building considered, the demand profile of each was estimated on hourly basis to analyse the energy demand patterns, peak loads, and overall consumption in order to tailor the fuel cell system's capacity and operation to match the building's specific needs and to define and the consequent demand of hydrogen.

#### 3.3.1 Maritime terminal - Estación Marítima 2 (EM2)

The first building profile that has been analysed for energy demand is the maritime terminal number 2 in Mallorca, which is already operational. The data regarding its electricity consumption was obtained from Autoridad Portuaria De Baleares, covering the period from June 26, 2019, to December 31, 2022. *Figure 9* shows the historical electricity demand within that period. The Y-axis indicates the average hourly electricity demand in kWh, expressed as kWh/h.

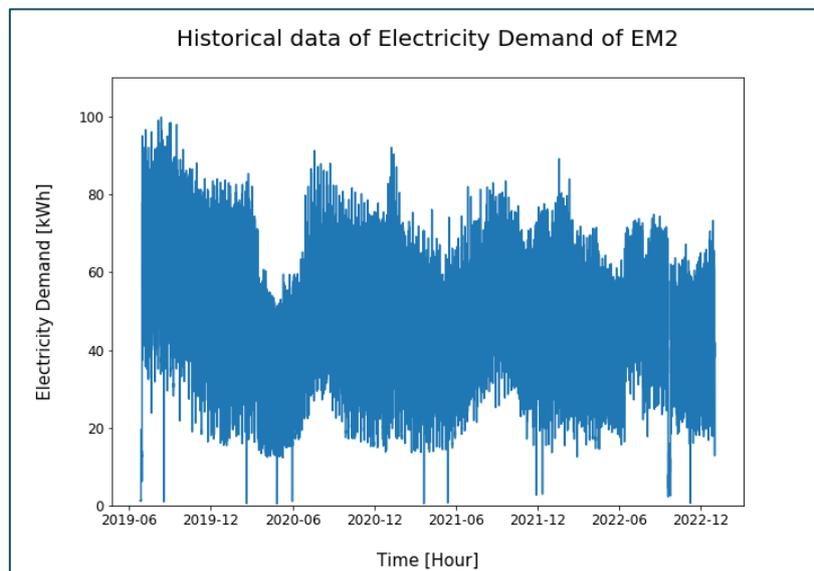


Figure 9: EM2 historical electricity demand, provided by *Autoridad Portuaria de Baleares*

From the historical electricity demand data shown in *Figure 9*, the COVID - lockdown period can be immediately recognized, between the end of February and July 2020, characterized by a lower consumption than in other periods.

To characterize the electricity needs of EM2, only the data from the last two years, specifically from January 1, 2021, to December 31, 2022, were considered, eliminating then the period linked to the stronger impact of the COVID lockdown observed in summer of 2020, as well as the last part of 2019, which clearly differs from the trend of the last two years.

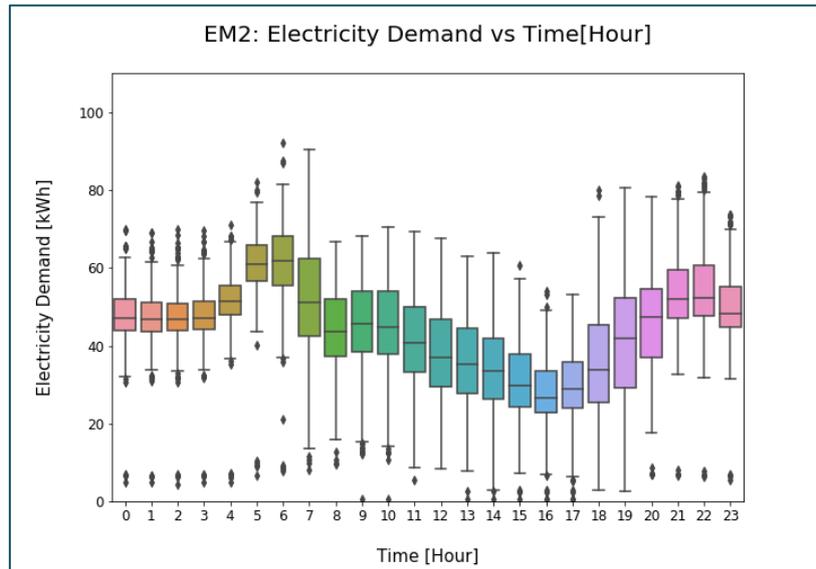


Figure 10: EM2 daily electricity demand as function of time (in hours)

In terms of the distribution of hourly electricity consumption throughout a typical day, it is observed that the highest values are generally recorded during the night, with the peak occurring between 5 to 6 am. Conversely, in the middle of the day, specifically around 4 pm, the consumption tends to reach its lowest value. This same pattern has been observed across all months.

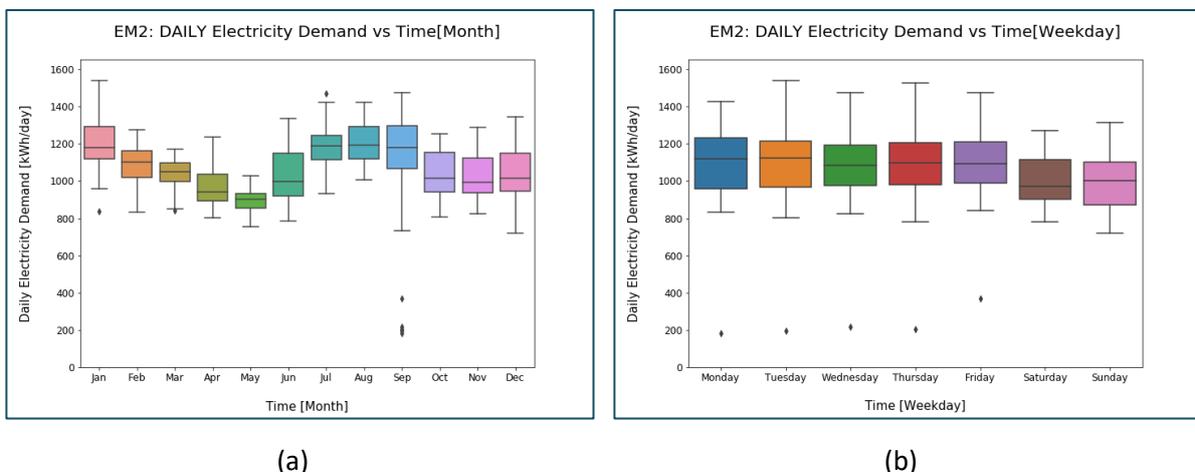


Figure 11: Daily demand of EM2 as function of time expressed in month (a) and weekday (b)

In *Figure 11(a)*, it can be observed that during the span of one year there are two periods with a high energy consumption: one during peak tourist seasons (summer months) and the other in December and January (Winter period), the outlying points in January July and September were excluded from the sample used in the model. *Figure 11(b)* shows EM2's daily energy demand for the different weekdays. Each week is characterized by a stable energy demand during the working days (between Monday to Friday), while during the weekends, there is a slight decrease in electricity demand, suggesting a decrease in activity or usage during those days. The outliers present in *Figure 11( b)* indicate that five working days of the same week in September 2022 have a daily electricity demand much lower than the average, probably due to a defect in the metering; for this reason, they were not considered to determine the definitive demand profile.

To characterize the energy consumption profile for EM2 e, the data was modelled in Python using a centred moving average (CMA) technique (Hyndman, 2009).

The difference between the trend with the actual data and the one obtained with the CMA is showed in the figure below.

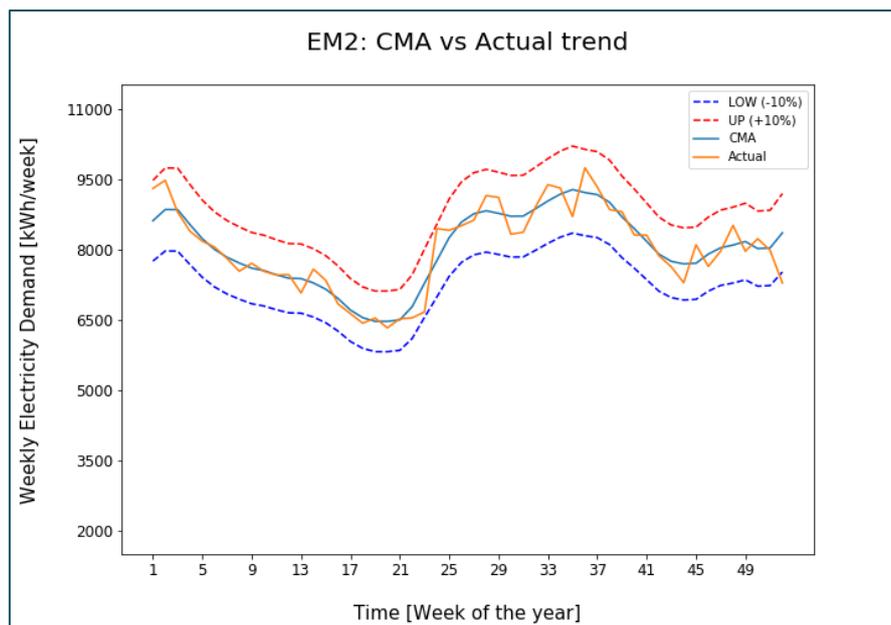


Figure 12: Comparison between actual trend and the one obtained with CMA for EM2

To verify that the estimation is accurate, the mean absolute percentage error (MAPE) was calculated: If the MAPE is smaller than 10%, then the approximation can be considered highly accurate (Lee, Tay, & Choy, 2018). In this case, the resulting MAPE was of 2.66%, which is a good result.

The resulting series had some values that were too low; close to zero. For those time steps in which the electricity demand was smaller than 5 kWh, it was decided to set as new value the average of the previous 24 hours. The new demand profile is the following.

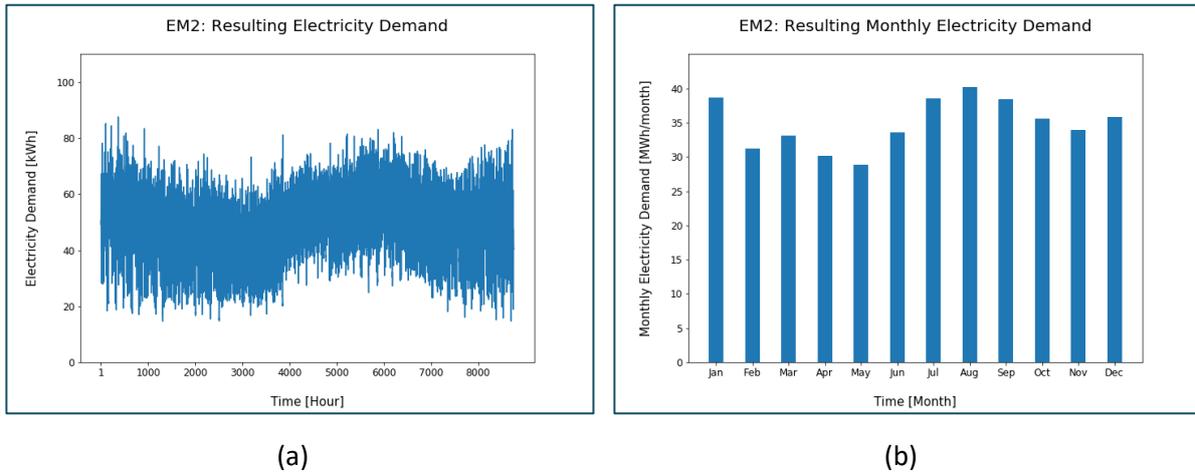


Figure 13: New demand profile of EM2 on hourly (a) and monthly (b) basis.

### 3.3.2 Maritime terminal - Estación Marítima 3 (EM3)

The electricity consumption data for EM3, obtained from *Autoridad Portuaria de Baleares*, covers the period from June 27, 2019, to December 31, 2022, on an hourly basis.

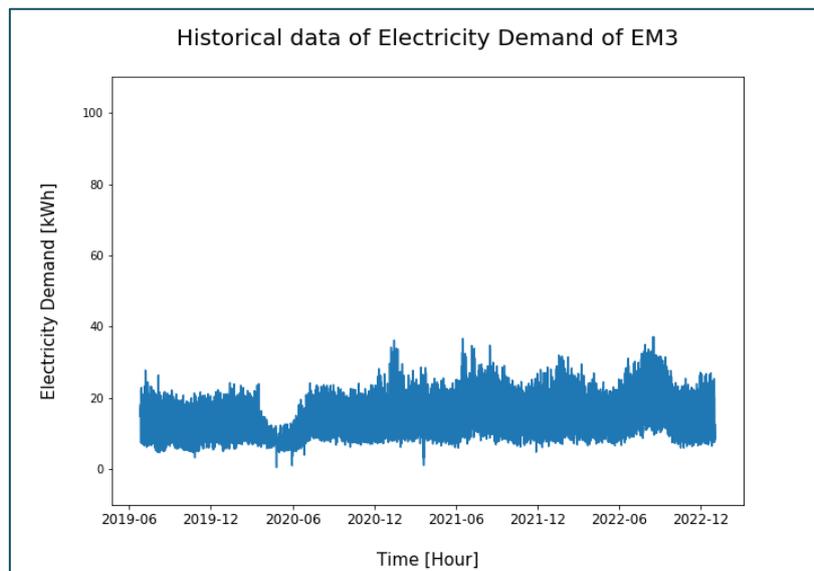


Figure 14: EM3 historical electricity demand, provided by *Autoridad Portuaria de Baleares*

Comparing the historical data of EM2 and EM3 (it can be noticed that *Figure 9* and *Figure 14* have the same scale on the vertical axis), it can be seen that the latter is characterised by a lower electricity demand: the peaks are smaller than those of EM2, as well as the difference between the maximum and the minimum values of demand. Also, in this case, the last two years show a very similar trend, allowing then to exclude the data before 2021.

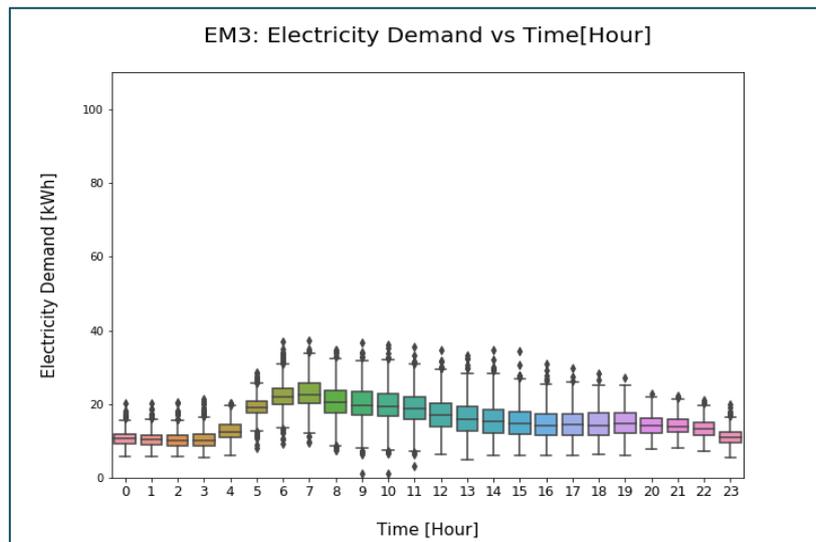


Figure 15: EM3 hourly electricity demand as function of time (in hours)

The distribution of the data is completely different with respect to the case of EM2: here the smallest values are attained during the night, while during the day the consumption increases; the range of the values is also smaller than in EM2.

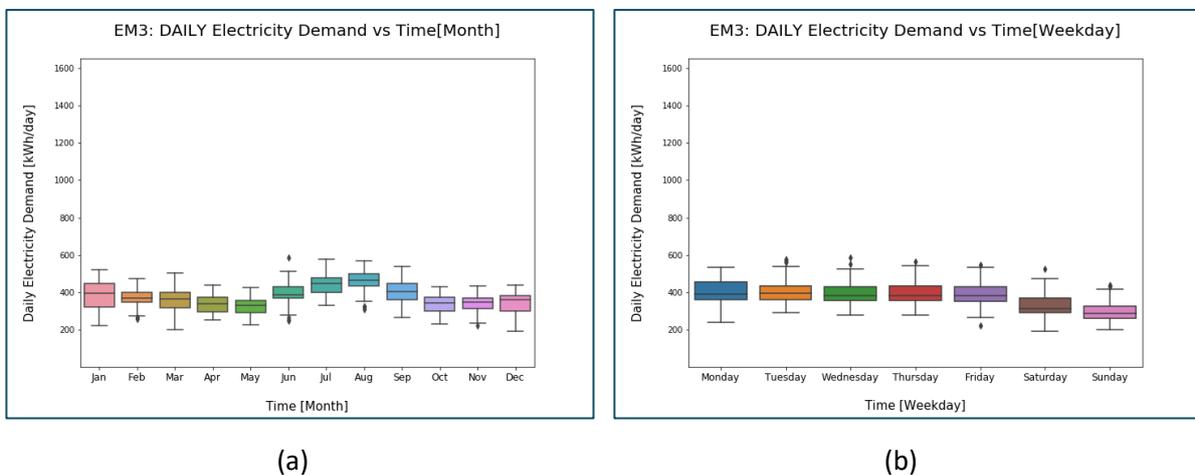


Figure 16: Daily demand of EM3 as function of time expressed in month (a) and weekday (b)

As expected, the daily electricity demand is higher in the summer months, and minimum in autumn and spring days, when the request of electricity for climatization purposes is lower (*Figure 16(a)*); during the weekend, it is generally lower than during weekdays (*Figure 16(b)*).

The steps to obtain the generic demand profile were the same as those adopted for EM2.

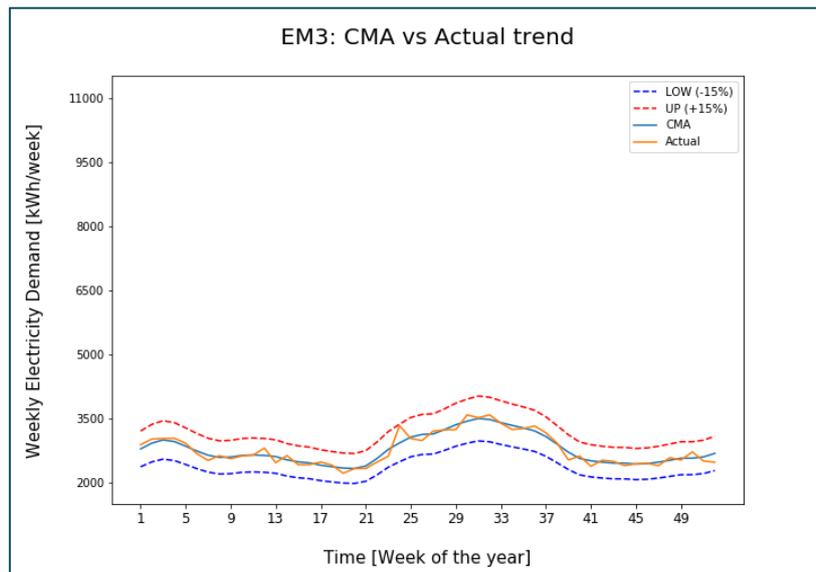


Figure 17: Comparison between actual trend and the one obtained with CMA for EM3

The demand profile on weekly basis is flatter than the one obtained in EM2. In this case, the correction factor considered was 15%, and not 10% as in the previous case; the resulting MAPE was 3.23%, indicating also in this case a good estimation.

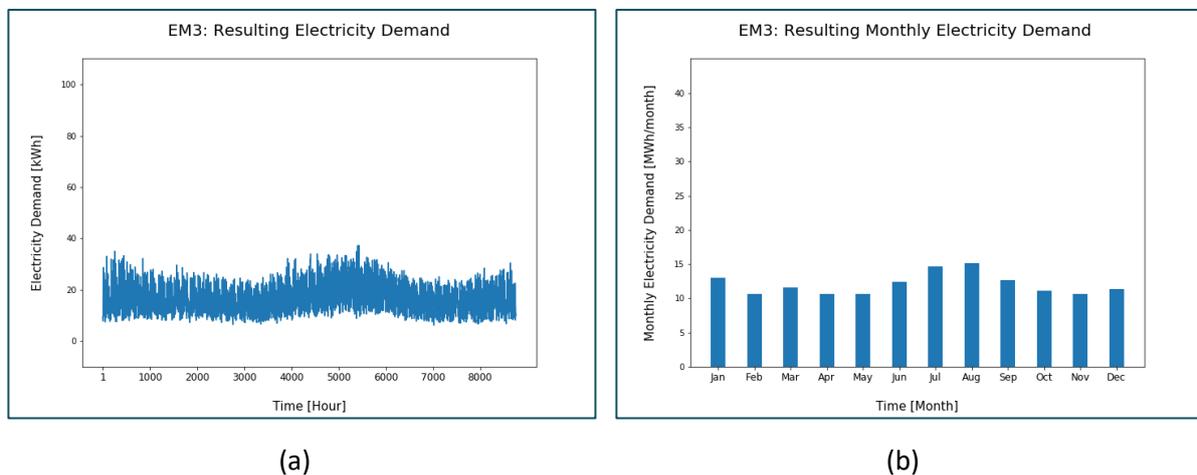


Figure 18: New demand profile of EM3 on hourly (a) and monthly (b) basis

For EM3, the maximum value of monthly demand (*Figure 18(b)*) is almost three times lower than that in EM2 (*Figure 13(b)*).

### 3.3.1 Maritime terminal - Estación Marítima 4 (EM4)

Contrary to the case of EM2 and EM3, the quality of the data for EM4 was not sufficient for the analysis: the values of 2022 led to an annual demand of around 37 MWh, which is just 11% than the annual demand estimated for the building in the document “*Informe de balance de potencia para consumo nulo del edificio de ampliación de la estación marítima n°4*” (IDOM, 2021). A possible explanation might be the fact that the maritime terminal has not started its full operations. As a result, the energy consumption data was sourced from the previously mentioned document, which provides an estimation of the building’s monthly expected electricity demand. The electricity demand profile is shown in *Figure 19*.

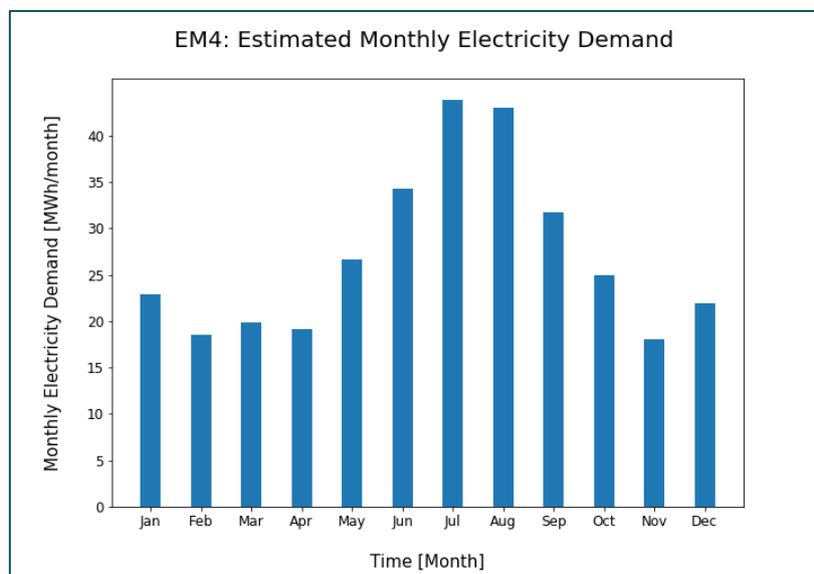


Figure 19: Projected monthly electricity demand for EM4 (IDOM, 2021)

Similar to EM2 and EM3, EM4 also exhibits a peak in electricity consumption during the summer months. However, the demand profile of EM4 is not as flat or consistent as the profiles observed in the previous two buildings analysed. This indicates that EM4 may have more variability in its energy consumption patterns throughout the year, with potentially higher fluctuations in demand during different seasons or periods.

To obtain the demand profile on hourly basis, EM3 was taken as reference, assuming that the hourly trend during a generic day for EM4 is going to be more similar to the one of EM3 (the peak in demand is attained during the central hours of the day) instead of EM2. The resulting profile is visible in *Figure 20*.

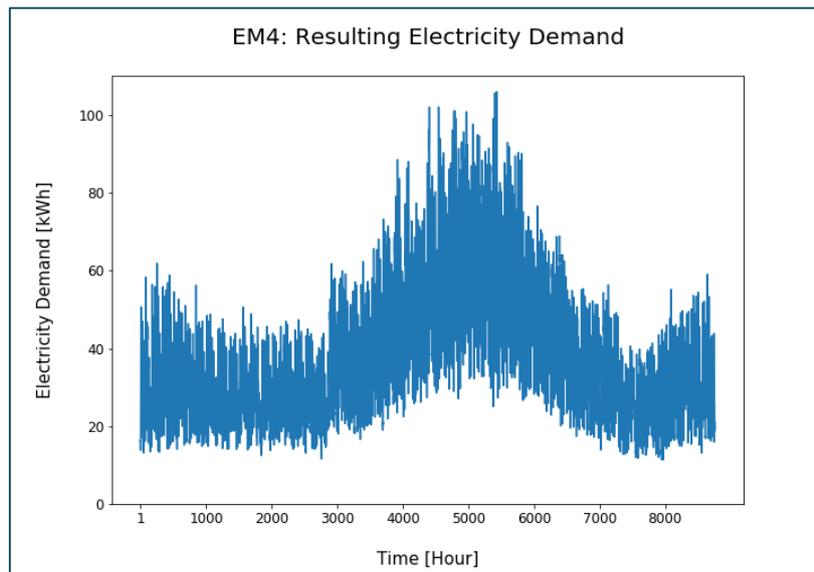


Figure 20: New demand profile of EM4 on hourly basis

### 3.3.2 Maritime terminal Botafoc- Estación Marítima Botafoc

This maritime terminal construction in Ibiza is still to be completed therefore, historical demand data is not yet available. A different approach was used for this building: at first, for a trend of the monthly electricity demand were estimated, then the hourly data were calculated using the hourly profile of EM4.

The document for Botafoc maritime terminal construction project (EM; AJ3; MCVALNERA, 2018) indicates that the building will have a total living area of 6,365.41 m<sup>2</sup> and that it will be fully electrified. Part of its energy demand requirements will be satisfied with two photovoltaic plants (24.65 KWp/plant) installed in the roof structures of the exterior vehicle parking and. The expected annual electricity generation was estimated for the present study using the *PVGIS* instrument (European Commission, 2022), resulting in an annual value of around 69 MWh to be entirely dedicated to the new maritime terminal. The value of the photovoltaic generation includes the losses that interest these systems (shadowing, dirt, inverter, etc.). *Figure 21* shows which input were entered in *PVGIS* to obtain the hourly data of the PV production in Botafoc. The results could be accessed in a csv and a json file.

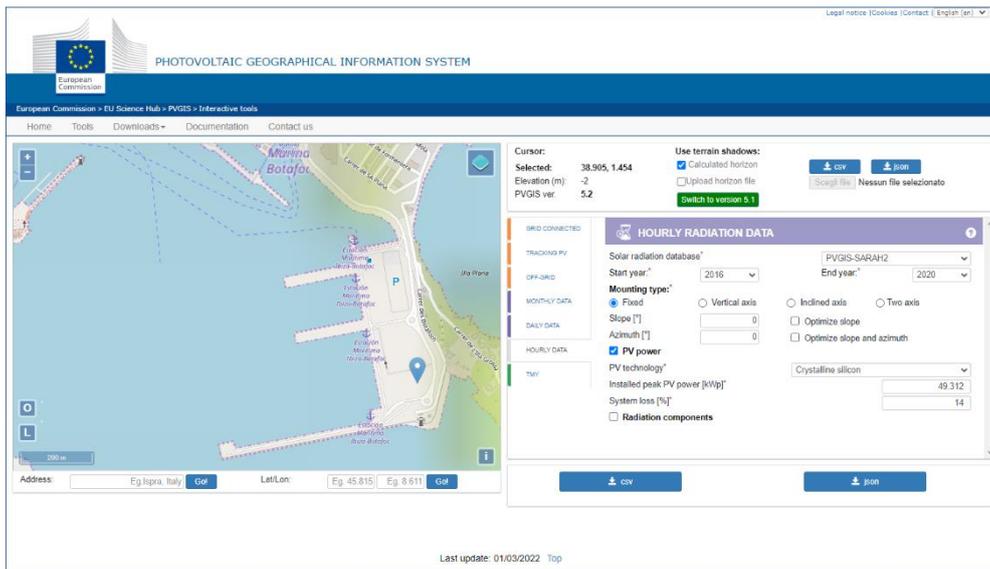


Figure 21: Screenshot from PVGIS to obtain the hourly PV production for Botafoc

The remaining demand will be fulfilled with electricity from the public grid, and it is equal to 210.15  $kWh/(m^2 \cdot year)$  (EM; AJ3; MCVALNERA, 2018).

The total yearly supply of the building is obtained by summing up these two contributions (PV plant and grid) and presented in the following table. The yearly demand coincides with the total annual supply.

Table 4: Botafoc yearly electricity demand and its allocation between PV plant and grid (source)

	Estimated Yearly electricity supply per unit of living surface [ $kWh / (m^2 \cdot year)$ ]	Estimated Yearly supply [ $kWh / year$ ]
<b>Electricity supply from PV (self-consumption)</b>	10.83	68,940
<b>Electricity supply from the GRID</b>	210.15	1,337,691
<b>TOTAL electricity supply</b>	220.98	1,406,631

The total yearly energy demand of Botafoc takes into account the same applications as in the buildings in Mallorca, electricity applications and heating of sanitation water. The thermal energy will be supplied by a hybrid system using thermal panels and electric boiler. The electric boiler provides thermal power when the solar panels cannot meet the entire energy requirement. The demand of electricity for the boiler is also included in the total yearly electricity demand.

The monthly electricity consumption for heating the sanitation water in the boiler was determined by considering the required thermal energy and the so-called seasonal yield of the boiler. This parameter indicates the performance of a facility depending on its immediate environment, and it is influenced by the average conditions of use, weather and the characteristics of its components (Certicalia, 2023); the seasonal average yield is defined as the ratio between the thermal demand requested by a certain

system and the energy consumption of this system (Cype, 2023), and for the boiler in *Botafoc* it is equal to 351%, meaning that the conditions under which the system works allow to have a relatively low electric consumption for sanitation water heating purposes. The annual electricity consumption associated to the electric boiler is then 9,103 kWh.

Secondly, the electricity consumption for climatization purposes (heating and cooling) is estimated to be 899,114 kWh/year, with monthly demand calculated proportionally to the reference building (EM4) based on available construction project documents (IDOM, 2021).

Lastly, the annual electricity demand for ventilation, lighting, and other uses is projected to be 479,895 kWh/year. The monthly consumption was determined by considering these categories collectively and comparing them with the demand of another maritime terminal in Ibiza (Letter Ingenieros, 2022).

A recap of the estimated monthly electricity demand is showed *Figure 22*.

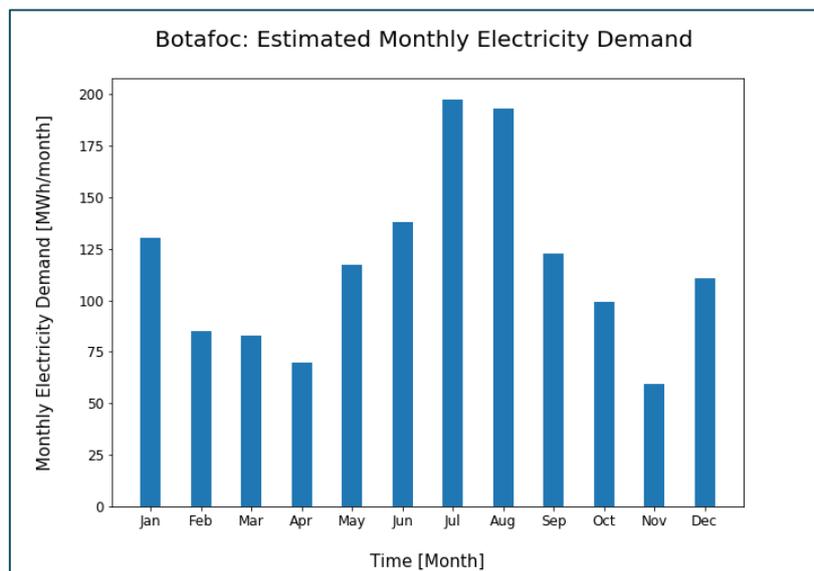


Figure 22 : Projected monthly electricity demand for *Botafoc*.

The consumption at a generic hour “*t*” was calculated using as reference the hourly demand of EM4:

The definitive profile on hourly basis is showed in the figure below.

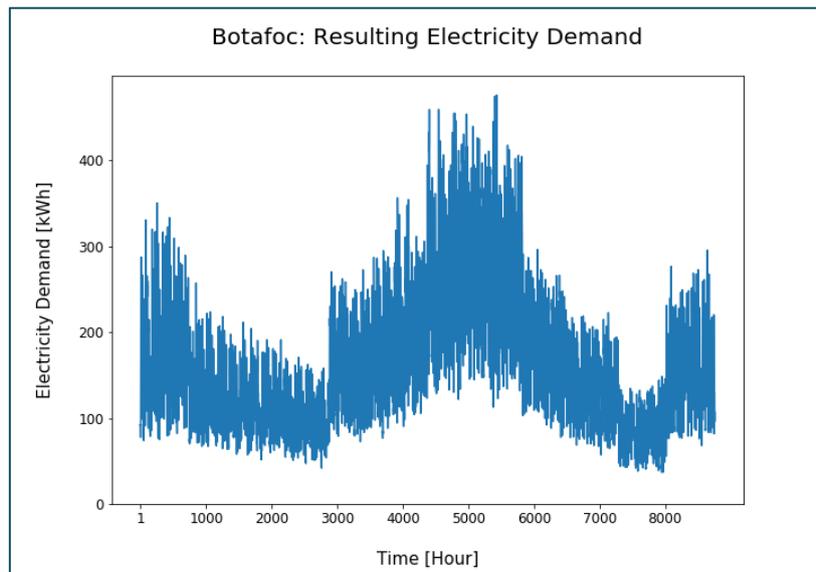


Figure 23: New demand profile on hourly basis for *Botafoch*

### 3.3.3 Maritime terminal Mahón - Estación Marítima Mahón (Menorca)

The construction of the building has not started yet. The only information available for the study about the new maritime terminal is its living surface, equal to 2,500 m<sup>2</sup>. By knowing the living surfaces of the buildings in *Mahón* and in *Botafoch*, the electricity consumption of the new maritime terminal in *Mahón* was calculated as a proportion of the other, excluding the element of the electric boiler for sanitation water. The resulting demand profiles are the following:

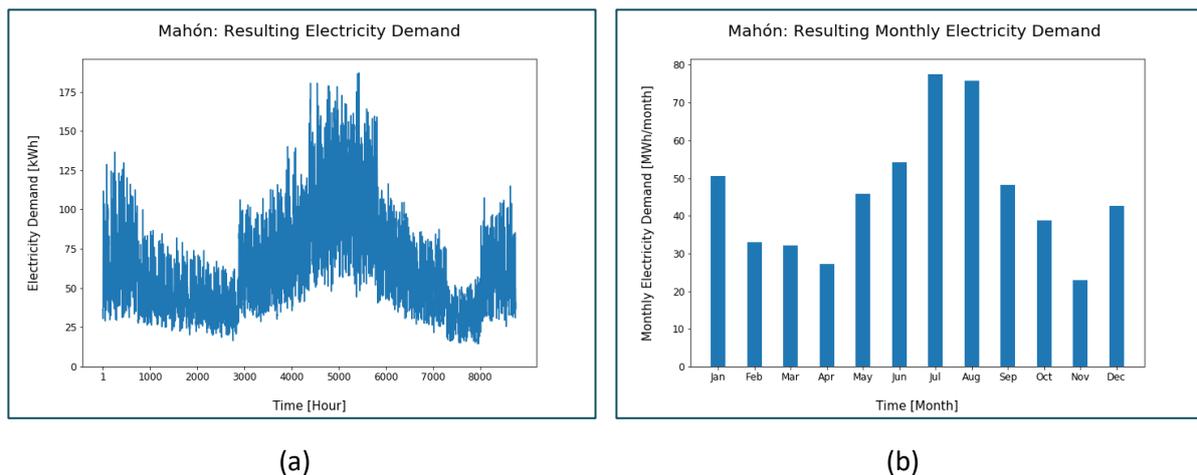


Figure 24: New demand profile of Mahón on hourly (a) and monthly (b) basis

### 3.4 Carbon dioxide emissions estimation in the current situation

The carbon dioxide emissions associated to the consumption of the buildings depend on the emission factor of the electric system of the islands of the archipelago. This factor was calculated on annual basis, using the 2019 data, provided by *Autoridad Portuaria De Baleares*, relating to the electricity demand of the different ports and the total CO<sub>2</sub> emissions related to this demand.

Table 5: Total emission factor of the different port sites

	Electricity Consumption [kWh/year]	CO <sub>2</sub> emissions [tonCO <sub>2</sub> /year]	Emission factor [tonCO <sub>2</sub> /MWh]
<b>Port of Mallorca</b>	23,302,150	7,424.025	0.319
<b>Port of Ibiza</b>	6,788,950	1,928.438	0.284
<b>Port of Menorca</b>	1,607,993	530.053	0.330

The emission factors are different between each other, but all of them are higher than the national emission factor in Spain, equal to 0.19 tonCO<sub>2</sub>/MWh in 2019 (Red Eléctrica de España (REE), 2021).

To calculate the CO<sub>2</sub> emissions due to the electricity consumption of the buildings, the amount of energy coming from the electric grid was multiplied by the emission factor of the port where the building is:

- For EM2, EM3, and the building in *Mahón*, this quantity coincides with the annual demand of the building.
- For the EM4 and the new maritime terminal in *Botafoc*, the electricity from the grid is the difference between the annual total demand and the electricity provided by the photovoltaic plant.

Table 6: CO<sub>2</sub> emissions due to electricity consumption of the maritime terminals

Maritime terminal	Total Demand [kWh/year]	Electricity from GRID [kWh/year]	CO <sub>2</sub> emissions [tonCO <sub>2</sub> /year]
<b>EM2</b>	418,179	418,179	133
<b>EM3</b>	144,487	144,487	46
<b>EM4</b>	324,978	168,751	54
<b>Botafoc</b>	1,406,631	1,337,691	380
<b>Mahón</b>	536,051	536,051	177

## 4 Technology assessment: current status and future developments

### 4.1 Fuel cells for primary heat and power

The interest in fuel cells for supplying electricity and heat has constantly grown during the last decades, because of the many benefits that this technology can bring. The main advantages are:

- High efficiency: the most advanced fuel cells have electrical efficiencies up to 60%, and if they are used in combined heat and power (CHP) mode, they can reach total efficiencies of 90%. The fuel cells are also characterized by great performances at partial loads, with the efficiency which does not decrease significantly (Roland Berger Strategy Consultants, 2015). This higher efficiency is explained by the fact that the chemical energy contained in the fuel is converted into electricity with only one conversion process, avoiding multiple passages occurring in systems such as Rankine cycles, in which the thermal energy of fuel is converted at first into mechanical energy, which is further converted into electricity.
- The acoustic emissions are almost inexistent, thanks to the lack of mobile parts.
- The emissions of pollutants are lower, and if the fuel cell is fed with hydrogen, the associated emissions are null.
- Different fuel cells can be placed in series. This modularity allows to have flexibility in operations.
- In case they used hydrogen as fuel, the fuel cells can rely on an energy source that can be produced closed to its position, reducing the distance between production and utilisation sites.

Fuel cells are suitable for a wide range of applications, from portable to stationary applications, to transport. The following table shows the number of fuel cells installed in thousands of units worldwide, between 2014 and 2018 (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019).

Table 7: Worldwide Installation of fuel cells in thousands of units, between 2014 and 2018 (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019)

Application	2014	2015	2016	2017	2018
<b>Portable</b>	21.2	8.7	4.2	5	5.6
<b>Stationary</b>	39.5	47	51.8	54.9	57.5
<b>Transport</b>	2.9	5.2	7.2	10.6	11.2

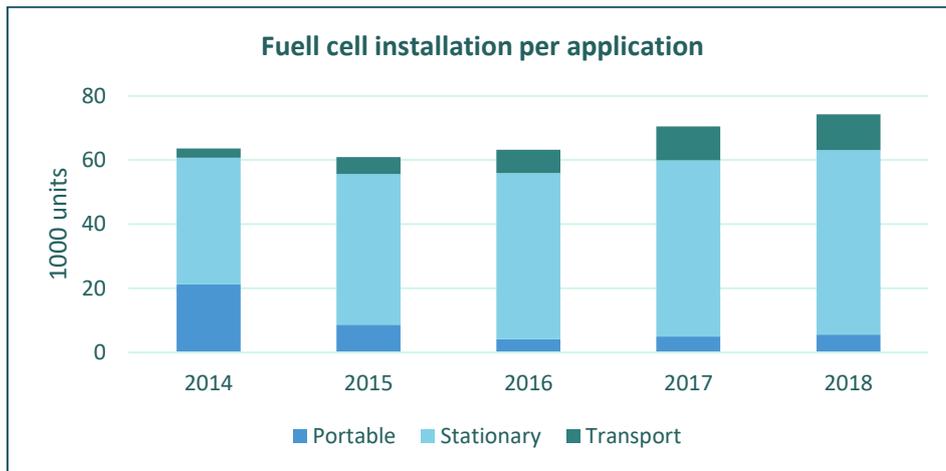


Figure 25: Installation of fuel cells in thousands of units worldwide, between 2014 and 2018

There are different types of fuel cell on the market, differing in manufacturing materials, operating temperature, and power range:

- Polymer Electrolyte Membrane Fuel Cells (PEMFC)
- Alkaline Fuel Cells (AFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cells (MCFC)
- Solid Oxide Fuel Cells (SOFC)

In 2018, PEMFCs and SOFCs represented together almost 95% of the total fuel cell shipments, covering respectively 57% and 37% of it. That is because AFCs are mainly deployed in military sector, while most of the PAFCs and MCFCs are being integrated in pilot projects (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019). MCFCs and PAFCs operate at high temperature above 150°C and are suitable for larger stationary CHP applications, which is not the case of the port buildings involved in the project; PEMFCs are acceptable for such applications, as well as high-temperature SOFCs, which can be adopted also for larger scale end-users. *Table 8* gives an overview of the power ranges which are more suitable for the different fuel cell types for stationary applications.

Table 8: Types of commercially available fuel cells suitable for different power ranges (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019) (Bednarek, Davies, Malkow, & Weidner, 2021)

Stationary application	MCFC	PAFC	PEMFC	SOFC
<b>SMALL (P &lt; 5 kW<sub>el</sub>)</b>			•	•
<b>MEDIUM (P: 5-400 kW<sub>el</sub>)</b>			•	•
<b>LARGE (P ≥ 400 kW<sub>el</sub>)</b>	•	•		•

Stationary applications are showing a constant growth in their deployment. The majority of fuel cells installed are in Europe, US, South Korea and Japan (International Energy Agency (IEA), 2022). It must be clarified that their installations are not equally distributed around the globe: in 2018, almost 75%

of the fuel cells were installed in Asia, mainly due to the efforts of Japan and its *Ene-farm* program, whose focus are micro-CHP fuel cells (up to 1 kW<sub>el</sub>) for residential buildings (Appliances, Home-use Fuel Cell, 2022).

Europe as well wants to play a key role in this promising sector, with the five-years project *Ene.field* (2012-2017) and the subsequent larger scale project *PACE*, both of them aiming to analyse the performances of PEMFCs and SOFCs used for micro-CHP generation, with nominal power up to 5 kW<sub>el</sub> (*ene.field*, 2022) (*PACE*, 2022).

The demonstrations of the fuel cells are not limited to small scale applications, but also to larger ones: this is the case of several buildings in Japan fed by 100% hydrogen-fed fuel cells, such as the ones in the Olympic village (International Energy Agency (IEA), 2022); or the NorthC data centre in Groningen (the Netherlands), which in September 2022 became the first data centre in Europe to install a 500 kW hydrogen-powered PEMFC used for emergency backup generation (International Energy Agency (IEA), 2022) (NorthC Data Centers, 2022) (Nedstack, 2022).

Through the implementation of an hydrogen valley in the northern Netherlands, under the name of *HEAVENN*, the Bytesnet data centre will be fitted with an emergency power supply powered by a hydrogen fuel cell (*HEAVENN*, 2023); within the *BIG HIT* project, a 75 kW<sub>el</sub> fuel cell was installed in 2017 in Kirkwall harbour, to provide electricity for ships (cold ironing) and other activities within the port, with the waste thermal power used to satisfy the heat demand of the nearby buildings (*BIG HIT* Project, 2022);

Within the ongoing EU project *TULIPS*, started in January 2022, the performances of a SOFC for electricity and heat production to decarbonize airport operations will be studied (*TULIPS*, 2022); another pilot project dealing with airports is taking place in Turin, where SOFC will be tested (International Energy Agency (IEA), 2022); Ghenai et al. (Ghenai & Bettayeb, 2018) designed and optimized a grid-connected hybrid PV and 100 kW<sub>el</sub> PEMFC system to cover the electrical consumption of a building of the University of Sharjah, concluding that higher renewable penetration leads to lower values of LCOE and of GHG emissions; Acha et al. (Acha, et al., 2020) compared the techno-economic performances of a 460 kW<sub>el</sub> PAFC with a 500 kW<sub>el</sub> ICE-CHP for a food-retail building, with the fuel cell system having better technical performances in terms of efficiency and primary energy demand, but worse economic behaviours (according to the study, a cost reduction of 15-20% should be achieved to make the new technology competitive).

So far, the projects involving hydrogen technologies in European port sites are scarce in number. Beyond the already mentioned *BIG HIT* project, another initiative under implementation is the so-called *enerPort II*, which aims to decarbonise the operations in the inland port of Duisburg (Germany) by installing hydrogen-fed fuel cells with a total output of 1.5 MW to cover the peak electrical loads of the port (Duisport, 2022). Hydrogen fuel cells will be introduced also in the port of Valencia, within the project *H2Ports*: however, the fuel cells will be deployed for port handling equipment in the port sites, and not for CHP purposes (*H2Ports*, 2022). The *GREEN HYSLAND* project is then a pioneer to assess the feasibility of using hydrogen fuel cells for stationary applications in port sites.

PEMFC and SOFC are the most used technologies for residential and commercial applications. PEMFC can count on a better technological maturity than SOFC, also thanks to the technical and economic achievements obtained by the automotive industry. Most of the PEMFCs work in power ranges between 1 and 100 kW<sub>el</sub>, while SOFCs can operate until 2 GW<sub>el</sub>. Both the systems can reach electrical efficiency of around 60% (DOE-Fuel cell technologies office, 2015). PEMFCs are very sensitive to the

CO concentration in the fuel, requiring then a CO-removal step if the hydrogen has been produced from hydrocarbons. That should not be a problem for the fuel cells to be deployed at the Balearic port sites in the Green Hysland project, since they are fed with green hydrogen produced locally from electrolysis, which has a high level of purity, normally > 99.99% H<sub>2</sub>, and a very low level of impurities; SOFCs are less sensitive to fuel purity, and they don't usually need a reformer (Cigolotti, Genovese, & Fragiaco, 2021) (DOE-Fuel cell technologies office, 2015) (Battelle Memorial Institute, 2017).

A great strength of PEMFC is their load-following capability, which is weaker in SOFC systems (Battelle Memorial Institute, 2017), due to the high operating temperature. PEMFC and SOFC differ from each other also in their operating temperature: the operating temperature of PEMFC is way lower than that of SOFC (around 80 °C for PEMFC, against 1000 °C for SOFC) (Hydrogen and Fuel Cell Technologies Office, 2022). The working temperature affects several parameters: first of all, the lower temperatures of PEMFC allow the fuel cell to have a quicker start-up time and less degradation effects, which make the maintenance costs decrease. But at lower temperatures a catalyst is required, increasing the capital expenditures for the fuel cell installation (Cigolotti, Genovese, & Fragiaco, 2021). The working temperature of a fuel cell affects the quality of the waste heat released from the system, it can potentially be used for other thermal applications: the higher the fuel cell operating temperature, the wider will be the range of applications for the waste heat. However, in the GREEN HYSLAND project, a thermal application for the fuel cells is not considered, which suggests that PEMFC may be a better option, because of their reliability, load flexibility and lower cooling power required. Talking about the systems durability, PEMFC are characterized by higher technology and commercial readiness level and higher durability than SOFC technologies.

Table 9 shows a summary of the main characteristics of the two technologies for stationary applications.

Table 9: Comparison of the main technical parameters of PEMFCs and SOFCs

	PEMFC	SOFC
<b>Technology Readiness Level (TRL)</b>	7-9 (Aricò, et al.)	7-9 (Aricò, et al.)
<b>(Max?) Electric efficiency</b>	60 %	60 %
<b>Working temperature [°C]</b>	80	1000
<b>Degradation effects [%/1000 h]</b>	0.4 (Hydrogen	0.6 (Hydrogen
<b>Warm start-up time [s]</b>	60 (Hydrogen Europe, 2020)	900 (Hydrogen Europe, 2020)
<b>Durability [1,000 h]</b>	60-80 (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019)	20-90 (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019)

All the previous considerations led to choose the PEMFC as the best solution to provide electricity to the buildings in the port sites.

PEMFCs are also characterized by a good availability: of 443 PEMFC analysed within the EU project ENE.FIELD (ene.field, 2022), 90% of the systems were available for at least 95% of the total operation time; the most sensitive part of the fuel cell is the BOP, which accounts for 64% of the total failures

occurred (Nielsen, et al., 2019). Although the aforementioned availability parameters correspond to micro-CHP systems ( $\leq 5 \text{ kW}_{el}$ ), they were assumed to be valid for the fuel cells considered in this study, given the lack of data about availability for larger fuel cells.

## 4.2 Fuel Cells Market developments

Nowadays, the adoption of PEMFCs for distributed generation is not cost-competitive with incumbent technologies, mostly due to their high investment costs. The biggest contributor comes from the stack, whose CAPEX are presented in *Table 10*, followed by the costs associated to the balance of plant, which accounts for about 20% of the stack costs (IDOM, 2022). It can be seen in *Table 10* that the stack CAPEX vary between 1,900 and 6,000 €/kW<sub>el</sub>; in comparison, the cost range for gas-based ICE-CHP is between 900 and 1,500 €/kW<sub>el</sub> (Acha, et al., 2020) (Zorg Biogas, 2022).

Contrarily on the CAPEX, the O&M costs for PEMFC stationary systems (shown in *Table 10*) are already competitive with the fossil fuel-based technologies: for gas ICE-CHP system, they are around 20 ct€/kWh (Acha, et al., 2020). A recap of the stack CAPEX and of O&M costs for the current PEMFC systems is presented in *Table 10*.

Table 10: Stack CAPEX and O&M costs for PEMFCs of different power ranges (Hydrogen Europe, 2020)

	$P_{NOMINAL} < 5 \text{ kW}_{el}$	$P_{NOMINAL}: 5 - 50 \text{ kW}_{el}$	$P_{NOMINAL}: 51 - 500 \text{ kW}_{el}$
<b>Stack CAPEX [€/kW]</b>	6,000	2,500	1,900
<b>O&amp;M [ct€/kWh]</b>	10	10	5

Fuel cells are already showing cost-reductions in the last years, thanks to the benefits associated to both economies of scale and technological innovations. The former has contributed mostly to the reduction of CAPEX, while the latter specially to decrease O&M costs and the installation volume per unit (measured in L/kW). A comparison between these values in 2012 and 2017 for micro-CHP applications can help to have a clearer vision (Cigolotti, Genovese, & Fragiacommo, 2021).

Table 11: Decrease in micro-CHP costs and installed volume per unit, between 2012 and 2017

	2012	2017	Reduction
<b>CAPEX [€/kW]</b>	16,000	13,000	≈ 20 %
<b>O&amp;M [ct€/kWh]</b>	40	20	50 %
<b>Inst. Vol. per unit [L/kW]</b>	330	240	≈ 30 %

The positive trend that has characterized these last years is very likely going to persist in the next years. The biggest efforts in this industry are aiming to reduce the capital expenditures and increase the reliability of the systems, which would have a positive impact also on the O&M costs.

In October 2020 *Hydrogen Europe* published the “*Strategic Research and Innovation Agenda*” (Hydrogen Europe, 2020), where future trends of both economic and technical parameters of PEMFCs and SOFCs are presented. The following table highlights some of the achievements that PEMFC systems are expected to attain by 2030; the data are referred only to PEMFC systems between 50 and 500 kW<sub>el</sub>, which are those more suitable to the project.

Table 12: Projected PEMFCs costs in the range of 50-500 kW (Hydrogen Europe, 2020)

	SoA	Target 2024	Target 2030
<b>Stack CAPEX [€/kW]</b>	1,900	1,200	900
<b>O&amp;M [ct€/kWh]</b>	5	3	2
<b>Electric efficiency (% LHV)</b>	50	52	58
<b>Degradation (%/1000h)</b>	0.4	0.2	0.2

What is expected in the next years is a contemporary cost-reduction and an improvement in the technical performances of the systems; higher efficiency and lower degradation effects are certainly necessary to decrease the O&M costs.

## 5 Hydrogen supply and infrastructure at Balearic Ports: overall requirements

### 5.1 Hydrogen supply (transport to location)

Regarding the maritime terminals in Mallorca considered within the scope of Green Hysland, hydrogen is planned to be transported by tube trailers driven from the production site in Lloseta to the different end-users across Mallorca. According to the initial concept designed by Calvera, each trailer will transport 143 cylinders divided in six sections, with a capacity of 153 litres per cylinder. Each cylinder contains gaseous hydrogen at 300 bars, meaning that at a reference temperature of 25°C, the total mass of hydrogen transported by the truck is around 450 kg. The set of cylinders is installed inside a 30 ft steel frame to avoid defects caused by vibration during transport.

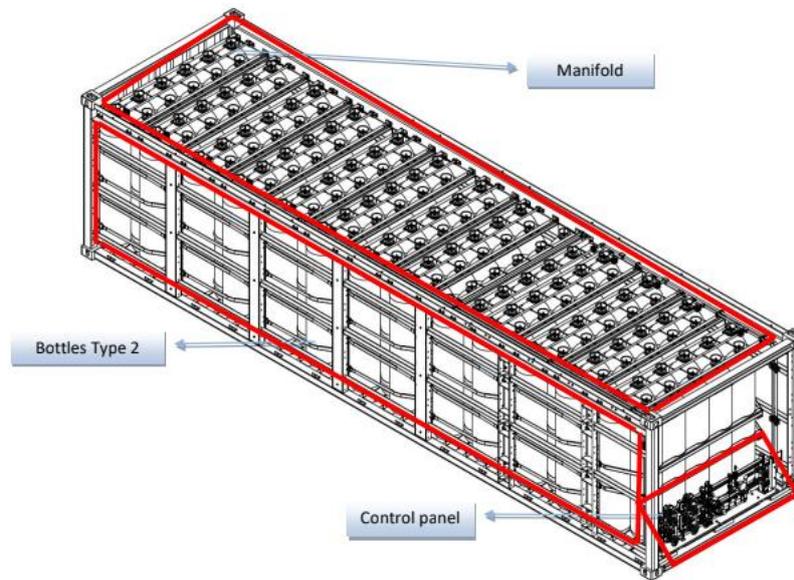


Figure 26: Main components of the tube trailer (CALVERA Hydrogen S.A., 2023)

The system is designed to operate safely in the following environmental conditions:

- Outdoor environment
- Ambient temperature between -20°C and 65°C
- Maximum relative humidity 85%

The distribution to the islands of Ibiza and Menorca will involve maritime transportation from the island of Mallorca to the other two locations. In this case, the tube trailers will be likely transported by ferries, following the example of what is already happening in the *BIG HIT* project in which gaseous hydrogen is brought from the island of Eday, where hydrogen is produced, to Orkney mainland, where there are the majority of the end-users (BIG HIT, 2022).

## 5.2 Hydrogen storage

The stationary storage system provided by CALVERA for the *Estación Marítima 4* in the Port of Palma was taken as reference the study (Autoritat Portuària de Balears, 2022). The storage was design to fulfil annual H<sub>2</sub> consumption of 40 tons for a 100-kW hydrogen fuel cell as established in the GREEN HYSLAND project Grant Agreement. Below is a description of the design for EM4.

The storage system (CALVERA Hydrogen S.A., 2023) can be composed by different units. Each unit contains 6 cylinders of 153 litres each one, for a total volume of 918 litres. All the cylinders are connected by a manifold. The storage unit is designed to work in the following conditions:

- Outdoor environment
- Pressure inside the cylinder between 0 bar and 300 bar.
- Ambient temperature between -20°C and +65°C

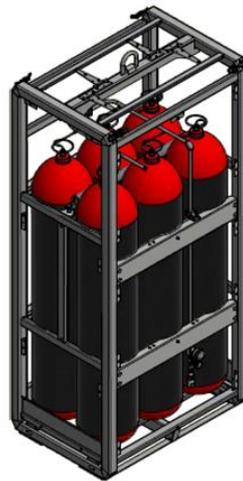


Figure 27: Mobile storage unit provided by CALVERA (Autoritat Portuària de Balears, 2022)

However, the minimum pressure in the storage should never be below 30 bar (CALVERA Hydrogen S.A., 2023), which means that not all the hydrogen present in the storage can be exploited by the fuel cell. Some clarifications are needed about the maximum pressure achievable too: it is true that the cylinder can contain the gas at pressure up to 300 bar, but the hydrogen that will reach the port sites is transported in tube trailers at a pressure of 300 bar, which means that the maximum pressure can be only achievable in presence of a compressor between the tube trailers and the stationary storage. In the study, no compressor was considered. In case the tube trailers arrive at the port at 300 bar and the storage units are all at their minimum pressure of 30 bar, the mass that can be transferred by the tube trailers to the single units is not constant, because it depends on the pressure difference between the storage units and the tube trailers. Once the tube trailers have completed the charge of the first unit, their pressure won't be anymore 300 bar but less, which leads to have a smaller pressure difference between the tube trailers and the second storage unit, which means that less hydrogen can be transferred into the second unit. The same reasonings can be applied for the other units (Autoritat Portuària de Balears, 2022) (IDOM, 2022). The details about the quantity of hydrogen transferrable to the storage unit can be found in the Section 7.2.4

The storage system is not only composed by the different storage units, but also by a filling panel, whose aim is to perform the charge operations (from the tube trailers to the storage units) as well as the discharge phase (from the mobile units to the fuel cell). This component can carry on both the operations at the same time (CALVERA Hydrogen S.A., 2022).

The footprint or area occupied by the storage units is also a critical aspect to consider. Taking as reference the deliverable D2.9 (Autoritat Portuària de Balears, 2022), *Table 13* shows how much space is required by the storage at different numbers of units installed:

Table 13: Hydrogen storage units vs surface occupied

N° Storage Units	Footprint [m <sup>2</sup> ]
------------------	-----------------------------

<b>10</b>	46
<b>20</b>	82
<b>50</b>	189
<b>100</b>	366

## 6 Other aspects to consider in the development of the energy system in the maritime terminals

### 6.1 Social acceptance

The social acceptance is essential for the positive outcome of the project, since social acceptance issues might either result in serious delays of the project or even lead to its complete cancellation (Hasturk, Kayacik, & Ursavas, 2022). In general, the lack of social acceptance manifests in those contexts where the knowledge about a certain technology is limited, and it is valid especially for the hydrogen sector (Vallejos-Romero, et al., 2022). The concerns can be of three different natures:

1. The citizens, and in particular the inhabitants of the archipelago, might be worried about the high costs of these new system, which would likely impact on the energy costs or taxes.
2. There can be a safety related concern. Hydrogen is highly flammable and should be handled with care. As it is relatively new to the energy sector, yet commonly used component in the chemical and steel industry, definitive regulations about its handling for its new applications are still to be confirmed (IDOM, 2022). This uncertainty about safety might interest the local population, and even more those people working in the port sites.
3. The third and last reason is related to the so-called “Not in My Backyard” (NIMBY) behaviour, according to whom people are reluctant to have new green technologies close to them, even though they are generally in favour of the introduction of new renewable energy sources.

All these apprehensions might lead the local population to pressure the Balearic government to abandon the installation of these hydrogen-based systems in the ports of the archipelago.

It is important then to mitigate the public concerns about the new hydrogen technologies that are going to be introduced in the port sites. A first way is surely increasing the knowledge and the information about the risks of the technology, which would alleviate feelings of fear and uncertainty (Vallejos-Romero, et al., 2022): this should be done with dissemination and communication activities, to be performed by all GREEN HYSLAND partners with the main objective of sharing the knowledge gained on hydrogen value chain deployment during the project activities. The participation of the public sector might play a key role in increasing the social acceptance, since its presence would give a higher perception of security (Vallejos-Romero, et al., 2022). Lastly, the environmental benefits of these systems should be emphasized, seen the growing interest of the citizens, towards the adoption of green technologies (Vallejos-Romero, et al., 2022).

### 6.2 Regulatory aspects

Regulatory barriers are highly relevant as well. Regulatory processes are mainly associated to licensing and permitting activities. Within this study, the regulatory framework is particularly important for the storage system and the fuel cell, since there are no specific regulations for any of them (Ministerio de

industria, comercio y turismo, 2019) (IDOM, 2022). For the former, one of the largest criticalities is about space occupation, and how it might affect the surrounding buildings in the port sites. The absence of a clear regulation might lead to higher safety concerns about the hydrogen technologies, on the other side a too strict regulation might discourage the investments, delay the project execution and the realization of the energy systems in the different ports (International Energy Agency (IEA), 2022).

Currently in Spain, the use of hydrogen fuel cells does not face any regulatory barriers (Asociación Española del Hidrógeno et Al, 2023). In the absence of a specific regulation for hydrogen, these fuel cells are governed by a set of rules called the Royal Decree 919/2006, which specifically deals with facilities that receive gas fuel. Since fuel cells produce electricity, they also need to follow another set of regulations. These rules ensure the safe installation and operation of low (<1000 V) or high voltage (> 1000) electricity generation facilities. In contrast to the fuel cell installation, the situation for hydrogen storage units associated to non-industrial scale use of hydrogen is not so specific. At national level, a regulation for the storage for the industrial use of Hydrogen is applied only to reservoirs with more than 200,000 tons of hydrogen for industrial use, for these storages, an Environmental Impact Assessment is needed for their construction (CMS, 2023) (Asociación Española del Hidrógeno et Al, 2023). For the storage applications that are object of this study, the rules adopted for industrial sectors are not necessarily suitable for the case of green hydrogen (Ministerio de industria, comercio y turismo, 2019).

The regulations on Hydrogen storage indicate that installations where storage of hydrogen in high-pressure buffer tanks (up to 10,000 bar) may be located will likely require an *ad hoc* review by local permitting authorities (CMS, 2023) (Asociación Española del Hidrógeno et Al, 2023) considering a risk assessment-based approach.

For both liquid and gas hydrogen storage, the regulations for Industrial Safety in Chemical Product Storage (APQ, Almacenamiento de Productos Químicos) apply. The safety distances specified in the APQ regulations are based on good practices developed by the chemical industry in handling chemical products. However, certain applications of hydrogen and fuel cells may not be compatible with these regulations. For example, installing a hydrogen storage unit in an urban area may not meet the required distances. Therefore, a specific evaluation of hydrogen safety is necessary for each application, considering potential interactions with other installed elements.

It is advisable that the regional government of the Balearic Islands comes up with a regulation valid at local level, keeping in mind that the rules should allow an efficient implementation of the projects without disregarding the safety aspects (International Energy Agency (IEA), 2022). It is suggested also that local authorities engage with the national government to define a clear regulatory framework on national level. In this respect, the dissemination and communication activities included in the GREEN HYSLAND project are contributing towards engagement with policy makers and regulatory bodies at local and national level, aiming to develop a more favourable regulatory framework for the implementation of hydrogen and fuel cells into port applications.

### 6.3 Safety aspects

As with all fuels and flammable substances, the main concern when handling hydrogen is mitigating the risk of explosion, which is a critical aspect for hydrogen, due to:

- A higher flammability range (4% - 75%) compared to the conventional fossil fuels (4.4% - 16.4% for methane) (Engineering ToolBox, 2023). It is defined as the concentration that the fuel should have in the air in order to be ignited.
- A lower value of minimum ignition energy than methane, 0.011 mJ vs 0.3 mJ respectively. (Thorne & Derrick International, 2023). The minimum ignition energy is the lowest energy required to ignite the flammable material in air or oxygen.
- A higher leakage probability than any other substance, because of the smaller size of the molecules and its low viscosity. This can also be cause of embrittlement and degradation of the material of the cylinders (Tretsiakova & McNally, 2016).

On the other hand, an advantageous property of hydrogen versus other fuels is its low density. Under atmospheric conditions it is a gas lighter than air. This means that if an unintentional release or leak occurs outdoors, hydrogen will typically rise in the air and disperse rapidly, reducing the risk of ignition at ground level. In comparison, propane and gasoline vapor are heavier than air, and thus they are more likely to remain at ground level, increasing potential safety risks.

To minimize the risks related to explosion, the following precautions should be taken, according to the indications given by CALVERA (CALVERA Hydrogen S.A., 2023):

1. Concerning the **installation** phase of the storage system:
  - The storage units must be placed in an adequately ventilated area; this is normally ensured by locating them outdoors in open air, as in the case of *Estación Marítima 4* (Autoritat Portuària de Balears, 2022).
  - The storage units must be separated from inflammable substances and to heat areas. The distance from the latter must be sufficiently big to keep the temperature of the surface of the cylinders below 50°C.
  - The storage units must be protected from natural elements like rain, snow, and strong solar radiation.
  - Concrete walls should be built between the storage system and the fuel cell, to prevent the latter from damaging in case of explosion of the storage system. At the *Estación Marítima 4*, the concrete wall is designed to support 172 mbar overpressure and 35 kW/m<sup>2</sup> radiation (ENAGAS Renewable, 2022).
  - A hazardous area should be defined around the storage system, where nothing can be built or installed. The hazardous area defined for the storage system at the *Estación Marítima 4* is shown in the following *figure 28*.<sup>2</sup>

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<sup>2</sup> Notice that the location of the Fuel cell system to be deployed in EM4 differs from the one presented in the deliverable D.2.9. after further evaluation by Port of Balears. (Latest update July 2023)

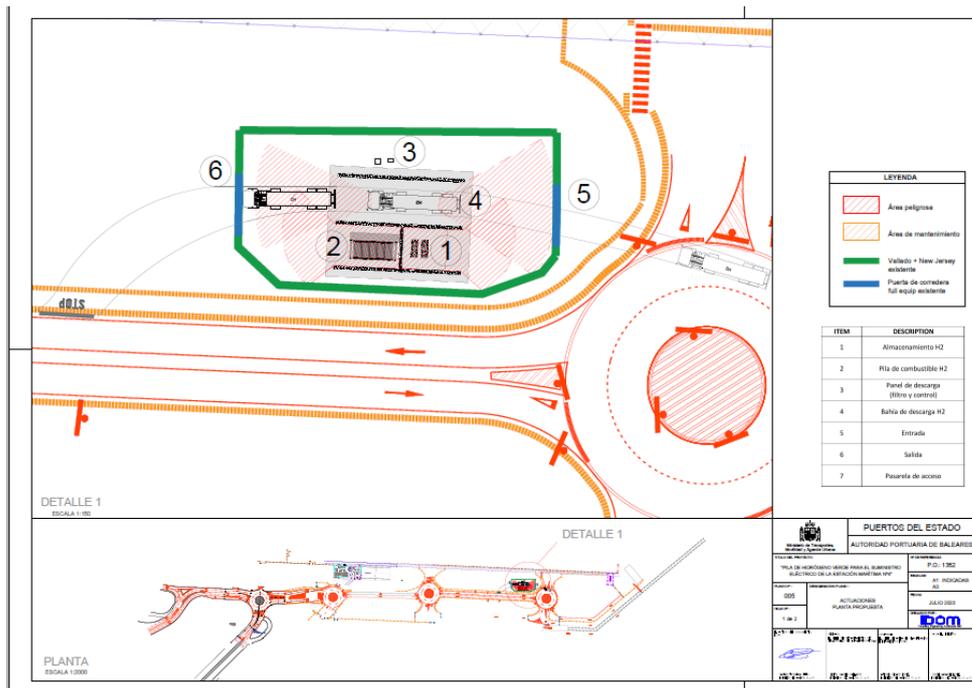


Figure 28: Planned fuel cell and storage system to be deployed at Estación Marítima 4. The hazardous zone is marked with a light striped red symbol within the figure and referred to as the "área peligrosa" in the legend (Autorita Portuària de Balears, 2023)

2. Concerning the **charge/discharge** operations:

- It is advisable to fill the storage units when the port site is not crowded, which means that the best options would be either in the morning or in the evening.
- The two phases must be conducted monitoring constantly the system pressure and eventual leakages.
- Further details about the charge and discharge operations are in the CALVERA Report (CALVERA Hydrogen S.A., 2023).

3. Concerning the **preparations for maintenance** activities:

- Before performing maintenance activities, the storage should be emptied (HydrogenTools, 2023). A first way to do it is by connecting the storage to a joint structure in which there is a vent line in order to perform the operation (draining process). The steps to follow for the draining process are described in the operational manual from CALVERA (CALVERA Hydrogen S.A., 2023).
- An alternative strategy is with an inerting process, which is done to minimise the level of oxygen in a given space and prevent oxygen and/or moisture from coming into contact with reactive or adsorptive products (Reinhardt, Himmen, & Kaltenecker, 2023). The inerting process reduces the probability of explosions when the gas is vented from the storage (HydrogenTools, 2023). Detailed instructions on how to perform it can be found in the operational manual (CALVERA Hydrogen S.A., 2023).

## 7 Techno-economic assessment

The principal objective of this investigation is to evaluate the techno-economic and environmental efficiency of energy systems utilizing renewable energies and hydrogen fuel cells. These systems will be designed to fulfil the energy requirements of specific maritime installations situated in different port locations across the Balearic Islands. A visual depiction of the proposed energy systems, illustrating their arrangement and essential components, is presented in *Figure 29*.

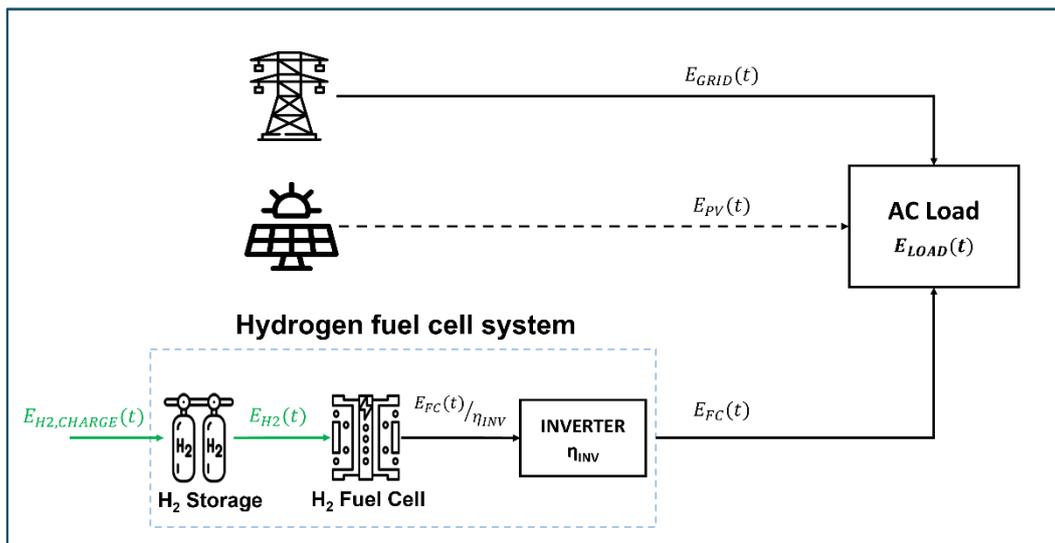


Figure 29: Scheme of the new energy system to provide electricity to the maritime terminals

Each maritime terminal has a specific electricity demand, referred to as  $E_{LOAD}$  in *Figure 29*. The values of this demand are expressed on an hourly basis, as described in each building within the maritime terminal requires electricity to power various appliances listed in *Table 3*. It is important to note that all these appliances operate on alternating current (AC).

In the new hybrid energy systems evaluated in the study the electricity may be supply from at least two sources (hydrogen fuel cell system and the grid), and, for other options a third source (solar PV) may be considered. In general, the order of priority in which the future energy system for the maritime terminal is expected to operate is:

1. A dedicated photovoltaic (PV) system: This option is currently available in EM4 in Mallorca and the maritime terminal in Botafoc. The flux indicated in *Figure 29* as  $E_{PV}$  represents alternating current (AC). It is important to note that a dedicated DC-AC converter for the PV system has already been considered in the design. The use of additional PV systems will be evaluated in the proposed new energy configuration systems in EM2 and EM3.
2. A hydrogen fuel cell system: This alternative involves coupling a hydrogen fuel cell with a hydrogen storage system and a DC-AC power converter (inverter). The fuel cell system allows the generation of electricity using hydrogen as a fuel source, and the DC-AC power converter ensures the compatibility of the generated electricity with the building's electrical system.
3. The electrical grid, which provides electricity in alternating current (AC).

## 7.1 Methodology

The evaluation relies on a Cost-Benefit Analysis (CBA) that considers the generation of renewable electricity through a hybrid system at a certain cost, while simultaneously achieving improved environmental performance. These aspects are closely interconnected and dependent on the manner in which the hydrogen fuel cell system is utilised: either in load following mode or constant power mode. The overall configuration of the hybrid energy system also significantly affects the results of the CBA, with the most influential factors being: storage size, FC power capacity and efficiency, and the presence or absence of other renewable energy generation technologies.

A Python-based mathematical model was developed to represent the energy systems, considering both current and future energy configurations for assessment. By incorporating the most influence parameters mentioned above, the model enables the quantification of energy hydrogen demand, fuel cell energy generation, energy surplus, as well as the chosen techno-economic and environmental indicators for the CBA assessment for this study.

The primary technical indicator focuses on the building's energy supply independence from the grid (Energy Autonomy). The economic assessment presented here utilizes indicators such as the LCOE (Levelized Cost of Electricity) of the proposed systems and cost reductions resulting from decreased grid electricity purchases (cost savings). The environmental impact assessment relies on CO<sub>2</sub> emissions reduction to evaluate the effects of the new solutions. The model generates outputs at both system and individual building levels.

### 7.1.1 Cost-Benefit Analysis (CBA) parameters

The parameters and formulas defined for the Cost-Benefit Analysis (CBA) modelling and assessment in this study are:

#### 7.1.1.1 Levelized cost of electricity

The levelized cost of electricity (LCOE) is a financial metric used to assess the average cost of producing a unit of electricity over the lifetime of a power generation system, in this case the fuel cell. It is a measure that takes into account all the costs associated with building, operating, and maintaining the hydrogen fuel cell system, as well as the expected energy output over its lifetime (20 years). The timespan of 20 years was chosen considering that many components of the energy system have an expected lifetime of 20 years or higher (PV panels, storage units, inverters, the BOP of the fuel cell). The LCOE is calculated according to the (Eq. 1 (Black & Veatch, 2011) (Khan, Yu, & Waseem, 2022) (Gharibi & Askarzadeh, 2019):

$$LCOE \left[ \frac{\text{€}}{\text{MWh}} \right] = \frac{\sum_{y=0}^{lifetime} \left( (CAPEX_y + OPEX_y) * \left( \frac{1 + inf}{1 + disc} \right)^y \right)}{\sum_{y=0}^{lifetime} \left( AEP_y * \left( \frac{1 + inf}{1 + disc} \right)^y \right)} \quad (Eq. 1)$$

Where:

*CAPEX<sub>y</sub>*: capital expenditures occurring at the year *y* (€/y),

*OPEX<sub>y</sub>*: the operational expenditures in a generic year *y* (€/y),

*inf*: inflation rate ( dimensionless)

*disc* : discount rate ( dimensionless)

*AEP<sub>y</sub>* : Annual Electricity Produced by the new energy system at the year *y* (MWh/y)

*lifetime* : timespan of the project (years)

The term Annual Electricity Produced by the new energy system coincides with the generation of the fuel cell; in case an additional renewable system is installed in combination with the hydrogen fuel cell its annual electricity output must be included as well.

The capital expenditures involve all the different devices that are part of the new energy system, namely the fuel cell, the storage, the inverter, and the civil works necessary to install the new equipment. The capital costs of an eventual additional renewable system should be accounted as well. Capital costs of the existing Solar PV systems are considered sunk costs.

OPEX take into account the operation and maintenance costs of the different devices of the energy systems (including the additional renewable systems), together with the costs associated to the purchase of hydrogen.

#### 7.1.1.2 Lifetime Costs savings

The LCOE primarily reflects the cost of generating electricity using the storage hydrogen-fuel cell system, but it does not directly indicate the savings that the end-user, in this case, the *Autoridad Portuaria de Baleares*, may achieve by reducing electricity purchases from the grid.

To assess the economic benefits of these potential cost savings, one approach is to calculate the total savings over the project's lifetime by considering the annual cost savings, adjusted for inflation and discounted to present value. This provides a measure of the economic benefit derived from the project, taking into account the reduction in electricity expenses.

The more the hybrid energy system reduces the electric dependence of the building on the public grid in term of quantity purchased, the higher will be the monetary savings for *Autoridad Portuaria de Baleares*; the reduction of electricity purchase from the grid coincides with the amount of electricity generated by the new system, which includes the electricity to cover the building demand, together with the surplus. The lifetime actualized costs savings (LACS) is defined for this study as:

$$LACS[\text{€}] = \sum_{y=0}^{lifetime} \left( \left( \sum_{h=0}^{8759} c_{GRID,y}(h) * E_{NEW\ SYSTEM,y}(h) \right) * \left( \frac{1 + inf}{1 + disc} \right)^y \right) \quad (Eq. 2)$$

Where:

$c_{GRID,y}(h)$  is the cost of electricity from the grid at a specific year *y* and a generic time of that year *h* (€/MWh);

$E_{NEW\ SYSTEM,y}(h)$  is the electricity generated by the new energy system at a generic time *h* of the generic year *y* (MWh)

#### 7.1.1.3 Energy Autonomy

The parameter useful to assess the technical performance of the new system is the **energy autonomy** (EA). This indicator gives an idea on how independent the energy system of the maritime terminals is from the grid. (Khezri & Mahmoudi, 2020).

$$EA[\%] = \frac{\sum (E_{LOAD}(t) - E_{GRID}(t))}{\sum E_{LOAD}(t)} \quad (Eq. 3)$$

Where  $E_{LOAD}(t)$  and  $E_{GRID}(t)$  are respectively the electric demand of the building and the electricity purchased from the public grid at a generic time  $t$ .

#### 7.1.1.4 Carbon Dioxide Emissions reduction

To assess the environmental benefits of the new system, the CO<sub>2</sub> emissions reduction ( $\Delta CO_2$ ) for each building should be calculated. Analogously to LACS, the emissions reduction depends on the amount of electricity generated by the new system, since it coincides with the reduction in grid electricity purchase. The avoidance in emissions depends also on the emission factor of the port that it is being considered, namely  $ef_{CO_2}$  (ton<sub>CO2</sub>/MWh):

$$\Delta CO_2 \left[ \frac{ton_{CO_2} eq}{y} \right] = ef_{CO_2} * \sum_{h=0}^{8759} E_{NEW\ SYSTEM,y}(h) \quad (Eq. 4)$$

### 7.1.2 Modelling the hydrogen fuel cell system

The mathematical model is divided into three sections, each focusing on different aspects of the hybrid energy system.

In the first section, the objective is to identify a configuration that can fully meet the building's energy demand, eliminating the reliance on the electrical grid. This involves sizing the nominal power of the fuel cells to ensure they can satisfy the demand, even during peak periods. Additionally, the storage system must be adequately sized to provide the necessary amount of hydrogen required by the fuel cells.

In the second section, the focus shifts to examining how the system's technical, economic, and environmental performance varies with different fuel cell power levels and storage sizes when the fuel operates at load following mode. It is acknowledged that there may be instances where electricity from the grid is needed, such as when there is an insufficient quantity of hydrogen in the storage system or when the fuel cells cannot provide enough power.

The third section specifically addresses the scenario where the fuel cells operate only at a constant power level if there is sufficient hydrogen available in the storage system. Otherwise, the fuel cells remain inactive. This analysis follows a similar approach to the second section, with the variation of fuel cell power and storage capacity considering the given constraints, and the evaluation of relevant CBA parameters of interest.

After applying all three steps of the modelling work, for each energy system configurations<sup>3</sup>, the solution that achieves a minimum target of 80 % energy autonomy at the lowest cost will be preliminary selected for further analysis.

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<sup>3</sup> In this study a configuration is a combination of possible elements to be part of the energy system maritime terminals: building(s), hydrogen fuel system, operational mode of the fc, frequency of refilling and eventual presence of other new renewable energy supply system (see Figure 29 and section 7.4).

### 7.1.2.1 Maximum Capacity required definition

In this section the model calculates the size of the main components, namely fuel cell nominal power and storage capacities that will allow the system to maximize its electricity output, aiming to meet the peak electrical demand of the maritime terminal where possible.

Considering the hourly demand for each building ( $E_{LOAD}(t)$ ), the nominal power required from the fuel cells to meet the energy needs of these buildings, in the absence of any dedicated photovoltaic system, can be determined as follows:

$$P_{FC,NOM}[kW] = \max(P_{FC}(t)) * k = \max\left(\frac{E_{LOAD}(t)/\eta_{INV}}{1 \text{ hour}}\right) * k \quad (Eq. 5)$$

Where  $k$  is a correction factor to be multiplied, to guarantee that the fuel cell will be able to provide electricity even in case the demand was higher than expected. The value of  $k$  can be chosen using as reference the coefficient utilized to find the upper bound and the lower bound for the building demand in *section 3.3*

For those buildings that are also served by photovoltaic energy, the nominal power of the fuel cell will be equal to:

$$P_{FC,NOM}[kW] = \max(P_{FC}(t)) * k = \max\left(\frac{(E_{LOAD}(t) - E_{PV}(t)) / \eta_{INV}}{1 \text{ hour}}\right) * k \quad (Eq. 6)$$

With  $k$  the correction factor already introduced.

The definition of the size of hydrogen storage facility will depend on several factors: (1) the amount of hydrogen required to satisfy the electricity demand over a period of time, (2) how often the storage is filled when the hydrogen is distributed by tube trailers or refilling trucks: if it occurs with a daily frequency, the capacity needed will be certainly lower than in case of a weekly recharge, (3) other practical considerations such as the footprint available for storage units and (4) safety aspects regarding the location of the storage facility, among others. The first three factors were incorporated in the model.

Given a generic frequency of recharge ( $f$ , in days), and assuming that the storage should always have a minimum level of hydrogen ( $E_{H2,MIN}$ )<sup>4</sup> to avoid critical operations, the size of the storage system is calculated as:

$$E_{H2,STORAGE} [kWh] = (\max(E_{H2,CHARGE,period_i}) + E_{H2,MIN}) * h \quad (Eq. 7)$$

Where  $h$  is a correction factor that has the same purpose of the one used for the power of the fuel cells. The amount of hydrogen replaced in the storage at each period depends on how much hydrogen was consumed by the fuel cell in the previous period, that is:

$$E_{H2,CHARGE,period_i} = \sum_{h=1}^{24*f} (E_{H2,FC}(h))_{period_{i-1}} \quad (Eq. 8)$$

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<sup>4</sup> Equal to 2.4 kg per storage unit at the minimum admitted pressure of 30 bar and 20 °C.

Where  $E_{H_2,FC}$  corresponds to the quantity of hydrogen required by the fuel cell, which in a general time  $t$  is:

$$E_{H_2,FC}(t) = \frac{E_{FC}(t)}{\eta_{FC}} \quad (Eq. 9)$$

Since the consumption of hydrogen depends on the technical specifications of the fuel cell to be used, as well as the operational modes, apart from the building's electricity demand and the potential supply of renewable energy from additional sources within the building and the supply, there can be multiple solutions to meet the sizing requirements that fulfil the needs of the *Autoridad Portuaria de Baleares*. These solutions aim to achieve energy autonomy through the integration of renewable energy sources into their system while also contributing to the reduction of electricity produced in the emissions in the Balearic Islands.

The mathematical model was designed to consider the aforementioned factors that influence the outcome. The model's output yields the values of the four CBA indicators at different combinations of fuel cell power and storage capacity.

In the next two sections (6.1.1.2 and 6.1.1.3) the modelling technique of the two different operational modes for the fuel cell are introduced: load-following and constant-load. The operational mode influences the electricity generation of the fuel cell  $E_{FC}(t)$  at any time, meaning that the sizing of the storage capacity will have different values for each operational mode. In terms for how the model considers potential footprints constraints, the *section 6.2.6* explains how "t" those constraints (among others) are incorporated in the mathematical model.

#### 7.1.2.2 Load Following formulation

The section studies how the four CBA parameters introduced for the study would change varying size of the two main components of the system: the fuel cell and the storage. The two variables can assume all the values between zero and their maximum limit, which coincides with the solution found in the previous section. It might be useful understand how the hybrid system would work at different values of storage capacity and fuel cell power. The following scheme could help to figure it out, remembering that the fuel cell works in load-following modality.

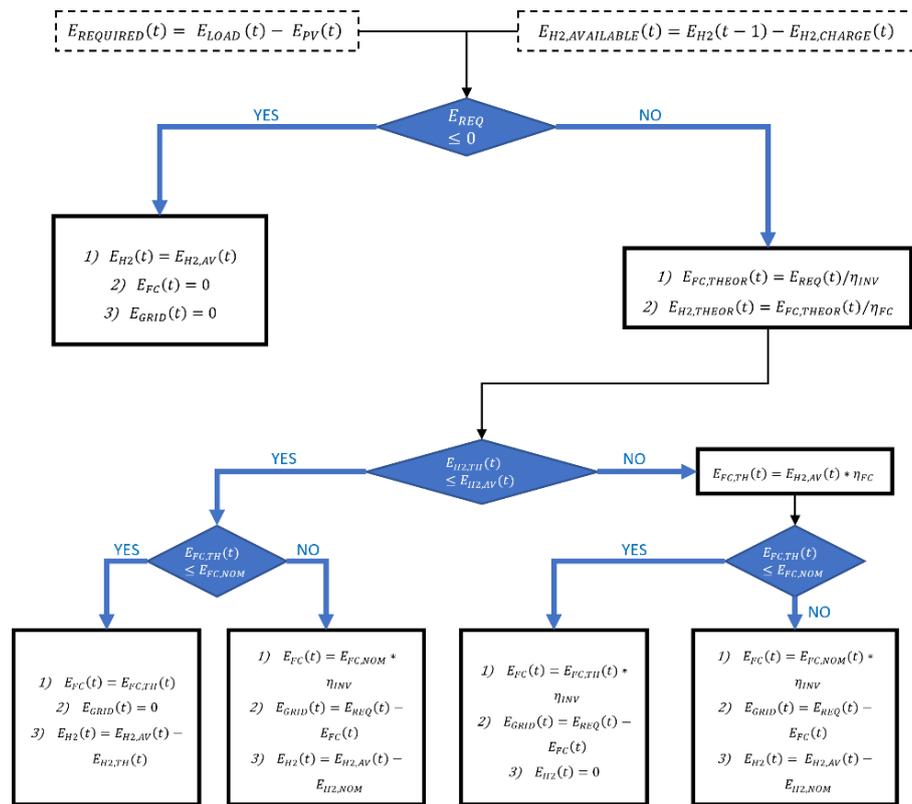


Figure 30: Flow diagram of the mathematical model of a hybrid system with a load-following fuel cell

The term  $E_{REQUIRED}(t)$  corresponds to the difference between the demand and the self-consumption from photovoltaic sources (when present). It will be null or lower than zero only when the photovoltaic production is high enough to satisfy the entire demand; in case the required energy is not null, the building will need additional energy, which can come exclusively from the dedicated fuel cell, exclusively from the grid, or from a combination of the two. Four different alternatives are possible.

1. If there is enough hydrogen in the storage system to satisfy the demand at a generic time  $t$ , and the fuel cell nominal capacity is higher than the requested power, the storage-fuel cell system can fulfil the remaining demand of the building;
2. If the quantity of hydrogen in the storage is sufficient, but the nominal power of the fuel cell is lower than the power needed, the system can only work at its maximum power, and the building will require a certain amount of electricity from the grid to fill the gap between the nominal capacity of the generator and the power required;
3. In case of an insufficient amount of hydrogen in the storage and a nominal capacity of the generator equal or higher than the power required, the storage will be emptied, and the fuel cell will work with the hydrogen available; the remaining demand will be provided by the grid;
4. If the quantity of hydrogen is not sufficient, and the fuel cell nominal power is lower than the requested one that can be extracted, the generator will work at nominal power, and the storage will not be totally emptied; also in this case, electricity from the grid will be necessary.

Since the grid electricity price is not constant along the year but changes depending on the daytime and on month (see *section 7.3.6*), the system is built to prioritize electricity production with the fuel cell in those periods when the electricity is more expensive, in order to maximize the cost savings.

### 7.1.2.3 Constant Load formulation

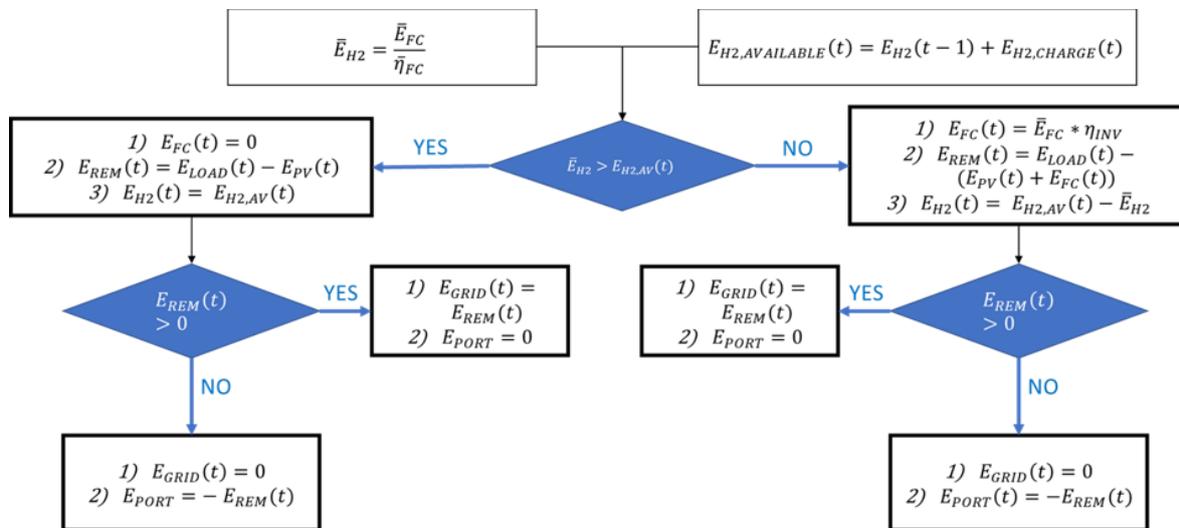


Figure 31: Flow diagram of the mathematical model of a hybrid system with fuel cell operating in constant mode.

The moments ( $t$ ) in which the energy from the fuel cell exceeds the demand are associated with the term  $E_{PORT}$ , which corresponds to the surplus energy from the fuel cell that can feed other utilities in the port site. This is possible because the ports have a radial electric grid (Autoritat Portuària de Balears, 2022), which allows then the exchange of energy fluxes between the various end-users in the port. This analysis might result useful for evaluating the possibility to feed part of the demand of the cold-ironing activities. In case the fuel cell couldn't generate electricity along the entire period requested, the priority will be given to those moments in which the electricity price from the grid is highest, to maximize cost savings, with the same principle of the previous formulation.

## 7.2 Main technical and operational input parameters, assumptions and boundaries

The mathematical model requires several inputs related to operational aspects, technical parameters for the fuel cell and the storage, the energy demand per building (aka load) and the energy supply by PV solar panels, if considered in the configuration.

### 7.2.1 Electricity demand per building

The energy demand per building was analysed in *section 3.3*. The mathematical model requires the energy input in an avg. energy demand per hour.

### 7.2.2 Fuel cell technical inputs

The fuel cell is the most important and critical part of the new system. When dealing with this device, three important characteristics must be considered: the efficiency, the degradation factor, and number operational hours during a year.

### 7.2.2.1 FC Efficiency

The conversion efficiency of a fuel cell has an impact on the hydrogen demand of the system to be calculated by the model. The partial load of a fuel cell is defined by the operating power ( $P$ ) in a specific time ( $t$ ) divided by the nominal fuel cell power ( $P_{NOM}$ ). The efficiency of the fuel cell is function of the partial load at which it operates, as shown in the figure below:

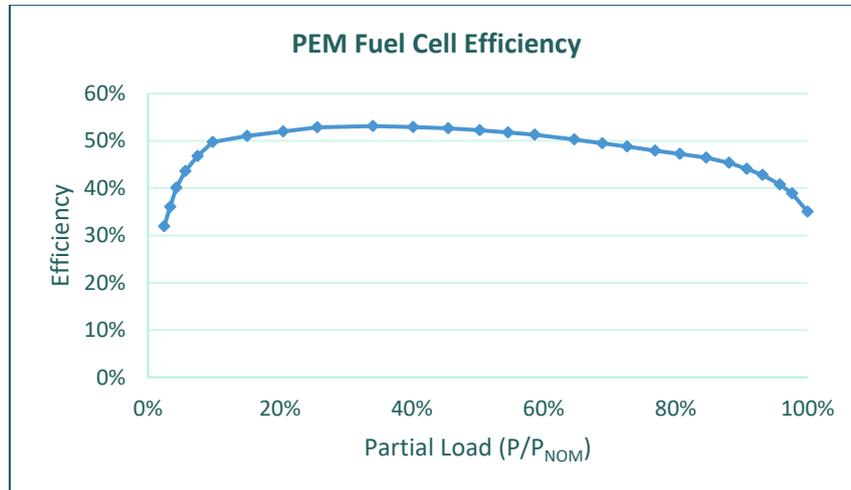


Figure 32: Fuel cell efficiency as function of the partial load (Eastlack et al., 2019)

The efficiency curve presented in *Figure 32* is referred to a 30 kW-PEMFC (Eastlack, et al., 2019), and a similar shape can be associated also to lower nominal capacities of 5 kW (Felseghi, Aschilean, Cobîrzan, Bolboacă, & Raboaca, 2021). No relevant sources were found about efficiency curves for fuel cells at higher capacities; in this study, this shape was assumed to be valid also for higher fuel cell powers, thanks to the fact that multiple fuel cells with the same characteristics can be combined in case of very high capacities need to be installed.

The analyses considering load-following fuel cells were performed using the efficiency curve shown in *figure 32*, which has an efficiency of 35% at 100 % nominal load, and a maximum efficiency of 53%, with a partial load of 30%.

If the fuel cell works only at constant load, which was assumed in this study to be 80% of the nominal load, the efficiency equal to 47% according to the same reference (*figure 32*).

### 7.2.2.2 Degradation factor

The fuel cell stack is subject to degradation over time. This has an impact on both the performance of the fuel cell (i.e., its electrical efficiency) and its durability. The degradation effect consists in a loss of power (%) every 1000 hours of operation (Hydrogen Europe, 2020),

To know how many degradations rounds of 1000 hours a fuel cell can operate before being replaced, it was considered a maximum power percentage loss of 20% with respect to the nominal one (Hydrogen Europe, 2020). The number of rounds will determine the useful lifetime of the fuel cell stack, expressed in hours.

If the fuel cell is working in load-following mode, a degradation factor of 0.6%/1,000h was used: this value was chosen basing on the fact that the degradation factor of PEMFC in dynamic operation (typical of the fuel cell vehicles) is around 0.88%/1000h (Stropnik, Mlakar, Lotric, Sekavcnik, & Mori, 2022),

while *Hydrogen Europe* gives a value of 0.4%/1000h (Hydrogen Europe, 2020) for static applications. A degradation factor of 0.6 was considered acceptable since the fuel cell is working in load-following mode, but the operations are not going to be as dynamic as for the fuel cell vehicles.

If the fuel cell will operate in constant load mode, a degradation factor of 0.4%/1000h was chosen, according to *Hydrogen Europe* (Hydrogen Europe, 2020).

For both the operational modes considered, a sensitivity analysis was performed varying the degradation factor from 0.8%/1,000h to 0.3%/1,000h, to observe its influence on the LCOE (the results are available in *section 8.5.1*).

### 7.2.2.3 Annual operating hours

The model built for the purpose of this study must consider all those moments in which the fuel cell does not generate electricity because of maintenance and shutdown reasons. The model deals with the effect of maintenance as follows:

- If the fuel cell works is expected to work more than 8,000 hours per year, the fuel cell will be stopped one day per month for regular planned maintenance purposes
- If the working hours are expected to be between 3,000 and 8,000 per year, the frequency of this event will be every two months;
- With less than estimated 3,000 operational hours, the fuel cell will be stopped one day every three months.

For all the other days, in order to take into account, the effect of the shutdown periods, the model multiplies the output of the fuel cell by a factor of 95% (according to the value of availability mentioned by Nielsen et al. (Nielsen, et al., 2019)).

These considerations applied in the model lead to an annual number of working hours of the fuel cell really similar to that estimated for the fuel cell in EM4 (Autoritat Portuària de Balears, 2022), where the maintenance and shutdown moments are considered to be 10% of the year; the difference is about 2% when considering a fuel cell operating more than 8,000 hours per year, and about 4% for a fuel cell working between 3,000 and 8,000 hours per year.

## 7.2.3 Inverter

The main function of the power converter is to transform the output of the fuel cell from DC to AC. The number of inverters units will be determined by the model. The model considers that different inverter units can be installed: it is assumed that each unit cannot accept a maximum DC input of 11 kW and has an efficiency of 91%; these two parameters imply that the maximum AC power that an inverter unit can release is 10 kW (inverter.com, 2022).

## 7.2.4 Hydrogen supply and storage

In order to determine the future demand of green Hydrogen to decarbonise the activity of the sea terminals under study and for modelling purposes, it was considered that there will be no limitations to the availability of green hydrogen in the market.

The storage is fundamental to provide the fuel cell with the hydrogen needed whenever it is needed. The size of the storage is calculated based on the hydrogen consumption of the fuel cell according to the electrical output required, which can vary for each capacity depending on the operating mode of the cell. The truck always arrives at the storage site at full capacity (300 bars)

A single truck can serve maximum 36 storage units per trip, which corresponds to 291 kg of hydrogen transferred into the storage system; however, in the model there is no limitation in the number of trucks (or trips) that can charge the units.

The design of the EM4 Hydrogen supply and storage system (tube trailer, stationary hydrogen storage units and filling panels) is used as a reference in the model., based on this design. It is given that storage system of EM4 required of 9 storage units for a 40 tons annual hydrogen demand to be refilled in a daily basis.

Due to the space limitations and safety considerations affecting its design, it was not possible to choose a larger storage system with a lower charging frequency, as it would have required a larger footprint than the available space in the EM4 area. For modelling purposes, the storage capacity of the stationary unit as design by CALVERA was used as a reference to express the storage capacity required of the maritime terminals in the port of Palma de Mallorca (EM2 and 3) given their vicinity.

Based on the information given by CALVERA, *Figure 33* shows how much hydrogen the storage system can receive from a single truck varying the number of storage units installed; the amount of transferable fuel coincides with the maximum quantity that can be sent to the hydrogen generator.

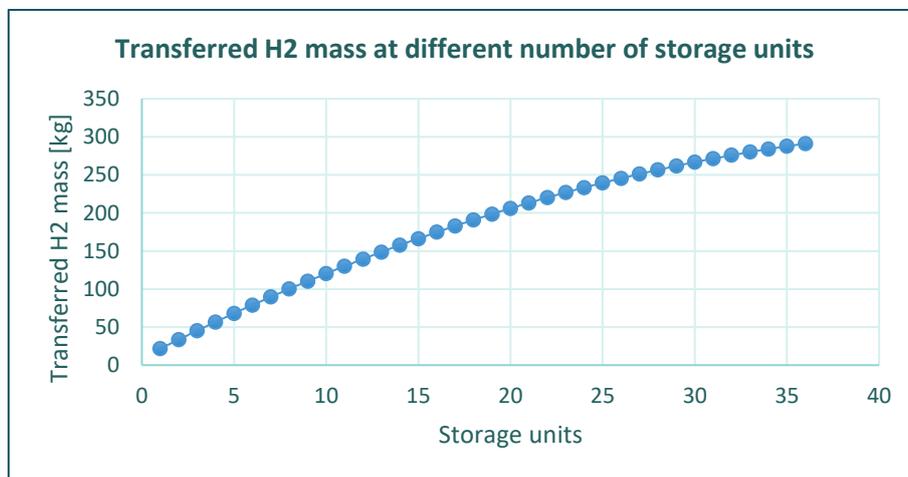


Figure 33: H<sub>2</sub> transferable in the storage varying the number of storage units (IDOM, 2022)

The same assumptions were used to model the Botafoc and Mahón maritime terminals. See *section 7.2.7* for more information about the model constraints and its limitations.

## 7.2.5 New PV systems

At the port of Balears facilities, photovoltaic systems are already installed in EM4 or considered in the design of the new maritime terminal in *Botafoc*, while no renewable sources are currently considered to feed EM2, EM3, and the projected building in *Mahón*. However, it is still interesting evaluating the benefits associated with the introduction of renewable plants to these buildings as well, which is why the case with a photovoltaic system dedicated to the building EM2+EM3 was studied. This was not done for the station in *Mahón* due to insufficient information about the building construction project the unique data about this building is the living surface.

The new PV system for EM2+EM3 would be added in combination with the fuel cell system, meaning that its main features (energy production and associated costs) must be considered as part of the new configuration (see *section 7.4*) with the explanation of new configuration and base case scenario.

The key information that allows to obtain the hourly electricity production and the associated costs is the nominal power of the system. Two main factors influence the choice of the maximum photovoltaic power installable. The first one is the surface available: the stations EM2 and EM3 do not have a flat roof, but they both have a flat parking roof placed next to them; the positions of the different buildings and the available surface of the two parking roofs are shown in *Figure 34*.



Figure 34: Satellite view of EM2, EM3, and the parking roofs associated, and available surface on these roofs.

Not all the roof space can be used for PV installation, as it is standard practice to maintain around 2 m of distance between the panels and the borders of the roof, to allow human operations to be performed safely: assuming this security distance, the available surface for the PV installation is estimated in 1,150 m<sup>2</sup> for EM2 and 950 m<sup>2</sup> for EM3. For the new PV system in EM4, 12.8 m<sup>2</sup> of surface are required for 1 kW<sub>p</sub> (IDOM, 2021); using this value as reference, the maximum power installable on the two roofs would be of 160 kW<sub>p</sub>.

The available surface is not the only variable to consider for the sizing of the PV array. The demand required from the buildings plays a key role as well: in case the nominal power was significantly higher than the average demand, the drawbacks associated to the additional costs would be more than the benefits gained in terms of electricity self-consumed. Looking at the load duration curve of EM2+EM3 in *Figure 35*, there are very few moments in which the demand is higher than 80 kW, suggesting that a nominal power larger than 80 kW<sub>p</sub> would not be necessary.

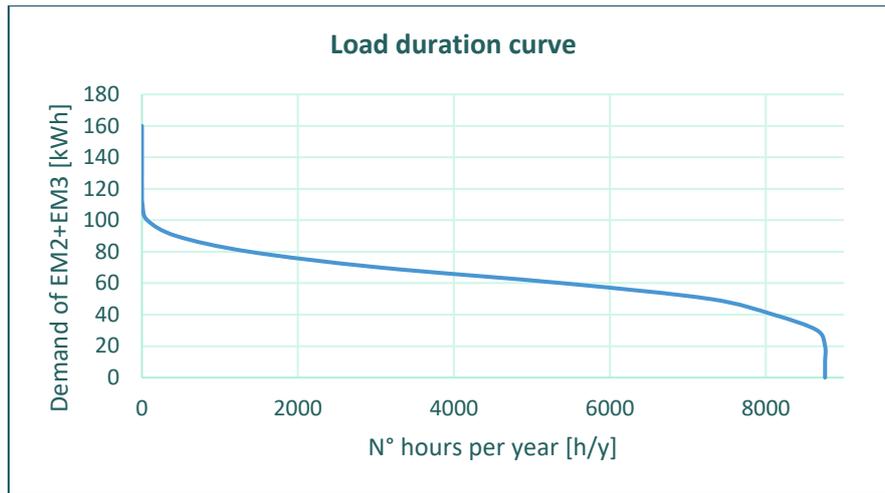


Figure 35: Load duration curve of EM2+EM3

The considerations of the available surface on the roofs and the load duration curve led to choose a nominal power of 80 kW<sub>p</sub> for the PV system dedicated to EM2+EM3.

The hourly electricity generation of the new PV installation was calculated as a proportion of the output of the system dedicated to EM4, which has a nominal power of 100 kW<sub>p</sub> (IDOM, 2021), and whose hourly production was calculated using the PVGIS instrument (European Commission, 2022). It must be remembered that the output found with this tool already takes into account different losses characterizing these systems, including those associated to the inverter.

### 7.2.6 Other operational inputs

The model takes into account operational aspects for the fuel cell-based system. It allows to consider two operational modes of the fuel cell: load following or constant power model. These considerations in the model are relevant for the dimensioning of the hydrogen-based energy system configurations for the maritime terminals within the scope (all except for EM4 which Fuel cell and storage size has been predetermined by the GH deployment plan).

The frequency of charge of the storage system expressed in number of days is also considered as an input by the user.

### 7.2.7 Model Boundaries and limitations

The mathematical model provides among other results, the CBA parameters (LCOE, EA, LACS,  $\Delta\text{CO}_2$ ) and the annual hydrogen demand. These outcomes are function of three input variables: the nominal power of the fuel cell, the number of storage units, the frequency of charge.

In these models, the three variables can assume only discrete values belonging to specific ranges, which are defined by a lower limit and an upper limit.

Regarding the fuel cell, the minimum value of capacity is 5 kW, while the upper boundary ( $P_{FC,MAX}$ ) is found following the steps explained in section 7.1.2.

$$5 \text{ kW} = P_{FC,MIN} \leq P_{FC} \leq P_{FC,MAX} \quad (\text{Eq. 10})$$

The lower limit for the installable storage units is 1, the frequency of hydrogen charge entered by the user must be equal to one day or larger.

Additionally, in order to constrain the range of solutions provided by the model, theoretical maximum number of units needed ( $N_{ST,MAX}$ ) corresponds to the one allowed by spatial constraints ( $N_{ST,LIMIT}$ ).

The information in the GREEN HYSLAND project deliverable dedicated to the fuel cell at the *Estación Marítima 4* (Autoritat Portuària de Balears, 2022) provided the surface needed for the storage. The constraints on the installable storage units were done assuming the maximum surface that can be occupied by the storage systems. These values were taken looking at the satellite images of the port sites. For the three stations in the port of Mallorca (EM2, EM3, and EM4) the space for installing the storage is very limited; it was assumed that in *Botafoc* a higher capacity can be installed it still can be considered as a quite empty area; for the new station in *Mahón*, a middle way between Mallorca and Ibiza was assumed.

Based on this information, the maximum number of storage units for each building considered in the study was assumed:

Table 14: Technical maximum number of storage units per building, and correspondent space occupied

Building	Maximum storage units	Surface occupied [m <sup>2</sup> ]
<b>EM2</b>	50	190
<b>EM3</b>	50	190
<b>EM2 + EM3</b>	100	370
<b>EM4</b>	50	190
<b>Botafoc</b>	120	440
<b>Mahón</b>	70	260

Note that number of storage units cap shown in *Table 14* was defined as a model constrain only. It does not take into account the full footprint of a recharging area as per the EM4 design (road for the truck, safety wall and recharging panel) or safety limitations in terms of the amount of hydrogen stored in situ. Therefore, in practice, the final design of the storage system and the refilling must be readjusted to the available space considering the footprint of the refiling area or another parameter if the supply hydrogen will be done by pipelines.

Moreover, since the projected energy demand for Mahón and Botafoch is higher than the demand the maritime terminals in Mallorca, then using the same assumptions of hydrogen supply and storage system design might as in Mallorca seem unrealistic. Taking this factor into account, the model can be run without any footprint limit providing an estimation of the hydrogen demand profile (tons/year) for each maritime terminal in a determined energy system configuration, which corresponds to the frequency of charge of 1 day. Therefore, once established the hydrogen demand by this model, the final storage concept design for Mahón and Botafoch, the operational assumptions may be refined once a more suitable storage systems design and technology of hydrogen distribution system is identified.

For example, the bespoke design may include a larger storage capacity per storage unit, the use mobile instead of a stationary storage unit. Other elements to be consider is if, in the future the hydrogen will be supplied by pipelines and/or if the production of hydrogen takes place in the island. In any case, the model can be updated for the economic assessments of other possible options in the future.

## 7.3 Economic parameters and lifetime of the various components

### 7.3.1 Fuel cell economic inputs

When dealing with the capital costs related to the fuel cell, the stack and balance of plant (BOP) must be treated separately.

The fuel cell stack has a useful lifetime that varies as function of the degradation factor and the annual working operations. The capital expenditure will occur at the year in which the stack replacement will be necessary. However, the CAPEX related to stack installation should decrease in the following years, as shown in the figure below. Major details about the choice of the values for the stack CAPEX can be found in the *Appendix A*.

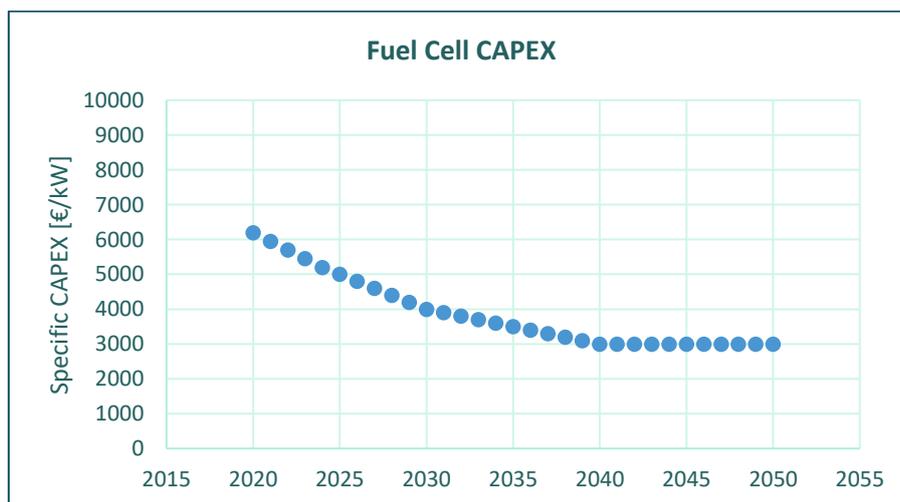


Figure 36: Future projection for CAPEX for the fuel cell stack (Bednarek, Davies, Malkow, & Weidner, 2021) (Hydrogen Europe, 2020)

The BOP has a useful lifetime of 20 years (Nedstack fuel cell technology B.V), and its specific CAPEX are considered to be 20% of those for the stack (IDOM).

The OPEX associated to the fuel cell are related to the entire system, without distinguishing stack and BOP. Just like the CAPEX, the OPEX are also expected to decrease along the years. OPEX are based on operation & maintenance costs, excluding both stack replacement costs (they are considered in the CAPEX) and fuel cost, which has a dedicated section (7.3.5). The *Appendix B* provides a detailed explanation of the methodology used to select the O&M costs projections over the years.

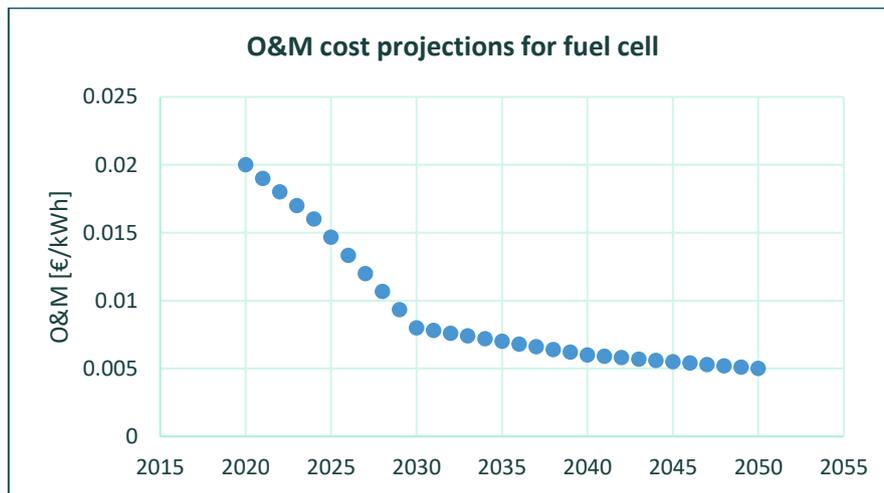


Figure 37: Future projections for O&M costs of fuel cell (Hydrogen Europe, 2020) (Okundamiya, 2021) (Singh, Chauhan, & Singh, 2020)

In this study, the annual specific O&M costs correspond to those occurring in the year of the fuel cell installation or stack replacement and are considered constant for the entire period between two stack replacements.

### 7.3.2 Hydrogen storage economic inputs

Bearing in mind that the hydrogen storage is composed by storage units and filling panel, the costs and useful lifetime for the two components are listed below:

Table 15: Lifetime costs of the different components of the hydrogen storage unit

Storage component	CAPEX	OPEX	Useful Lifetime
<b>Storage unit</b>	21,000 €/unit	100 (€/unit /year)	20 years
<b>Filling panel</b>	112,000 €	1000 €/year	20 years

The CAPEX for each storage unit and the filling panel were given by CALVERA, while the OPEX were assumed as follows:

Singh et al. (Singh, Chauhan, & Singh, 2020) used a O&M cost of 0.6 \$/year/kg (ca. 0.49 EUR/year/kg) for the hydrogen tank. Applying this number to a storage unit, which contains around 17 kg of hydrogen, the annual O&M costs would correspond to 10 €/year/unit. It was assumed to multiply this value by a factor of 10.

For the filling panel, no information was found in the literature, then it was assumed to be 10 times higher than a single storage unit, given its higher complexity.

### 7.3.3 Inverter

The main characteristics for the power converter are:

- CAPEX: 5,000 €/unit (inverter.com, 2022)
- OPEX: 40 €/unit/year? It was an assumption based on (Singh, Chauhan, & Singh, 2020), which considered 1 \$/year for an inverter of 1 kW. Remembering that the converter used in this study are of 10 kW, a multiplying factor of 4 was chosen to obtain the final value of OPEX for the inverter.
- Useful lifetime: 20 years

### 7.3.4 Civil works

The civil works are needed to prepare the location for the fuel cell and the storage system. They occur only at the beginning of the project, and their values are:

- For the fuel cell: 80,000 €
- For the storage system: 500 €/unit

Both the data have as reference the cost for the civil works needed for the installation of the fuel cell and storage at the *Estación Marítima 4* (IDOM).

### 7.3.5 Hydrogen prices

The hydrogen purchase price is influenced by the costs occurring in the previous steps of the value chain, which concern the production and the distribution, and the commercial agreements in between the hydrogen supplier and off takers. In this study a hydrogen purchase price was estimated building up production costs, distribution costs and profit margins per sectors found in the literature, market reports and by interviewing hydrogen sector experts.

At the time of writing this study, the actual production cost for hydrogen in the GREEN HYSLAND project was not yet available, therefore, the production cost and the future trend were taken from external sources (PwC, 2023), as well as the gross margin, assumed equal to 60% (New York University, 2023). *Figure 38* shows the projection of the hydrogen production costs summed up with the related profit margin.

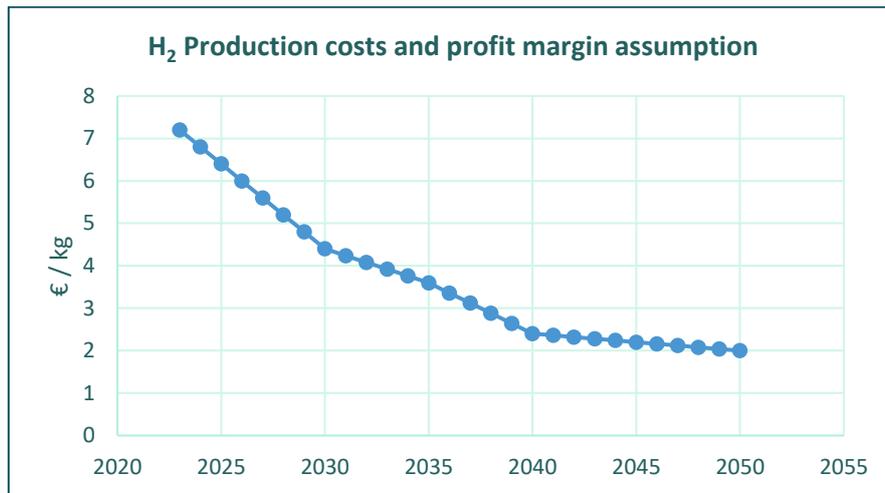


Figure 38: Assumed H<sub>2</sub> production cost and profit margin in Mallorca.

The distribution costs depend on three main different factors:

- The way in which hydrogen is transported: with dedicated pipelines, in trucks or ferries (either in gaseous or liquid phase);
- The distance that must be covered from the production site to the final end-user;
- The amount of hydrogen transported by the different distribution devices.

The GREEN HYSLAND project in Mallorca, plans to distribute hydrogen by trucks. For the islands of Menorca and Ibiza, it has been assumed that for the first 10 years the hydrogen will also reach the final end-user by trucks sent from Mallorca.

On the mainland, for short distances (less than 100 km, which is the case of the maritime terminals in the Port of Palma from Lloseta, the hydrogen distribution costs are around 1 €/kg of hydrogen delivered, and it progressively decreases with the increase of hydrogen delivered per day (AG, GmbH, Held, & GmbH, 2021). It is reasonable to expect that the costs would be higher in the Balearic Islands, for a number of reasons, such as the fact that the delivery trucks would go to the mainland to refuel, which increases distances and costs. The following costs for truck transport were assumed:

Table 16: Road transport costs at different amount of hydrogen delivered, in the mainland and in the Balearic Islands for the first ten years

Mass delivered [kg/delivery]	Road transport cost on the mainland [€/kg] (AG, GmbH, Held, & GmbH, 2021)	Road transport cost in the Mallorca Island [€/kg] (after industry expert interview)
< 1000	1	3
1000 – 2000	0.9	2.7
>2000	0.8	2.4

The gross margin was considered equal to 30% (New York University, 2023), while the cost increment in Menorca and Mallorca was assumed 10% higher than the road in Mallorca, since it includes the maritime transport in between islands.

The Figure 39 and Figure 40 show the projection along the project years of the hydrogen purchase price, which includes production costs, distribution costs, and the profit margins applied to them. In the model, the production cost estimated for the year 2023 was taken to calculate the hydrogen purchase price for the first project year (year 0). The starting value for Mallorca is in a range between 10.32 and 11.10 €/kg, while for Menorca and Ibiza it varies between 10.63 and 11.49 €/kg, due to the presence of the maritime transport.

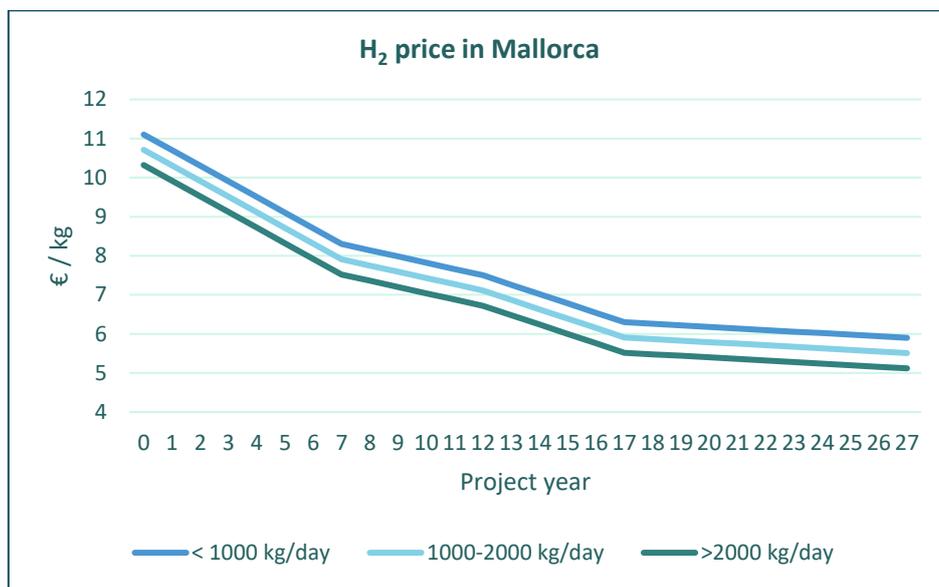


Figure 39: H<sub>2</sub> purchase price for the buildings in Mallorca, and future trend.

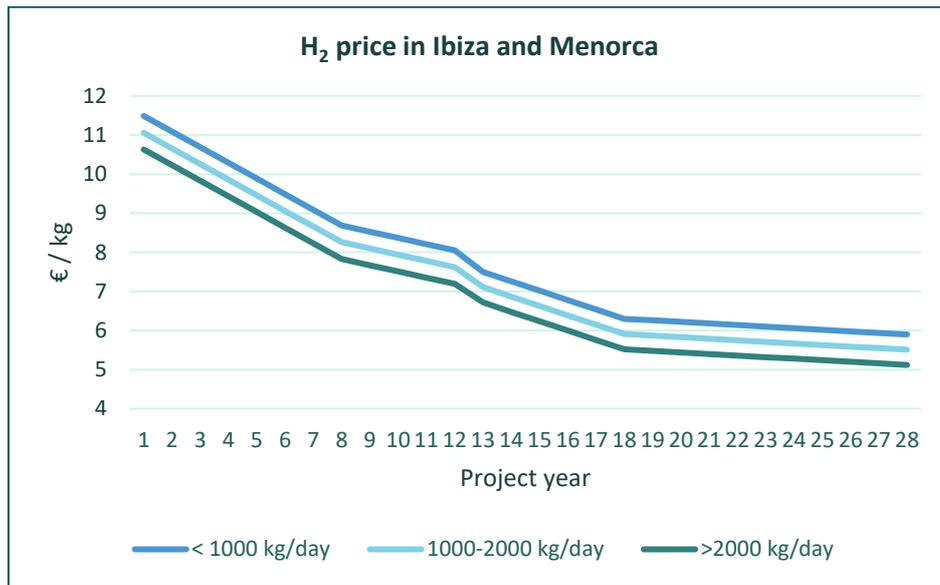


Figure 40: H<sub>2</sub> purchase price for the buildings in Ibiza and Menorca, and future trend.

The price for the different locations will differ only in the first decade, due to the necessity of maritime transport of hydrogen to Menorca and Ibiza, while in the second half of the period considered the prices will coincide as it was assumed that in the future hydrogen might be produced in the same island where it is consumed. The range for the hydrogen price in the last project year for all the islands is between 5.44 and 6.22 €/kg.

### 7.3.6 Grid electricity costs

The costs related to the electricity consumption from the grid were given by *Autoridad Portuaria de Baleares*, and they refer to the tariff 6.1TD (3.1A). The electricity prices are differentiated into six different periods, depending on the month of the year and the time of the day.

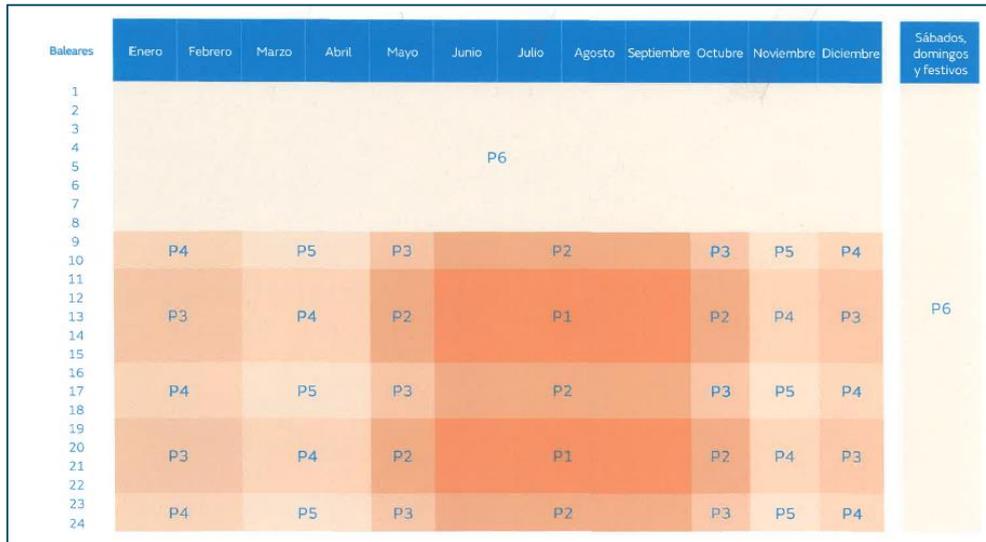


Figure 41: Tariff periods for Balearic Islands, provided by Autoridad Portuaria de Baleares (Naturgy, 2022)

Each period is characterized by a different cost. The cost is composed by a fix part and a variable part. The fix part depends on the power at which the end user is connected to the grid, and it is expressed in €/kW; the variable part depends on the amount of electricity that is consumed during the different periods, and it is in €/kWh.

The table below lists the total electricity cost in the different tariff periods specified in Figure 41.

Table 17: Fixed and variable costs related to the electricity consumption from the grid

Cost of Electricity	P1	P2	P3	P4	P5	P6
<b>Fixed (€/kW)</b>	22.965215	19.841178	10.327582	8.560662	1.908583	1.148958
<b>Variable (€/kWh)</b>	0.05663473	0.04844873	0.03493273	0.03053673	0.02494473	0.01769973

Both of the price categories include the total cost of grid electricity, as well as the cost for the operation of the grid, and the cost of the guarantee of origin certificates<sup>5</sup>. The new fuel cell system can potentially allow the buildings to reduce their variable electricity costs, thanks to a lower dependency on the grid, but it will not impact on the fixed costs, since the buildings will still be connected to the grid. In this study, it has been assumed that the electricity cost will stay constant in the economic horizon.

### 7.3.7 New PV systems Costs

The costs associated to the new PV system dedicated to EM2+EM3 depend on the nominal power installed, which is 80 kW<sub>p</sub> (see section 7.2.5): the specific CAPEX were assumed to be equal to 750

<sup>5</sup> Total grid electricity consumer purchase costs including all fees, taxes and capacity payments.

€/kW and the OPEX were considered to be 1% of the CAPEX, the useful lifetime is considered higher than 20 years (Rodríguez-Martínez & Rodríguez-Monroy, 2021).

### 7.3.8 Other Financial parameters

To calculate the LCOE and the actualized savings an inflation rate of 1.5% was chosen (WorldData, 2023), which is the average value between 2017 and 2021 (5 years) for Spain; in 2022, the country's inflation rate increased up to 8.4%, due to the high instability given by the end of the COVID pandemic and recent war in Ukraine. However, it is unlikely that such a high value will be present for long (in March 2023, the inflation rate in Spain already fell down to 3.3% (Rate Inflation, 2023)), which is why the value of 1.5% was assumed as more suitable for a longer period of 20 years.

A discount rate of 6% was chosen, which is the typical value associated to green energy projects in Spain (Grant Thornton, 2019). No sensitivity analysis was performed for the discount rate.

## 7.4 Hydrogen fuel cell-based concepts analysed

There are multiple energy systems configurations that can be applied to the maritime terminal with different combinations or their key elements: the hydrogen fuel cell system of different capacities incorporating or not solar PV panels, buildings sharing storage space etc.

In this study, different potential new configurations of the hydrogen fuel cell system were analysed, classified into two categories: (1) stand-alone configuration (2) combined configuration. For both categories the reference case the current situation. Both configurations contemplate the grid connection at all teams for security of supply.

### 7.4.1 Stand-alone configurations

In the case of stand-alone systems, the analysed building or group of buildings have at least one dedicated hydrogen system each. In these analyses the incorporation of new solar panels is not considered and the buildings have always a connection to the grid.

Table 18 presents the different stand-alone configurations considered in this study. For each stand-alone configuration the three-step CBA methodology described in section 7.1 was applied, except for EM4 for which power and storage size has been predetermined for the deployment of the system by the GREEN HYSLAND project.

Note that a configuration considering EM2 and EM3 (EM2+EM3) was also studied as single unit due to the proximity of the buildings, in order to establish if there is a benefit their share hydrogen storage facilities (and two fuel cells operating for each building).

Table 18 Stand-alone configurations analysed and their reference case for CO<sub>2</sub> emissions and costs savings calculations

Stand -alone Configuration	PV solar	Hydrogen Fuel system	Grid Connection	Reference case
<b>EM2</b>	no	Yes	Yes	Grid connection only

<b>EM3</b>	no	Yes	Yes	Grid connection only
<b>EM2+EM3</b>	no	Yes	Yes	Grid connection only
<b>EM4</b>	Yes	Yes	Yes	Grid connection only + PV
<b>Botafoc</b>	Yes	Yes	Yes	Grid connection only + PV
<b>Mahón</b>	no	Yes	Yes	Grid connection only

### 7.4.2 Combined system configuration

For the purposes of this study, combined systems were specifically defined as systems in which two or more maritime terminals can operate as an integrated energy system, exchanging the electricity generated by one hydrogen fuel cell system and/or any surplus generated by the presence of PV. The combined system configurations were only defined for the port of Palma de Mallorca, since this is the only port site for which more than one building are included.

The selection of these configurations builds upon the analyses of the stand-alone configurations of EM4 and EM2+EM3. The rationale is also based on the complexity level, configuration CB-1 being the least complex to CB-4 being the more complex given the incorporation of new PV panels for EM2 and EM3 buildings and hydrogen fuel cell system.

Table 19: Combined configurations analysed and their reference case for CO<sub>2</sub> emissions and costs savings calculations

Combined Configuration	Maritime terminal	PV solar in EM2+EM3	Hydrogen Fuel System in EM2+EM3	Grid Connection	Reference case (Current situation)
<b>CB-1</b>	EM2 +EM3, EM4	no	no	yes	Grid connection only + PV EM4
<b>CB-2</b>	EM2 +EM3, EM4	yes	no	yes	Grid connection only + PV EM4
<b>CB-3</b>	EM2 +EM3, EM4	no	Yes	yes	Grid connection only + PV EM4
<b>CB-4</b>	EM2 +EM3, EM4	yes	yes	yes	Grid connection only + PV EM4

The CB-1 considers EM4 hybrid as per the deployment design, and EM2+EM3 as a single unit. This configuration was contemplated due to a physical constraint in the location of the stations EM2 and EM3 in order to determine the storage system unit that meets both stationary storage unit's requirement from both operational and regulations point of view. The operational requirements are to have enough space for the footprint of the storage and fuel cell units, allows the circulation of the truck for refilling operations, and it is located at least 35 meters from any building's operation mode selected for EM4 is constant load since is the only configuration that allows to have surplus electricity to share with other maritime terminals.

The calculations of CO<sub>2</sub> and costs savings use the actual current situation in the Mallorca port site: EM4 with solar panels installed, no PV in EM2 nor in EM3, no fuel cells in any maritime situation. Figure 42 illustrates the reference case.

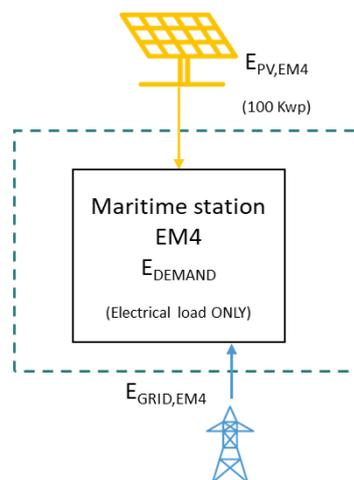


Figure 42: Schematic representation of the reference case for the combined system configurations for costs and emissions savings calculations (current situation)

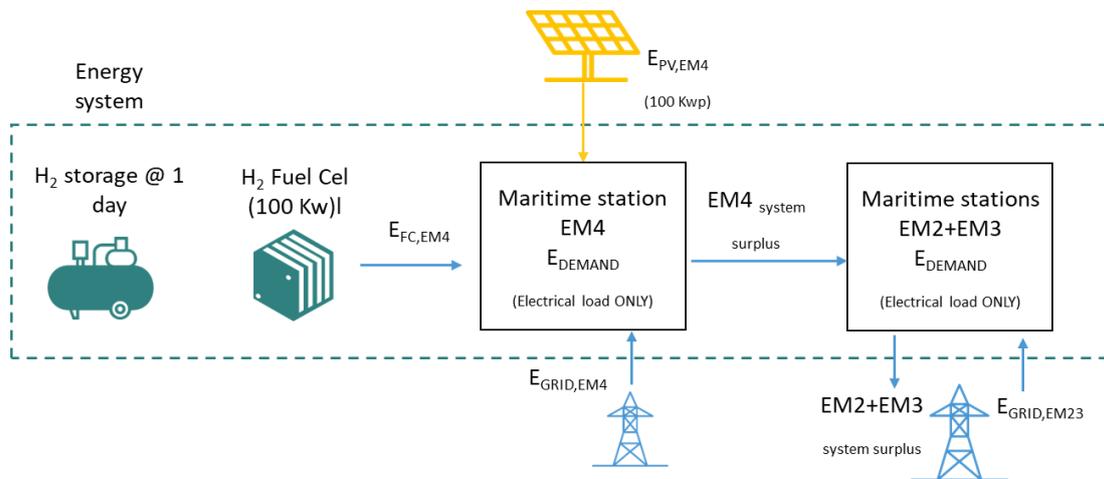


Figure 43: Schematic representation of the combined system configuration CB-1

CB-2 builds up in CB-1 being the main difference the addition of a solar PV panels in EM2 and EM3 (See Figure 44). The PV solar panel nominal power for EM2 & EM3 was determined using the methodology presented in section 7.2.5 – new PV systems.

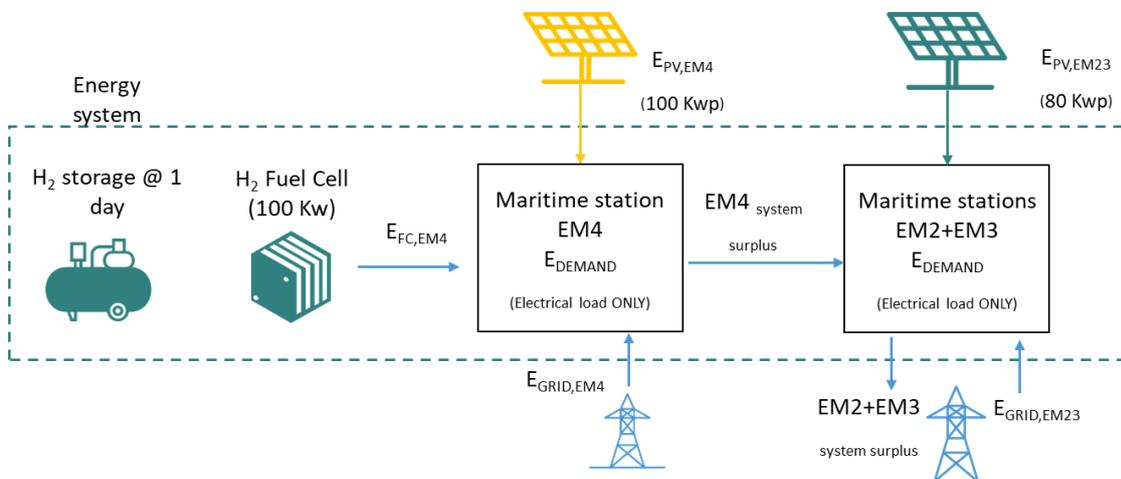


Figure 44: Schematic representation of the combined system configuration CB-2

In CB-3 also builds in CB-1 only adding the Fuel cell for EM2& EM3 (no solar PV), as represented in Figure 45.

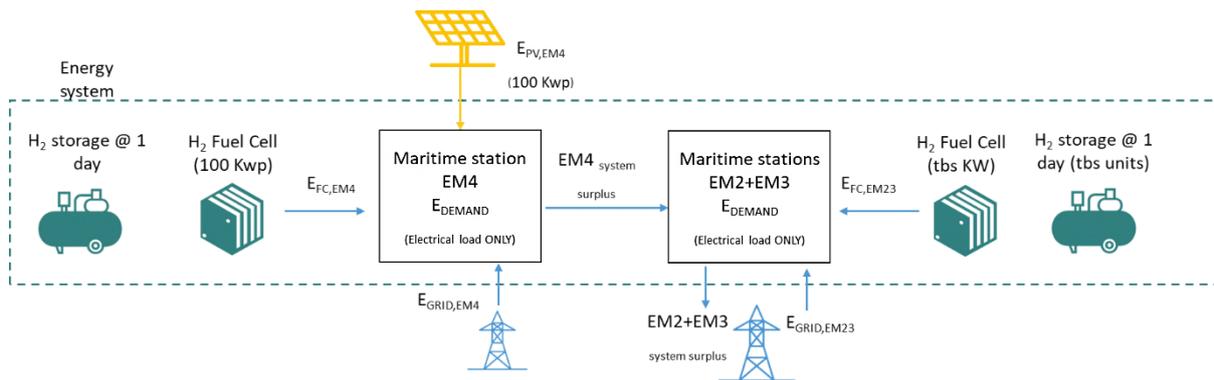


Figure 45: Schematic representation of the combined system configuration CB-3

Last but not least, the CB-4 is the full system with both solar panels and dedicated hydrogen fuel cell system for each building, illustrated below in Figure 46.

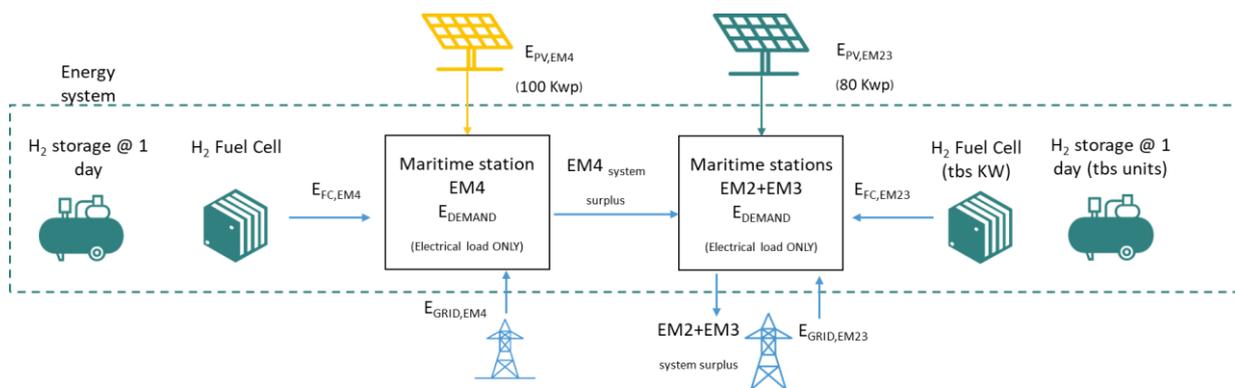


Figure 46: Schematic representation of the combined system configuration CB-4

The reason for the addition of the CB2-CB3 cases is to understand the impact of including solar panels in the systems when combined without and with fuel cells, respectively.

Another technical factor to specify in the model is the operation mode of the fuel cells in the maritime terminals. For the fuel cell in EM4 a constant mode operation was selected, since it is the only mode that provides surplus electricity that can be utilized in EM2 and EM3. In the stations EM2&3 we assumed load following mode excuse the hydrogen consumption is lower and therefore, meets the condition of minimizing storage space usage. The dimensioning of the fuel cell in EM2&3 will be calculated by the model.

The below table shows a summary of the additional technical assumptions for combined configurations.

Table 20: Additional technical specifications assumed for the combined configurations cases

Combined Configuration	FC <sub>EM4</sub> Mode	PFC <sub>EM4</sub> [kW]	NST <sub>EM4</sub>	PPV <sub>EM23</sub> [kW]	FC <sub>EM4</sub> Mode	PFC <sub>EM23</sub> [kW]	NST <sub>EM4</sub>
<b>CB-1</b>	CL	100	9	0	LF	0	0
<b>CB-2</b>	CL	100	9	80	LF	0	0
<b>CB-3</b>	CL	100	9	0	LF	TbS	TbS
<b>CB-4</b>	CL	100	9	80	LF	TbS	TbS

CL = Constant Load;    LF = Load-Following;    TbS = To be Sized by the model

## 8 Results

Throughout this chapter, we will explore the major findings and implications arising from the CBA (Cost Benefit Analysis) study. By analysing and interpreting the results of the modelling work done representing different energy systems configurations maritime terminals in the Balearic Islands, we aim to highlight the strengths and weaknesses of each energy system configuration, emphasizing their implications for economic factors, system reliability, emissions reduction, and overall sustainability, providing valuable insights into the trade-offs involved in choosing one configuration over another.

### 8.1 Stand-alone configurations

#### 8.1.1 Maximum technical output Fuel cell system identification

This subsection presents the results of establishing the upper limits for the nominal installed power of the fuel cell and the storage capacity for each building. These limits were determined based on the steps outlined in section 7.2.7.

The nominal installed power must be able to fulfil the highest demand, *Table 21* gives the nominal power required by the fuel cell to cover the peak electricity demand of the different maritime terminals; it does not show EM4, the capacity and hydrogen demand was predetermined by the deployment plan in the GREEN HYSLAND project.

Table 21: Fuel cell nominal power required for the different stand-alone systems

Configuration	Load-following: $P_{NOM,FC,MAX}$ [kW]	Constant-Load: $P_{NOM,FC,MAX}$ [kW]
<b>EM2</b>	120	120
<b>EM3</b>	60	60
<b>EM2+EM3</b>	165	165
<b>Botafoc</b>	700	300
<b>Mahón</b>	265	265

Note that the only case in which the fuel cell has a different power depending on the operational mode is *Botafoc*. The nominal power of 300 kW cannot supply the peak demand, but it is still enough to satisfy the demand of the building for more than 85% of the year.

Once the power of the fuel cell was selected, the next step was to calculate the capacity of the storage that allows to feed at every time the necessary amount of hydrogen requested by the fuel cell. *Table 22* shows the number of storage units ( $N_{ST,UNITS}$ ) requested with a daily frequency of hydrogen charge, highlighting that the fuel cells operating in constant-load request a higher storage capacity.

Table 22: Size of the systems at maximum energy output and corresponding CBA parameters, for the systems with load-following fuel cell and frequency of charge of 1 day

Configuration	Load-Following			Constant Load		
	P <sub>FC, NOM</sub> [kW]	N <sub>ST, UNITS</sub>	H <sub>2</sub> stored [kg]	P <sub>FC, NOM</sub> [kW]	N <sub>ST, UNITS</sub>	H <sub>2</sub> stored [kg]
<b>EM2</b>	120	10	120.3	120	18	190.9
<b>EM3</b>	60	3	45.4	60	8	100.2
<b>EM2+EM3</b>	165	14	157.6	165	28	256.6
<b>Botafoc</b>	700	73	604	300	52	465.9
<b>Mahón</b>	265	25	239.5	265	46	411.5

The subsequent stage of the analysis examines the variations in the four CBA indicators for different configurations of fuel cell nominal power and storage capacity. Different simulations were performed in order to understand the impact of the fuel cell operation mode and the frequency of charge in the costs and benefits analysis for all the energy system configurations under study.

In general, there are different solutions that are a trade-off between the preferred value of LCOE (the minimum LCOE) and the highest energy autonomy achievable, the technical solution that maximizes Energy Autonomy, the one that provides the absolute minimum LCOE and the one that brings at least 80 % at a minimum LCOE. These three feasible solutions (combination of hydrogen fuel cell power and storage capacity) were analysed and compared using the CBA indicators.

Three possible hydrogen fuel cell systems solutions were identified per case study and compared based on the CBA indicators. Moreover, the energy supplied and hydrogen consumption were also estimated and presented in this report.

## 8.1.2 Load Following (LF) fuel cell system configuration

### 8.1.2.1 CBA parameters results

Figure 47 illustrates the CBA results for the EM2+EM3 configuration. The maximum value for energy autonomy, lifetime actualized cost savings, and CO<sub>2</sub> emissions avoided, are achieved in the top-right corner of their respective plot, which corresponds to the maximum energy configuration given in Table 21. However, the heat map of the LCOE suggests the configurations with the maximum energy output is not the one with the minimum LCOE.

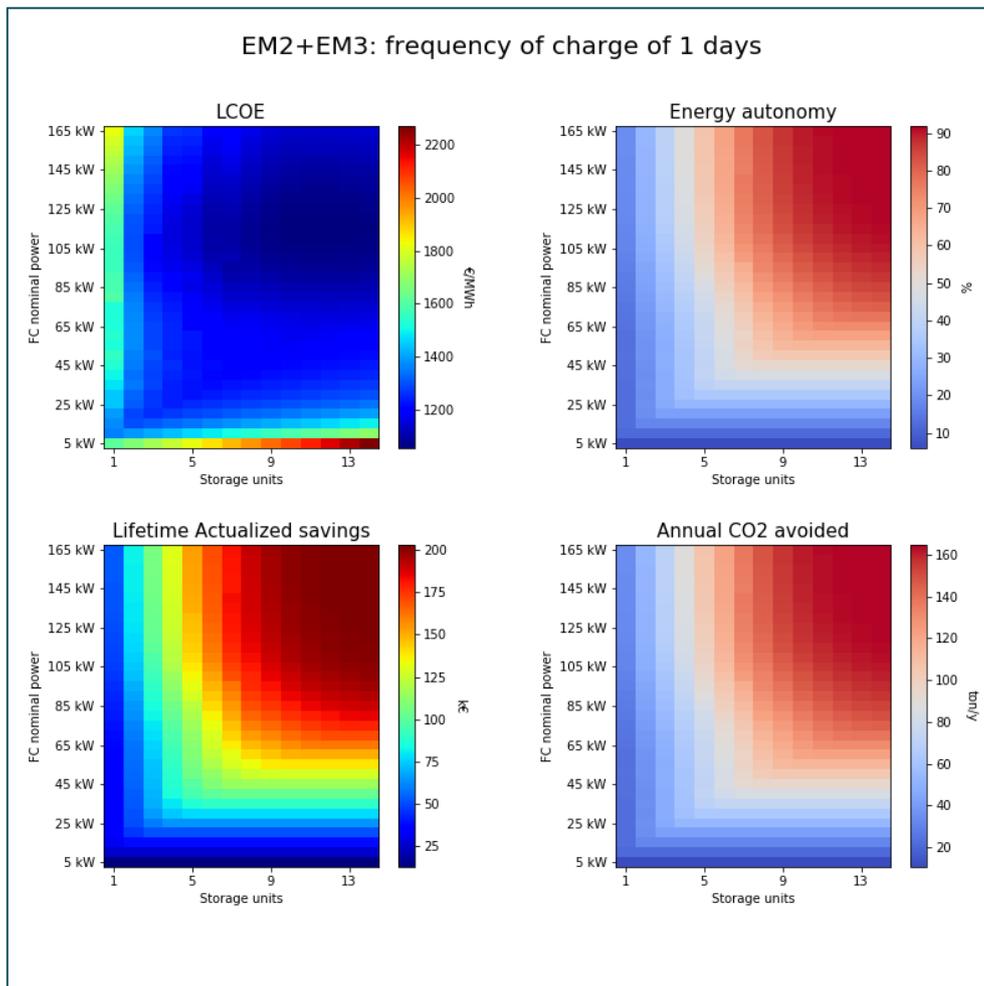


Figure 47: CBA parameters for EM2+EM3 (load-following fuel cell and daily frequency of charge)

The observation mentioned above can also be deduced from the plot displayed in *Figure 48*. This plot represents a 2-D visualization of the LCOE (Levelized Cost of Energy) and EA (Energy Autonomy) for various combinations of fuel cell power and storage capacity studied. The legend on the plot indicates three distinct fuel cell system solutions characterized by their fuel cell nominal power and storage capacity. These solutions include: the one that minimizes the LCOE, the one that maximizes energy autonomy, and the one that achieves an 80% energy autonomy target at the minimum cost. All three solutions ensure an energy autonomy level of at least 80%.

Notably, the green dot on the plot signifies a specific solution demonstrating that the system can achieve 80% energy autonomy, which is considered an acceptable level, while maintaining a relatively low LCOE. In fact, the LCOE for this solution is approximately 10% lower than the LCOE for the solution with the maximum attainable energy autonomy, as presented in *Table 23*. Although all the CBA (Cost-Benefit Analysis) indicators for this particular solution (80% EA) are lower than the other two solutions, the primary advantage lies in the fact that this particular solution can deliver a very similar outcome with a lower initial capital investment and a smaller hydrogen storage requirement.

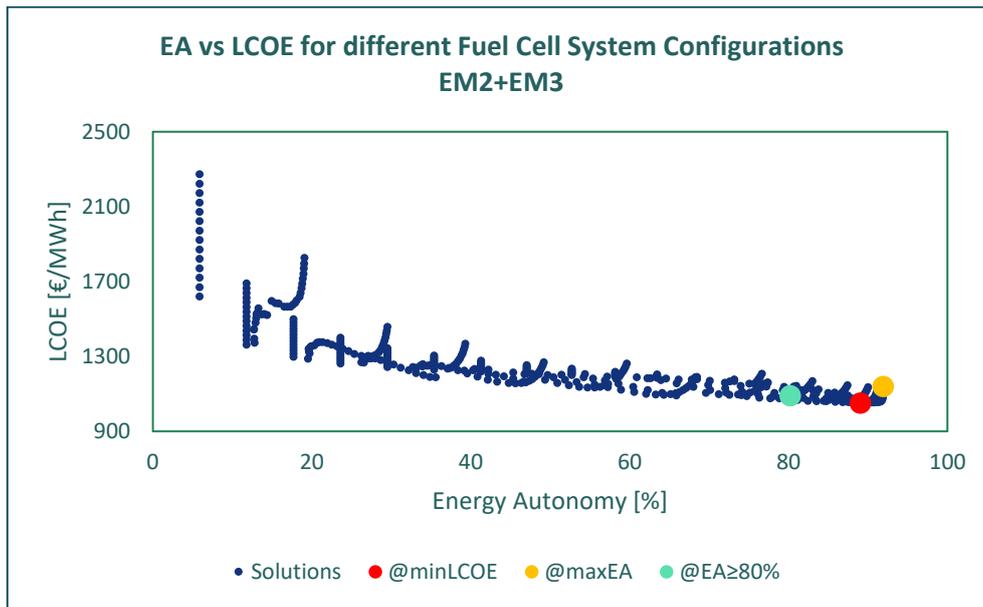


Figure 48: Relationship between energy autonomy and LCOE for EM2+EM3 (load-following fuel cell and daily frequency of charge)

Table 23: Solutions for EM2+EM3 based on CBA criteria (load-following fuel cell and daily frequency of charge)

EM2+3 Solutions	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	LCOE [€/MWh]	EA [%]	LACS [€]	$\Delta CO_2$ [ton/y]
<b>Min LCOE</b>	115	11	1,053	89	198,911	159.6
<b>EA ≥ 80%</b>	90	10	1,090	80.2	184,513	143.7
<b>Max EA</b>	165	14	1,140	91.9	202,746	164.7

Notice that the solution that provides a minimum LCOE for the EM2+EM3 configuration, also allows to obtain an energy autonomy higher than 80%. However, this does not occur for Botafoc ((b)) and, for Mahón (Figure 49(a)).

In the case of Mahón (Table 24), the solutions at minimum LCOE and EA ≥ 80 % are practically the same. However, maximizing the energy autonomy implies an increment in fuel cell installed capacity 2.65 times higher than the other two solutions, and an increment of 30 % in LCOE (352 EUR/MWh) with only 11.7 % EA benefit.

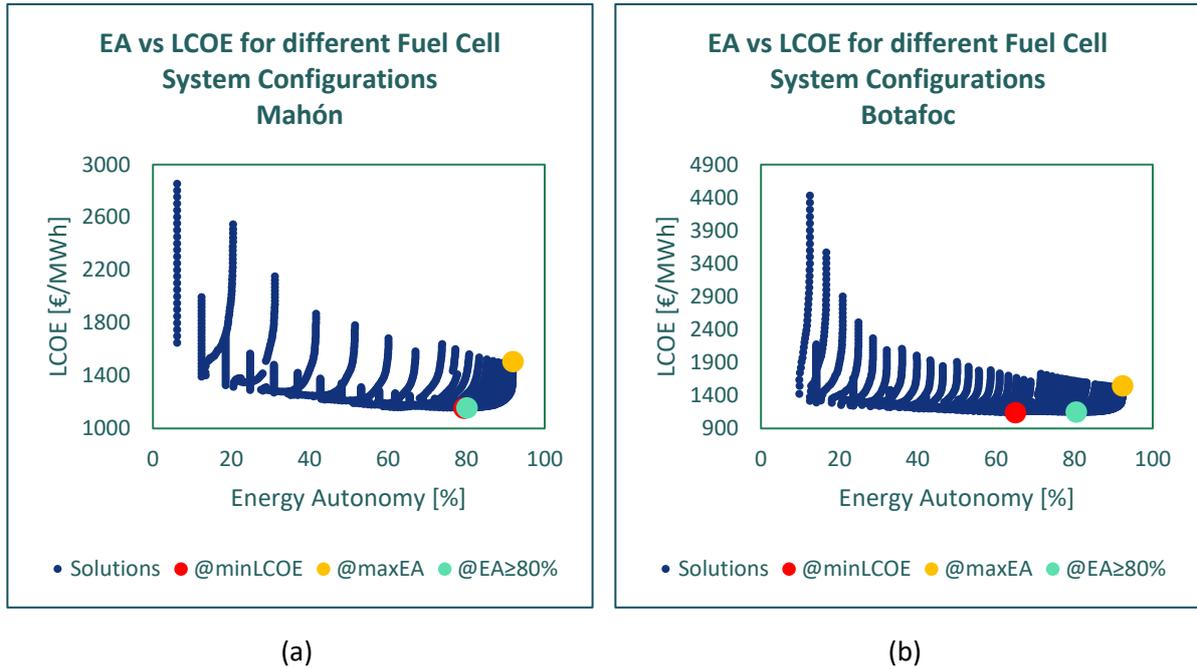


Figure 49: Relation between energy autonomy and LCOE for Mahón (a) and Botafoch (b) (load-following fuel cell and daily frequency of charge)

Table 24: System solutions for Mahón based on CBA criteria (load-following fuel cell and daily frequency of charge)

Mahón Solution	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>Min LCOE</b>	95	13	1,154	79.3	179,119	140.2
<b>EA ≥ 80%</b>	100	13	1,156	80.1	181,921	141.6
<b>Max EA</b>	265	25	1,508	91.8	208,031	162.3

The outcome is noticeably different for Botafoch (see Table 25), the building with the highest estimated energy demand of all. The minimum LCOE solution does not provide the desired EA. Similarly, maximizing the energy autonomy implies an increment in fuel cell installed capacity almost three times higher than the other two solutions, yet the incremental costs and EA% are in the same order of magnitude as in Mahón: 30% in LCOE with only 14.6 % EA benefit.

Table 25: System configuration solutions for Botafoch based on CBA criteria (load-following fuel cell and daily frequency of charge)

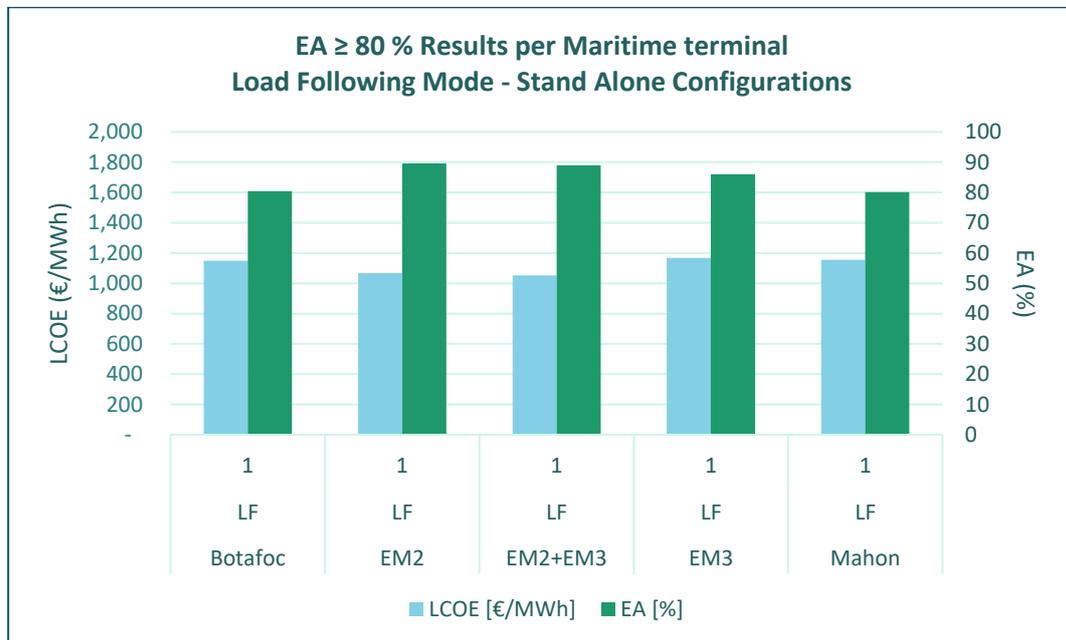
Botafoch Configuration	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>Min LCOE</b>	240	23	1,138	64.9	374,645	240.6
<b>EA ≥ 80%</b>	240	42	1,148	80.4	448,249	302
<b>Max EA</b>	700	73	1,546	92.2	515,746	349.8

Table 26 lists the solutions achieving the minimum energy autonomy target of 80% at minimum costs, for all the stand-alone configurations. The same table includes the equivalent mass consumption of hydrogen in a daily basis.<sup>6</sup> The results for the min LCOE and Max EA solutions can be found in the Appendix C.

Table 26: System size to achieve the minimum energy autonomy target of 80% at the minimum cost for stand-alone configuration (load-following fuel cell at daily frequency of charge)

Stand Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Max. H <sub>2</sub> working mass [Kg/d]	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>EM2</b>	60	8	100.2	1,139	80.3	132,859	107.0
<b>EM3</b>	25	2	33.7	1,180	82.7	49,491	38.1
<b>EM2+EM3</b>	90	10	120.3	1,090	80.2	184,513	143.7
<b>Botafoc</b>	240	42	370.1	1,148	80.4	448,249	302.0
<b>Mahón</b>	100	13	148.7	1,156	80.1	181,921	141.6

It can also be observed in Table 26 that having one hydrogen fuel cell system supplying energy to both EM2 and EM3 combined is a better option than installing individual systems per building because of the lower LCOE and EA performance, electricity costs savings shows just a small improvement thought, as they depend on the hydrogen energy demand, which remains the same. Therefore, the analysis of results and identification of the technical configurations for the Island of Mallorca will carry on only scenarios with a stand-alone configuration EM2+EM3.



<sup>6</sup> It should be noted that all the previously shown results are derived from simulations that were conducted without utilizing the spatial constraint option in the model (Model Spatial Constrain, MSC).

Figure 50: LCOE and EA values for All stand-alone configurations  
 (load-following fuel cell and daily frequency of charge)

### 8.1.2.2 Energy supplied by the Fuel Cell system and hydrogen consumption over lifetime (20 years)

The following figure illustrates the contribution of the different energy sources to the supply of the yearly energy demand for the configuration EM2+EM3.

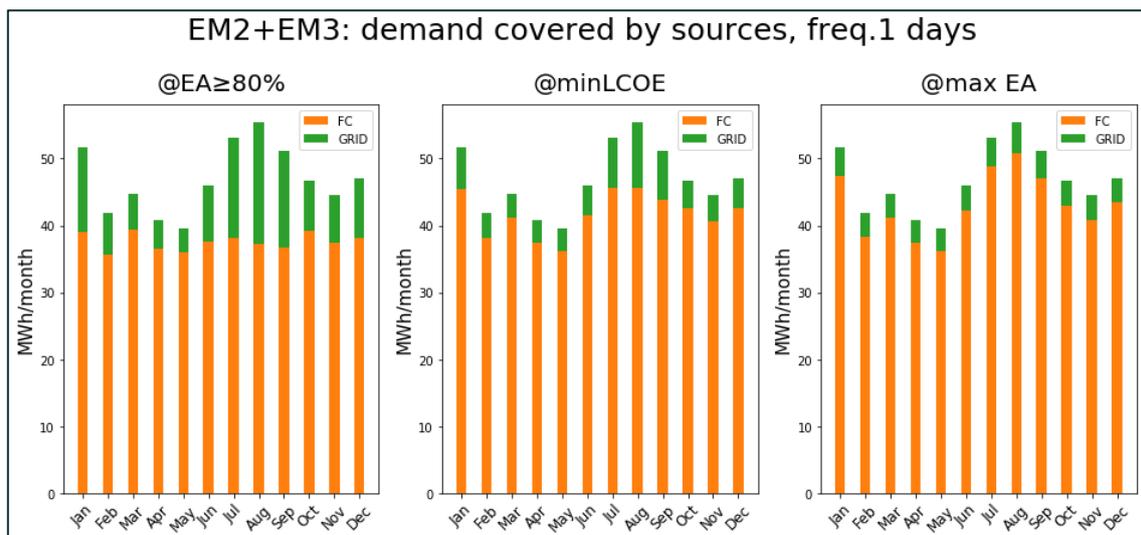


Figure 51: Electricity supplied by different energy sources for EM2+EM3  
 (load-following fuel cell and daily frequency of charge)

The solution at minimum LCOE and EA= 80% mainly differs from the maximum Energy autonomy configuration in the fulfilment of the demand in the summer period (June to September), first of all because in summer period and in the months of January and February, the daily demand exceeds more often the maximum output of the fuel cell, therefore more input from the grid is required in that period when the minimum LCOE configuration.

In the case of Botafoc, clearly, for the EA = 80 % solution, the gap in between the demand and the energy supply in winter is smaller in proportion to the same months in EM2+EM3, yet in summer is still the period with the lowest contribution to the overall estimated demand.

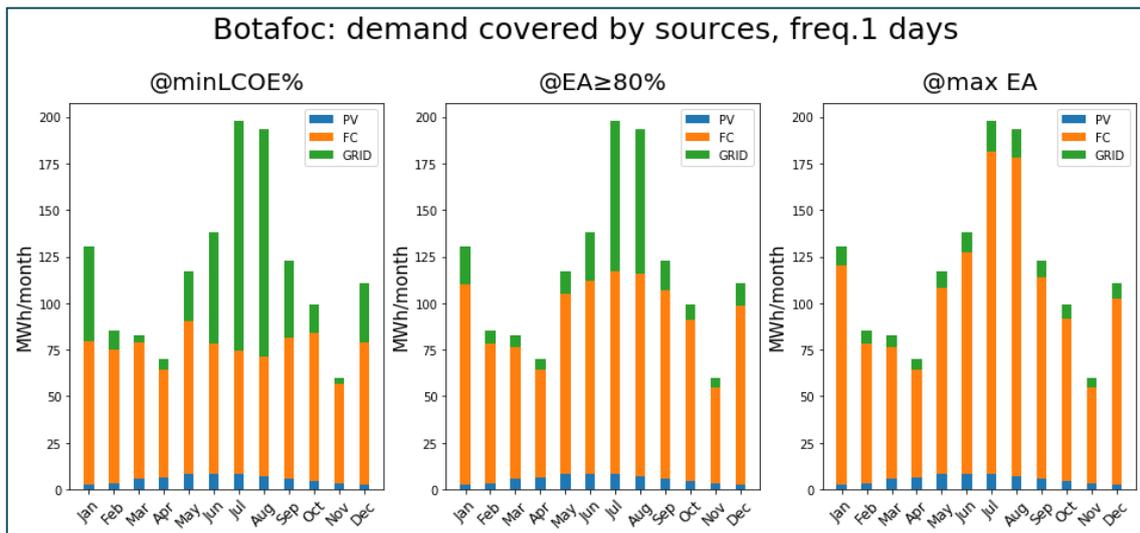


Figure 52: Electricity supplied by different energy sources for Botafoc (load-following fuel cell and daily frequency of charge)

For Mahón (see Figure 53), the solutions for min LCOE and EA= 80% coincide in absolute values since it's the same system configuration technical requirements, which means that fulfilling the gap in the high demand periods brings an increment of 356 EUR/MWh as per the previous analyses.

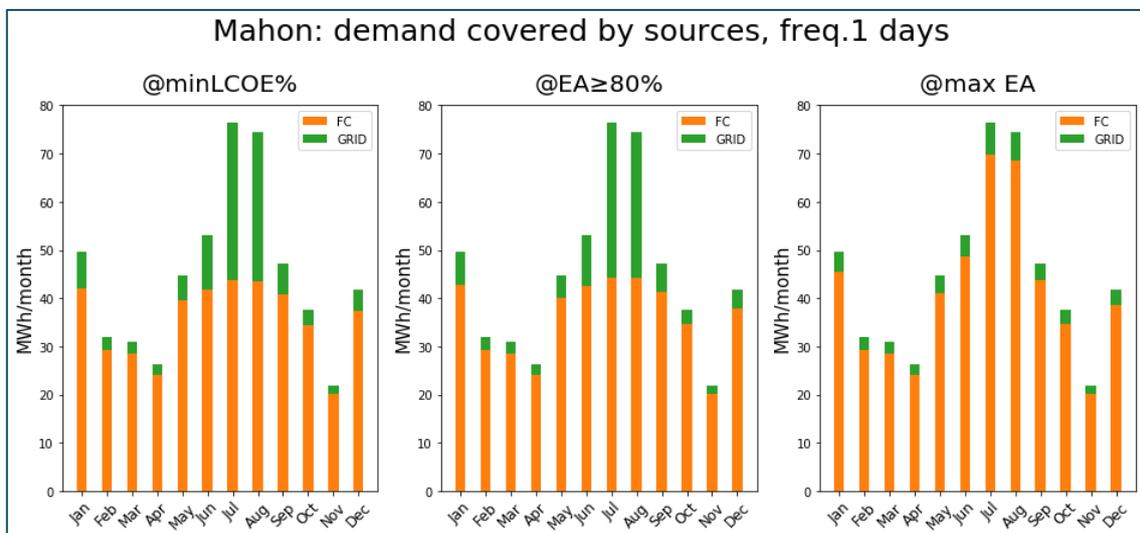


Figure 53: Electricity supplied by different energy sources for Mahón (load-following fuel cell and daily frequency of charge)

The Table 27 shows the energy output of the fuel cell over the entire project lifetime for all the stand-alone configurations considered, indicating the allocation of the energy generated by the fuel cell in terms of system self-consumption and surplus, together with the hydrogen demand for the entire hydrogen fuel cell system lifetime. Notice that in this case the column of the energy surplus contains null values only, since with load-following fuel cells the output generated must match the demand

required and never exceed it. The results for the energy output for the solutions can be found in the *Appendix D*.

Table 27: Energy output and hydrogen demand over the entire project lifetime for the configurations at energy autonomy higher than 80% (load-following fuel cell and daily frequency of charge)

Stand- Alone Config.	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	$E_{FC,TOT}$ [MWh]	$E_{FC,self-cons.}$ [MWh]	$E_{FC,PORT}$ [MWh]	$H2_{lifetime}$ [ton]
<b>EM2+EM3</b>	90	10	9,023	9,023	0	769
<b>Botafoc</b>	240	42	21,296	21,296	0	1,787
<b>Mahón</b>	100	13	8,588	8,588	0	711

### 8.1.3 Constant Load (CL) fuel cell system configuration

#### 8.1.3.1 CBA parameters results – configuration selection

The variation of the four parameters for EM2+EM3 at daily hydrogen charge and by a fuel cell operating in CL mode is shown in *Figure 54*.

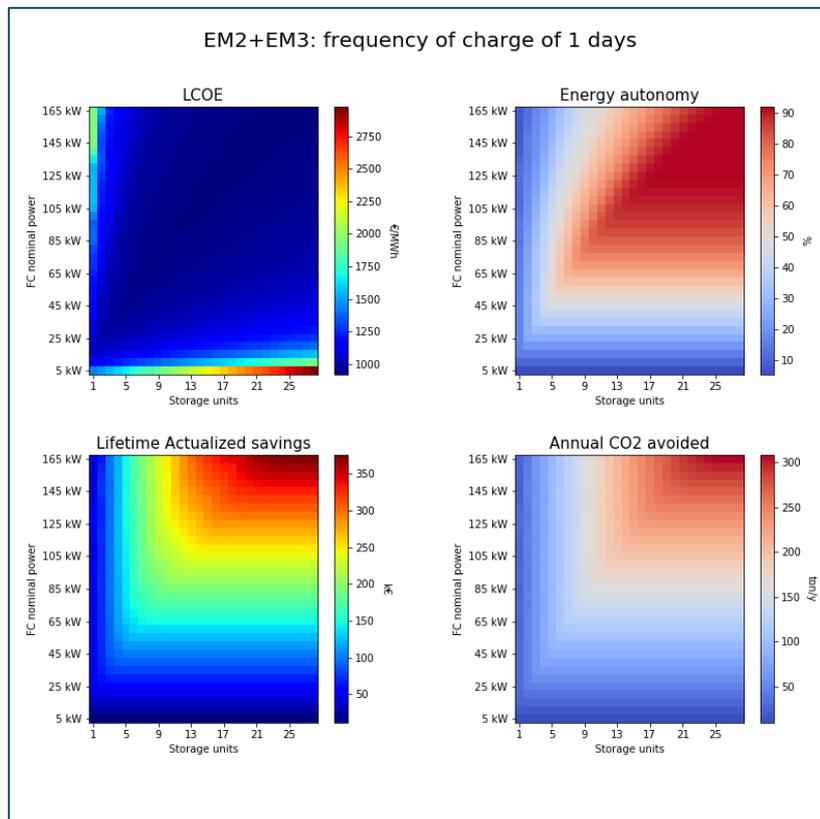


Figure 54: CBA parameters for EM2+EM3 constant-power fuel cell and daily frequency of charge.

The results with the higher LCOE are also towards the right top corner of the graphs for every variable. That was not the case for the LCOE indicator in LF mode. This observation is confirmed in the plot LCOE vs Energy Autonomy (*Figure 55*) in which the values for the min LCOE can be found towards the high end of the range of solutions presented EA values. An additional observation is that for all buildings, the solution of the energy autonomy equal to 80% has a slightly highest LCOE than the rest (see table 28).

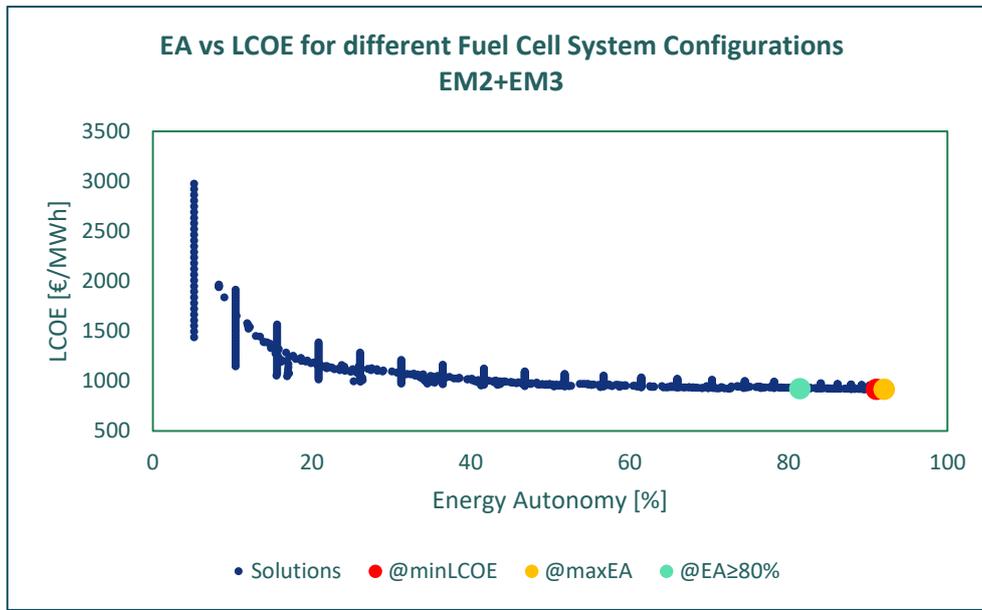


Figure 55: EA and LCOE for EM2+EM3 at constant-power fuel cell and daily frequency of charge

Table 28: Results at different values of LCOE and energy autonomy for EM2+EM3  
 (constant-load fuel cell and daily frequency of charge)

EM2+EM3 Config.	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	LCOE [€/MWh]	EA [%]	LACS [€]	$\Delta CO_2$ [ton/y]
<b>Min LCOE</b>	150	21	919	91.0	339,965	278.1
<b>EA <math>\geq</math> 80%</b>	85	11	926	81.4	193,648	159.0
<b>Max EA</b>	165	26	920	92.0	375,904	308.6

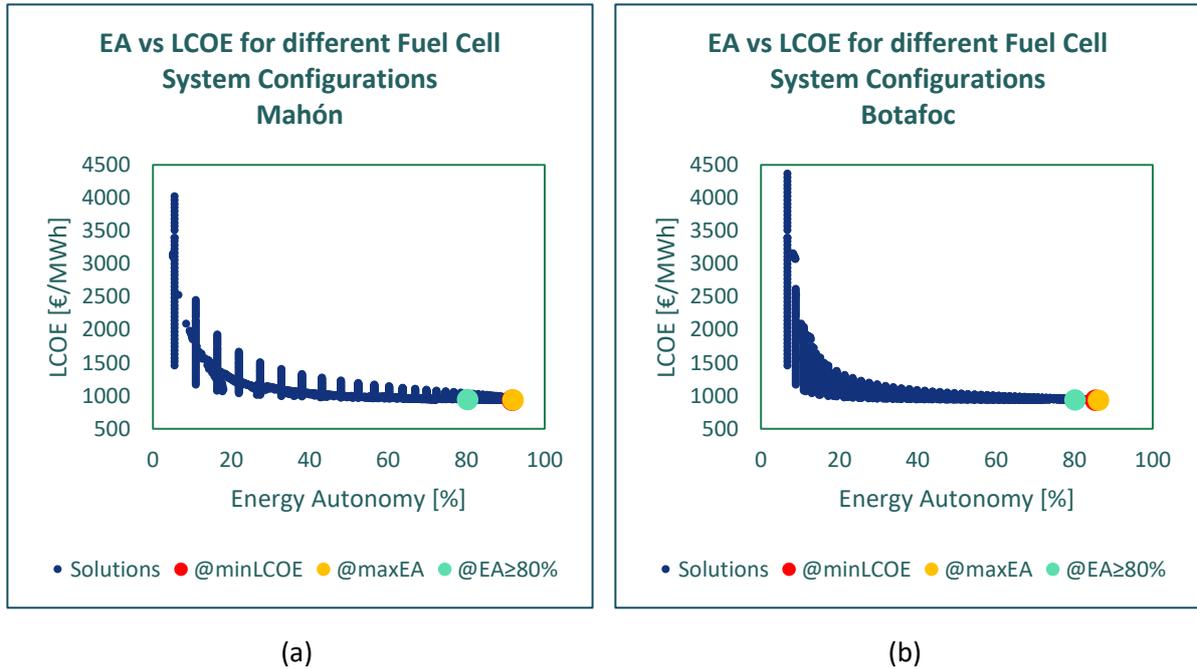


Figure 56: Relation between energy autonomy and LCOE for Mahón (a) and Botafoc (b) (constant-load fuel cell and daily frequency of charge)

In general, for all three configurations in Load Following mode operations, the solution that achieves the minimum LCOE is closer in size to the solution that brings the maximum energy autonomy.

Table 29: System solutions for Mahón based on CBA criteria (constant-load fuel cell and daily frequency of charge)

Mahón Config.	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	LCOE [€/MWh]	EA [%]	LACS [€]	$\Delta CO_2$ [ton/y]
<b>Min LCOE</b>	265	44	938	91.7	603,349	512.3
<b>EA ≥ 80%</b>	100	13	944	80.3	227,782	193.5
<b>Max EA</b>	265	45	939	91.8	603,726	512.8

Table 30: System configuration solutions for Botafoc based on CBA criteria (constant-load fuel cell and daily frequency of charge)

Botafoc Config.	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	LCOE [€/MWh]	EA [%]	LACS [€]	$\Delta CO_2$ [ton/y]
<b>Min LCOE</b>	300	48	936	85.4	680,883	497
<b>EA ≥ 80%</b>	240	41	940	80.1	546,771	400.2
<b>Max EA</b>	300	50	937	86.1	683,463	500.3

The *Figure 57* shows that for all configurations, if operated in CL mode, the LCOE remain in the same order of magnitude for the 80 % configurations, however the initial investments are lower in the 80 percent case, because the equipment required is in smaller in size. See section 8.3 for more details on costs.

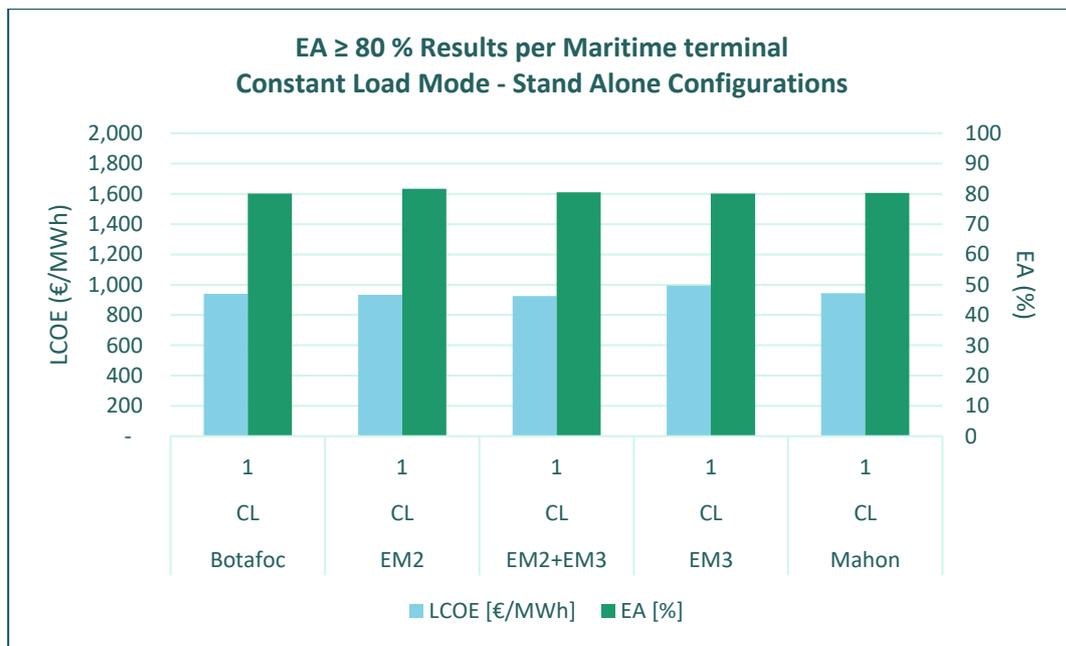


Figure 57: LCOE and EA values for All stand-alone configurations (constant fuel cell - daily frequency of charge)

The *Table 31* presents a summary the solutions that achieves the energy autonomy target at minimum costs, for all the configurations when the fuel cells are operated at.

Table 31: System size to achieve the minimum energy autonomy target of 80% at the minimum cost for all the configurations (constant-load fuel cell at daily frequency of charge)

Stand Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Max. H <sub>2</sub> working mass [Kg/d]	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>EM2+EM3</b>	85	11	130	927	81.4	193,648	159.0
<b>Botafoc</b>	240	41	359.2	940	80.1	546,771	400.2
<b>Mahón</b>	100	13	148.7	944	80.3	227,782	193.5

### 8.1.3.2 Energy supplied by the Fuel Cell system and hydrogen consumption over lifetime (20 years)

Based on observations from Figure 58 and Figure 59, it can be noted that the EA  $\geq$  80% solution is the solution with the lowest energy contribution all year long, compared to the other two solutions. For both Mahón and EM2+EM3 configurations.

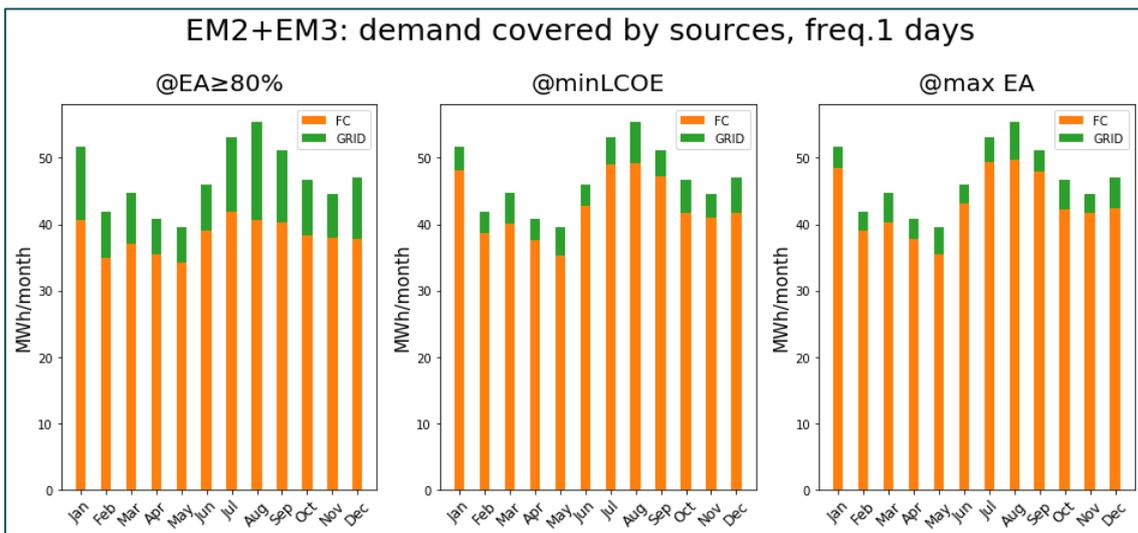


Figure 58: Electricity supplied by different energy source by sources for EM2+EM3 (constant-load fuel cell and daily frequency of charge)

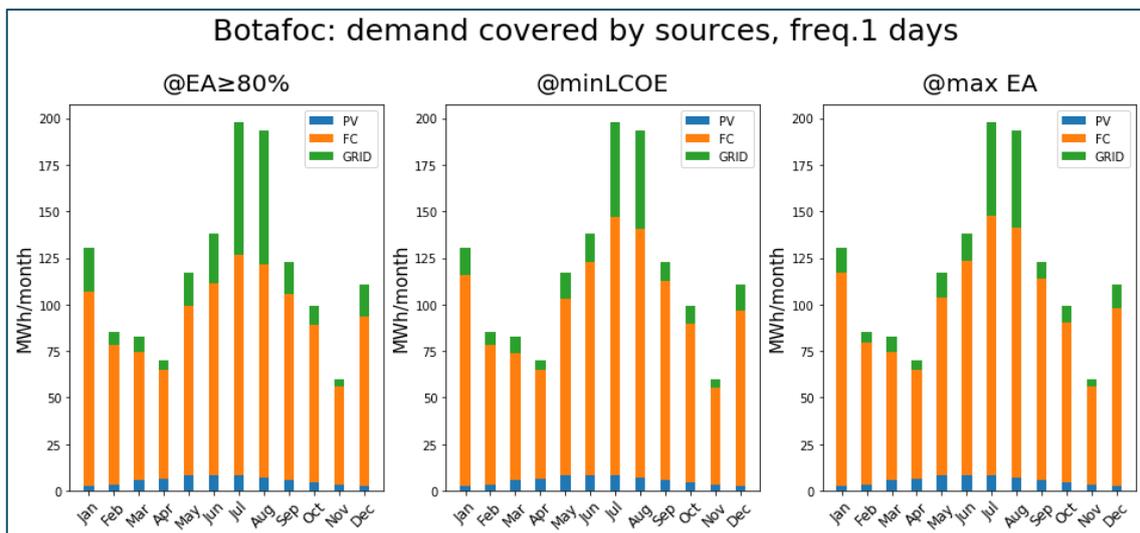


Figure 59: Electricity supplied by different energy source to Botafoc (constant-load fuel cell and daily frequency of charge)

For Botafoc (Figure 59) all three solutions assessed reach an EA  $\sim$  80%. The performance on the independence of the grid can be improved by increasing the contribution of solar energy source.

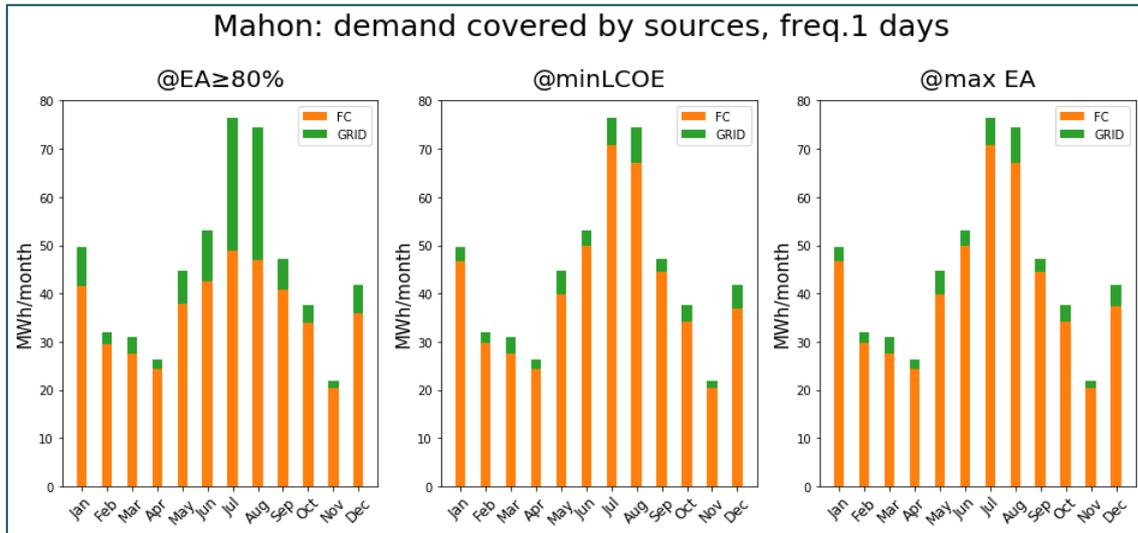


Figure 60: Electricity supplied by different energy source by sources for Mahón (constant-load fuel cell and daily frequency of charge)

The total energy output of the fuel cell and hydrogen demand for the solutions of are summarized in the table below, and the ones for the minEA and maxEA can be found in *Appendix E*.

Table 32: Energy output and hydrogen demand over the entire project lifetime for the configurations at energy autonomy higher than 80% (constant-load fuel cell and daily frequency of charge)

Stand- Alone Config.	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	$E_{FC,TOT}$ [MWh]	$E_{FC,self-cons.}$ [MWh]	$E_{FC,surplus}$ [MWh]	$H_{2lifetime}$ [ton]
<b>EM2+EM3</b>	85	11	9,980	9,162	818	767
<b>Botafoc</b>	240	41	28,179	21,225	6,954	2,165
<b>Mahón</b>	100	13	11,738	8,604	3,134	901

When comparing the solution of one of the configurations (E.g.EM2+EM3) (*see Table 32*), it can be noticed that for a given selection criteria (EA  $\geq$  80%) the sizes for the hydrogen fuel cell system are the same regardless of the operational mode. The main difference is the Energy surplus that can be generated and distributed to other locations in the port and the lifetime costs savings will be also larger for the CL case. The results for the min LCOE and Max EA solutions can be found in the *Appendix F*.

Table 33: Energy output and hydrogen demand of the two operational modes for the configuration EM2+EM3 (daily frequency of charge)

EM2+EM3 Operational mode	$P_{FC,NOM}$ [kW]	$N_{ST,UNITS}$	$E_{FC,TOT}$ [MWh]	$E_{FC,self-cons.}$ [MWh]	$E_{FC,surplus}$ [MWh]	$H_{2lifetime}$ [ton]
<b>Load-following</b>	90	10	9,023	9,023	0	769
<b>Constant-load</b>	85	11	9,980	9,162	818	767

### 8.1.4 Frequency of Hydrogen fuel recharge

It is useful assessing the impact of the frequency of charge on the results, since it influences the number of storage units requested and the overall systems costs, it is especially important when there are footprint limitations or potential caps in the hydrogen storage capacity allowed at the port site, due to regulations, that, at the moment remain uncertain. It is indeed particularly relevant to large maritime terminals such as Mahón and Botafoc where a large demand of hydrogen is expected whereas the case of EM2+EM3 and potentially other locations in the port of Mallorca, where there is not much room available in the existing infrastructure to accommodate the infrastructure required for hydrogen storage and refilling system.

To evaluate the impact of charge frequency on systems with storage restrictions in the design or MSC (see section 7.2.4), several iterations were conducted. The first iteration used a charge frequency of seven days, as shown in Figure 7. Subsequent iterations tested higher frequencies until a solution was found that met the CBA selection criteria while considering the specified MSC in the model. In this study, the evaluation was done for Botafoc and Mahón, where the uncertainty on the storage size and the maximum allowed refuelling frequency is highly uncertain. Moreover, a weekly frequency of charge requires a higher number of storage units, which might be in contrast with the model spatial limitations assumed. EM2+EM3 is the only configuration in which the spatial limitations do not impact the storage system, because of a relatively low demand of the building. The operational mode was also taken into account in the analysis as depicted in Figure 61 and Figure 62.

For the configurations in Menorca and Ibiza, at a weekly frequency of charge, the storage cap was reached clearly reducing the maximum energy autonomy that can be achieved, and consequently also to the cost savings and the emissions avoided. The results for a weekly hydrogen recharge of Mahón (70 % EA in LF mode) and Botafoc (less than 50%) indicated so, therefore the frequency could be higher.

Overall, charging less frequently the hydrogen storage leads to a general increase in the LCOE of the energy systems and to a general reduction in the value of energy autonomy achieved, that could lower than the minimum criteria.

For Botafoc, the maximum frequency of recharged allowed when considering the MSC is 2 (see Figure 61) as these cases meet the criteria of reaching at least 80% EA. When running the fuel cell in a different mode (CL) with the same configuration and charge frequency, the notable difference lies in the levelized cost of electricity (LCOE), which is lower for the constant load operating mode.

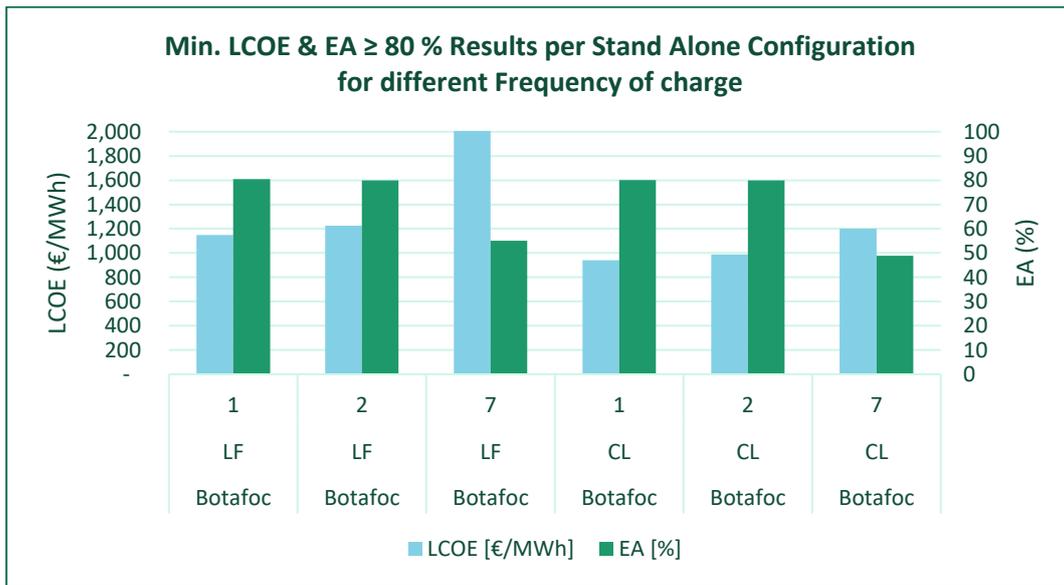


Figure 61: Hydrogen Fuel cell system - Frequency of charge at different operational modes (MSC active) -Botafoc

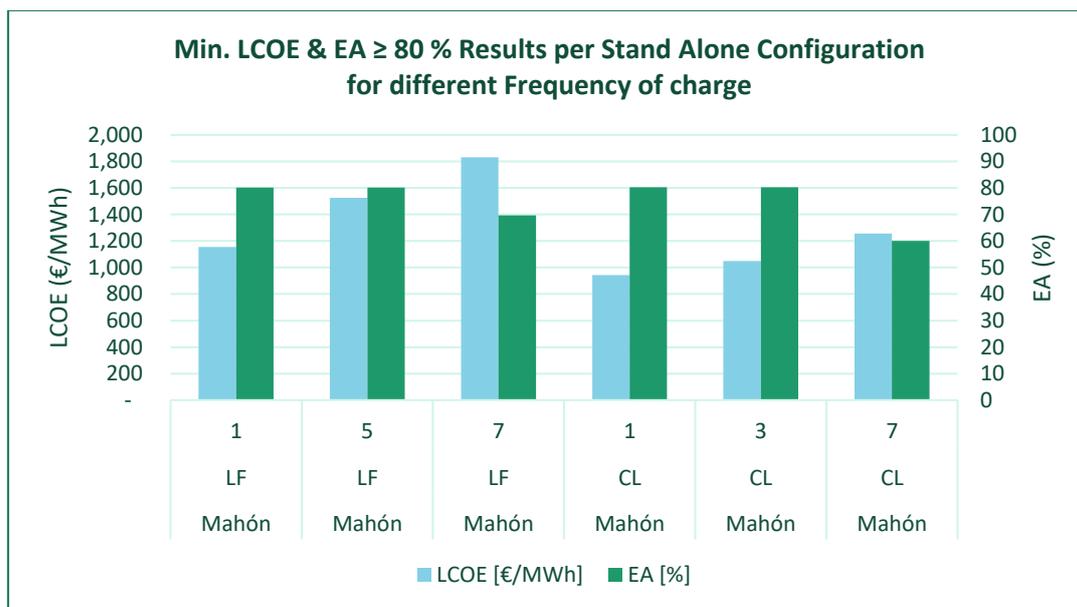


Figure 62: Hydrogen Fuel cell system - Frequency of charge at different operational modes (MSC active) -Mahón

Under the MSC constrain and all assumptions made for modelling Mahón energy demand, it seems that three days frequency is the minimum frequency allowed for CL operational mode and five days frequency when the fuel cell is run in LF mode, for the system to reach at least, 80 % EA. The results for the minLCOE and max EA are presented in appendix G (Botafoc) and H (Mahón).

## 8.2 Combined system configurations

This section presents the CBA results obtained after the modelling work done for the configurations described in Section 7.4.2. The selection of these configurations builds upon the analyses of the stand-alone configurations of EM4 and EM2+EM3. The rationale is also based on the complexity level, configuration CB-1 being the least complex to CB-4 being the more complex given the incorporation of new PV panels for EM2 and EM3 buildings and hydrogen fuel cell system.

The combined system configurations are only applicable to the maritime terminals located in the island of Mallorca, since is the only island with multiple maritime terminals within the scope of the study.

The assessment is based on the same four indicators defined for the study: LCOE, Energy Autonomy, costs savings and CO<sub>2</sub> emissions savings. For the combined case, the results are expressed both at system level and at EM2&3 levels.

The results are presented in *Table 34* and *Table 35*. They display the values for the CBA indicators obtained for each studied combined configuration, for different solutions. The first results to stand out is that CB-1 and CB-2 do not meet the evaluation criteria of Energy Efficiency greater than or equal to eighty percent ( $EA \geq 80\%$ ) at system level. Therefore, only by including a hydrogen-based fuel system for each building the criteria is satisfied, considering a hydrogen fuel cell in EM4 as per the project design.

By comparing the results of CB-1 and CB-2 at system level, one can gain an understanding of the impact of incorporating photovoltaic (PV) systems in EM2&3 after implementing the fuel cell in EM4 and connecting these two buildings. This setup enables the surplus electricity generated in EM4 to power the electrical system of EM2&3.

Additionally, the results in *Table 34* shows that installing only solar panels in EM2 & 3 results in a 30% increase in CO<sub>2</sub> emissions savings and a 26% reduction in electricity costs. Additionally, PV panels lead to a 20% decrease in LCOE. However, the impact on energy autonomy benefits is less than 5.5%.

Table 34: Combined Configuration Results summary table (at system level)

	P <sub>FC,EM4</sub> [kW]	N <sub>ST,EM4</sub>	EA <sub>EM4</sub> [%]	P <sub>PV,EM23</sub> [kW]	P <sub>FC,EM23</sub> [kW]	N <sub>ST,EM23</sub>	LCOE <sub>SYS</sub> [€/MWh]	EA <sub>SYS</sub> [%]	LACS <sub>SYS</sub> [€]	ΔCO <sub>2</sub> SYS [t/y]
<b>CB-1</b>	100	9	75.7	-	-	-	931	63.4	204,847	153.8
<b>CB-2</b>	100	9	75.7	80	-	-	744	66.3	265,634	194.5
<b>CB-3</b>	100	9	75.7	-	50	5	1,024	80.6	262,305	202.3
<b>CB-4</b>	100	9	75.7	80	45	3	842	80.4	310,494	234.2

When comparing CB-3 and CB-4 (also configurations without and with PV but incorporating hydrogen fuel cells in both buildings) one can observe that, in this case, having the PV improves the LCOE and system savings, while reaching a similar EA at the desire percentage in both cases. Therefore, configuration CB-4 full hybrid system is preferred according to the selection criteria. It corresponds to a new PV solar panel system of 80 KWp, a PEM fuel cell with a 45 KW and 2 hydrogen storage units for EM2 and EM3, allowing to deploy up to 33.7 kg of hydrogen for EM2&EM3. A positive impact in the CBA on including PV combined with the fuel cell as it is considered in the CB-4 at building level is presented in *Table 35*.

Table 35: Combined Configuration Results summary table (at EM2+EM3 level)

	$P_{FC,EM4}$ [kW]	$N_{ST,EM4}$	$EA_{EM4}$ [%]	$P_{PV,EM23}$ [kW]	$P_{FC,EM23}$ [kW]	$N_{ST,EM23}$	$LCOE_{EM23}$ [€/MWh]	$EA_{EM23}$ [%]	$LACS_{EM23}$ [€]	$\Delta CO_2_{EM23}$ [t/y]
<b>CB-1</b>	100	9	75.7	-	-	-	-	56.2	121,457	89.9
<b>CB-2</b>	100	9	75.7	80	-	-	39	60.9	135,863	99.4
<b>CB-3</b>	100	9	75.7	-	50	5	1320	83.3	178,915	138.5
<b>CB-4</b>	100	9	75.7	80	45	3	671	83	227,104	170.3

In the below figure the contribution to the annual demand is presented at system level (to the left) and buildings levels (right hand side of the plot). In the latter, one can observe the contribution of the surplus electricity from the EM4 and the hybrid system elements in the configuration EM2+EM3. The surplus electricity of EM4 has an important contribution over the year, based on the data available and the assumptions made for the analyses.

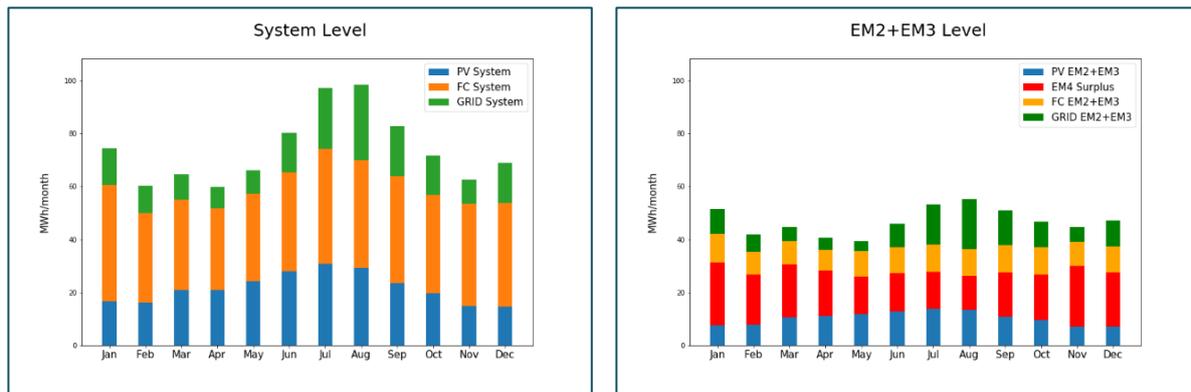


Figure 63: Monthly demand coverage for CB-4, at the solutions that achieve the target of 80% energy autonomy (daily frequency of charge)

Table 36: Combined Configuration Results summary table

<b>CB-4</b>	$P_{FC,EM4}$ [kW]	$N_{ST,EM4}$	$P_{PV,EM23}$ [kW]	$P_{FC,EM23}$ [kW]	$N_{ST,EM23}$	$E_{TOT}$ <sup>7</sup> [MWh]	$E_{self-cons.}$ [MWh]	$E_{surplus}$ [MWh]	$H_2$ lifetime [ton]
<b>System Level</b>	100	9	80	45	3	14,701	11,545	3,156	974
<b>EM2+EM3 Level</b>	100	9	80	45	3	5,047	4,967	80	234

<sup>7</sup> At system level, the term Energy total includes the electricity generated by: the fuel cell systems and Solar panels in EM4 & EM2+EM3

## 8.3 Costs Estimates

In this subsection, we provide a summary of the estimated costs for the configurations evaluated in this study. These costs are expressed in terms of total Actualized Capex (EUR), Initial Capital investments (EUR), and Average Annual Operating costs (EUR/y). Furthermore, we present a detailed breakdown of the costs per element included the calculation of Actualized CAPEX and OPEX.

### 8.3.1 Stand-alone configurations costs

For all the stand-alone configurations, regardless of the operational mode the EA $\geq$ 80% solution brings the lowest initial total capital investment compared to the other two options (max EA and minLCOE).

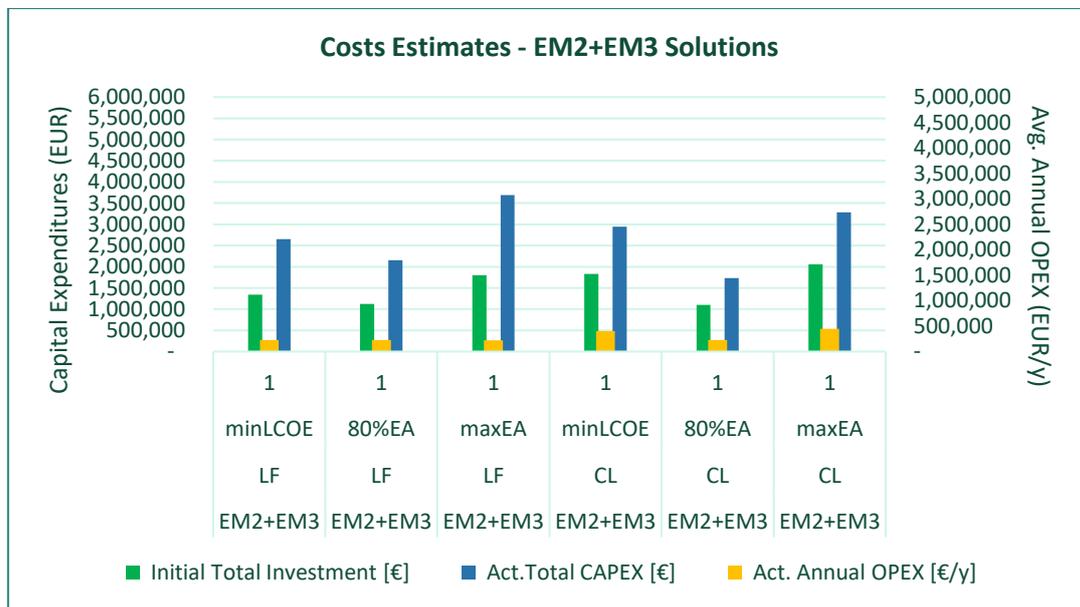


Figure 64: Cost Estimates - EM2+EM3 Solutions

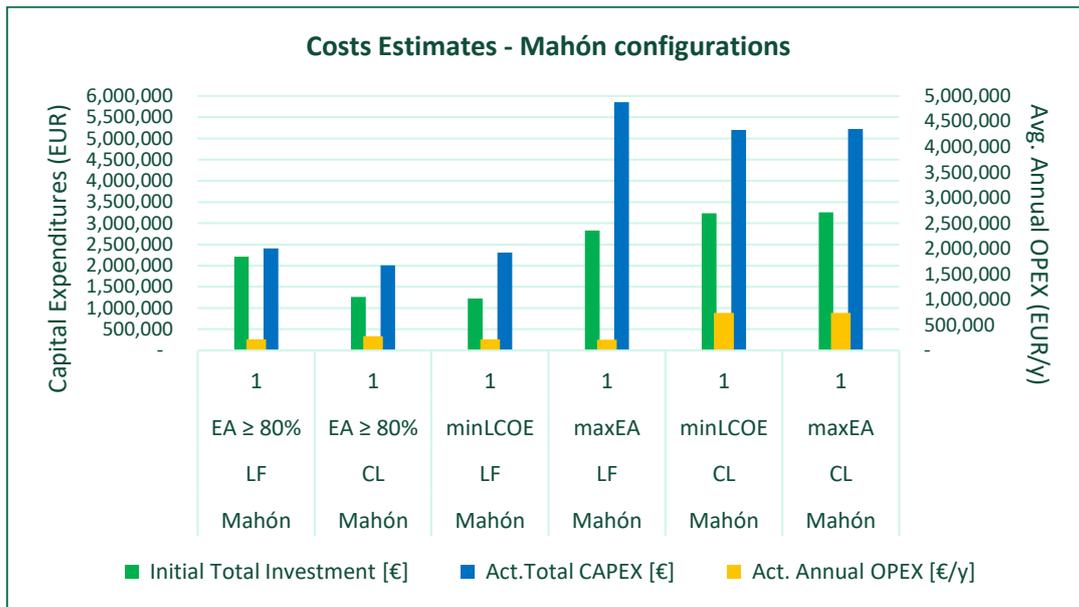


Figure 65 (b): Cost Estimates - Mahón

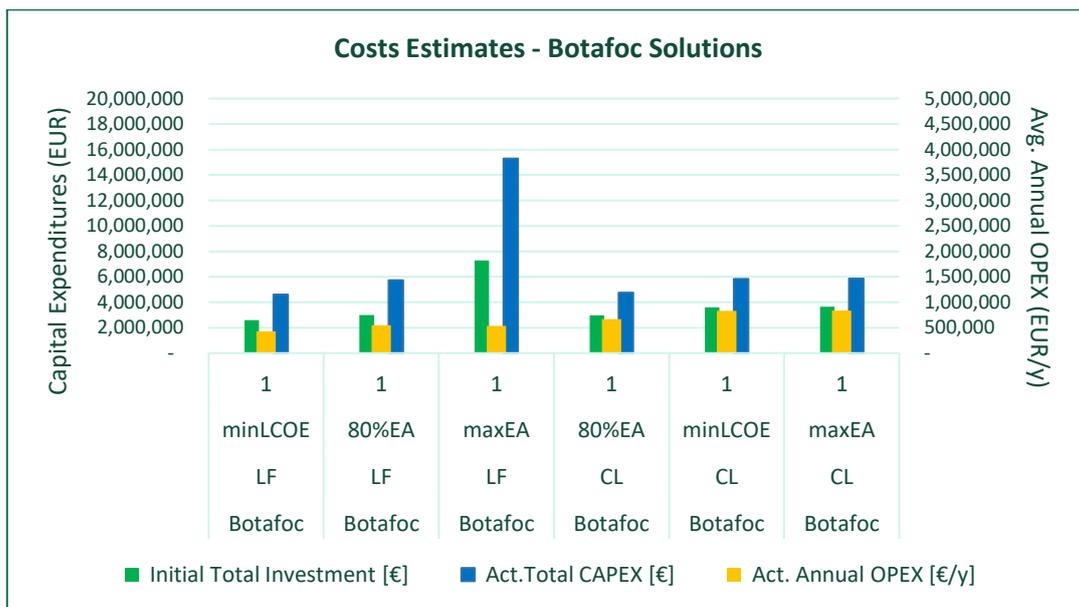


Figure 66: Costs Estimates – Botafoc configuration

When the fuel cell is operated in LF scaling up the fuel cell system capacity that brings EA ≥ 80% to the maximum EA. requires a large lifetime cost increments due to the initial investment’s requirements and the replacements the fuel cell stack. For example, in Botafoc that step up requires in the EA max = 96% actualized cost increment of 2.7 times with respect to the EA = 80 % solution., approx. 597 K€/ %EA. In constant load the scale-up is achievable yet with a lower incremental cost.

The scale up cost to achieve maximum grid independency and therefore maximize the CO<sub>2</sub> emissions reduction are more difficult to reach, capital investment wise and because of the larger footprint and their consequence as discussed in previous section.

If the objective is to minimize LCOE, with a noticeably seasonal demand with initial investment constrain then LF is a more convenient solution than one operating in CL mode, however, in the long-term run, Capex investments are required due to the need of replacing the fuel cell stack more often than in the CL mode, for yearly electricity demands profiles that are rather flat, such EM2+EM3 profile, then the CL option provides better economics and other benefits. The LF mode will bring lower operational costs in the long term, due to the more restricted use of hydrogen as a fuel.

For all the solutions presented in *sections 8.1 and 8.2*, the allocation of costs between CAPEX and OPEX in systems incorporating load-following fuel cells is nearly identical to other systems. In this case, CAPEX represents just under 30% of the total Levelized Cost of Electricity (LCOE). According to the model and assumptions for the studied cases the Fuel Cell system and stacks replacements constitute the element with the highest contribution to the overall CAPEX whereas the hydrogen costs are the main contributors to both LCOE costs and OPEX. The *Figure 67* displays the cost distribution for each element within the cost structure:

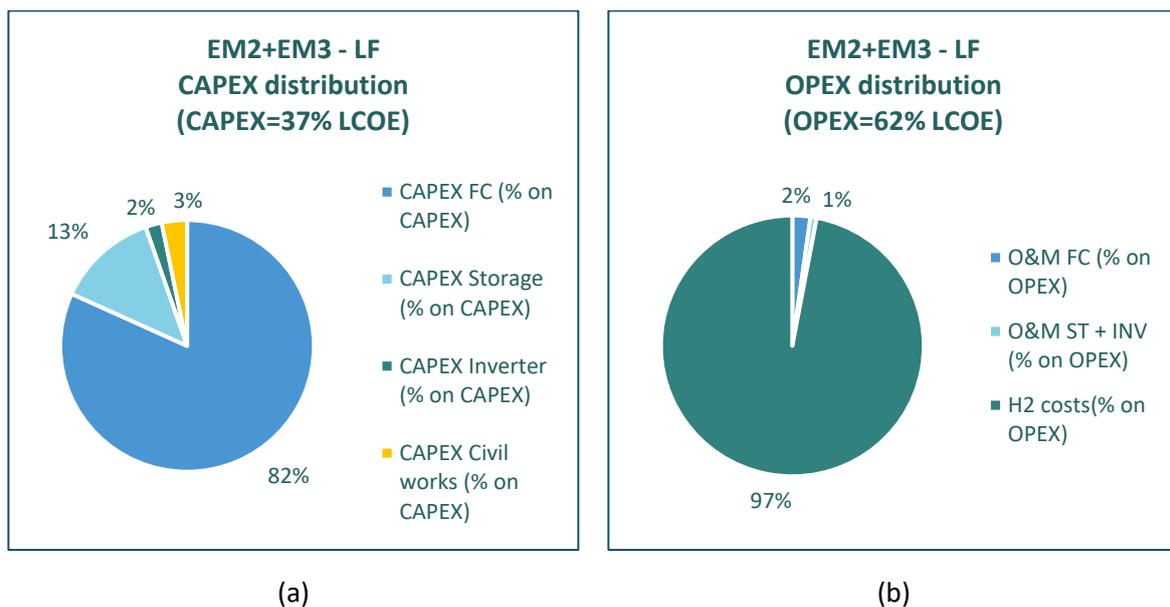


Figure 67: Distribution of CAPEX (a) and OPEX (b) for EM2+EM3 (LF fuel cell and daily frequency of charge)

The summary table for of costs all stand-alone configurations are in Appendix I.

### 8.3.1 CBA configurations costs

For the combined configurations the cost breakdown to be presented are in line with the findings reported in section 8.2 where it was established that energy system approach with the integration of Solar PV system brings significant economic performance compared to the stand-alone solution for the maritime terminals in the port of Palma de Mallorca, as depicted in Figure 68. They all meet the EA  $\geq$  80 %. The solution with min LCOE has a lower EA ( $\sim$ 60%). The reasons for the cost reductions in the

CBA case are two folded: the CAPEX is lower because of the size of the hydrogen system is smaller (45 Kw, 3 storage units) than in the stand-alone system (FC power= 85 Kw, 11 storage units), and the OPEX is lower in the CB-4 case thanks to an important reduction of hydrogen consumption estimated in 70 percent.

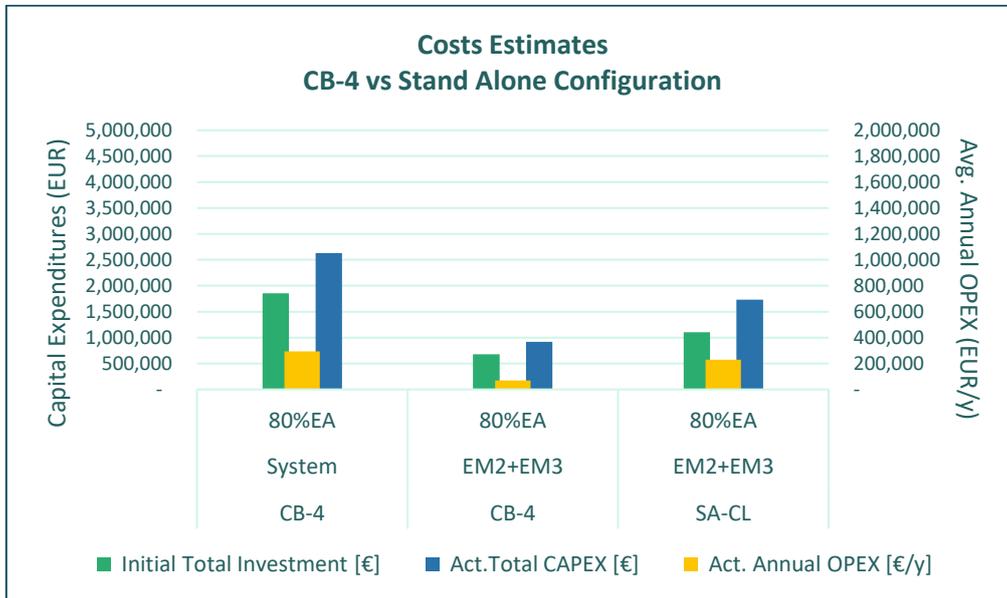


Figure 68: Comparison of Costs Estimates for EA ≥ 80% energy systems solutions in Mallorca

The next figure shows the costs allocation per system element for the CB-4, both at system and EM2+EM3 level. The relative proportion of cost of fuel is still high and the main contributor to the LCOE's estimations.

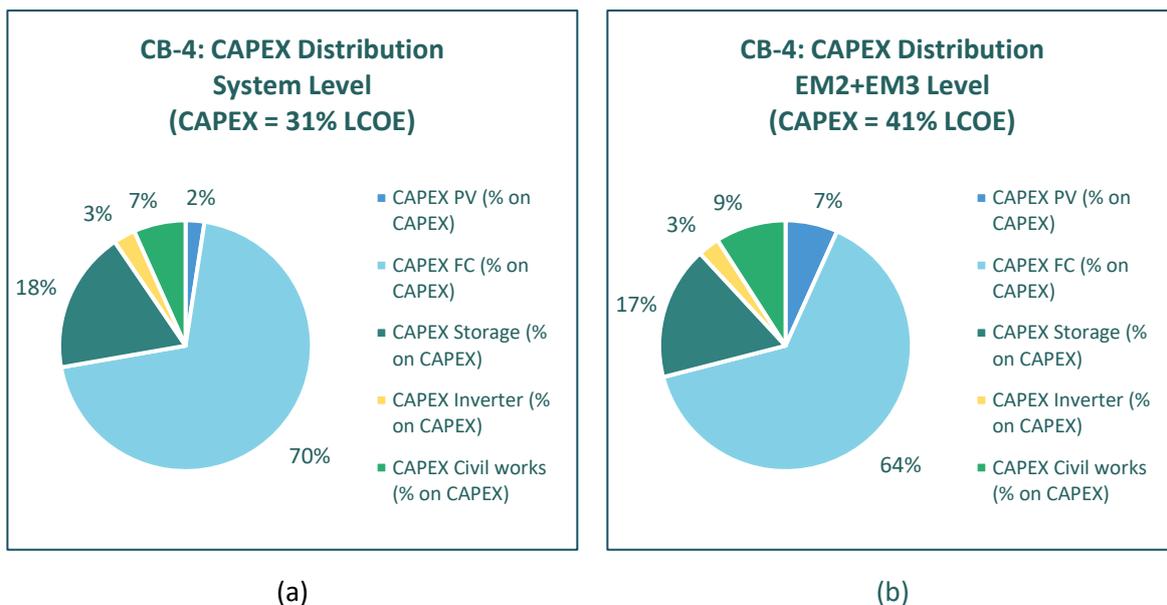


Figure 69: Distribution of CAPEX for CBA-4, at the solutions that achieve the minimum target of 80% of energy autonomy (daily frequency of charge)

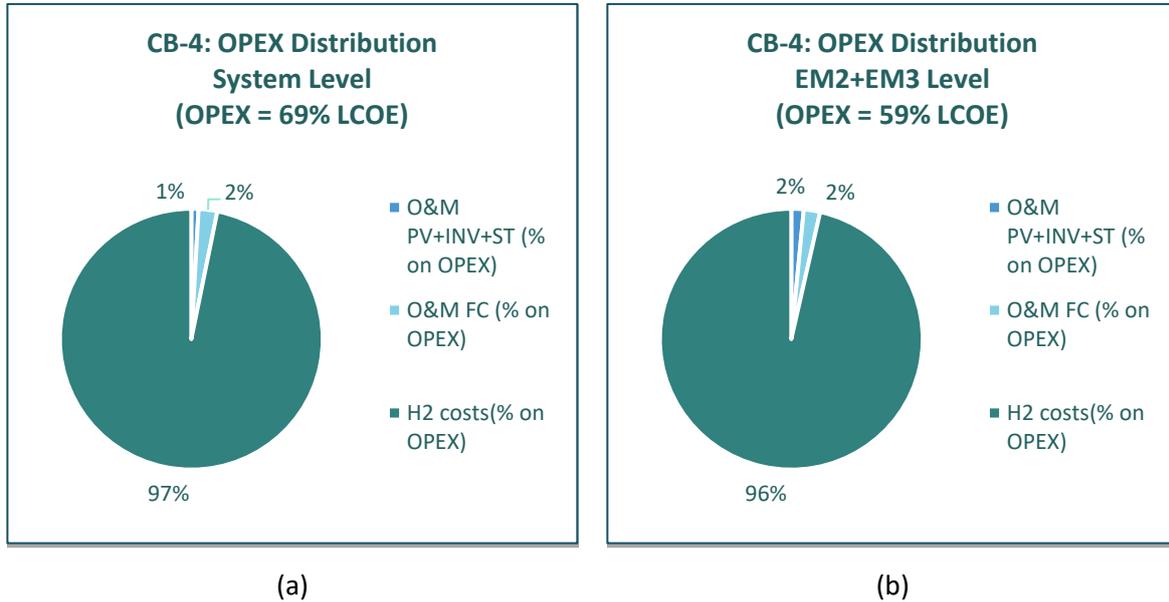


Figure 70: Distribution of OPEX for CBA-4, at the solutions that achieve the minimum target of 80% of energy autonomy (daily frequency of charge)

The summary table for of costs all stand-alone configurations are described in detail in Appendix J.

#### 8.4 Cost for frequency of charge case

The selected case to showcase the impact in costs by using a frequency of charge is Mahón, since the power of the fuel cell in the selected configuration to meet the EA 80% solutions are the same regardless of the operational mode they operate. The *Figure 71* depicts the costs estimations for this study case:

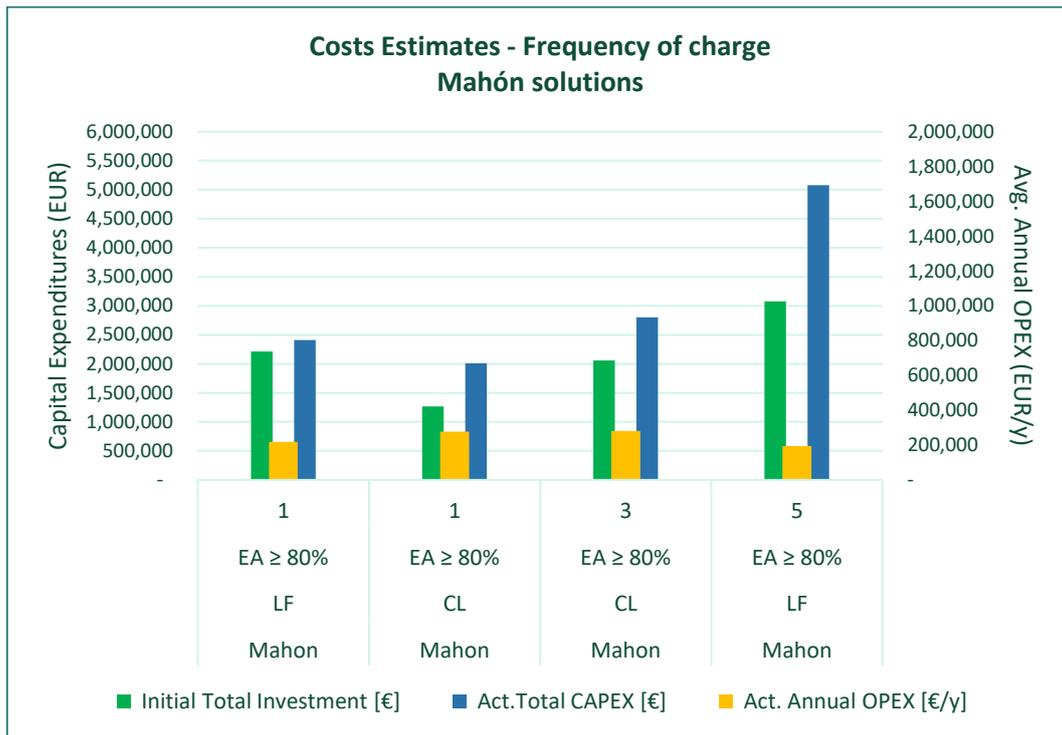


Figure 71: Comparison of Costs Estimates for EA≥ 80% energy systems solutions in Menorca

In this case the LF mode has two advantages compared to operating in CL mode since the minimum allowed frequency of charge provides (1) more flexibility due to a longer operational period allowed, and (2) a lower OPEX consumption of hydrogen.

### 8.5 Sensitivity analysis

Several sensitivity analyses were conducted for both operational modes, focusing on solutions that achieved a minimum target of 80% energy autonomy while keeping costs low. The analyses examined the relationship between the Levelized Cost of Electricity (LCOE) of each solution and five variables, as described below: The impact of the degradation factor of the fuel cell is the first one to be studied. This sensitivity analysis was performed varying the degradation factor between 0.8 %/1,000h and 0.3 %/1,000h. the reference value for the LC mode is 0.6 %/1000h and for the CL mode is 0.4 %/1,000h

The second variable considered is the maximum allowed power loss of the fuel cell stack that the fuel cell can undergo with respect to its initial nominal power. In the model, the reference value end of lifetime (EoL) of the fuel cells stack corresponds to a power loss of 20 %; changing this percentage has an effect on the maximum operating hours of the fuel cell itself (impacting the frequency of the stack replacement), as well as on the hydrogen consumption. To perform the sensitivity analysis, the power loss cap was set in the model to values that are 25% and 50% lower than reference value.

The third variable selected is connected to the fuel cell CAPEX, as they account for at least 20% on the entire LCOE: they were varied within a range of between -50% and +50%, in steps of 25%.

The fourth variable analysed is the efficiency of the fuel cell. An improvement in the efficiency would imply a reduction in hydrogen usage, leading to lower costs for fuel purchasing and lower investment costs for the storage. A relative variation between -25% and 25% was considered, with steps of 12.5%, keeping in mind that this relative variation changes the efficiency curve for the fuel cells in load-following operational mode, as shown in *Figure 72*.

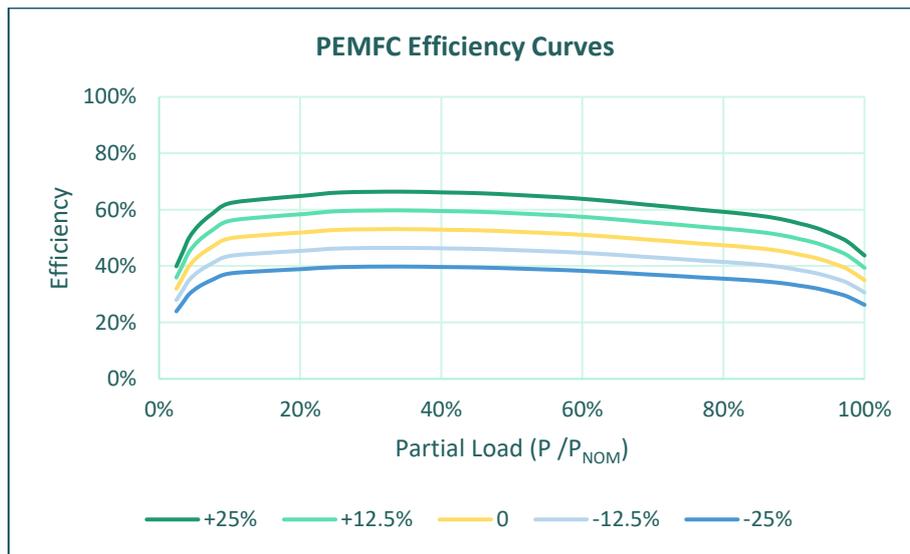


Figure 72: Efficiency curves considered in the sensitivity analysis for the load-following fuel cells

The fifth and last sensitivity analysis was performed modifying the hydrogen price. It was varied in two ways: by applying a price variation in absolute terms, between -2 and +2 €/kg, and by defining different decline rates of the price itself, using coefficients between -25% and +25%, with steps of 12.5%. *Figure 73*, referred to EM2+EM3 at daily frequency of charge (quantity of hydrogen delivered is always lower than 1,000 kg) helps in visualizing these two different ways.

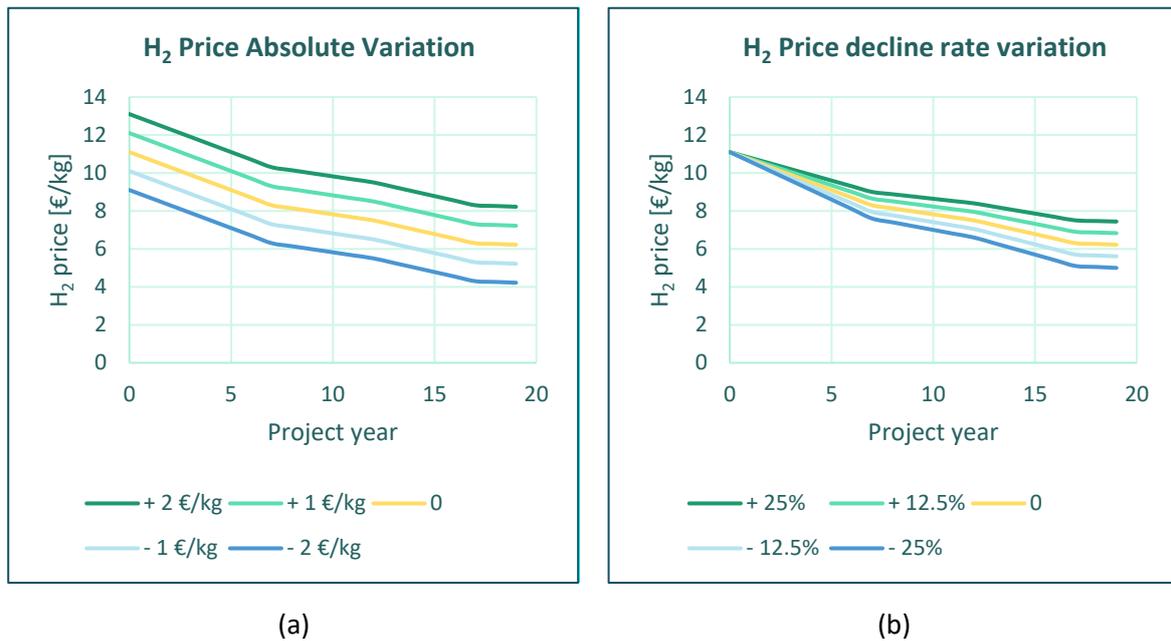


Figure 73: Hydrogen prices considered for the sensitivity analyses  
 (case of EM2+EM3 at daily frequency of charge)

### 8.5.1 Fuel cell degradation factor

The degradation factor of the fuel cell influences different aspects that characterize the system cost: a lower degradation leads to have a longer lifetime for the fuel cell, requiring then stack replacements less frequently, but also a lower hydrogen consumption, which has an effect also on the storage system necessary. *Figure 74* highlights the effect that the degradation factor has on the LCOE of the energy systems of all the stand-alone configurations, trying to catch the eventual differences between the two operational modes. It must be remembered that the reference value for the load-following fuel cells is 0.6%/1,000h, while for the constant-load ones it is 0.4%/1,000h.

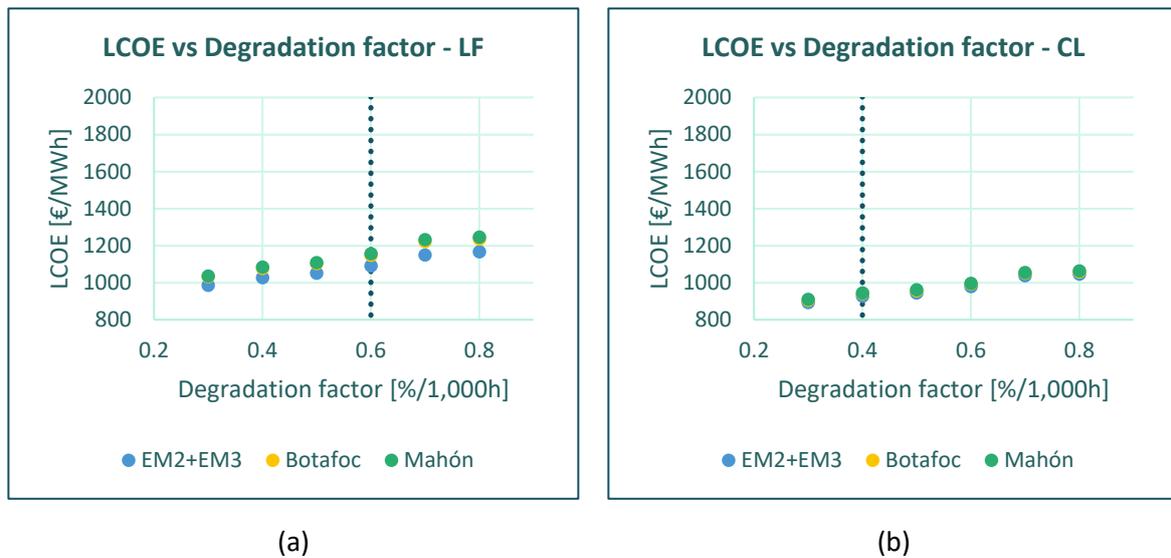


Figure 74: Relation between LCOE and degradation factor of the fuel cell

Lower degradation factors allow the fuel cell to undergo more degradation rounds before the stack replacement, implying that the EOL will be reached later. This can lead to costs reduction due to a lower number of stack replacements over the project lifetime; moreover, since the specific capital costs related to the generator stack decrease over time instead of staying constant (see *Figure 36*), changing later the stack is also less costly. The combination of these two factors leads to have lower values of LCOE. Its percentage variation between the two extremes is slightly higher for the load-following fuel cell (17% in LF against 15% in CL for Botafoch and Mahón, 16% in LF and 15% in CL for EM2+EM3) because for these systems the fuel cell CAPEX represents a higher share in the LCOE than in the systems with constant-load fuel cells.

### 8.5.2 Sensitivity Power Loss factor

The value of power loss admitted before replacement impacts on the useful lifetime of the hydrogen generator, as well as on the consumption of hydrogen along the years. *Figure 75* shows how the LCOE depends on this parameter in all the stand-alone configurations, remembering that the reference value corresponds to a power loss of 20%, and the other extreme refers to a percentage power loss of 10% (the relative reduction is then 50% with respect to the reference value).

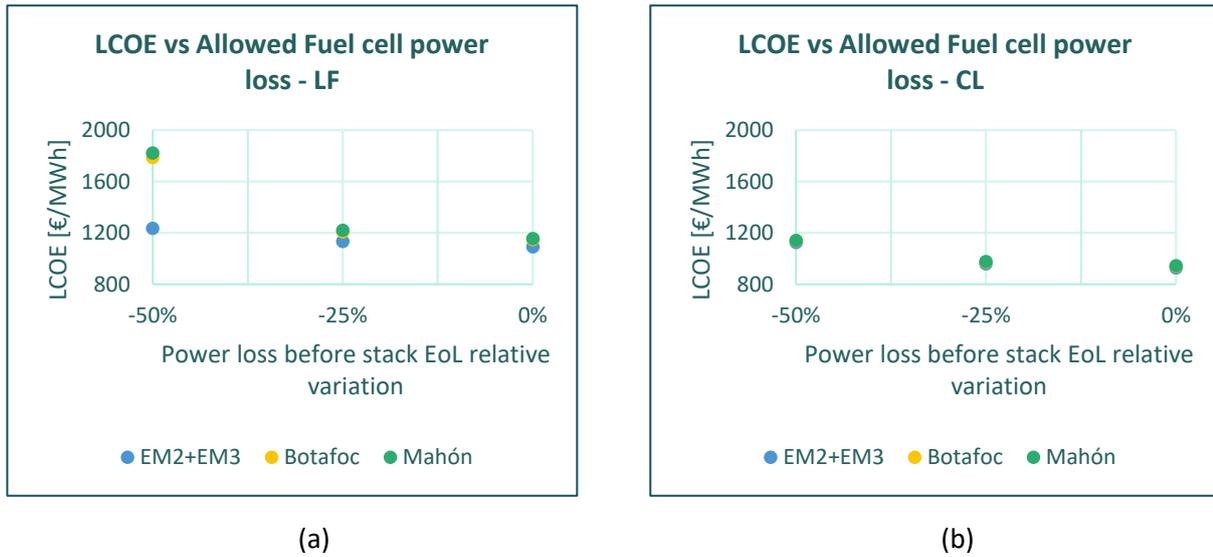


Figure 75: Relation between LCOE and the maximum allowed power loss before the fuel cell stack replacement

Anticipating the fuel cell EoL allows to consume less hydrogen and at the same time to generate more energy along the entire project lifetime; however, the weights of these contributions are not sufficient to contrast the higher capital costs related to more frequent stack replacements. For the configurations with constant-load fuel cells the difference in LCOE is lower than in those with load-following generator, due to the adoption, in the model, of a smaller degradation factor for the operational mode in constant-load (see *section 7.2.2.2*), which guarantees longer lifetime for these fuel cells; it does not occur for EM2+EM3, given the behaviour of the load-following fuel cell very similar to the constant-load one.

### 8.5.3 Fuel cell Capex sensitivity

In all the stand-alone configurations analysed, the LCOE shows a linear dependence with the CAPEX associated to the fuel cell stack, as shown in *Figure 76*.

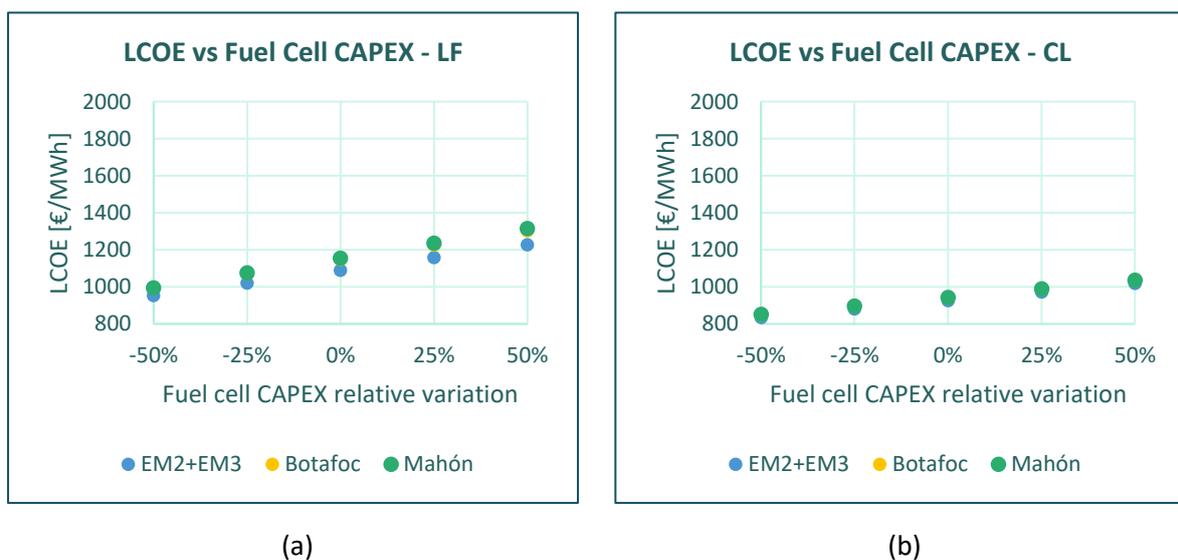


Figure 76: Relation between LCOE and the fuel cell stack CAPEX

The slope for the load-following system is slightly higher than the CL mode due to the larger size of the fuel cell CAPEX in the long run, and the higher frequency of replacing the fuel cell stack.

### 8.5.4 Fuel Cell Efficiency sensitivity

Contrary to the analysis with the fuel cell CAPEX, the relation between the LCOE and the efficiency is not linear, as shown in *Figure 77*.

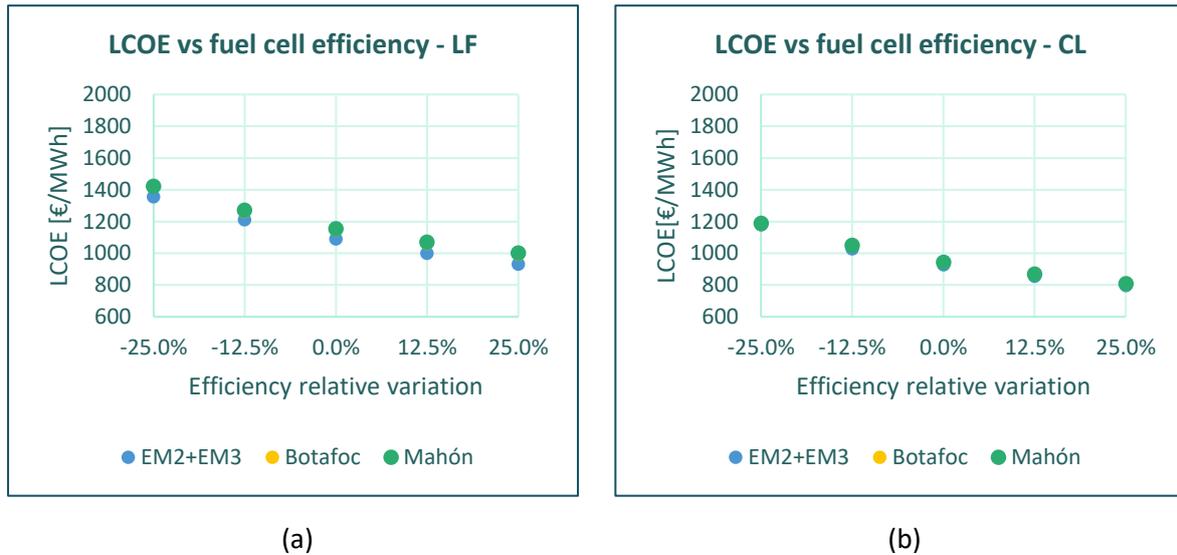


Figure 77: Relation between LCOE and the fuel cell efficiency

At lower efficiencies, the trend of LCOE as a is steeper: the fuel costs are higher since more hydrogen is needed to produce the same amount of electricity, and at the same time the amount electricity generated is lower, because the fixed number of storage units limits the quantity of hydrogen that can feed the fuel cell. At higher efficiencies than the reference value, the costs related to hydrogen purchase are lower and the energy output is higher, leading to a decrease in the LCOE; however, the difference in the energy production is not as significant as it happens at lower efficiencies: this is the reason behind the flatter nature of the curve at higher efficiencies. In this case, the relative differences in the trend are similar for both the operational modes.

### 8.5.5 Hydrogen price sensitivity

*Figure 78* shows how the LCOE changes as an absolute variation is applied to the hydrogen purchase price; the figure highlights a linear relation between the two variables.

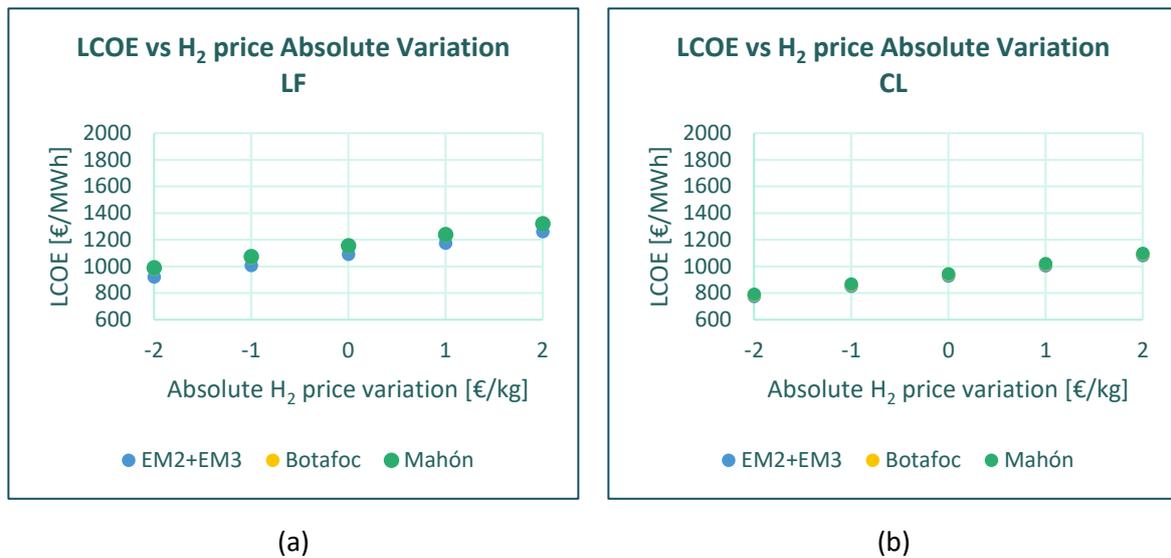


Figure 78: Relation between LCOE and hydrogen purchase price (absolute variation)

By applying an absolute difference of 2 €/kg in hydrogen purchase price, the fuel expenditures over the entire project lifetime differ by around 23% from the reference case (this is valid for all the configurations independently on the operational mode), leading to a relative variation in LCOE by around 16% in LF and 18% in CL; this slight discrepancy between the two operational modes is due to the higher weight that the fuel costs have in CL systems.

The variation of LCOE at different decline rates for the hydrogen price is shown in *Figure 79*; as in *Figure 78*, a linear relation can be seen between the two variables, with a slope that is three times lower than in the case where an absolute variation in price is applied.

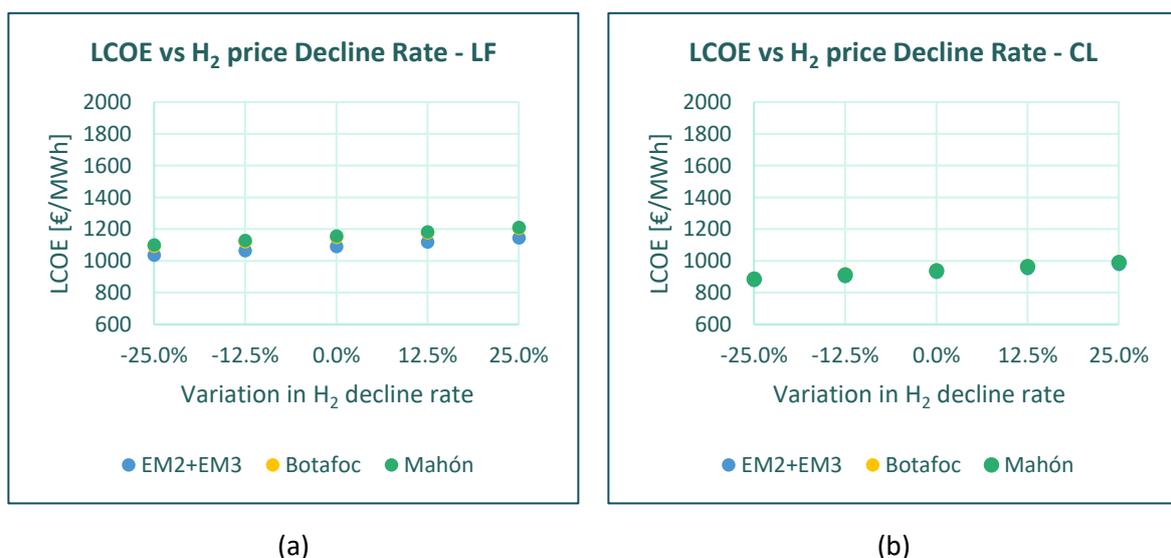


Figure 79: Relation between LCOE and different hydrogen price decline rate

Also in this case, the relative LCOE variation from the reference value is slightly higher for the CL systems (6% for CL against 5% for LF, with a 25% difference in declining rate) for the same reasons of the previous case.

## 8.6 Hydrogen demand Estimations

In *Figure 80*, the estimation of hydrogen demand is given for four different configurations: the combined configuration CB-4 in Mallorca, and the three stand-alone configurations EM2+EM3, Botafoc and Mahón.

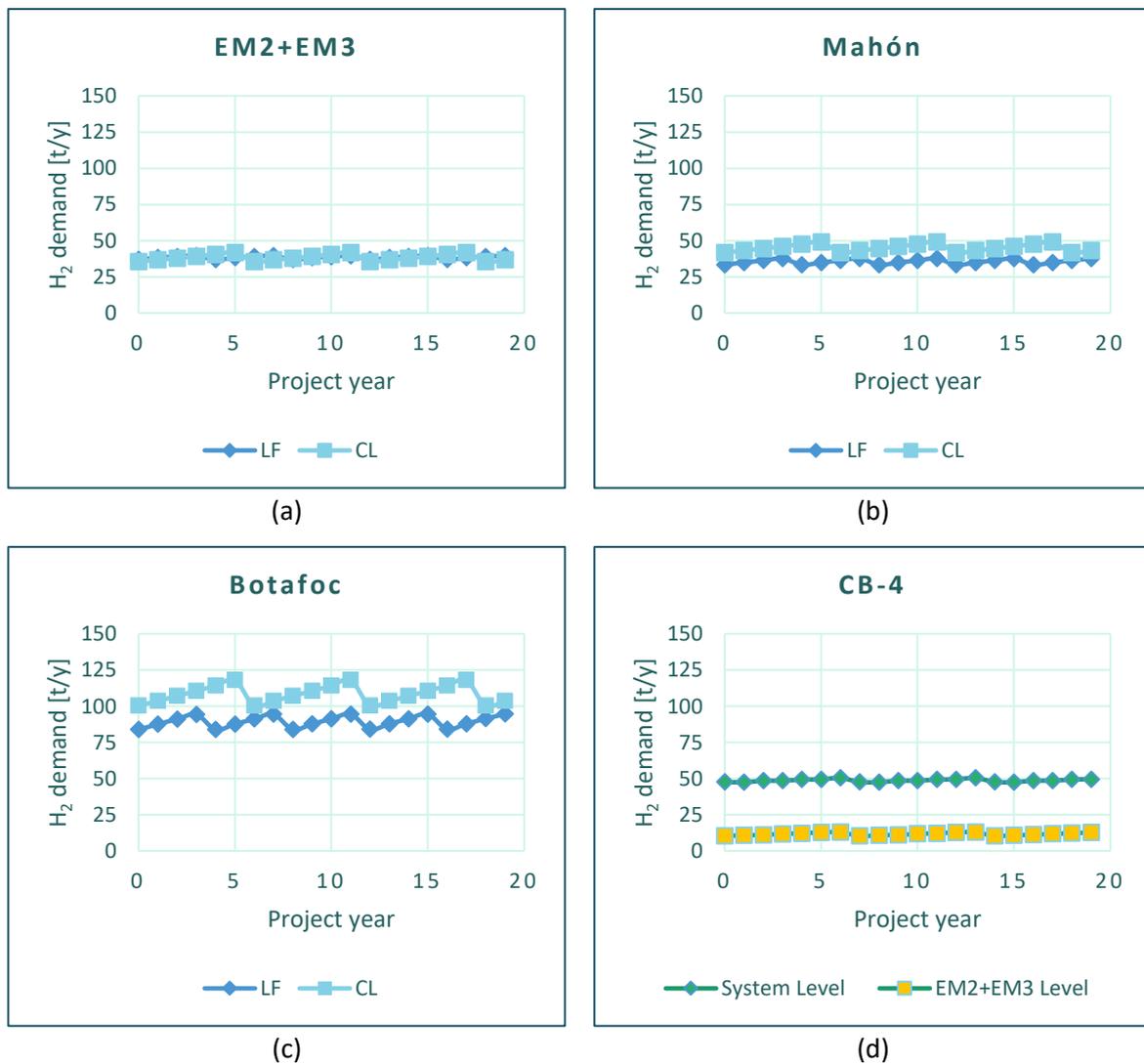


Figure 80: Annual hydrogen demand profiles for the three stand-alone configurations and CB-4, at daily frequency of charge and for both the operational modes

For the configuration EM2+EM3, the two operational modes are characterized by a very similar demand along the years; it does not occur in the other two stand-alone configurations, where the gap between the two trends at LF and CL are larger. This is related to the different demand profile of

EM2+EM3, which is flatter than those of the other two buildings: the power that the fuel cell generates is then less oscillating than in the other stand-alone configurations, meaning that its operational mode will be more similar to that of a CL generator.

In all the configurations, the moments characterized by a marked decrease in the hydrogen demand indicate that in that year the fuel cell stack has been replaced; in the stand-alone configurations, it can be noticed that the constant-load fuel cells are replaced later than the load-following ones, due to a lower degradation factor considered for this operational mode: this affects the number of replacements performed over the entire project period (4 stack replacements for the load-following fuel cell against 3 for the constant-load), and consequently the capital expenditures related to the fuel cell stack. Between two replacements, the annual hydrogen demand progressively increases because the higher degradation leads to consume more energy in order to generate the same amount of electricity.

For the combined configuration, the demand at system level is the sum of the constant-load fuel cell associated to EM4 plus the load-following dedicated to EM2+EM3. Its trend appears parallel to the one at EM2+EM3 level, meaning that the hydrogen consumed by the constant-load generator of EM4 maintains practically constant along the entire project lifetime (ca. 37 t/y).

An overview of the expected hydrogen demand over the entire project lifetime for the configurations analysed is shown in *Table 37*.

Table 37: Hydrogen demand over the entire lifetime for the selected configurations

Configuration	Operational mode / Level	Energy produced over the project [MWh]	Lifetime H <sub>2</sub> demand [ton]
<b>EM2+EM3</b>	LF	9,023	769
	CL	9,980	767
<b>Mahón</b>	LF	8,588	711
	CL	11,738	901
<b>Botafoc</b>	LF	21,296	1,787
	CL	28,179	2,165
<b>CB-4</b>	System Level	10,078	974
	EM2+EM3 Level	3,459	234

## 8.7 Potential CO<sub>2</sub> emissions avoidance estimations

The introduction of the proposed energy systems will allow to reduce the carbon footprint of the maritime terminals in the ports of the Balearic archipelago. The annual trends of the emissions avoided in the different configurations are presented in *Figure 81*, keeping in mind that each profile coincides qualitatively with that of the associated annual electricity produced (the two variables are linked between each other by the emission factor).

For all the stand-alone configurations with CL generators, the annual profile is constant, meaning that for each building the fuel cell and the storage selected are large enough to generate a constant electric output over the entire project lifetime. The emissions avoided with this operational mode are always higher than those with LF fuel cells due to the contribution of the electricity surplus.

The sudden increments in the LF profiles correspond to the years in which stack replacements occur, contrarily to the case of the hydrogen demand. With this operational mode, the trend of the emissions

avoided progressively decreases between two stack replacements, although the hydrogen consumption follows the opposite path.

### Annual CO<sub>2</sub> emissions avoided

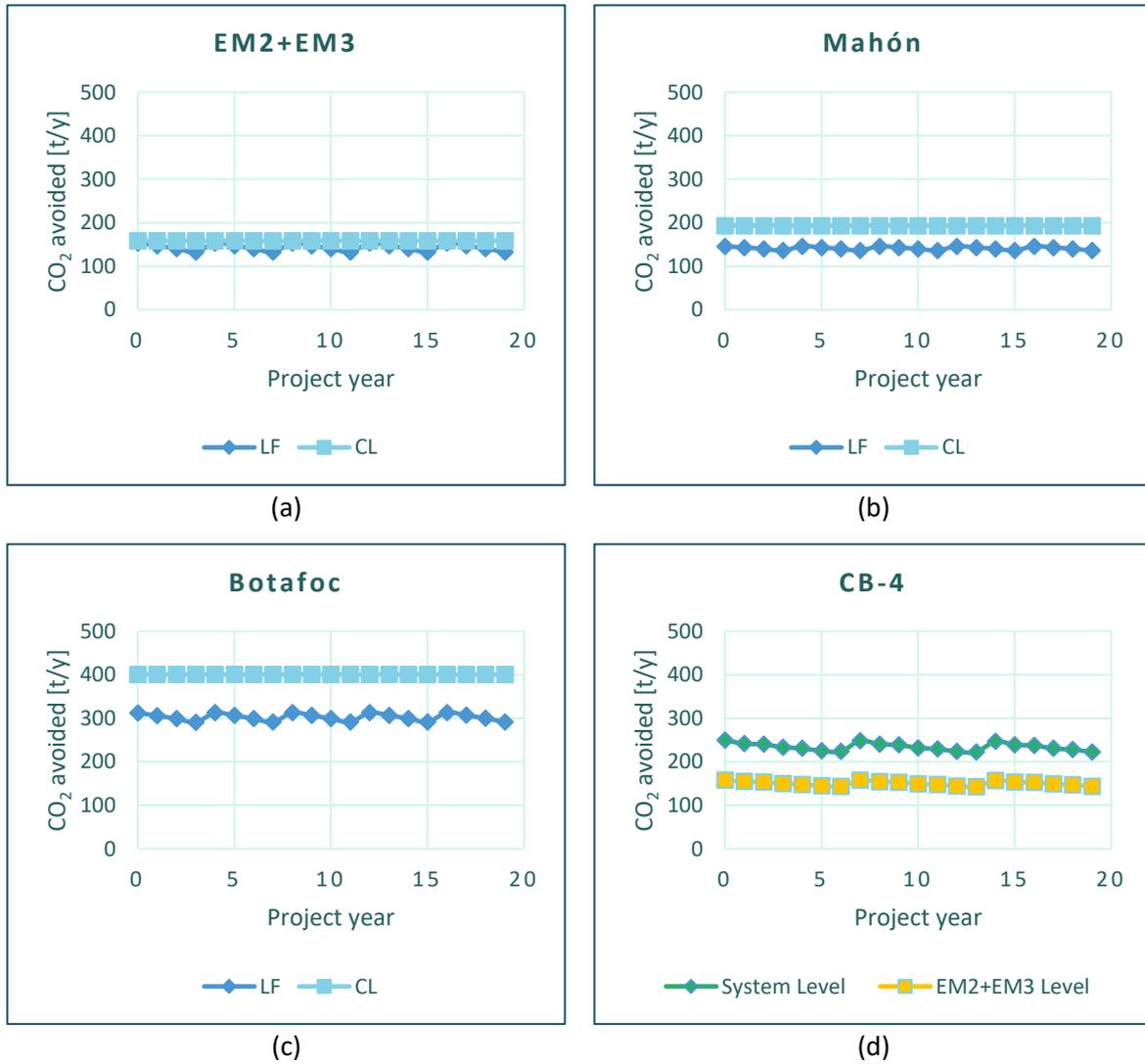


Figure 81: Annual profiles of CO<sub>2</sub> emissions avoided for the three stand-alone configurations and CB-4, at daily frequency of charge and for both the operational modes.

For the combined configuration, the emissions avoided are not only associated to the production of the two fuel cells, but also to the new photovoltaic system dedicated to EM2+EM3. Comparing the profile at EM2+EM3 level with the LF one for the same building, the former shows slightly better results at this level, however, from the economic point of view the system configuration brings more benefits overall, thanks to the combination of a new PV system and the use of the electricity surplus coming from EM4. The estimations of the emissions that would be avoided over the entire project lifetime are recapitulated in *Table 38*.

Table 38: Estimation of the emissions reduction over the entire project lifetime for the selected configurations

Configuration	Operational mode / Level	Energy produced over the project [MWh]	Lifetime CO <sub>2</sub> avoided [ton]
<b>EM2+EM3</b>	LF	9,023	2,875
	CL	9,877	3,147
<b>Mahón</b>	LF	8,588	2,831
	CL	11,738	3,869
<b>Botafoc</b>	LF	21,296	6,049
	CL	28,179	8,004
<b>CB-4</b>	System Level	10,078	4,684
	EM2+EM3 Level	3,459	3,002

## 9 Risks assessment

The risk matrix analysis is a tool used in project management to assess and address risks associated with an electricity production project using fuel cells. It focuses on identifying specific risks related to project operations and provides a framework for evaluating the probability and impact of each identified risk.

In this context, the deployment phase of the GREEN HYSLAND project already has its own risk assessment identified in the deliverable D3.1 (Enagás S.A., 2022), indicating that risks associated with that phase have been identified and analysed. It covers areas such as the safety, aspects of a regulatory nature where criticalities might rise due to a lack of regulations suitable for hydrogen projects, tendering processes issues, or due to unforeseen regulatory barriers that could restrict, or dimension some during the permitting procedures. However, continuous risk analysis throughout the project is important, to ensure that operational risks are properly managed, and measures are taken to mitigate them. The table below present additional risks and their mitigations measures.

Table 39: Risk matrix of the system analysed.

Risk description	Implications	Likelihood	Impact	Mitigation measures
<b>The equipment delivered presents some defects; the component cannot be used in the site.</b>	The system cannot operate if some of its components are defective.	Low	High	<ul style="list-style-type: none"> <li>Quality Assurance and Inspection: Implement a comprehensive quality assurance process to thoroughly inspect the equipment upon delivery.</li> <li>Supplier Communication and Contractual Clauses</li> <li>Pre-Installation Testing</li> </ul>
<b>There are delays in the delivery of one or more components.</b>	The system is not ready to operate.	Medium	High	<ul style="list-style-type: none"> <li>Be in constant communication with the suppliers, to be immediately informed in case of delay.</li> <li>Keep contact with different suppliers, as alternative of the first-choice supplier.</li> </ul>
<b>Changes in the use of the site and therefore changes in</b>	H <sub>2</sub> logistics might need to be adapted	Low	Medium	<ul style="list-style-type: none"> <li>Flexibility in Design</li> <li>Regular Monitoring and Forecasting</li> </ul>

Risk description	Implications	Likelihood	Impact	Mitigation measures
<b>the expected H<sub>2</sub> consumption</b>				<ul style="list-style-type: none"> <li>• Flexible Supply Agreements</li> <li>• Scenario Planning</li> </ul>
<b>Components failure during operations</b>	The system would stop operating	Low	High	<ul style="list-style-type: none"> <li>• Warranty and Maintenance Agreements</li> <li>• Come up with a monitoring plan</li> <li>• Performing predictive maintenance on regular basis</li> </ul>
<b>Incidents associated to the operations</b>	Physical or chemical hazards could cause physical harm to personnel or equipment	Low	High	<ul style="list-style-type: none"> <li>• Comprehensive Training and Procedure</li> <li>• Incident Reporting and Investigation:</li> <li>• Safety Protocols</li> <li>• Continuous Monitoring and Improvement</li> </ul>
<b>Safety review of the site takes longer than planned</b>	Delays in the execution and final commissioning	Low	Medium	<ul style="list-style-type: none"> <li>• Taking a comprehensive and structured approach to identifying risks and complete the associated actions to de-risk</li> </ul>
<b>Safety concerns of the general public about the new systems</b>	Delays, lack of acceptance of the technologies	Low	Low/Medium	<ul style="list-style-type: none"> <li>• Sharing knowledge about these new technologies</li> <li>• Transparent Communication</li> <li>• Collaborate with regulatory Authorities</li> <li>• Demonstrate Safety Measures</li> </ul>

## 10 Conclusions and recommendations

The techno-economic assessment conducted for the decarbonisation of sea-ferry stations in the Balearic Islands has provided valuable insights into the potential of integrating renewable energies, hydrogen storage, and fuel cells to deliver clean and efficient electricity to the targeted maritime terminals. This was achieved through the development of a comprehensive methodology and a mathematical model, enabling a cost-benefit assessment (CBA) based on performance indicators specifically defined for this study, included the Levelized Cost of Electricity (LCOE) Energy Autonomy (EA), lifetime cost savings (LCAS), and CO<sub>2</sub> emissions reduction. Therefore, the study effectively evaluates the economic viability and environmental benefits of implementing a green hydrogen-based hybrid energy under assessment.

Moreover, the model allows to include the effect of three operational aspects such as the fuel cell operational mode, the frequency of recharge of the hydrogen fuel cell system and transferrable mass of hydrogen during recharge ops. The storage design used as a reference is the one proposed for the EM4 in Mallorca in the context of the deployment of the GREEN HYSLAND project.

Following extensive research on the hydrogen fuel cells market and their latest technical developments, as well as a comprehensive analysis of the economic and environmental factors specific to the Balearic Islands and the European context, a preliminary assessment of hydrogen technologies has been conducted for various technical solutions at the maritime terminals in Mallorca, Menorca, and Ibiza. The identified technologies primarily include PEM fuel cells, complemented by PV solar systems where applicable.

Moreover, during this process, the energy demand of the buildings within the scope of the project was determined. This step was crucial for determining the optimal sizing and capacity requirements of the hydrogen systems, ensuring they can effectively meet the energy needs of the maritime terminals. The forecast of the annual energy demand of the two maritime terminals projected to be operational in the future, Mahón in Menorca and Botafoc in Ibiza, has been thoroughly estimated based on available information to date, although they remain uncertain.

Based on the above, the study has identified the conceptual design of different configurations that would provide low carbon energy to the different buildings, providing a range of technical solutions for different combinations of fuel cell, hydrogen storage and PV solar installed capacity if applicable. The selection of the configurations to be considered is based on a selection criterion:

- The system should achieve at least 80 % energy autonomy (independence from the grid) at the lowest cost possible.
- At the same time, this criterion allows to identify the highest emissions reduction possible and costs savings for Port of Balears because of the decrease of the electricity consumption from the grid.

Overall, for all four buildings under study (EM2, EM3, Botafoc (Ibiza) and Mahón (Menorca)), the estimated future annual green hydrogen demand ranges from 160 to 215 tons per year, while the estimated range for CO<sub>2</sub> reduction is between 700 and 910 tons per year.

When comparing the results between fuel cells operated in load following (LF) mode and constant load (CL) mode, several advantages were identified and quantified by the study. In the LF mode, certain benefits were observed, including a smaller footprint required in facilities compared to the CL mode.

This means that the LF mode allows for more compact installations, potentially saving space and reducing infrastructure costs. In contrast to the advantages mentioned earlier, one disadvantage of load-following (LF) fuel cells is that they tend to have higher long-term capital expenditures (CAPEX) compared to constant load (CL) mode. This is primarily due to the more frequent replacement of the fuel cell stack in LF mode. The continuous adjustments in power output and varying operating conditions in LF mode can lead to increased wear and tear on the stack, necessitating more frequent replacements over the system's lifetime.

When evaluating the choice between LF and CL modes, it becomes essential to consider the trade-off between higher long-term CAPEX in LF mode and lower initial investments. This assessment should take into account the specific needs and priorities of the project, such as the expected lifetime of the system, budget constraints, and operational requirements. The model developed in this study allowed to perform that analysis in a quantitative manner, it was determined, under the assumptions of the study, that the actualised capital costs can of the stack 15 to 17 % LCOE reduction every degradation factor unit reduction (0.1 % /1000 h).

Another specific finding from the analysis is that in cases where the demand profile of a building exhibits minimal or negligible oscillations due to seasonal changes, constant load (CL) mode becomes more favourable compared to load-following (LF) mode. In such situations, where the power requirements remain relatively stable throughout the year, CL mode offers a simpler and potentially more cost-effective solution. That was the case for the combined configuration of maritime terminals EM2 and EM3.

The CL mode provides benefits in terms of surplus power generation, resulting in economic savings and overall reduction in CO<sub>2</sub> emission higher for an equivalent equipment operating in LF mode. However, it is important to consider that CL mode often requires larger initial investments, particularly in terms of storage infrastructure. The application of CL mode may be limited by constraints related to the available space for storage facilities or other regulatory or safety barriers, which can be solved by choosing an LF operational mode instead, as described in the analysis of the maritime terminal of Mahón in Menorca.

It is evident that the minimum levelized cost of electricity (LCOE) does not always correlate with achieving the highest energy autonomy (EA) efficiency. The trade-off between lower LCOE and greater energy independence depends on the shape and characteristics of the demand profile. Solutions that achieve an energy autonomy equal to or greater than 80% at minimum LCOE costs represent well-balanced choices based solely on these indicators. The difference in LCOE costs between achieving EA > 80% at minimum LCOE and reaching the absolute minimum while attaining the same EA target is relatively small in most the analysed cases. However, the scale up cost reduction required to achieve maximum grid independency and therefore maximize the CO<sub>2</sub> emissions reduction are more difficult to reach.

Consequently, the incremental capital investment costs to achieve an additional 10-16% increase in EA are extremely high especially for Load following operations. For example, the results for Mahón indicate there is an increase of 30 % in LCOE with only an additional 14.6 % EA benefit, and excessive initial capital investments and operational expenditures.

The integration of a solar photovoltaic (PV) system into the energy system for the maritime terminals in the port of Palma de Mallorca offers significant economic advantages, especially in the selected combined configuration (CB4). This configuration leverages surplus electricity from the EM4 maritime

terminal, which includes a 110-kW fuel cell system deployed by the GREEN HYSLAND project, existing PV panels in EM4, and proposed additional PV solar panels for EM2+EM3, complemented by a hydrogen fuel cell. In the Balearic Islands setting, there is a favourable combination of high solar energy output during the summer period, which coincides with the peak activity level in the maritime terminals. This means that the demand for electricity is higher when solar energy production is at its peak. Consequently, the gap to be filled by the energy supplied by the fuel cell is smaller compared to a scenario without the input from EM4 and solar panels.

Another advantage is that by utilising surplus electricity generated by the PV systems and the fuel cell, the maritime terminals can significantly reduce their reliance on external energy sources, such as the grid. This leads to substantial cost savings by offsetting the need to purchase electricity from conventional sources. Additionally, the integration of solar PV systems reduces operating costs. A comparison of the hybrid fuel cell system with other available options like battery-based systems, in order to improve LCOE values versus those presented here, may be the subject of further work.

It is acknowledged that a combination of wind and solar power (e.g. via PPAs) may provide green electricity potentially yielding lower LCOE values than those obtained in this analysis. However, as of today, the deployment of wind power in the Balearic Islands is unlikely due to significant public opposition and planning permission challenges (mainly due to visual impacts and environmental concerns). Therefore, solar PV is currently the most favourable option to supply green electricity under the scenarios considered in the Balearic islands, and therefore other renewable electricity sources are not considered have not been considered in this analysis.

The analysis of a combined configuration for EM2+3 can be replicated in future analyses for Botafoc and Mahón maritime terminals. However, there are certain factors that need to be taken into consideration for each location. In the case of Mahón, there is a need for further definition in the maritime terminal construction project to gain a better understanding of their energy demand. This is necessary to accurately assess the feasibility and design of the energy system integration.

On the other hand, for Botafoc, there is a high level of uncertainty in the energy demand forecast. This uncertainty poses a challenge in determining the optimal configuration and sizing of the energy system. Therefore, additional analysis and data gathering are required to obtain a clearer picture of the energy requirements in order to replicate the successful CB configuration analysis carried out for EM2+3. The assumptions over the transferrable mass per hydrogen storage system recharge is valid for the design used as a reference and is particularly valid for the Mallorca Island. This is another assumption, that will need to be revised in the future to more accurately assess the hybrid system solutions in Menorca and Mallorca.

With regards to the frequency of charge and by comparison of Costs Estimates for EA ≥ 80% energy systems solutions in Menorca, cost wise, CL mode is a better option with a frequency of hydrogen recharge of 3 days, if a lower frequency is required because of logistics issues or the distribution if hydrogen could be done by pipelines, then LF mode recharging every five days seems to be a better choice despite its higher costs.

The hydrogen fuel costs constitute the primary element of the operational expenditure (OPEX) according to the economic model outlined in the study. Through the sensitivity analysis of hydrogen prices, it was determined that the absolute variation in price has a more significant influence on the levelized cost of electricity (LCOE) compared to the rate of decline in price over the next 20 years. Consequently, it is essential to focus on reducing costs throughout the entire value chain upstream.

The quantified impact reveals that a reduction of one euro in hydrogen price leads to a 7% decrease in LCOE.

In the context of the GREEN HYSLAND project in the Balearic Islands, key learnings are expected to emerge regarding OPEX costs beyond hydrogen price. Specifically, the project aims to gain insights into the OPEX associated with the storage system and fuel cell technologies. These areas remain open questions and present opportunities for further understanding of the operational costs involved in maintaining and operating these components of the energy system.

The study acknowledges several limitations. Firstly, the explicit assessment of distribution costs is not possible as it is not defined as a separate variable. Additionally, the impact of subsidies is not evaluated in the cost estimations, which may influence the overall economic analysis. Furthermore, the study highlights the uncertainty surrounding regulations for green hydrogen applications, their implications in the results of the study remain uncertain and will need further assessment in the future.

In the long term, an upgrade of the interconnection between the island of Majorca and mainland Spain could potentially facilitate an increase of renewable electricity supply from Spanish Wind and also PV to complement the PV supply deployed in the Balearic islands, potentially reducing LCOE. However, at the time of the completion of the analysis presented here, an upgrade of the existing interconnector between Majorca and mainland Spain is currently unlikely due to planning permission challenges and significant public local opposition (due to potential impacts on local ecosystems). Therefore, this has not been considered in this analysis and may need further assessment in the future.

In addition to these limitations, the study incorporates a risk assessment, primarily focusing on the operational phase of the project. This risk assessment complements the existing one conducted for the overall project, providing a more comprehensive understanding of the potential risks involved.

Overall, these limitations and risk assessments provide valuable insights into the areas that require further attention and consideration in future studies and project implementation.

## 11 List of Figures

Figure 1: View of the sea-ferry passengers terminal buildings EM4 (front) in the Port of Palma de Mallorca (Autorita Portuària de Balears, 2023)

Figure 2: Shows the relative location of the ports included in this report: Palma, Ibiza and Mahón (Autoritat Portuaria de Balears, 2022)

Figure 3: Schematic view of the *Puerto de Palma* (Autoritat Portuaria de Balears, 2021), with zoom on EM2, EM3 and EM4

Figure 4: Schematic view of the *Puerto de Eivissa (Ibiza)* (Autoritat Portuaria de Balears, 2020), with zoom on the maritime terminal of *Botafoc*

Figure 5: Schematic view of the *Puerto de Mahón* (Autoritat Portuaria de Balears, 2021), with zoom on the future location of the new maritime terminal

Figure 6: Generic schematic of GREEN HYSLAND project, with focus on the system dedicated to the port buildings for the present study.

Figure 7: Electricity interconnections of the Balearic Archipelago (Red Electric Española, 2022)

Figure 8: Electricity demand and generation mix in the Balearic Islands between 2010 and 2021 (IBESTAT, 2022)

Figure 9: EM2 historical electricity demand, provided by *Autoridad Portuaria de Baleares*

Figure 10: EM2 daily electricity demand as function of time (in hours)

Figure 11: Daily demand of EM2 as function of time expressed in month (a) and weekday (b)

Figure 12: Comparison between actual trend and the one obtained with CMA for EM2

Figure 13: New demand profile of EM2 on hourly (a) and monthly (b) basis

Figure 14: EM3 historical electricity demand, provided by *Autoridad Portuaria de Baleares*

Figure 15: EM3 hourly electricity demand as function of time (in hours)

Figure 16: Daily demand of EM3 as function of time expressed in month (a) and weekday (b)

Figure 17: Comparison between actual trend and the one obtained with CMA for EM3

Figure 18: New demand profile of EM3 on hourly (a) and monthly (b) basis

Figure 19: Projected monthly electricity demand for EM4 (IDOM, 2021)

Figure 20: New demand profile of EM4 on hourly basis

Figure 21: Screenshot from PVGIS to obtain the hourly PV production for Botafoc

Figure 22: Projected monthly electricity demand for *Botafoc*

Figure 23: New demand profile on hourly basis for *Botafoc*

Figure 24: New demand profile of Mahón on hourly (a) and monthly (b) basis

Figure 25: Installation of fuel cells in thousands of units worldwide, between 2014 and 2018

Figure 26: Main components of the tube trailer (CALVERA Hydrogen S.A., 2023)

Figure 27: Mobile storage unit provided by CALVERA (Autoritat Portuària de Balears, 2022)

Figure 28: Planned fuel cell and storage system to be deployed at Estación Marítima 4. The hazardous zone is marked with a light striped red symbol within the figure and referred to as the "área peligrosa" in the legend (Autorita Portuària de Balears, 2023)

Figure 29: Scheme of the new energy system to provide electricity to the maritime terminals

Figure 30: Flow diagram of the mathematical model of a hybrid system with a load-following fuel cell

Figure 31: Flow diagram of the mathematical model of a hybrid system with fuel cell operating in constant mode

Figure 32: Fuel cell efficiency as function of the partial load (Eastlack et al., 2019)

Figure 33: H<sub>2</sub> transferable in the storage varying the number of storage units (IDOM, 2022)

Figure 34: Satellite view of EM2, EM3, and the parking roofs associated, and available surface on these roofs

Figure 35: Load duration curve of EM2+EM3

Figure 36: Future projection for CAPEX for the fuel cell stack (Bednarek, Davies, Malkow, & Weidner, 2021) (Hydrogen Europe, 2020)

Figure 37: Future projections for O&M costs of fuel cell (Hydrogen Europe, 2020) (Okundamiya, 2021) (Singh, Chauhan, & Singh, 2020)

Figure 38: Assumed H<sub>2</sub> production cost and profit margin in Mallorca

Figure 39: H<sub>2</sub> purchase price for the buildings in Mallorca, and future trend

Figure 40: H<sub>2</sub> purchase price for the buildings in Ibiza and Menorca, and future trend

Figure 41: Tariff periods for Balearic Islands, provided by Autoridad Portuaria de Baleares (Naturgy, 2022)

Figure 42: Schematic representation of the reference case for the combined system configurations for costs and emissions savings calculations (current situation)

Figure 43: Schematic representation of the combined system configuration CB-1

Figure 44: Schematic representation of the combined system configuration CB-2

Figure 45: Schematic representation of the combined system configuration CB-3

Figure 46: Schematic representation of the combined system configuration CB-4

Figure 47: CBA parameters for EM2+EM3 (load-following fuel cell and daily frequency of charge)

Figure 48: Relationship between energy autonomy and LCOE for EM2+EM3 (load-following fuel cell and daily frequency of charge)

Figure 49: Relation between energy autonomy and LCOE for Mahón (a) and Botafoc (b) (load-following fuel cell and daily frequency of charge)

Figure 50: LCOE and EA values for All stand-alone configurations (load-following fuel cell and daily frequency of charge)

Figure 51: Electricity supplied by different energy sources for EM2+EM3 (load-following fuel cell and daily frequency of charge)

Figure 52: Electricity supplied by different energy sources for Botafoc (load-following fuel cell and daily frequency of charge)

Figure 53: Electricity supplied by different energy sources for Mahón (load-following fuel cell and daily frequency of charge)

Figure 54: CBA parameters for EM2+EM3 constant-power fuel cell and daily frequency of charge.

Figure 55: EA and LCOE for EM2+EM3 at constant-power fuel cell and daily frequency of charge

Figure 56: Relation between energy autonomy and LCOE for Mahón (a) and Botafoc (b) (constant-load fuel cell and daily frequency of charge)

Figure 57: LCOE and EA values for All stand-alone configurations (constant fuel cell - daily frequency of charge)

Figure 58: Electricity supplied by different energy source by sources for EM2+EM3 (constant-load fuel cell and daily frequency of charge)

Figure 59: Electricity supplied by different energy source to Botafoc (constant-load fuel cell and daily frequency of charge)

Figure 60: Electricity supplied by different energy source by sources for Mahón (constant-load fuel cell and daily frequency of charge)

Figure 61: Hydrogen Fuel cell system - Frequency of charge at different operational modes (MSC active) -Botafoc

Figure 62: Hydrogen Fuel cell system - Frequency of charge at different operational modes (MSC active) -Mahón

Figure 63: Monthly demand coverage for CB-4, at the solutions that achieve the target of 80% energy autonomy (daily frequency of charge)

Figure 64: Cost Estimates - Mahón

Figure 65: Costs Estimates – Botafoc configuration

Figure 66: Distribution of CAPEX (a) and OPEX (b) for EM2+EM3 (LF fuel cell and daily frequency of charge)

Figure 67: Comparison of Costs Estimates for EA $\geq$  80% energy systems solutions in Mallorca

Figure 68 : Distribution of CAPEX for CBA-4, at the solutions that achieve the minimum target of 80% of energy autonomy (daily frequency of charge)

Figure 69 : Cost Estimates - EM2+EM3 Solutions

Figure 70 : Distribution of OPEX for CBA-4, at the solutions that achieve the minimum target of 80% of energy autonomy (daily frequency of charge)

Figure 71 : Comparison of Costs Estimates for EA $\geq$  80% energy systems solutions in Menorca

Figure 72 : Efficiency curves considered in the sensitivity analysis for the load-following fuel cells

Figure 73 : Hydrogen prices considered for the sensitivity analyses (case of EM2+EM3 at daily frequency of charge)

Figure 74 : Relation between LCOE and degradation factor of the fuel cell

Figure 75 : Relation between LCOE and the maximum allowed power loss before the fuel cell stack replacement

Figure 76 : Relation between LCOE and the fuel cell stack CAPEX

Figure 77 : Relation between LCOE and the fuel cell efficiency

Figure 78 : Relation between LCOE and hydrogen purchase price (absolute variation)

Figure 79 : Relation between LCOE and different hydrogen price decline rate

Figure 80 : Annual hydrogen demand profiles for the three stand-alone configurations and CB-4, at daily frequency of charge and for both the operational modes

Figure 81 : Annual profiles of CO<sub>2</sub> emissions avoided for the three stand-alone configurations and CB-4, at daily frequency of charge and for both the operational modes.

## 12 List of Tables

Table 1: Sea-Ferry stations considered in the decarbonisation study

Table 2: Electricity generation by source in the Balearic islands in 2019 (IBESTAT, 2022)

Table 3: Main functions and characteristics of the buildings analysed

Table 4: *Botafoc* yearly electricity demand and its allocation between PV plant and grid (source)

Table 5: Total emission factor of the different port sites

Table 6: CO<sub>2</sub> emissions due to electricity consumption of the maritime terminals

Table 7: Worldwide Installation of fuel cells in thousands of units, between 2014 and 2018 (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019)

Table 8: Types of commercially available fuel cells suitable for different power ranges (Felseghi, Carcadea, Raboaca, Trufin, & Filote, 2019) (Bednarek, Davies, Malkow, & Weidner, 2021)

Table 9: Comparison of the main technical parameters of PEMFCs and SOFCs

Table 10: Stack CAPEX and O&M costs for PEMFCs of different power ranges (Hydrogen Europe, 2020)

Table 11: Decrease in micro-CHP costs and installed volume per unit, between 2012 and 2017

Table 12: Projected PEMFCs costs in the range of 50-500 kW (Hydrogen Europe, 2020)

Table 13: Hydrogen storage units vs surface occupied

Table 14: Technical maximum number of storage units per building, and correspondent space occupied

Table 15: Lifetime costs of the different components of the hydrogen storage unit

Table 16: Road transport costs at different amount of hydrogen delivered, in the mainland and in the Balearic Islands for the first ten years

Table 17: Fixed and variable costs related to the electricity consumption from the grid

Table 18: Stand-alone configurations analysed and their reference case for CO<sub>2</sub> emissions and costs savings calculations

Table 19: Combined configurations analysed and their reference case for CO<sub>2</sub> emissions and costs savings calculations

Table 20: Additional technical specifications assumed for the combined configurations cases

Table 21: Fuel cell nominal power required for the different stand-alone systems

Table 22: Size of the systems at maximum energy output and corresponding CBA parameters, for the systems with load-following fuel cell and frequency of charge of 1 day

Table 23: Solutions for EM2+EM3 based on CBA criteria (load-following fuel cell and daily frequency of charge)

Table 24: System solutions for Mahón based on CBA criteria (load-following fuel cell and daily frequency of charge)

Table 25: System configuration solutions for Botafoç based on CBA criteria (load-following fuel cell and daily frequency of charge)

Table 26: System size to achieve the minimum energy autonomy target of 80% at the minimum cost for stand-alone configuration (load-following fuel cell at daily frequency of charge)

Table 27: Energy output and hydrogen demand over the entire project lifetime for the configurations at energy autonomy higher than 80% (load-following fuel cell and daily frequency of charge)

Table 28: Results at different values of LCOE and energy autonomy for EM2+EM3 (constant-load fuel cell and daily frequency of charge)

Table 29: System solutions for Mahón based on CBA criteria (constant-load fuel cell and daily frequency of charge)

Table 30: System configuration solutions for Botafoç based on CBA criteria (constant-load fuel cell and daily frequency of charge)

Table 31: System size to achieve the minimum energy autonomy target of 80% at the minimum cost for all the configurations (constant-load fuel cell at daily frequency of charge)

Table 32: Energy output and hydrogen demand over the entire project lifetime for the configurations at energy autonomy higher than 80% (constant-load fuel cell and daily frequency of charge)

Table 33: Energy output and hydrogen demand of the two operational modes for the configuration EM2+EM3 (daily frequency of charge)

Table 34: Combined Configuration Results summary table (at system level)

Table 35: Combined Configuration Results summary table (at EM2+EM3 level)

Table 36: Combined Configuration Results summary table

Table 37: Hydrogen demand over the entire lifetime for the selected configurations

Table 38: Risk matrix of the system analysed

Table 39: Estimation of the emissions reduction over the entire project lifetime for the selected configurations

## 13 References

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## Appendix A. Model inputs: Fuel cell stack CAPEX

The starting value for the stack CAPEX is 6200 €/kW, taking as reference the fuel cell installed in Estación Marítima 4. The values for the future years were calculated considering the decreasing trend in CAPEX given in the *Strategic Research and Innovation Agenda* (Hydrogen Europe, 2020), as follows.

Year	CAPEX Hydrogen Europe (%)	CAPEX Report
0	6,000 €/kW	6,200 €/kW
4	5,000 €/kW (83%)	5,200 €/kW (84%)
10	4,000 €/kW (67%)	4,000 €/kW (65%)
20	NO info available	3,000 €/kW (assumed a reduction equal to 50% of that occurred in the first decade)
30	NO info available	3,000 €/kW (no changes were assumed)

These values are compatible with those reported in the technical report *Historical Analysis of FCH 2 JU Stationary Fuel Cell Projects* for the PEMFC between 5 and 400 kW (Bednarek, Davies, Malkow, & Weidner, 2021).

## Appendix B. Model inputs: Fuel cell OPEX

The OPEX include only O&M costs. The starting value was set equal to 0.02 €/kWh. The following sources have been consulted:

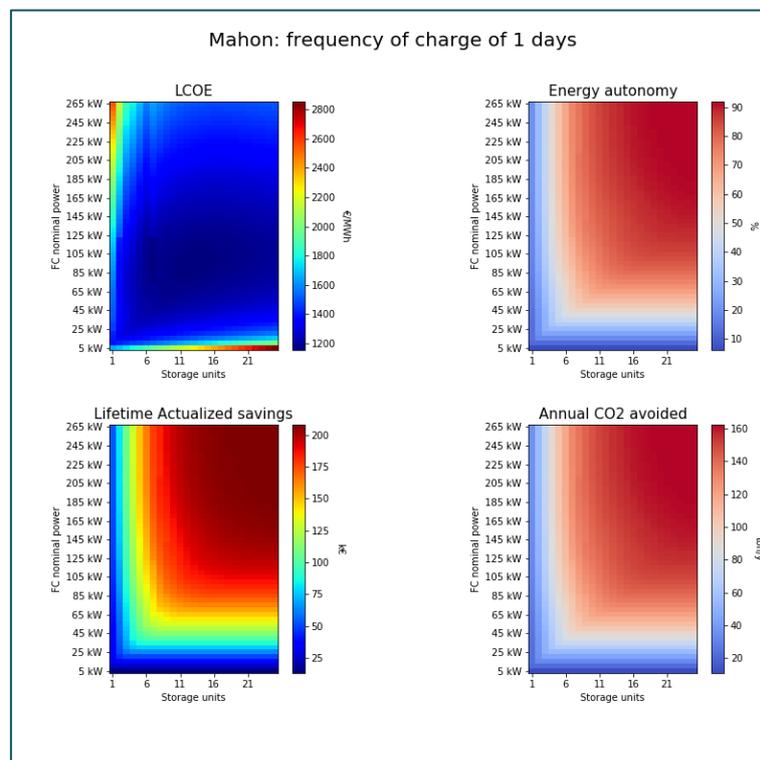
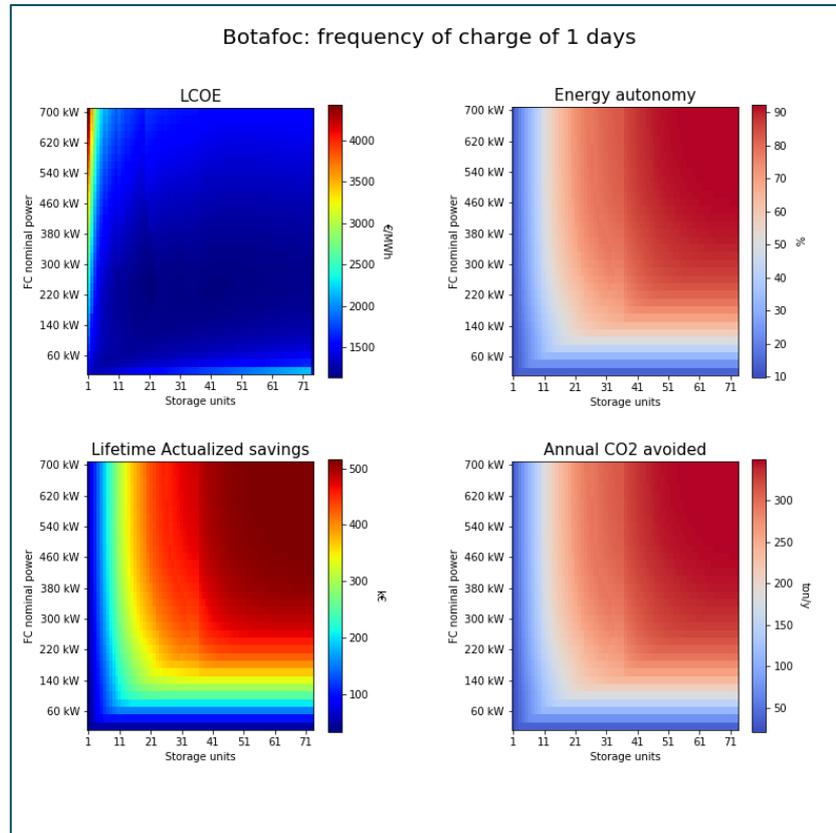
- Singh et al. (Singh, Chauhan, & Singh, 2020) used 0.01 \$/kWh for a PEMFC of 1 kW. Since the study deals with fuel cells of bigger size, a higher value should be chosen;
- Okundamiya (Okundamiya, 2021) used 0.015 \$/kWh for PEMFC of different size.

The values for the future years were calculated with the same approach adopted for the stack CAPEX.

Year	O&M Hydrogen Europe (%)	Resulting O&M
<b>0</b>	0.01 €/kWh	0.02 €/kWh
<b>4</b>	0.008 €/kWh (80%)	0.016 €/kWh (80%)
<b>10</b>	0.004 €/kWh (40%)	0.008 €/kWh (40%)
<b>20</b>	NO info available	0.006 €/kWh (assumed a reduction equal to 15%-20% of that occurred in the first decade)
<b>30</b>	NO info available	0.005 €/kWh (assumption)

## Appendix C. LF-FC at 1 day charge: CBA parameters

The heatmaps of the four CBA parameters are presented for Mahón and Botafoç.



## Appendix D. LF-FC at 1 day charge: energy output and H<sub>2</sub> demand

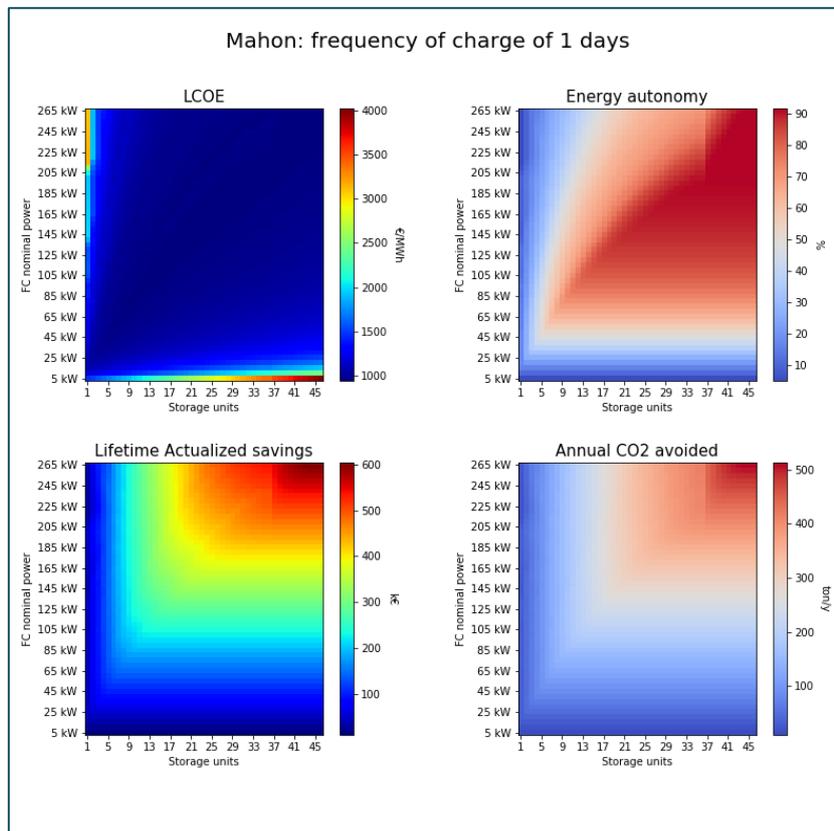
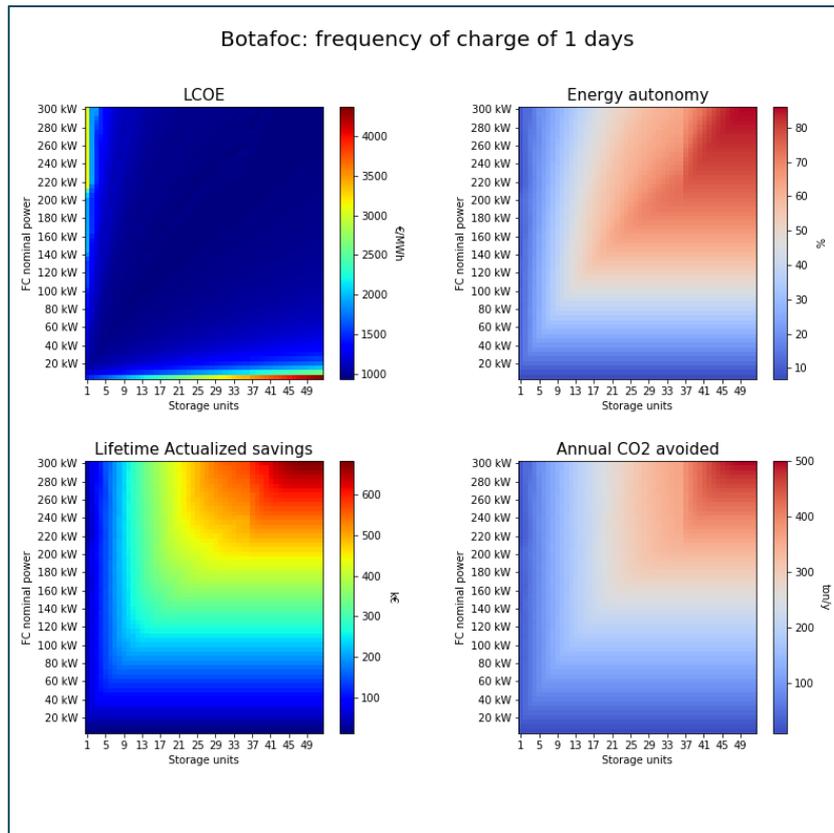
The following table is done with the solutions that minimize the LCOE of each configuration.

Stand- Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	E <sub>FC,TOT</sub> [MWh]	E <sub>FC,self-cons.</sub> [MWh]	E <sub>FC,PORT</sub> [MWh]	H <sub>2</sub> <sub>lifetime</sub> [ton]
<b>EM2+EM3</b>	115	11	10,016	10,016	0	763
<b>Botafoc</b>	240	23	16,940	16,940	0	1,398
<b>Mahón</b>	95	13	8,504	8,504	0	716

The following table is done with the solutions that maximize the EA of each configuration.

Stand- Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	E <sub>FC,TOT</sub> [MWh]	E <sub>FC,self-cons.</sub> [MWh]	E <sub>FC,PORT</sub> [MWh]	H <sub>2</sub> <sub>lifetime</sub> [ton]
<b>EM2+EM3</b>	165	14	10,341	10,341	0	728
<b>Botafoc</b>	700	73	24,627	24,627	0	1,725
<b>Mahón</b>	265	25	9,845	9,845	0	690

## Appendix E. CL-FC at 1 day charge: CBA parameters



## Appendix F. CL-FC at 1 day charge: energy output and H<sub>2</sub> demand

The following table is done with the solutions that minimize the LCOE of each configuration.

Stand- Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	E <sub>FC,TOT</sub> [MWh]	E <sub>FC,self-cons.</sub> [MWh]	E <sub>FC,PORT</sub> [MWh]	H <sub>2</sub> <sub>lifetime</sub> [ton]
<b>EM2+EM3</b>	150	21	17,456	10,245	7,212	1,340
<b>Botafoc</b>	300	48	34,994	22,702	12,293	2,687
<b>Mahón</b>	265	44	31,081	9,831	21,250	2,388

The following table is done with the solutions that maximize the EA of each configuration.

Stand- Alone Config.	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	E <sub>FC,TOT</sub> [MWh]	E <sub>FC,self-cons.</sub> [MWh]	E <sub>FC,PORT</sub> [MWh]	H <sub>2</sub> <sub>lifetime</sub> [ton]
<b>EM2+EM3</b>	165	26	19,373	10,354	9,019	1,489
<b>Botafoc</b>	300	50	35,224	22,896	12,328	2,706
<b>Mahón</b>	265	45	31,114	9,842	21,272	2,391

**Appendix G. Botafoç: results at different frequencies of H<sub>2</sub> charge**

Stand-Alone Config.	Operational mode	Freq CHARGE [days]	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Max. H <sub>2</sub> working mass [Kg/deliv.]	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>Botafoç</b>	LF	1	240	42	370.1	1,148	80.4	448,249	302
<b>Botafoç</b>	CL	1	240	41	359.2	940	80.1	546,771	400.2
<b>Botafoç</b>	LF	2	220	91	780.9	1,226	80.0	435,981	301.0
<b>Botafoç</b>	CL	2	240	82	702.6	989	80.0	546,231	400
<b>Botafoç</b>	LF	7	700	120	1,012.9	2,009	55.1	285,467	201.4
<b>Botafoç</b>	CL	7	130	120	1,012.9	1,202	48.9	255,609	186

**Appendix H. Mahón: results at different frequencies of H<sub>2</sub> charge**

Stand-Alone Config.	Operational mode	Freq CHARGE [days]	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Max. H <sub>2</sub> working mass [Kg/deliv.]	LCOE [€/MWh]	EA [%]	LACS [€]	ΔCO <sub>2</sub> [ton/y]
<b>Mahón</b>	LF	1	100	13	148.7	1,156	80.1	181,921	141.6
<b>Mahón</b>	CL	1	100	13	148.7	944	80.3	227,782	193.5
<b>Mahón</b>	LF	5	175	70	575.1	1,526	80.2	176,620	141.7
<b>Mahón</b>	CL	3	100	50	448.8	1,049	80.3	227,821	193.5
<b>Mahón</b>	LF	7	265	70	575.1	1,832	69.7	154,300	123.2
<b>Mahón</b>	CL	7	65	70	575.1	1,257	60	139,604	119

## Appendix I. Stand-alone configurations at 1 day charge: costs summary

The following table refers to the solutions that minimize the LCOE of each configuration.

Stand- Alone Config	Operational mode	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Initial Investment [€]	Total Act. Capex [€]	Act Annual. Total opex [€/y]
<b>EM2+EM3</b>	LF	115	11	1,339,100	2,654,442	227,813
<b>EM2+EM3</b>	CL	150	21	1,829,500	2,943,035	400,827
<b>Botafoc</b>	LF	240	23	2,582,100	4,608,439	430,478
<b>Botafoc</b>	CL	300	48	3,596,000	5,823,071	828,397
<b>Mahón</b>	LF	95	13	1,223,300	2,309,887	220,332
<b>Mahón</b>	CL	265	44	3,234,600	5,201,846	735,799

The following table refers to the solutions that maximize the EA of each configuration.

Stand- Alone Config	Operational mode	P <sub>FC,NOM</sub> [kW]	N <sub>ST,UNITS</sub>	Initial Investment [€]	Total Act. Capex [€]	Act Annual. Total opex [€/y]
<b>EM2+EM3</b>	LF	165	14	1,800,600	3,687,830	218,139
<b>EM2+EM3</b>	CL	165	26	2,058,600	3,283,489	444,882
<b>Botafoc</b>	LF	700	73	7,289,500	15,295,932	535,196
<b>Botafoc</b>	CL	300	50	3,639,000	5,866,071	833,757
<b>Mahón</b>	LF	265	25	2,826,100	5,857,107	214,391
<b>Mahón</b>	CL	265	45	3,256,100	5,223,346	736,629

## Appendix J. Combined configurations: costs summary

In CB-1 and CB-2, the components of the energy system have fixed size. The costs assessment for the solutions the minimize the LCOE and maximize the EA can be done for CB-3 and CB-4 only.

The following table is referred to the solutions that minimize the LCOE of CB-3 and CB-4.

Combined conf.	Level	P <sub>FC,EM4</sub> [kW]	N <sub>ST,EM4</sub>	P <sub>PV,EM23</sub> [kW]	P <sub>FC,EM23</sub> [kW]	N <sub>ST,EM23</sub>	Initial Investment [€]	Total Act. Capex [€]	Act. Annual total Opex [€/y]
<b>CB-3</b>	System	100	9	-	5	1	1,435,200	2,007,979	236,865
<b>CB-3</b>	EM2+EM3	100	9	-	50	5	696,500	1,067,678	83,627
<b>CB-4</b>	System	100	9	80	5	1	1,495,200	2,067,979	235,662
<b>CB-4</b>	EM2+EM3	100	9	80	5	1	315,700	292,818	12,814

The following table is referred to the solutions that maximize the EA of CB-3 and CB-4.

Combined conf.	Level	P <sub>FC,EM4</sub> [kW]	N <sub>ST,EM4</sub>	P <sub>PV,EM23</sub> [kW]	P <sub>FC,EM23</sub> [kW]	N <sub>ST,EM23</sub>	Initial Investment [€]	Total Act. Capex [€]	Act. Annual total Opex [€/y]
<b>CB-3</b>	System	100	9	-	165	14	2,980,100	4,740,650	319,776
<b>CB-3</b>	EM2+EM3	100	9	-	165	14	1,800,600	3,025,489	97,337
<b>CB-4</b>	System	100	9	80	165	10	2,954,100	4,714,650	309,032
<b>CB-4</b>	EM2+EM3	100	9	80	165	10	1,774,600	2,939,489	86,184



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