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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

OPTIMAL ENERGY MANAGEMENT OF A MICROGRID TO PRODUCE GREEN HYDROGEN.

Autor: Pablo Mansilla Barrionuevo

Director: Andrés Ramos Galán

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

“Optimal energy management of a microgrid to produce green hydrogen”

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2021/22 es de mi autoría, original e inédito y

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Fdo.: Pablo Mansilla Barrionuevo Fecha: 29/ 06/ 2022

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OPTIMAL ENERGY MANAGEMENT OF A MICROGRID TO PRODUCE GREEN HYDROGEN.

Author: Mansilla Barrionuevo, Pablo.
Supervisor: Ramos Galán, Andrés.
Collaborating Entity: ICAI – Universidad Pontificia Comillas

Abstract – **Hydrogen has been considered an alternative long-term energy storage to accelerate the transition to net-zero emissions. Determining its optimal generation its crucial. The project presents an hourly decision-based model to optimize the microgrid energy management and hydrogen production on a yearly basis. It establishes the daily quantity of energy to be bought, sold, stored, and produced, under hydrogen demand limitations that must be satisfied. The model is designed to be executed every day in a rolling-horizon mode, optimizing the hydrogen production by minimizing costs. Results show the main decisions to be taken when managing the microgrid. Hydrogen and energy storage behaviour are also covered. Particular attention is being paid when considering different sunlight situations and the system behaviour. Finally, a sensitivity analysis is also carried out to optimize possible future decisions.**

Keywords – Green hydrogen, microgrid, optimization model, energy storage system, electrolyser, renewable energy.

I. INTRODUCTION

The urge into developing new green hydrogen technologies and creating a more sustainable society is the main point of focus of this project. Hydrogen has been considered a possibility of long-term energy storage, along with the capability to be used in many other situations. The optimization of its generation is crucial. Determining the appropriate way to handle its behaviour may be critical to establish it as the alternative the current generation system requires.

With a 150M € investment, Iberdrola has seen the opportunity to establish Europe's biggest hydrogen production plant ever built in large-scale production, being built in Puertollano [1]. In fact, the company has seized the opportunity to become a pioneer hydrogen producer. Thus, a project has been established to determine its optimal operational functionality, which will be highly illustrated by this existing plant.

The project focuses on determining the optimal energy management of a microgrid to produce green hydrogen, by establishing an hourly decision-based model on a yearly basis. The model provides decisions regarding the purchase, sale and storage of energy, as well as production and storage of green hydrogen.

II. PROJECT DEFINITION

The plant components, in which the model is based, as described in Illustration 1, are:

- A 100MW Photovoltaic plant.
- 5MW Lithium-Ion batteries with a 20MWh capacity.
- The possibility of renewable energy purchase, mainly conformed by wind resources.
- The possibility of selling exceeding energy to the market.
- A PEM Electrolyser.
- Hydrogen Storage.

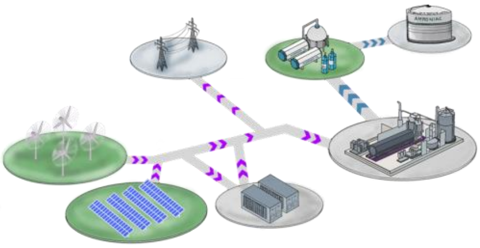


Illustration 1. Plant description.

III. OPTIMIZATION MODEL

The theoretical formulation of the electrolyser functioning has followed a usual optimization model structure, distinguishing between sets, parameters, variables, and objective function, restricted by different model constraints. The optimization model is being described hereunder:

SETS	
h	Hours, within a period of one year. [Hours]
s	Storage system (BATT, ELZ)

PARAMETERS	
$PtoH$	Production function of H2. [kg H_2/MW]
LOH^0	Initial Level of Hydrogen storage. [m^3]
BC	Battery aging cost. [€/MW]
C_s	Battery and electrolyser capacity. [MWh, m^3]
$Perf_s$	Round-trip efficiency of the storage (battery/electrolyser) system [%]
$MINsto_s$	Minimum storage. [p.u., m^3]
$MAXsto_s$	Maximum storage. [p.u., m^3]
EC_h	Energy Cost. [€/MWh]
P_{PV_h}	Photovoltaic plant power. [MW]
P_{WIND_h}	Wind farm power. [MW]
D_h	Hydrogen demand. [kg H_2]

VARIABLES	
p_{pur_h}	Power purchased. [MW]
p_{sale_h}	Power sold. [MW]
p_{charge_h}	Charge of the battery. [MW]
$p_{discharge_h}$	Discharge of the battery. [MW]
p_{elz_h}	Power entering the electrolyser. [MW]
soc_h	State of charge of the battery. [p.u.]
loh_h	Level of hydrogen. [m^3]
$prodH2_h$	Hydrogen production. [kg H_2]

Binary variables	
${\varsigma^{ps}}_h$	Binary disjunctive variable for purchasing/selling every hour. {0 selling, 1 purchasing}

OBJECTIVE FUNCTION

$$min\left(\sum_h \begin{matrix}(EC_h(p_{pur_h} - p_{sale_h}) \\ +BC \cdot p_{charge_h})\end{matrix}\right) \qquad (1)$$

CONSTRAINTS

$$p_{pur_h} \leq P_{WIND_h} \qquad \forall h \qquad (2)$$

$$p_{pur_h} \leq 100 \cdot {\varsigma^{ps}}_h \qquad \forall h \qquad (3)$$

$$p_{sale_h} \leq 100 \cdot (1 - {\varsigma^{ps}}_h) \qquad \forall h \qquad (4)$$

$$prodH2_h = p_{elz_h} \cdot PtoH \qquad \forall h \qquad (5)$$

$$\sum_h prodH2_h = \sum_h D_h \qquad (6)$$

$$loh_h = loh_{h-1} + \frac{Perf_{ELZ} \cdot prodH2_h}{C_{ELZ}} - \frac{Perf_{elz} \cdot D_h}{C_{ELZ}} \qquad \forall h \qquad (7)$$

$$\frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} + \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \leq 1 \qquad \forall h \qquad (8)$$

$$soc_h = soc_{h-1} + \frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} - \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \qquad \forall h \qquad (9)$$

$$p_{pur_h} + p_{discharge_h} + P_{PV_h} = p_{sale_h} + p_{charge_h} + p_{elz_h} \qquad \forall h \qquad (10)$$

A model representation is being displayed in Illustration 2. On it, variables are represented in lower-case letters, as well as with purple arrows. Conversely, parameters are represented in upper-case letters and with black arrows. Moreover, power flows are denoted with continuous lines, whereas hydrogen flows are displayed with dashed lines. This representation shows the model structure, identifying which elements does the model control.

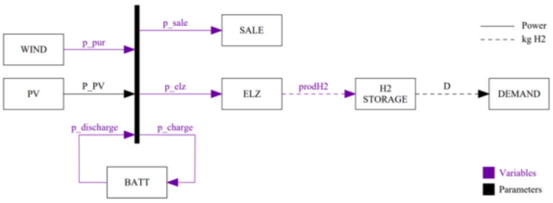


Illustration 2. Model Representation.

IV. RESULTS

After introducing every parameter data into the optimization model, specific days have been considered to describe the electrolyser plant functioning, showcasing the most and least favourable situations the plant may confront. The results show the relationship in the hourly energy balance with the energy price, as well as with the status of battery and hydrogen storage.

In High-Light Periods (Illustration 3), the amount of energy produced by the photovoltaic plant is much higher than the maximum energy required for hydrogen production, which forces the microgrid to sell the exceeding energy to the market.

Illustration 3. High-Light Period Energy Balance.

Contrarily, Low-Light Periods require energy purchase, when there is not enough photovoltaic energy generation, as displayed in Illustration 4. However, hydrogen generation is comparatively similar to the previous case.

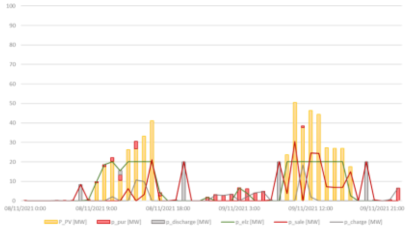
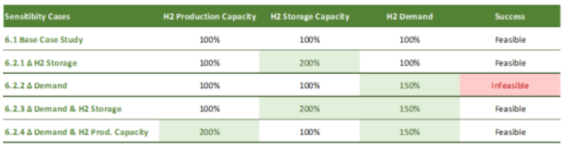


Illustration 4. Low-Light Period Energy Balance.

The Level of Hydrogen has no relationship with the light period in which is observed and depends on the relative energy cost. A relative decrease in the energy cost in a certain period prompts the system to produce during non-usual time periods (e.g., at night), even purchasing energy when having exceeding photovoltaic power generation during daylight.

As a summary of the sensitivity analysis, Diagram 1 shows whether, after modifying certain parameters of the basic model (H2 Production and Storage Capacity, and H2 Demand), the system keeps on being feasible or not.



Sensitibity Cases	H2 Production Capacity	H2 Storage Capacity	H2 Demand	Success
6.1 Base Case Study	100%	100%	100%	Feasible
6.2.1 Δ H2 Storage	100%	200%	100%	Feasible
6.2.2 Δ Demand	100%	100%	150%	Infeasible
6.2.3 Δ Demand & H2 Storage	100%	200%	150%	Feasible
6.2.4 Δ Demand & H2 Prod. Capacity	200%	100%	150%	Feasible

Diagram 1. Sensitivity Analysis.

V. CONCLUSIONS

Most of the energy produced by the photovoltaic plant is being sold to satisfy the energy balance established. Hydrogen is mainly produced using photovoltaic power, unless the energy relative cost drops heavily and producing during night periods becomes more profitable. Under low-light photovoltaic situations, when the system is not capable of providing the sufficient energy to satisfy the demand, the plant relies on purchasing energy from the market. Batteries, though, are not usually used for hydrogen production. They are mainly used for the energy sale when its cost is higher than expected.

Level of Hydrogen has been proved not to be light-dependent. The model determines that the Level of Hydrogen mainly depends on the specific relative energy costs of the period observed. This means that hydrogen will be highly produced in situations where the relative energy cost drops, independently of whether it is a high-light or a low-light period.

The current system is not capable of satisfying an increase in 50% of the demand with the basic specifications, as hydrogen production relies heavily on photovoltaic resources and large quantities of hydrogen cannot be stored. Possible solutions cover from incrementing the hydrogen storage capacity to including an additional electrolyser to increase hydrogen production.

VI. REFERENCES

[1] Iberdrola, Planta de hidrógeno verde de Puertollano. [online]. Available: https://www.iberdrola.com/conocenos/lineas-negocio/proyectos-emblematicos/puertollano-planta-hidrogeno-verde

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GESTIÓN ÓPTIMA DE ENERGÍA DE UNA MICROGRID PARA LA PRODUCCIÓN DE HIDRÓGENO VERDE.

Autor: Mansilla Barrionuevo, Pablo.
Director: Ramos Galán, Andrés.
Entidad colaboradora: ICAI – Universidad Pontificia Comillas

Abstract – El hidrógeno es una alternativa en el almacenamiento de energía a largo plazo, en aras a acelerar la transición hacia energías libres de carbono. Determinar su generación óptima es crucial. El proyecto presenta un modelo de decisión horario para optimizar la gestión energética de una microgrid y la producción de hidrógeno con carácter anual. Establece la cantidad de energía a comprar, vender, almacenar y producir sujeto a satisfacer ciertas limitaciones de demanda de hidrógeno. El modelo está diseñado para ser ejecutado diariamente en modo continuo, optimizando la producción de hidrógeno minimizando los costes. Los resultados muestran las principales decisiones a tomar durante la gestión de la microgrid. También estudia el comportamiento del almacenamiento de hidrógeno y energía. Presta especial atención a diferentes situaciones de luz solar y el comportamiento del sistema. Finalmente, lleva a cabo un análisis de sensibilidad para optimizar posibles decisiones futuras.

Palabras claves – Hidrógeno verde, microgrid, modelo de optimización, sistema de almacenamiento de energía, electrolizadora, energía renovable.

I. INTRODUCCIÓN

La principal prioridad de este proyecto es la necesidad de desarrollar nuevas tecnologías de hidrógeno verde y de crear una sociedad más sostenible. El hidrógeno se considera una posibilidad de almacenamiento de energía a largo plazo, además de usarse en muchas otras situaciones. La optimización en su generación es crucial. Determinar la forma apropiada de manejar su comportamiento puede ser crítico a la hora de considerarlo como la alternativa que el sistema de generación actual requiere.

Con una inversión de 150M €, Iberdrola ha visto la oportunidad de construir en Puertollano la mayor planta de producción de hidrógeno a gran escala a nivel europeo jamás construida [1], aprovechando la oportunidad de convertirse en pionera en la producción de hidrógeno. Por tanto, se ha establecido un proyecto para determinar su óptimo funcionamiento operacional, basado principalmente en esta planta.

El proyecto se centra en determinar la gestión energética óptima por parte de una microgrid para producir hidrógeno verde, estableciendo un modelo horario de decisión de carácter anual. El modelo proporciona decisiones relativas a la compra, venta y almacenamiento de energía, así como la producción y almacenamiento de hidrógeno verde.

II. DEFINICIÓN DEL PROYECTO

Los componentes de la planta en los que se basa el modelo, descritos en la Illustration 1, son:

- Una planta fotovoltaica de 100MW.
- Baterías de Ion-Litio de 5MW, con una capacidad de 20MWh.
- La posibilidad de adquisición de energía renovable, fundamentalmente eólica.
- La posibilidad de vender el exceso de energía en el mercado.
- Una electrolizadora PEM.
- Almacenamiento de hidrógeno.

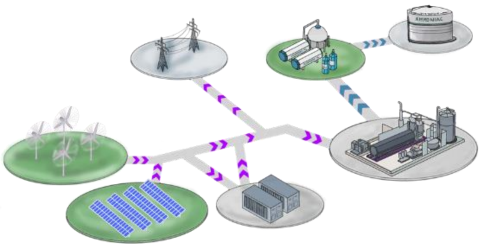


Ilustración 5. Descripción de la planta.

III. MODELO DE OPTIMIZACIÓN

La formulación teórica del funcionamiento de la electrolizadora sigue una estructura común en los modelos de optimización, distinguiendo entre conjuntos, parámetros, variables y función objetivo, restringidos por las diferentes condiciones del modelo. El modelo de optimización se describe a continuación:

CONJUNTOS

h	Hours, within a period of one year. [Hours]
s	Storage system (BATT, ELZ)

PARÁMETROS

$PtoH$	Production function of H2. [kg H_2/MW]
LOH^0	Initial Level of Hydrogen storage. [m^3]
BC	Battery aging cost. [€/MW]
C_s	Battery and electrolyser capacity. [MWh, m^3]
$Perf_s$	Round-trip efficiency of the storage (battery/electrolyser) system [%]
$MINsto_s$	Minimum storage. [p.u., m^3]
$MAXsto_s$	Maximum storage. [p.u., m^3]
EC_h	Energy Cost. [€/MWh]
P_{PV_h}	Photovoltaic plant power. [MW]
P_{WIND_h}	Wind farm power. [MW]
D_h	Hydrogen demand. [kg H_2]

VARIABLES

p_{pur_h}	Power purchased. [MW]
p_{sale_h}	Power sold. [MW]
p_{charge_h}	Charge of the battery. [MW]
$p_{discharge_h}$	Discharge of the battery. [MW]
p_{elz_h}	Power entering the electrolyser. [MW]
soc_h	State of charge of the battery. [p.u.]
loh_h	Level of hydrogen. [m^3]
$prodH2_h$	Hydrogen production. [kg H_2]

<u>Variables binarias</u>

${\varsigma^{ps}}_h$	Binary variable for power purchased every hour. {0,1}

FUNCIÓN OBJETIVO

$$min \left(\sum_h (EC_h \cdot (p_{pur_h} - p_{sale_h}) + BC \cdot p_{charge_h}) \right) \quad (1)$$

CONDICIONES

$$p_{pur_h} \le P_{WIND_h} \quad \forall h \quad (2)$$

$$p_{pur_h} \le 100 \cdot {\varsigma^{ps}}_h \quad \forall h \quad (3)$$

$$p_{sale_h} \le 100 \cdot (1 - {\varsigma^{ps}}_h) \quad \forall h \quad (4)$$

$$prodH2_h = p_{elz_h} \cdot PtoH \quad \forall h \quad (5)$$

$$\sum_h prodH2_h = \sum_h D_h \quad (6)$$

$$loh_h = loh_{h-1} + \frac{Perf_{ELZ} \cdot prodH2_h}{C_{ELZ}} - \frac{Perf_{elz} \cdot D_h}{C_{ELZ}} \quad \forall h \quad (7)$$

$$\frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} + \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \le 1 \quad \forall h \quad (8)$$

$$soc_h = soc_{h-1} + \frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} - \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \quad \forall h \quad (9)$$

$$p_{pur_h} + p_{discharge_h} + P_{PV_h} = p_{sale_h} + p_{charge_h} + p_{elz_h} \quad \forall h \quad (10)$$

La Illustration 2 muestra una representación del modelo. En ella, las variables se representan con letras minúsculas, así como con flechas moradas. Al contrario, los parámetros se representan con letras mayúsculas y con flechas negras. Además, los flujos de potencia se representan con línea continua, mientras que los flujos de hidrógeno se representan con línea discontinua. Esta representación muestra la estructura del modelo, identificando qué elementos controla éste.

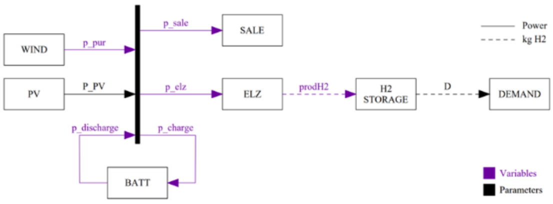


Ilustración 6. Representación del modelo.

IV. RESULTADOS

Una vez introducidos los datos de cada parámetro en el modelo de optimización, se han considerado días específicos para describir el funcionamiento de la planta electrolizadora, mostrando las situaciones más y menos favorables que la planta podría afrontar. Los resultados muestran la relación en el balance de energía con el precio de esta, así como con el estado de almacenamiento de la batería y del hidrógeno.

En periodos de mucha luz (Illustration 3), la cantidad de energía producida por la planta fotovoltaica es mucho mayor que la energía máxima exigida para la producción de hidrógeno, lo que lleva a la microgrid a vender el exceso de energía en el mercado.

Ilustración 7. Balance de energía con mucha luz.

Por el contrario, los periodos de poca luz requieren compras de energía, cuando no hay suficiente generación de energía fotovoltaica, como muestra la Illustration 4. Sin embargo, la generación de hidrógeno es comparativamente similar al caso anterior.

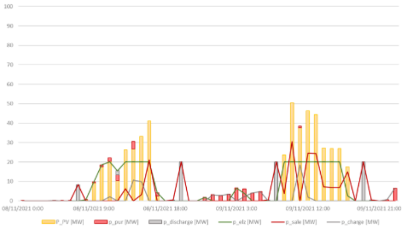
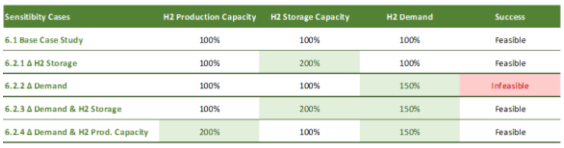


Ilustración 8. Balance de energía con poca luz.

El Nivel de Hidrógeno no tiene relación con el periodo de luz en el que se observa y depende fundamentalmente del coste relativo de la energía. Una disminución relativa en el coste de la energía, en un cierto periodo, lleva al sistema a producir durante periodos de tiempo inusuales (de noche), incluso comprando energía a pesar de tener un exceso de generación de energía fotovoltaica durante el día.

Como resumen del análisis de sensibilidad, el Diagram 1 muestra si el sistema sigue siendo viable o no, alterando ciertos parámetros del modelo inicial (Producción y Capacidad de Almacenamiento de H2 y Demanda de H2).



Sensitibity Cases	H2 Production Capacity	H2 Storage Capacity	H2 Demand	Success
6.1 Base Case Study	100%	100%	100%	Feasible
6.2.1 Δ H2 Storage	100%	200%	100%	Feasible
6.2.2 Δ Demand	100%	100%	150%	Infeasible
6.2.3 Δ Demand & H2 Storage	100%	200%	150%	Feasible
6.2.4 Δ Demand & H2 Prod. Capacity	200%	100%	150%	Feasible

Diagrama 2. Análisis de Sensibilidad.

V. CONCLUSIONES

La mayoría de la energía producida por la planta fotovoltaica se vende para cumplir con el balance de energía establecido. El hidrógeno se produce fundamentalmente con energía fotovoltaica, salvo que el coste relativo de la energía caiga considerablemente y la producción nocturna se torne más rentable. En situaciones de poca luz, cuando el Sistema no es capaz de proporcionar la suficiente energía para satisfacer la demanda, la planta se apoya en la compra de energía en el mercado. Las baterías, sin embargo, no se usan normalmente para la producción de hidrógeno, sino que se usan para la venta de energía cuando su coste es mayor que el esperado.

Se ha demostrado que el Nivel de Hidrógeno no depende de la luz. El modelo determina que el Nivel de Hidrógeno depende fundamentalmente del coste relativo de la energía de cada periodo específico. Esto significa que se producirá mucha cantidad de hidrógeno en situaciones donde el coste relativo de la energía cae, independientemente de si es un periodo de mucha o poca luz.

El sistema actual no es capaz de satisfacer un incremento en el 50% de la demanda con las especificaciones originales, ya que la producción de hidrógeno depende fundamentalmente de los recursos fotovoltaicos, y no se pueden almacenar grandes cantidades de hidrógeno. Incrementar la capacidad de almacenamiento de hidrógeno o incluir una electrolizadora adicional son algunas de las posibles soluciones.

VI. REFERENCIAS

[1] Iberdrola, Planta de hidrógeno verde de Puertollano. [online]. Available: https://www.iberdrola.com/conocenos/lineas-negocio/proyectos-emblematicos/puertollano-planta-hidrogeno-verde

[2] A. Ramos, Open Stochastic Daily Unit commitment of Thermal and ESS Units (openSDUC). [online]. Available: https://pascua.iit.comillas.edu/aramos/openSDUC/index.html

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Chapter 1. INTRODUCTION

Climate change is becoming a leading priority through the years, gaining more and more relevance, and becoming one of the main aspects to consider in daily-basis decisions. For instance, air pollution has been considered one of the greatest human health threats in the century, causing an estimated 7 million deaths annually (World Health Organization, n.d.). For this reason, an action must be made to reduce air pollution levels and, thus, reduce morbidity derived from cerebrovascular accidents, lung cancer, and chronic and acute neuropathies.

To tackle this problem, among many others, a universal 2030 Agenda for Sustainable Development was adopted in September 2015 by the United Nations General Assembly, which included 17 Sustainable Development Goals (SDGs) (United Nations, 2015) under the motto “Act Now”. These SDGs cover from fighting poverty and dignity to protecting the planet from degradation, including sustainable consumption and production. One main objective is to reduce at least 45% of the emissions in comparison with 2010 levels, which is reflected in goals 7, Affordable and clean energy, and 13, Climate Action. (United Nations, 2015).

These measures taken in the 2030 Agenda are only the beginning to achieving their main goal: the transition to net-zero emissions by 2050. Starting by eliminating highly polluting resources such as coal, entirely reducing non-renewable resources and transitioning to CO2-free generation sources. 77 countries and more than 100 cities pledged to reduce their emissions to promote prosperity while protecting the planet in the near future. (IISD, 2019).

Nevertheless, even if there is a continuous effort to achieve sustainability, there is still much work to be done. In 2020, 66.9% of the electricity demand in Spain was satisfied by net-zero emissions technologies, of which only 43.6% stemmed from fully renewable energies. (Red Eléctrica de España, 2020). In comparison, Europe’s renewable energy production was 37.5%, which shows how Spain is one of the leading countries in transitioning to renewable energies, behind Austria, Sweden, and few other countries, described in Figure 1 (Eurostat, 2022).

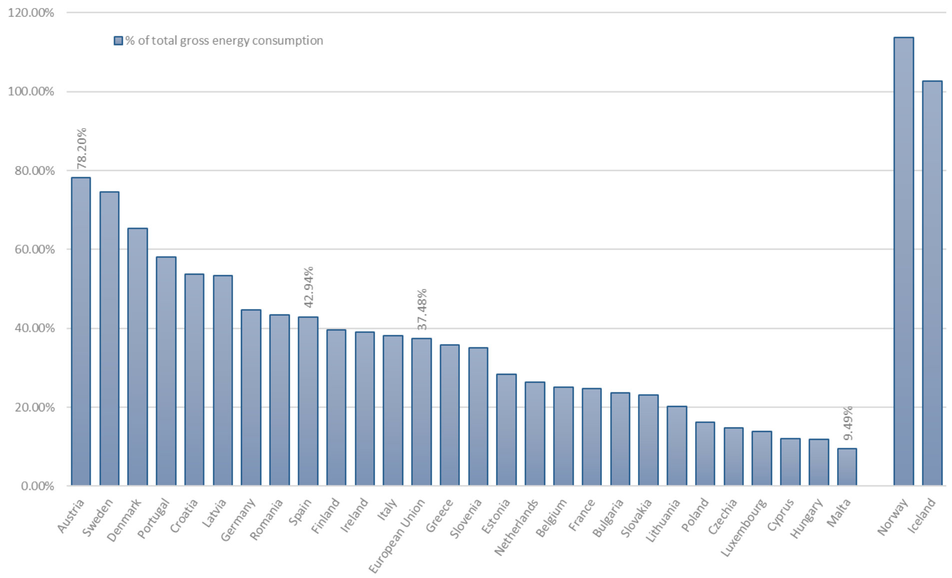

Figure 1. Electricity from renewable sources. (Source: Eurostat)

However, there is a great debate about considering energies as renewable or not. For instance, the European Commission has decided to move forward with considering gas and nuclear activities as a “transition bridge” to renewable energies subjecting them to strict conditions. This recent consideration includes gas and nuclear energy in a green labelling system known as the “taxonomy for sustainable finance”, which fosters investments in these resources. This decision has been considered as a key role in achieving climate neutrality and meeting the 2030 and 2050 targets. It also strengthens transparency and shows a clear view of the path to follow to achieve future requirements. (European Commission, 2022).

Under these assumptions, Spain’s demand in 2020 was satisfied with 66.4% of the total generation under renewable and transitional resources (Red Eléctrica de España, n.d.), increasing as well mostly in every other country, making the objective of the net-zero emissions by 2050 far more reachable. However, Spain is still far away from achieving its objectives, and laying in transitional energies won’t ensure carbon neutrality. For this reason, renewable energies should be the special focus of private investments, as they will become the key role in this change.

1.1 *ENERGY GENERATION STRUCTURE*

As discussed above, the Spanish generation structure (Figure 2) is highly evolving through the years, as the global pressure for climate change impacts directly on the generation decision-making. Renewable energies have experienced a growth of 38.3% compared to levels of 2010 (Eurostat, 2022), as there has been high investment in these areas. In fact, in 2020, renewable energies, as stated before, constituted 43.6% of the global generation system. Led mainly by wind energy (21.7%), which experienced its major growth ever seen. In addition, solar and hydroelectric energy constitute a great portion of the generation as well. However, there are still many more non-renewable resources along with transitional energies that make the generation profile still highly polluted. Nevertheless, 66.9% of the generation produced was CO_2-free, which shows the transformation the Spanish generation profile is performing, and how crucial these transitional energies can be to reach climate neutrality. (Red Eléctrica de España, 2020)

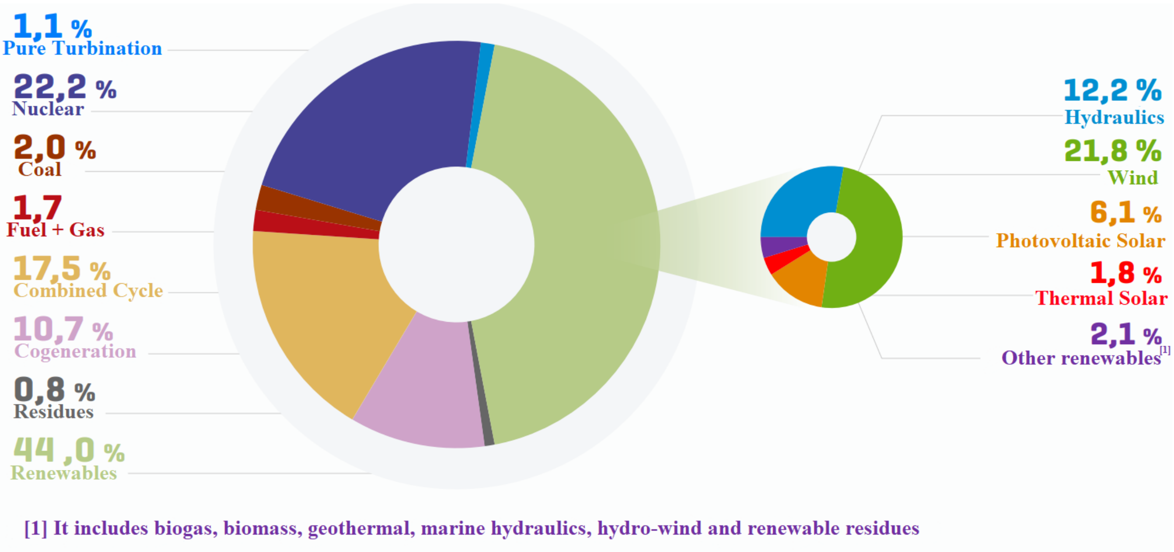

Figure 2. Electric generation structure in 2020 (Spain). (Source: REE)

However, renewable energy's major drawback is the variability of its generation (Figure 3). It is definitely affected by the everyday conditions and does not guarantee a specific production at every hour. It may vary depending on the season, wind intensity, and varies clearly during different time periods. In fact, photovoltaic plants can only produce in daylight periods. For this reason, transitional energies are a great support in the Spanish generation system. It provides reliable generation, regardless of external factors, and contributes to satisfying everyday demand. It may not be considered green energy, as it isn't totally renewable, but provides an alternative path to achieving carbon neutrality.

Therefore, increasing the renewable capacity installed will probably improve the overall renewable generation under perfect conditions. However, the global sustainable generation will still lack in not ideal situations. Ideally, we could produce the global daily demand during specific daily periods, where the energy is almost fully renewable, store it and provide it when necessary. Nevertheless, energy storage isn't possible when considering these large quantities. Not only because of the investment that producing such large batteries would require, but also considering that ion-lithium batteries can only store energy in a short time period horizon, being inconsistent with what is needed.

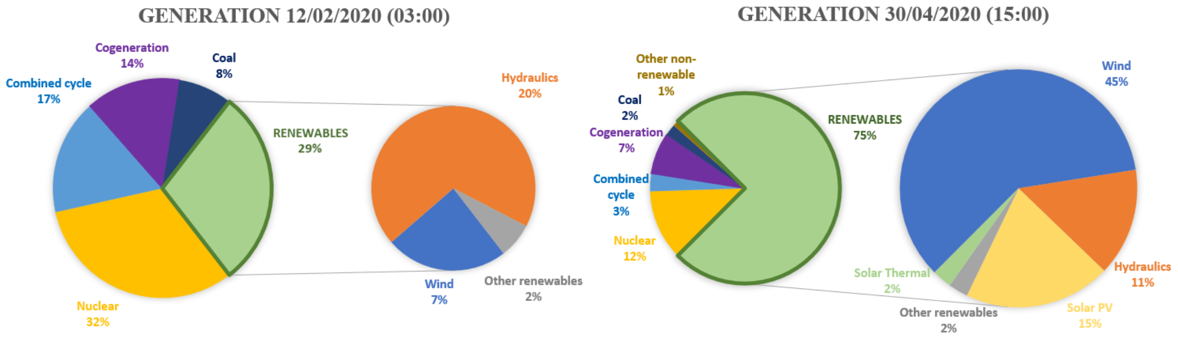

Figure 3. Comparison of the generation structure under different conditions.

Consequently, the objective is to find a long-term way of energy storage to save most of the energy produced when renewables are producing at their limits. For instance, as photovoltaic plants are the most increasing renewable technologies nowadays, being able to store all the energy produced during daylight will ease the system in less sustainable hours, when these plants are unable to produce.

As a matter of fact, hydrogen has now been considered an alternative sustainable energy to focus on, as it could provide an alternative long-term energy storage to accelerate this transition.

1.2 HYDROGEN AS AN ALTERNATIVE

Hydrogen, as well as being the most abundant element in the universe, is the simplest and lightest element on the periodic table, along with being the fuel with the highest energy content per unit mass, much more than methane and gasoline. At the moment, 96% of the hydrogen produced is being extracted from fossil fuels, being only 4% from water. Nevertheless, fossil fuel methods are only considered as a transitional manner of producing hydrogen, being even more relevant its extraction from water, as it is easily integrated with renewable sources. (Ursúa et al., 2012).

Electrolysis is the main method of obtaining hydrogen from water, being a widely used mature process. It consists of circulating current through water to separate hydrogen from oxygen, achieving high pure hydrogen. There is a special focus on these new technologies, as they are seen as the only manner to produce large amounts of sustainable hydrogen without any emission or environmental disruption. (Ursúa et al., 2012).

In addition to its practical use, one main factor in the development of hydrogen generation is the possibility of its storage. Hydrogen is much less expensive to be stored in comparison with the common battery storage, being as well much lighter and simpler to transport. Therefore, this opens up many possibilities to transform as much hydrogen as possible, being able to store it, to afterwards use it as a mean of power, which opens new ways of producing renewable energies.

Hydrogen production is strictly classified to determine whether its precedence is renewable or not. In fact, there is a clear distinction in the production certification depending on the precedence of the energy and the quantity of CO_2 emissions they produce (CertifHy, n.d.). The labelling system is being described in Table 1:

Green Hydrogen	Originated from renewable sources and having a green house balance under 91gCO2eq/MJ.
Low-Carbon Hydrogen	Originated from non-renewable origin (nuclear or fossil energy using carbon capture storage or utilization), as well as having a green house balance under 91gCO2eq/MJ.

Table 1. Hydrogen labelling system.

What makes hydrogen so efficient is the variety of uses it can be given. It can be used from being a fossil fuel substitute, providing a sustainable mobility alternative, to affecting directly to the industry and domestic use, such as replacing natural gas networks or producing ammonia fertilizers. However, around 90% of it is still being produced in industry in a non-sustainable way.

The urge into developing new green hydrogen technologies and creating a more sustainable society is the main point of focus of this project. Hydrogen, as described, has been considered a possibility of long-term energy storage, along with the capability to be used in many other situations. The optimization of its generation is crucial. Determining the appropriate way to handle its behaviour may be critical to establish it as the alternative the current generation system requires.

This project will focus on determining the optimal energy management of a microgrid to produce green hydrogen, by establishing an hourly decision-based model on a yearly basis. The model provides decisions regarding the purchase, sale and storage of energy, as well as production and storage of green hydrogen.

Climate change problems and how to face them has been addressed in this chapter, together with the current energy generation structure, and how hydrogen could be an alternative. Chapter 2. deals with the decision-making process and contains a basic description of optimization models. Chapter 3. describes the technologies applied and their alignment with the SDGs. It also covers the plant description, its components and the relationship among them. Chapter 4. describes the project, its objectives, the methodology followed and the business description.

The optimization model is described in Chapter 5. It includes the description of the sets, parameters and variables of the problem, its main objective function and the constraints restricting the model. Project results of the base case study are shown at Chapter 6. Additionally, a sensitivity analysis is carried out. Finally, conclusions are drawned in Chapter 7. and the model programming is included in ANNEX I – Source Code.

Chapter 2. STATE OF THE ART

This case study is an optimization model-based problem related to the management of a microgrid. Key decisions will be taken considering specific inputs and outputs, special limitations in the system, and its main objectives. The model, which is mainly developed using Pyomo, an optimization library included in Python, will determine the most optimal solution for the problem established. Optimization methods are often used into determining key decisions in everyday basis. Companies rely on these methods to ensure their actions and decisions are carefully premeditated.

2.1 PREVIOUS DECISION-MAKING METHODS

Decision-making has not always been supported by mathematical formulations, though. Indeed, different decision-making techniques have been studied to determine the principal factors and circumstances to be considered in every decision-making process.

One main decision-making field of study is the relationship between rationality and decisions. The rational model ensures that human behaviour has some purpose, whose objectives determine the possible consequences of every action. However, establishing goals has been demonstrated to be inconsistent during certain situations. They lack, principally, when behaviour is mainly local and when standard procedures guide considerably organizational behaviour. (Eisenhardt & Zbaracki, 1992).

For this reason, a specific decision-making agenda had to be developed to determine a more optimal decision-making procedure. This agenda was being developed by Eisenhardt and Zbaracki in “Strategic Decision Making”, included in the Strategic Management Journal in 1992. In fact, after considering every other theory of decision-making processes, they determined a more optimal method, gathering every other study related to the topic. Their decision-making study mainly relies on considering three main factors: cognition, normative implications, and conflict. They ensure that these three factors directly affect the decision outcomes, thus having to be considered in the decision-making process. (Eisenhardt & Zbaracki, 1992).

The first factor is cognition, which becomes one main priority when studying a decision. A three-step to achieving a more realistic view includes studying the heuristics of a strategic choice, incorporating insight, and integrating intuition. The second main factor is normative research, which mainly relies on exploring when specific outcomes are more important and how effectively these outcomes can be simultaneously achievable. Having an effective decision and pretending it to be implemented in a short-time period may not be realistic. Ultimately, the last factor to consider is conflict. Conflict must be considered in every decision, whether the benefits or the costs of conflict would affect the situation. Exploring which sources of conflict are more beneficial than others and, most importantly, how conflict relates to emotion and decision speed is a key factor in every decision-making process. (Eisenhardt & Zbaracki, 1992).

2.2 APPROACH TO OPTIMIZATION MODELLING

Given the unprecedented nature of today's world, there is a clear need in accompanying every decision-making technique with technological advances. With the implementation of artificial intelligence in our actual society, decisions are now heavily approached by these new arising technologies. These new methods often learn from previous situations to perform in a better way in future ones. However, as seen during the Covid-19 pandemic, future decisions don't often follow rational behaviours. For this reason, including operation research techniques in every crucial decision-making may facilitate a better performance of the company. These optimization methods aren't a substitution for previous decision-making techniques or artificial intelligence. In fact, they rely heavily on this information and the way the company wants to confront a problem, from which the optimization model selects the most optimal solution. As a matter of fact, optimization models are only the technology used to represent all the actual data to perform better as a company.

Optimization models are being nowadays heavily used. In fact, around 85% of top 500 American companies use optimization models to perform better in their everyday decisions. (Gurobi Optimization, n.d.). This shows the significance operation research is now having and may have critical significance in company results. These models are being more common and required elsewhere, regardless of the area the company is focused in.

A mathematical optimization model is a clear reflection of a company's situation, including every area in which the business performs. Having a clear representation of a company, firstly, allows having a clear view of its organization, in addition to becoming more profitable. As an optimization model is a mathematical representation of a certain situation, it can be easily included in every firm, regardless of the sector the company is involved in. (*How A Mathematical Optimization Model Can Help Your Business Deal With Disruption*, 2020).

One of the main strengths of a model is the capability to represent a certain situation. Every situation can be deployed mathematically in a simpler representation or including every factor the company must consider, making it much more sophisticated. In fact, optimization models can be easily updated to include real-world circumstances, to tackle actual problems with updated information. Information can be easily updated to become a totally up-to-date model.

Every mathematical optimization model is being divided into four main features:

- Parameters: Every actual data known by the company that may be relevant to its functioning.
- Decision Variables: Every decision that must be made, such as the number of products to be produced, the optimal price for the product to be sold…
- Constraints: Business rules that the company must follow. Every decision must compulsorily follow every constraint established.
- Objective Function: The company's main objective to achieve. They may be many of them and probably, differ from each other.

Having deployed a company situation into these four main factors, the optimization model determines the most optimal solution that fulfils given constraints. A specific business objective has been included in the model. For obtaining the best optimal solution, the model determines the best possible variable values that satisfy the primary goal.

Including a mathematical optimization model, in addition to finding the best possible solution, may as well increase the firm's performance in many other factors. By developing an optimization model, which requires a clear representation of a firm's functioning, may help in gaining a deep understanding of the business dynamics and disruptions. In addition to analysing every possible scenario the company can be included in, as well as, identifying risks and opportunities the company may encounter. Decision-making is now heavily influenced by these optimization methods, and therefore, given how effective they are, a special focus on these new methods must be considered. (How A Mathematical Optimization Model Can Help Your Business Deal With Disruption, 2020).

2.3 APPLICATIONS OF OPTIMIZATION MODELS

Most of the optimization model applications are being described by one of the most known mathematical optimization solvers worldwide, Gurobi, which claims to be the world's fastest solver. Mathematical optimization solvers are widely used in more than 40 industries, including non-technological industries such as healthcare, the food industry, and the retail industry, among many others.

However, optimization models are used especially in four different industries: Financial Services, Telecom, Supply Chain and Energy.

Optimization models are now well-established in the finance world, as it provides helpful information in the decision-making process. It primarily helps in the portfolio optimization, as well as in the cash management flow and trades to be established. Increasing profitability is the main objective of the finance industry, which is highly compatible as an objective function in an optimization model. It also reduces risks in decision-making as these methods are objectively based.

The telecommunications industry relies as well upon these optimization models. With the implementation of 5G in a near future, organizations must ensure their decisions are made in a suitable manner to transform their business with these changes. The network configuration and operation are one of the main focuses of the model, along with the adaptability to shifting market conditions.

The supply chain industry is one of the most demanding industries regarding optimization technologies. Supply chain processes, firstly, rely directly on the expected demand, that needs to be forecasted. Optimization models allow better visibility and control of the supply chain process and develop a more responsive performance to fulfilling demand. Furthermore, this specific area of the industry is constantly changing, which requires an optimized background to ensure optimal performance. These processes often follow a long chain from the producer to the supplier, which requires perfect control of its functioning and development in the supply chain.

Ultimately, the energy industry benefits from optimization methods, as many of their decisions are driven by these models. Optimization enables organizations to perform in a balanced manner. In fact, as the demand is extremely changing, electrical companies rely on these methods in many aspects of their functioning, such as resource planning, unit commitment, reservoir management, and their overall functioning and production.

Chapter 3. DESCRIPTION OF THE TECHNOLOGIES

With a 150M € investment, Iberdrola has seen the opportunity to establish Europe's biggest hydrogen production plant ever built in large-scale production, being built in Puertollano. In fact, the company has seized the opportunity to become a pioneer hydrogen producer. The agreement the company has reached with Fertiberia ensures the generation of green hydrogen to satisfy the production of ammoniac and other fertilizers. Actually, it is expected to prevent 39.000 tCO2/year, along with being one of the special targets of interest, as hydrogen has been considered a feasible alternative of long-term storage to lead the energy transition into full carbon neutrality. (Iberdrola, n.d.)

To indicate the importance of this agreement and its feasibility, forecasts estimate the decarbonisation of almost 25% of the hydrogen consumed in Spain by 2030, obtaining 800MW from electrolysis. (Iberdrola, 2020a). Thus, a project has been established to determine its optimal operational functionality. The project will be highly illustrated by this existing plant and will focus mainly on optimizing the energy management the microgrid requires, including existing energy inputs and the optimization of the actual hydrogen production.

However, as shown in Table 1 above, green hydrogen must be produced from 100% renewable sources, which may reduce the possibility of energy purchase in the market. Energy sources included in the production cover from intrinsic photovoltaic resources to wind energies to produce when photovoltaic plants aren't available. Still, as the system can store energy, in short-term (battery), or in long-term (producing hydrogen) situations, setting specific time periods for selling energy and increasing profitability may be especially significant.

3.1 ALIGNMENT TO THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

Sustainability is in the very core of renewable energies. In most situations, the use of non-renewable energies might be more cost-efficient. However, Iberdrola's commitment to sustainability is the main factor that drives this project, which covers several Sustainable Development Goals (United Nations, 2015), as shown in Figure 4:

Figure 4. UN Sustainable Development Goals (SDGs). Source: (United Nations, 2015).

- Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all. The plant provides an infrastructure for supplying innovate green energy.
- Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. The plant adopts clean technologies for industrial processes and leads the implementation of green hydrogen for industrial use.
- Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable. Among the different uses of hydrogen as a source of energy, it is a fundamental part of sustainable transport systems.

- Goal 12. Ensure sustainable consumption and production patterns. The technologies applied lead to the efficient use of natural resources, as well as eliminate waste generation.
- Goal 13. Take urgent action to combat climate change and its impacts. The project follows national climate change policies and raises awareness for sustainable development and lifestyle.

3.2 PLANT DESCRIPTION

Before determining the variables and parameters of the study problem, a quick description of the system must be made. Figure 5 shows a quick representation of the microgrid itself.

The plant components included in the system are:

- A 100MW Photovoltaic plant.
- 5MW Lithium-Ion batteries with a 20MWh capacity.
- The possibility of renewable energy purchase, mainly conformed by wind resources.
- The possibility of selling exceeding energy to the market.
- A PEM Electrolyser.
- Hydrogen Storage.

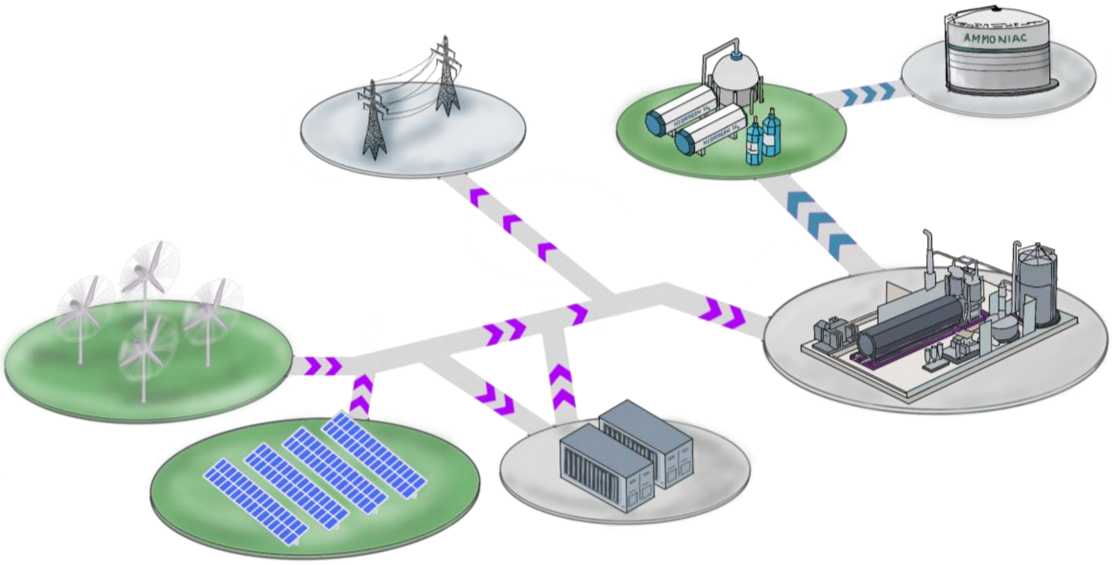

Figure 5. Plant description.

The system deployed is forced to operate under hydrogen demand conditions. However, the plant has the freedom to determine whether is more profitable to produce under certain conditions. Energy storage systems, such as batteries or hydrogen tanks, provide the possibility of storing energy during low generation periods.

Specific elements of the microgrid will be developed hereunder.

3.2.1 PHOTOVOLTAIC PLANT

The microgrid's main renewable source is a 100MW photovoltaic solar plant, with several innovations to provide better performance. One main innovation is bifacial panels, which provide greater production because of having two light-sensitive surfaces. In addition, the plant has been installed with cluster inverters (string), which highly improves the use of the surface. (Iberdrola, n.d.).

3.2.2 WIND POWER

There is an inevitable need in obtaining renewable power when the photovoltaic plant isn't capable of producing energy. For this reason, other sources of renewable energy must be considered to complement these technologies. Even though wind power isn't extremely consistent, it may provide sufficient energy for hydrogen production during low-light periods or when the photovoltaic plant isn't active. By including both types of energy, the system can now be considered as a hybrid generation microgrid with the possibility of a consistent generation.

To be clear, wind power isn't considered in the actual Iberdrola's microgrid. For this reason, the possibility of an agreement on the energy purchase of a near 36 MW wind farm has been contemplated. This provides the electrolyser to produce during unavailable photovoltaic energy hours. This consideration is of great importance, as it may be a future action to be taken in the microgrid itself: to include other sources of renewable energy generation to increase hydrogen production and increase profitability.

3.2.3 LITHIUM-ION BATTERIES

Another main advantage of the photovoltaic system installed is the inclusion of a 5MW ion-lithium battery installed. A storage capacity of 20MWh allows better manoeuvrability, which opens many energy-storing alternatives. Energy might be stored to increase hydrogen production during less sustainable hours, as well as becoming more profitable when selling more energy during high-peak time periods. (Iberdrola, n.d.).

3.2.4 ELECTROLYSER

Iberdrola has signed an agreement with Nel, the world leader electrolyser manufacturer, to integrate Nel electrolysers in Puertollano's plant. The production process is being done with the inclusion of a 20MW electrolyser being able to produce 360 kg/h of hydrogen, at its limits. (Iberdrola, 2020b). The electrolyser installed corresponds to a Polymer Electrolyte Membrane (PEM) (described in Figure 6), which is considered the technology with the finest response time, greater production rate, and most importantly, higher purity of gases, among any other technology. (Shiva Kumar & Himabindu, 2019).

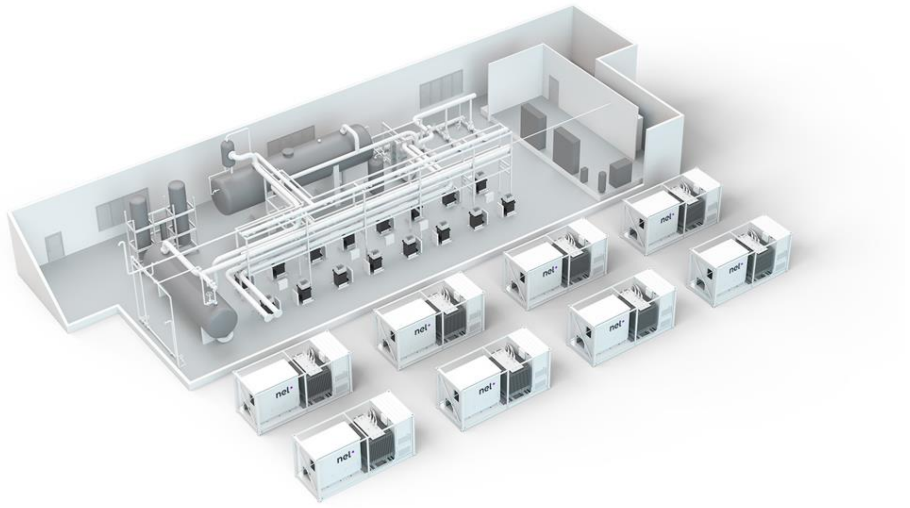

Figure 6. Nel PEM electrolyser. (Source: nelhydrogen.com)

Nel PEM electrolysers are mainly characterised by their low maintenance and sitting requirements. Proper machine characteristics are being deducted from the total production rate Iberdrola aims to satisfy. (Nel Hydrogen, n.d.). These specifications are being directly obtained from the manufacturer itself, being described in Table 2.

nel PEM Electrolyser *		
Net Production Rate	Nm3/h @0ºC, 1 bar	4,920 Nm3/h
	kg/24h	10,618 kg/24h
Production Capacity Dynamic Range		10-100%
Average Power Consumption at Stack		4.5 kWh/Nm3
Purity		99.9995%

*Characteristics obtanied from the M5000 nel electrolyser

Table 2. PEM electrolyser characteristics. (Source: nelhydrogen.com)

3.2.4.1 Electrolysis process

In the electrolysis process, water is dissociated into hydrogen and oxygen under the influence of electricity. There are different electrolysis processes depending on the electrolyte, operating conditions, and ionic agents. However, the main principle remains the same. As stated previously, the electrolyser installed is PEM water electrolysis based. The process starts with the splitting of oxygen (O_2), protons (H^+), and electrons (e^-) on the anode.

Afterward, electrons are transferred to the cathode side. Ultimately, protons are recombined with electrons to form hydrogen. The process of splitting water into hydrogen and oxygen requires energy inevitably, which is specified in the proper electrolyser. The process is described in Figure 7. (Shiva Kumar & Himabindu, 2019).

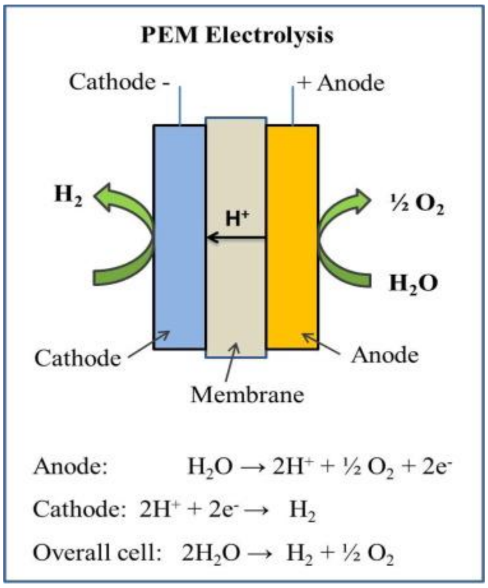

Figure 7. Schematic illustration of PEM water electrolysis. (Source: Shiva Kumar & Himabindu, 2019)

3.2.5 HYDROGEN STORAGE

Storing hydrogen has great importance in satisfying Fertiberia's hydrogen demand, as well as giving the system much more flexibility, becoming more efficient in the production process. It is composed of 11 hydrogen tanks to store up to 6.000 kg of green hydrogen at 60 bars. Each tank has 133m^3 of volume, weighing when empty 77 tons. Consequently, in an aggregative way, the total hydrogen storage capability is 1.463m^3. Hydrogen will be extracted from these tanks to satisfy a total of 1080 tH_2/year, which may increase during future investments in the production of fertilizers. (Iberdrola, n.d.).

Chapter 4. PROJECT DESCRIPTION

4.1 JUSTIFICATION

Having considered the importance of optimization models in the energy sector, and considering Iberdrola's electrolyser plant, there is a clear need for developing an optimization model for its functioning. Energy industry decisions, as stated, are mainly driven considering these models and therefore, creating an optimization model would be one of the main focus points of this new plant. Its importance relies on being Europe's biggest electrolyser plant for industry production, which determines the urge of developing a specific optimization model. The model is not intended to substitute the decision-maker, in fact, it is designed to exhibit the most optimal solution for the situation presented.

The model to be considered is crucial and may have great similarity to any microgrid related with the established one. Other optimization models have been developed in relation with a microgrid optimal functioning. However, none of them were easily applied to the presented situation. None of them were focused on determining the optimal hydrogen production, or more specifically, did not include hydrogen production and storage in the system. Moreover, most of the models developed were extremely specific and specialised for their own situations, which created very sophisticated models hardly transposable. Thus, the system presented has been developed in the simplest manner for it being eligible for any similar energy grid management. The model is being developed with the actual information of the Iberdrola's plant, including every aspect and component of it.

One main advantage of the model described is the possibility of its continuous refreshment. System parameters are being constantly updated, which means every optimal solution is being drawned from up-to-date information. Every section of the model can be easily modified, which means, the model can be continuously developed and therefore, creating a more sophisticated model. For this reason, this only shows a simpler representation of the actual capacity of the model and its possibility to develop it to represent the reality as accurate as possible.

Optimization models are widely used in the industry sector, and undoubtedly in any microgrid. The importance of the project presented shows a clear representation of a possible optimization model used worldwide. Microgrid's functioning is certainly driven by these simulations.

4.2 OBJECTIVES

Having described the conditions under which the system is being developed, some of the main objectives the project aims to cover are the following:

- Developing an optimization model that provides solutions regarding energy decisions, including the purchase, sale, or storage of it. It will establish the daily quantity of energy to be bought, sold, stored in batteries, and especially produced, under hydrogen demand limitations that must be satisfied. The model will be designed to be executed every day in a rolling-horizon mode.
- Determining the optimal hydrogen production, taking into consideration the possibility of its storage for later use, and the cost associated with its production.
- Studying the sensitivity analysis of the hydrogen production plant. Noticing how much changes the production when slightly modifying parameters of the model, such as the photovoltaic plant production or the number of batteries and registering the effect on the model to consider any possible investment. It may be useful for considering the company's future decisions already established.

4.3 METHODOLOGY

The methodology used in developing this optimization model has followed different steps through the process, which will be described hereunder.

Firstly, there needs to be a great understanding in what refers to Iberdrola's electrolyser plant, as the model is totally based on it. Every single element of the plant must be considered, its functioning determined and the decisions to be taken in a daily basis examined. As the project is nowadays being developed, and recently launched, there is no exceeding information related to the topic, which has prompted assumptions over some characteristics of the plant. However, the main components and specifications have been collected from official sources, producing a quite representative model of the microgrid.

As the project is an innovative design in what refers to green hydrogen production, it needs to follow specific considerations to be established as a renewable source. For this reason, part of the preparation was focused on determining the needed plant specifications according to certain legal limitations described in Table 1. A deep understanding in hydrogen production and its process leaded the way into determining the energy sources required and its limitations.

Subsequently, once determined the specific elements required in the microgrid, an initial theoretical optimization model was established to ascertain the optimal functioning of the plant. In this model, different components of the microgrid were considered as parameters, that is, known data from which the model determines the optimal solution, whether others were considered as variables, i.e., unknown data whose value will be determined from the model. This theoretical model is the basis of the mathematical formulation, and for this reason, was the key process in the project, to determine which information was relevant and decisive and its relationship with every other variable. This theoretical model will be further developed at a later stage of the document.

Parameters, as described previously, are known data that directly affect the model decisions. They cover from the hourly energy price to the collection of historical data of energy production required. Some information was easily gathered, such as the hourly energy price, which was collected directly from the ESIOS official web page, as this information is freely distributed. However, independent energy generation profiles aren't as accessible.

The microgrid main source of power was a 100MW photovoltaic plant, which its generation profile has been estimated with a photovoltaic simulation program named "PVsyst". (*PVsyst – Photovoltaic Software*, n.d.). The simulation considers location characteristics (introducing geographic coordinates), determining the daylight radiation profile and concluding with an hourly estimation of the generation of a 100MW photovoltaic plant studied. This information is then included in the mathematical model as a parameter.

Another source of energy that has been considered is the energy produced from a wind farm. Iberdrola's microgrid does not include wind power as a generation source, but as established previously, the possibility of renewable energy purchase from a 36MW wind farm has been considered. The system does not acquire all the energy produced from these sources; however, the hourly production was needed to determine the maximum energy to be acquired at every hour. As this information is reserved, the source of the wind generation profile can't be described.

Obtaining the photovoltaic and wind power profile was doubtlessly one of the main issues of the project. Nevertheless, after gathering all the information and determining every element of the model, an optimization code was developed. The code was built once mastering the use and the environment from a recently learned programming language, Python, and more specifically, its optimization package Pyomo. The code introduced known data (parameters) from CSV files, and every variable value obtained after the simulation was as well deployed into a CSV file. Ultimately, a master document was developed including specific parameters and variables of the optimization model to represent a clear view of the daily optimized results, including many different graphs of the microgrid elements (including hourly battery and hydrogen storage status). The importance of including parameters and exporting results into CSVs rely on the possibility of using the existing code during many different situations. The master document would automatically update with every parameter change, and the code doesn't need to be modified.

4.4 BUSINESS DESCRIPTION

As opposed to a standard business model, the Iberdrola's plant main objective is not mainly focused on profitability. Instead, the main objective is being able to provide the necessary amount of hydrogen to the ammoniac factory. That is, the objective is supplying a certain amount of green hydrogen in an hourly basis, being costs a secondary objective.

Of course, the objective cannot be producing hydrogen at any cost. Indeed, the optimization model seeks to minimize the cost of producing hydrogen, while satisfying that demand.

How is this cost minimized? The model provides the amount of energy to be purchased or sold and the time to do so, according to the hourly cost of energy. The system still produces large amounts of photovoltaic energy and will still focus on selling this energy in the market to maximize profitability and therefore, optimizing the whole model. The system also purchases renewable energy from the market, not only when the photovoltaic plant is not able to satisfy the demand, but also considering when relative cost of energy provides an opportunity.

A different business model would arise, if considering a sale price for hydrogen, i.e., if the system were able to sale hydrogen to third parties as well as providing its internal demand. It would turn the current business objective into one of profitability.

Chapter 5. OPTIMIZATION MODEL

The theoretical formulation of the electrolyser functioning has followed a usual optimization model structure, distinguishing between sets, parameters, variables, and objective function, restricted by different model constraints. This model is directly based on Iberdrola's electrolyser plant, whose elements were previously formulated in "Description of the Technologies" and, more specifically, on Figure 5. Plant description.

The mathematical representation is then transcribed to a programming language and ran in Python's algebraic modelling language Pyomo. The source code is being attached in ANNEX I – Source Code. The source code has been properly developed and potentially influenced by the "*Open Stochastic Daily Unit commitment of Thermal and ESS Units (openSDUC)".* (Ramos, n.d.)

5.1 SETS, PARAMETERS & VARIABLES

The time period considered has been a natural year, more specifically 2021. The model considers two different types of storage systems: a more conventional short-term energy storage, batteries, and the possibility of hydrogen storage.

The model is based on a known constant demand of hydrogen for the production of ammoniac, which is mainly satisfied by the photovoltaic plant included in the microgrid. The possibility of a renewable energy purchase to the market, limited with its maximum wind production at every hour, is also considered. This is equivalent to having a physical PPA with the wind farm.

Hydrogen production is being then derived to hydrogen tanks for its storage. The system has the capability of producing more hydrogen than demanded, which opens up the possibility of producing large quantities of hydrogen in more profitable time periods and store it.

Consequently, the electrolyser won't necessarily be used at every hour, as the hydrogen tanks permit the system to satisfy demand when needed.

The electrolyser is not considered an isolated microgrid. Hence, as the microgrid is not able to use all the energy produced by the photovoltaic plant at every hour, energy surplus will be sold to the market.

Therefore, the system will assign values to variables related to energy purchase and sale, hydrogen production, as well as battery and hydrogen levels of storage.

For ease of understanding, the theoretical formulation considers lower-case letters for variables and upper-case letters for parameters. This consideration has the intention of brightening which elements are being estimated by the model and which are being considered for dimensioning and operating the system, respectively.

The optimization model is being described hereunder:

SETS	
h	Hours, within a period of one year. [Hours]
s	Storage system (BATT, ELZ)

PARAMETERS	
$PtoH$	Production function of H_2. [kg H_2/MW]
LOH^0	Initial Level of Hydrogen storage. [m^3]
BC	Battery aging cost. [€/MW]
C_s	Battery and electrolyser capacity. [MWh, m^3]
$Perf_s$	Round-trip efficiency of the storage (battery/electrolyser) system [%]
$MINsto_s$	Minimum storage. [p.u., m^3]
$MAXsto_s$	Maximum storage. [p.u., m^3]
EC_h	Energy Cost. [€/MWh]
$P_{PV\,h}$	Photovoltaic plant power. [MW]

P_{WIND_h}	Wind farm power. [MW]
D_h	Hydrogen demand. [kg H₂]

VARIABLES

p_{pur_h}	Power purchased. [MW]
p_{sale_h}	Power sold. [MW]
p_{charge_h}	Charge of the battery. [MW]
$p_{discharge_h}$	Discharge of the battery. [MW]
p_{elz_h}	Power entering the electrolyser. [MW]
soc_h	State of charge of the battery. [p.u.]
loh_h	Level of hydrogen. [m^3]
$prodH2_h$	Hydrogen production. [kg H_2]

Binary variables

$\varsigma^{ps}{}_{h}$	Binary disjunctive variable for purchasing/selling every hour. {0 selling, 1 purchasing}

A model representation is being displayed in Figure 8. On it, variables are represented in lower-case letters as stated, as well as with purple arrows. Conversely, parameters, in upper-case letters, are represented with black arrows. Moreover, power flows are denoted with continuous lines, whereas hydrogen flows are displayed with dashed lines. This representation shows the model structure, identifying which elements does the model control.

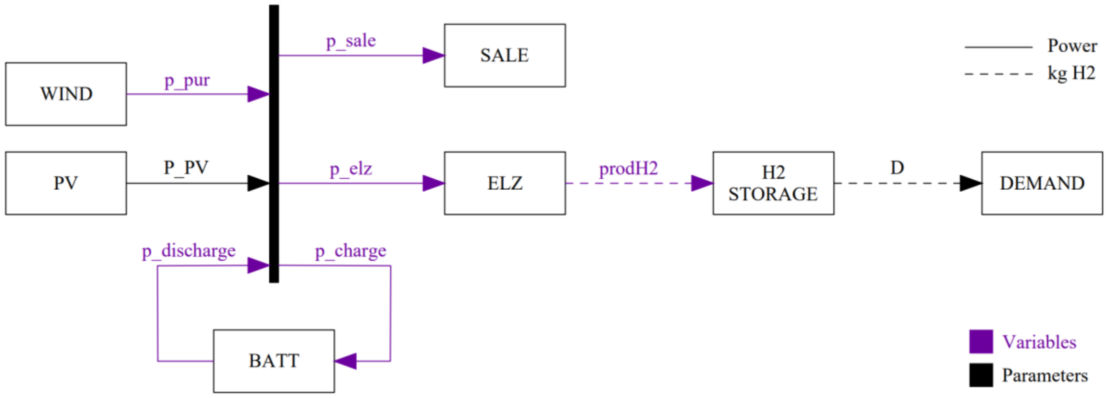

Figure 8. Optimization model structure.

5.2 OBJECTIVE FUNCTION

The main objective function of the model is the cost reduction of its functioning. The major objective is to increase its profitability bounded to the system requirements. The system costs include the energy bought and sold at every hour, which depends on the energy cost, as well as a battery aging cost for every battery charge. The objective function may include in a further developed model a sale price for hydrogen, which would compensate the total cost. It has not been included as the system does not sell hydrogen to third parties, and only focuses its production to satisfy the ammonia demand. The makes sense if the contract with the ammonia factory sets a fixed H2 price and allows the flexibility considered in the model.

$$min\left(\sum_h EC_h({p_{pur}}_h - {p_{sale}}_h) + BC \cdot {p_{charge}}_h\right) \tag{1}$$

5.3 MODEL CONSTRAINTS

The model objective function is being obtained subject to satisfying every constraint required. These constraints will be described down below, each one related to a different element of the optimization model.

5.3.1 ENERGY PURCHASE & SALE

Energy purchase may not exceed the maximum wind generation power at every hour. At most, the system would purchase the maximum power generated.

$$p_{pur_h} \leq P_{WIND_h} \qquad \forall h \qquad (2)$$

It has been considered that the system can't purchase and sale power at the same time period. Constraints (3) and (4) establish that if the energy is bought, it cannot be sold at a certain time.

$$p_{pur_h} \leq 100 \cdot {\varsigma^{ps}}_h \qquad \forall h \qquad (3)$$

$$p_{sale_h} \leq 100 \cdot (1 - {\varsigma^{ps}}_h) \qquad \forall h \qquad (4)$$

5.3.2 HYDROGEN PRODUCTION & STORAGE

A relationship between power and hydrogen generation had to be established. Constraint (5) determines the conversion factor from power to kilograms of hydrogen produced hourly.

$$prodH2_h = p_{elz_h} \cdot PtoH \qquad \forall h \qquad (5)$$

The total production at a year must be equal to the total demand of the same year. Every kilogram of hydrogen demanded must be produced in that year.

$$\sum_h prodH2_h = \sum_h D_h \qquad (6)$$

Constraint (7) determines the Level of Hydrogen (loh) at the hydrogen tanks. It considers the quantity of hydrogen entering the tanks and the hydrogen demanded at every hour. This constraint is updated hourly with the previous value of the Level of Hydrogen (loh). It includes hydrogen transformation performance as well as a conversion factor of transforming kilograms of hydrogen into m^3.

$$loh_h = loh_{h-1} + \frac{Perf_{ELZ} \cdot prodH2_h}{C_{ELZ}} - \frac{Perf_{elz} \cdot D_h}{C_{ELZ}} \qquad \forall h \qquad (7)$$

5.3.3 BATTERY STORAGE

Constraint (8) restricts the hourly charge and discharge of the battery, subject to its maximum capacity. Nevertheless, battery use isn't totally restricted as it is in constraints (3) and (4), which restricted to only purchase or sale of the energy at any given hour.

$$\frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} + \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \leq 1 \qquad \forall h \qquad (8)$$

The State of Charge (soc) of the battery follows the same structure as the Level of Hydrogen (loh) described in constraint (7). Likewise, the battery storage status is hourly updated with the input power entering the battery, p_{charge}, and the output power leaving the battery, $p_{discharge}$.

$$soc_h = soc_{h-1} + \frac{Perf_{BATT} \cdot p_{charge_h}}{C_{BATT}} - \frac{Perf_{BATT} \cdot p_{discharge_h}}{C_{BATT}} \qquad \forall h \qquad (9)$$

5.3.4 ENERGY BALANCE

The main constraint that needs to be satisfied is the energy balance in the system. This balance can be easily identified in Figure 8. The power balance distinguishes between input and output elements. A constant equilibrium in the system is required.

$$p_{pur_h} + p_{discharge_h} + P_{PV_h} = p_{sale_h} + p_{charge_h} + p_{elz_h} \qquad \forall h \qquad (10)$$

Chapter 6. CASE RESULTS

After introducing every parameter data into the optimization model described, specific days have been considered to describe as better as possible the electrolyser plant functioning. The main elements will be described, and a deep understanding in their performance will be developed. This specific time periods have been elected for showcasing the most and least favourable situations the electrolyser may confront. Results will be mainly showing the relationship in the hourly energy balance with the energy price, as well as with the status of battery and hydrogen storage.

6.1 BASE CASE STUDY

6.1.1 HIGH-LIGHT PERIOD

Considering two sunny days, e.g., beginning of April 2021, the model determines the most optimal solution for the parameter values from this specific period.

The specific energy balance for the two sunny days is described in Figure 9, where input elements are being described as bar charts, whereas output variables are being showcased as lines.

The photovoltaic plant is producing at its highest production rate, as it is performing in ideal conditions. It is of great importance noting that most of the energy produced by the photovoltaic plant is being sold to the electricity market when the electrolyser isn't producing hydrogen or when the battery is not being charged. Moreover, the amount of energy produced by the photovoltaic plant is much higher than the maximum energy required for hydrogen production, which forces the microgrid to sell the exceeding energy to the market.

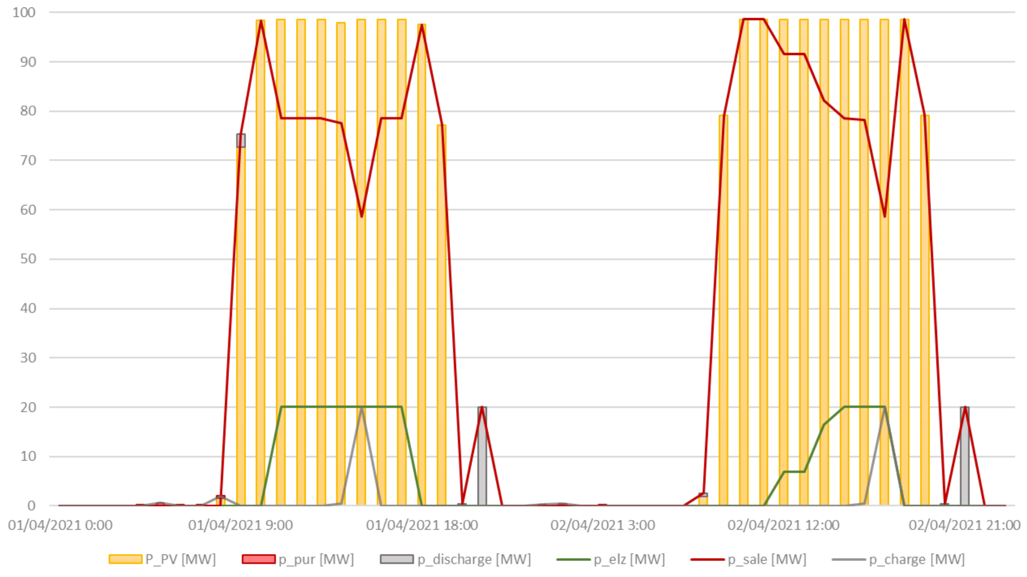

Figure 9. Energy balance for a high-light period.

In addition, as described in Figure 10, energy is being sold when the energy cost is at its highest. Comparing both figures illustrates the relationship between the energy cost, the amount of energy sold, and the power entering the electrolyser for hydrogen production. The production of hydrogen is being reserved for low-cost energy periods when selling the photovoltaic generated power isn't as profitable. The model determines that producing hydrogen during these periods makes the microgrid more cost-efficient.

The lack of energy purchased from renewable sources during sunny periods is quite relevant, as it is almost non-existent. The system is individually capable of satisfying the hydrogen demand with the total energy produced by the photovoltaic plant.

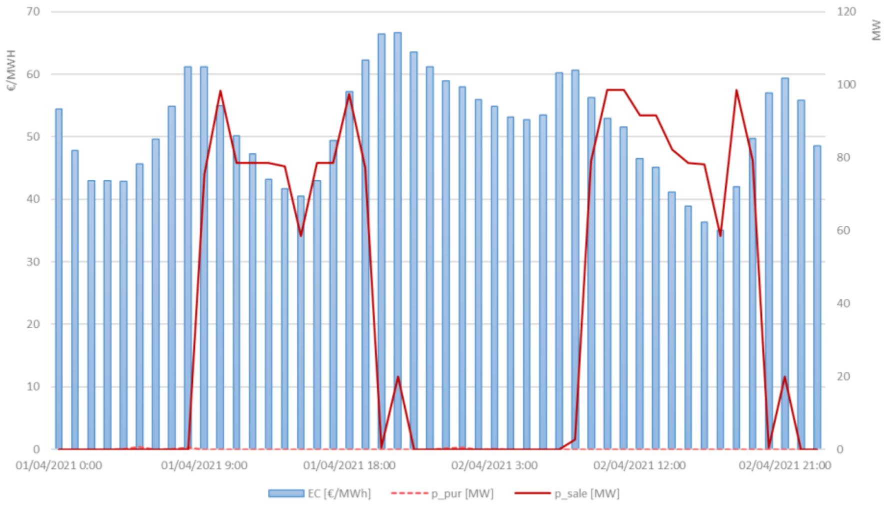

Figure 10. Relationship between energy cost and power purchased and sold for a high-light period.

Alongside, considering that the microgrid sells most of the energy produced by the photovoltaic plant, the battery is being fully charged during high-peak periods. The energy is then being sold to the electricity market when the energy costs rise. The State of Charge of the battery is being described in Figure 11. As the battery is a short-time storage system, a minimal loss has been considered when discharging the battery. This minimal loss is shown as bezels in Figure 11.

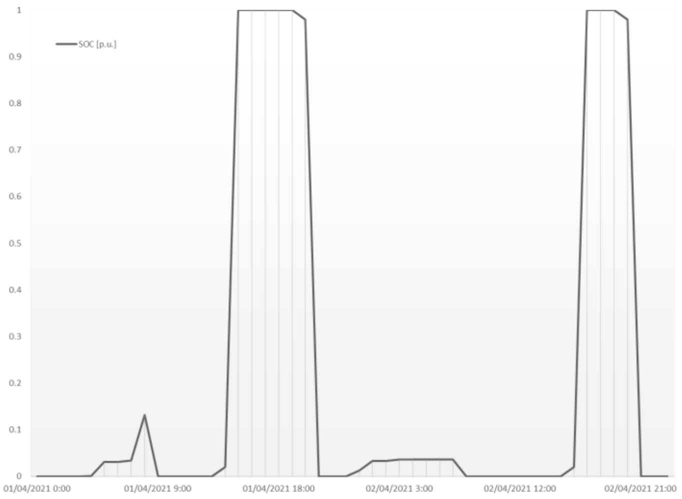

Figure 11. SOC of the battery for a high-light period.

Finally, the level of hydrogen (LOH) is being showcased in Figure 12. As previously stated, hydrogen is produced in daylight periods. This describes the variation the LOH presents during the specific period presented. The LOH increases with the production of hydrogen, and decreases during night-time, as there is no production.

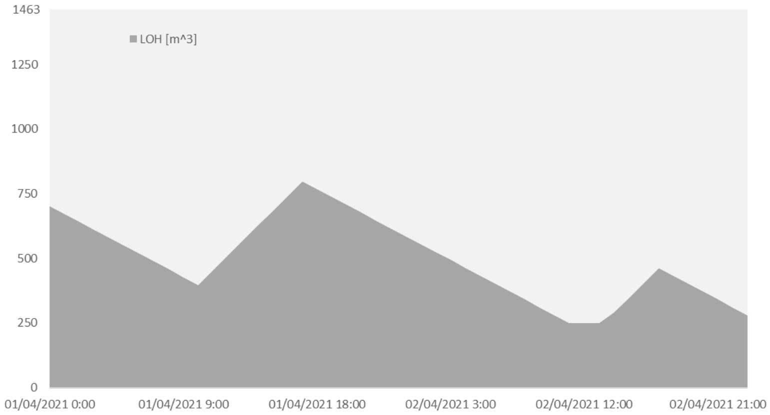

Figure 12. LOH of the hydrogen tanks for a high-light period.

6.1.2 LOW-LIGHT PERIOD

It may be significant to consider other periods when the photovoltaic plants functioning differs from the previously explained. Middle November, as an example, describes a low-light situation when the photovoltaic production is much lower than the earlier situation described.

Figure 13 shows an energy balance representation of a low-light period. Photovoltaic generation is doubtlessly much lower than in the previous situation. There is not as much exceeding energy to be sold as before. In fact, there are some situations when the system requires energy purchase for hydrogen production. The microgrid, when experiencing these circumstances, is being forced into producing in more efficient production hours.

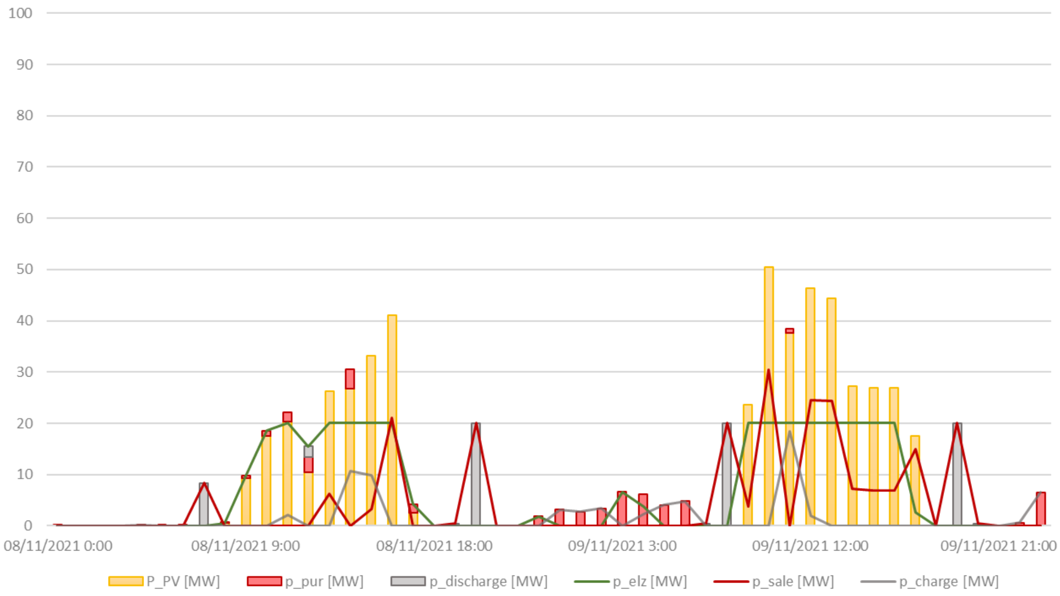

Figure 13. Energy balance for a low-light period.

Energy, as in the previous ideal situation, is being bought at its lower cost and sold when the energy cost rises, being described in Figure 14. However, there is now a need for the purchase of energy in order to satisfy the hydrogen demand. Energy is being bought during night periods and producing hydrogen during non-available photovoltaic resources becomes a priority.

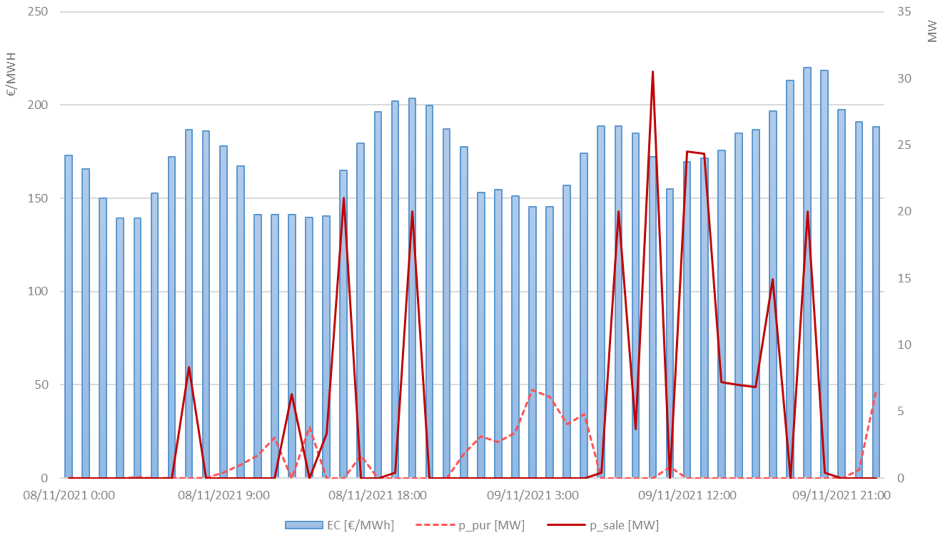

Figure 14. Relationship between energy cost and power purchased and sold for a low-light period.

Nevertheless, the battery is now much more used. The state of charge (SOC) of the battery is being displayed in Figure 15. Batteries are charged with lower cost energy and then sold when the energy cost increases. In comparison with the previous situation, the battery use has considerably increased.

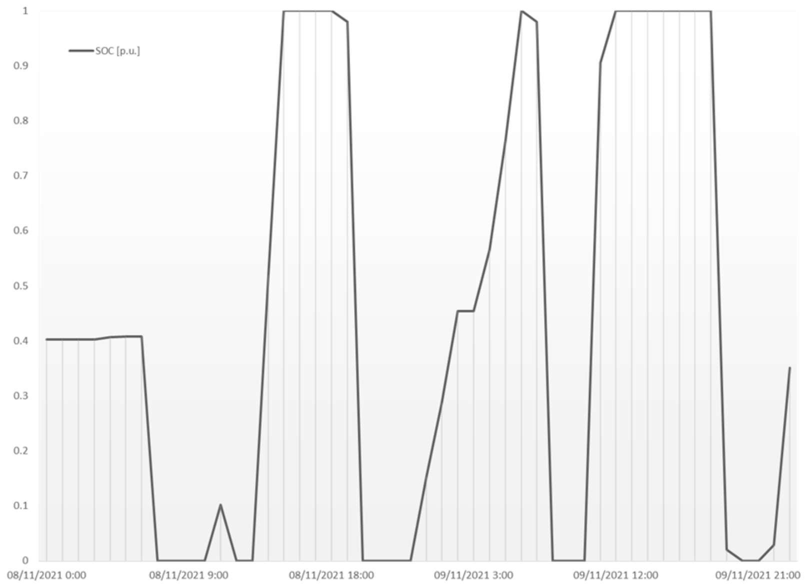

Figure 15. SOC of the battery for a low-light period.

Figure 16 describes the level of hydrogen during this specific period. The system still produces its most during daylight periods. However, hydrogen is being produced as well during night periods due to the energy bought in these situations.

Comparing it to the previous level of hydrogen during high-light periods (described in Figure 12), the actual level of hydrogen (Figure 16) differs completely. High-light level of hydrogen periods could be characterised with a lower hydrogen storage compared with the low-light situations.

Conclusions are easily made up only focusing on this information: level of hydrogen in high-light periods might be much higher than in low-light situations. However, does level of hydrogen only depend on the quantity of daylight a period receives? Are there any additional elements to be considered when characterising the level of hydrogen status?

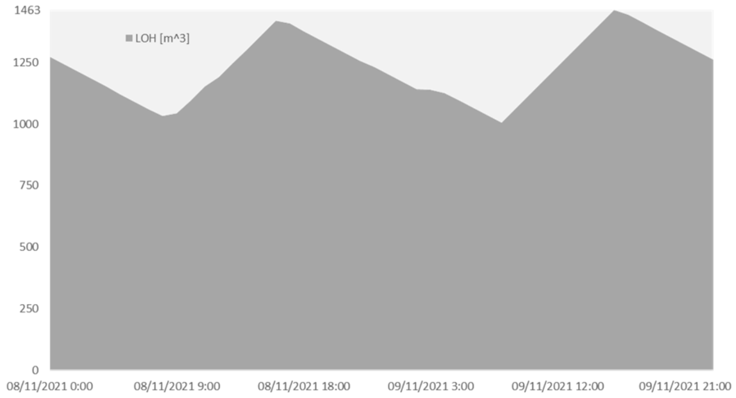

Figure 16. LOH of the hydrogen tanks for a low-light period.

6.1.3 LEVEL OF HYDROGEN

Focusing only on the LOH and the hydrogen production, a wider view is needed for a better understanding. Incrementing the time period in low-light situations, to a 15-day period, displays a more general view of the hydrogen tank status, shown in Figure 17. In fact, conclusions reached during previous points, which stated that low-light periods may store more hydrogen than high-light periods, are being disputed. Figure 17 shows a critical increase in the hydrogen production during these periods.

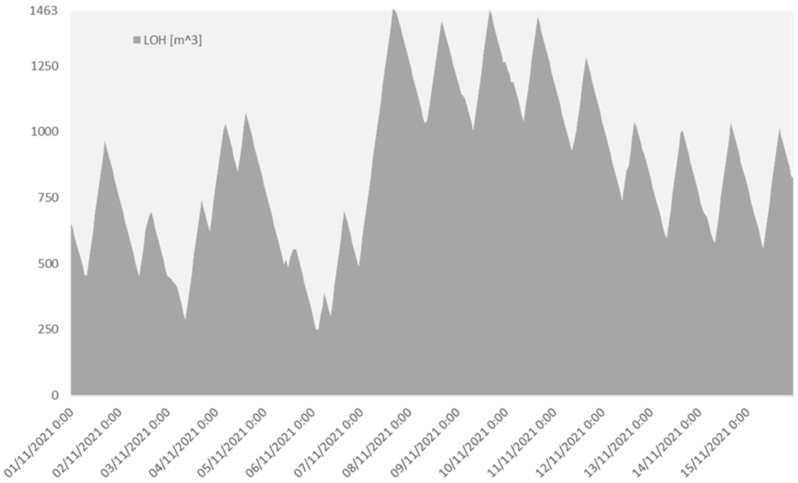

Figure 17. LOH comparison for low-light periods.

This increase in the hydrogen production during these unfavourable periods, evolving from a semi-empty hydrogen storage to an almost fully hydrogen storage, is being described in Figure 18. Focusing deeply on the specific period where this change happens, it can be seen a high increase in the power entering the electrolyser. It is worth noting the variation the photovoltaic plant experiments, from almost non-existent photovoltaic generation power to a high increase in its generation.

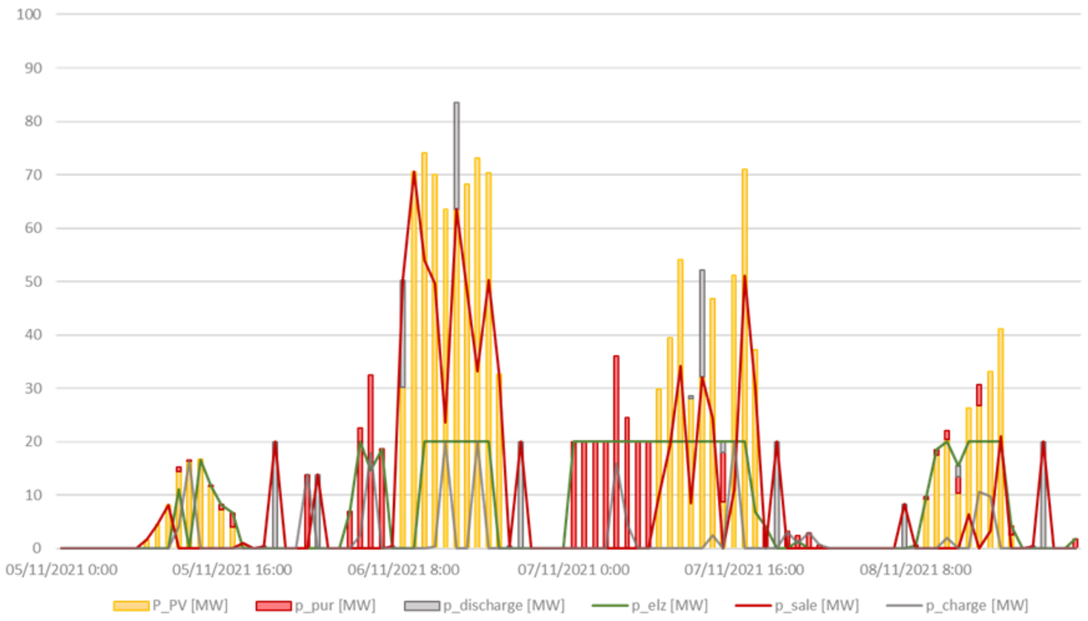

Figure 18. Energy balance for LOH comparison in low-light periods.

Exceeding photovoltaic power is still being mostly sold for satisfying the hourly energy balance. However, as described in Figure 19, there is a high increase in the energy purchase, when the energy cost drops from the mean energy price. In this specific situation described, there are two main energy purchases, one during night period for fulfilling minimum level of hydrogen requirements, and another one during daylight period. This second energy purchase situation is of great significance. The energy cost drops considerably during these specific hours; hence, the system increases its hydrogen production during this low-cost energy periods as well as complementing them with the photovoltaic power produced.

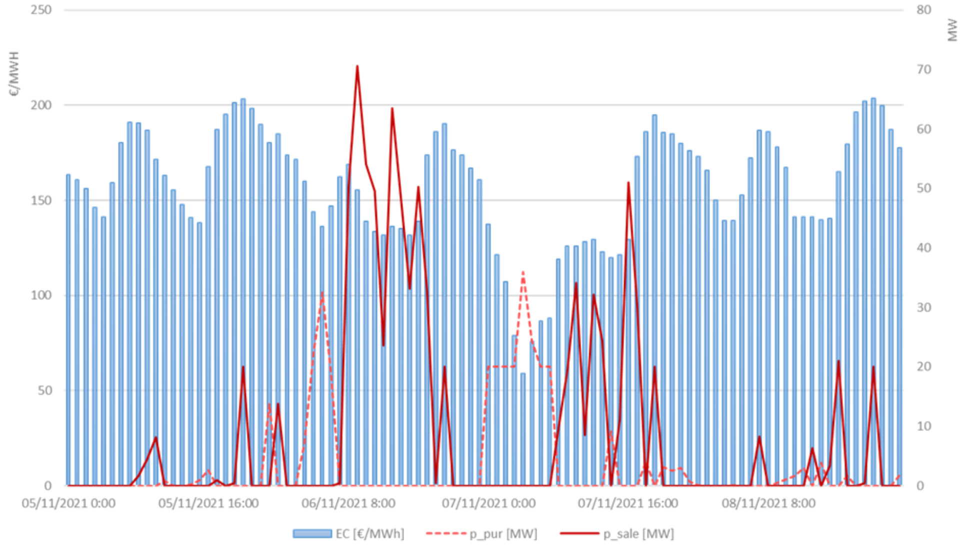

Figure 19. Energy cost for LOH comparison in low-light periods.

This specific relationship described has only been tested during low-light daylight periods. For this reason, high-light daylight periods must be considered. To sum up, this specific period was described as self-sufficient, mostly producing with photovoltaic power without purchasing any energy from the market. The level of hydrogen previously presented showed a semi-empty storage status. However, a wider view has been considered during that specific period, focusing on the quantity of hydrogen produced and sold.

The situation previously described corresponded to the first period of Figure 20, which as shown, clearly reveals a massive hydrogen generation during that period, increasing the level of hydrogen considerably. This new situation is very similar to the one described for a low-light period. In that previous case, it was stated that the increase in the hydrogen production was produced by a considerable energy cost reduction during a specific time period.

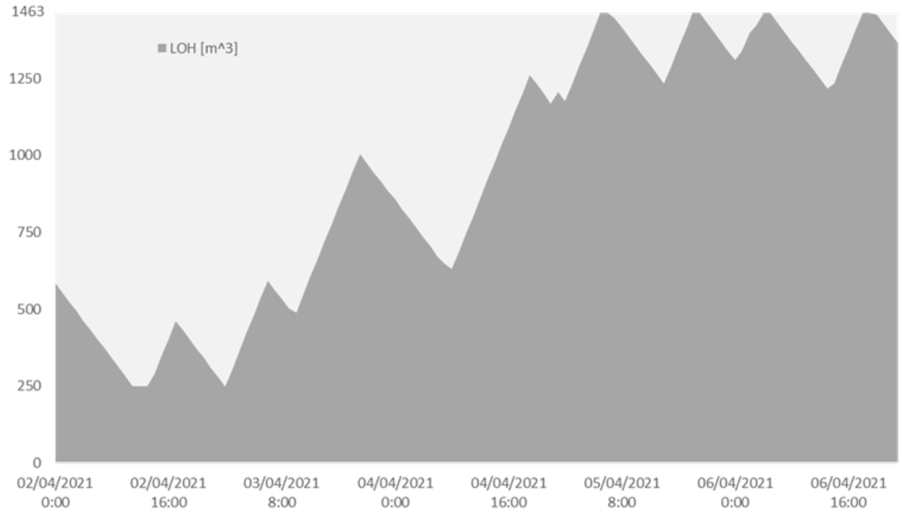

Figure 20. LOH comparison for high-light periods.

Figure 21 still shows the great amount of photovoltaic power produced. As in previous points, most of this generation is being sold, as well as produced when the energy cost drops. However, still having exceeding intrinsic energy during daylight periods for producing hydrogen, the system even produces hydrogen from the energy purchased during night periods.

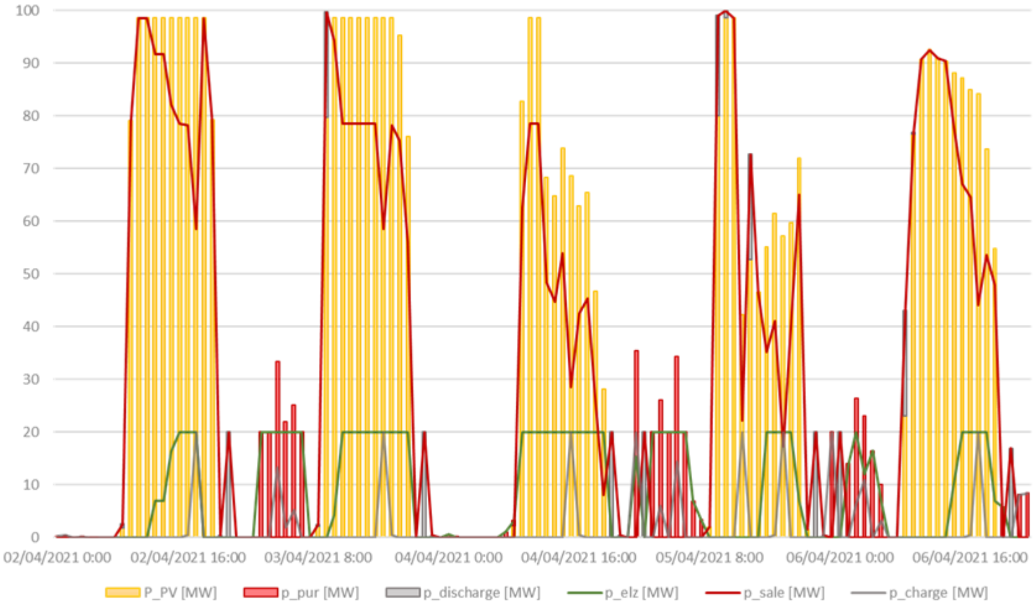

Figure 21. Energy balance for LOH comparison in high-light periods.

As described in Figure 22, exceeding solar energy is still being sold for the energy balance to be satisfied. However, the system now starts to purchase energy mostly during night periods, in low-peak energy costs, even producing enough energy from the photovoltaic plant to satisfy hydrogen demand. The system considers a more profitable solution, to purchase energy during low-peak energy costs and increment the level of hydrogen by producing during night periods.

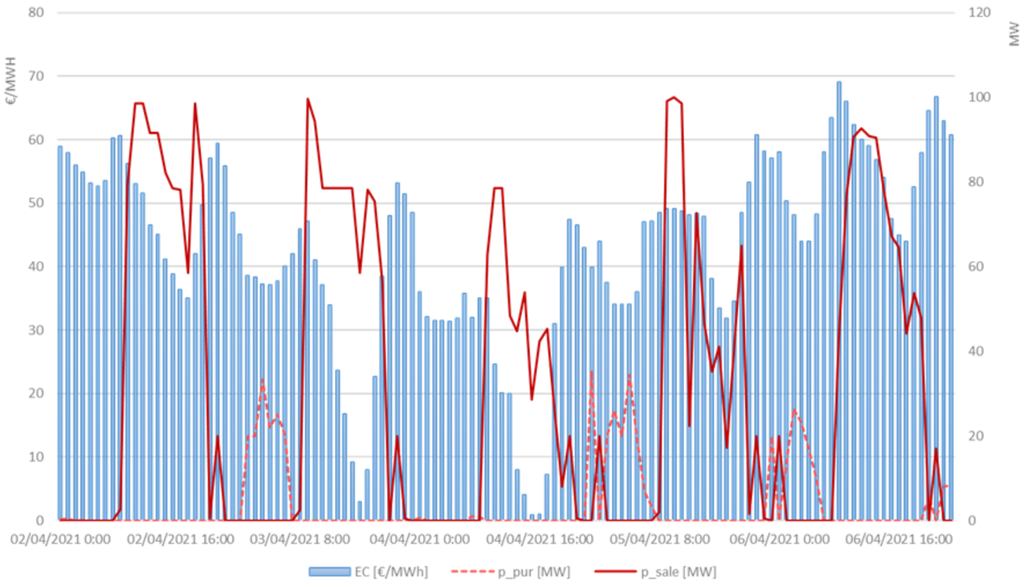

Figure 22. Energy cost for LOH comparison in high-light periods.

As a result of the different situations described comparing the level of hydrogen (LOH) under different conditions, several conclusions may be drawn from it.

An initial consideration estimated that level of hydrogen could be determined depending on the solar period. Nevertheless, as described in this point, level of hydrogen has still no relationship with the period in which is observed. Level of hydrogen depends clearly on the relative energy cost. A relative decrease in the energy cost in a certain period, prompts the system to produce during non-usual time periods (e.g., at night), even purchasing energy when having exceeding photovoltaic power generation during daylight.

The model is set knowing the energy cost at every moment, as well as the hourly photovoltaic and wind power production, making the hydrogen production highly efficient.

6.2 SENSITIVITY ANALYSIS

One of the main objectives of Iberdrola's plant is to scale up the microgrid. As the objective remains in increasing profitability, any change presented will be determined according to the objective function previously established. These changes would determine the best possible solutions and may highlight plant behaviours when implementing these changes. The sensitivity analysis presented would help determining how the system reacts under a specific change. All the following analysis are still being focused on the same time period (beginning of April), to be easily compared.

6.2.1 AN INCREASE IN THE HYDROGEN STORAGE

Is the maximum hydrogen capacity established sufficient for providing the best optimal solution? Would the system perform better when increasing this capacity? It has been simulated how the system would react when storing twice as much hydrogen as in the base case study. Hydrogen tanks have been scaled up to 200% of the original value.

Figure 23 displays the level of hydrogen when incrementing its capacity twice as much. As displayed, the behaviour of the hydrogen demand still remains in similar conditions than in the previous situation (Figure 20).

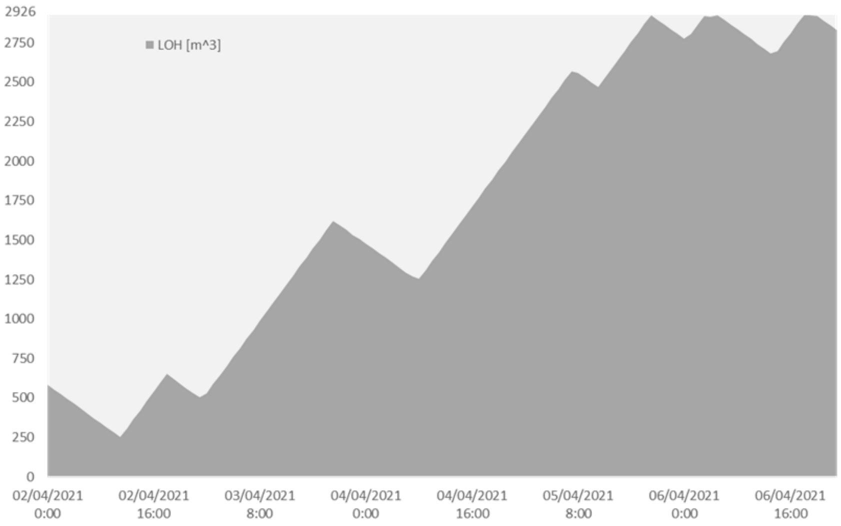

Figure 23. LOH for double hydrogen capacity.

However, as displayed in Figure 24, the hydrogen production becomes more of a priority, reducing the amount of photovoltaic energy sold to the market when in low energy cost situations. As hydrogen tanks are being fully filled during these specific periods, the system can reduce hydrogen production when high energy cost situations appear, therefore, selling more photovoltaic energy.

Nevertheless, comparing it to Figure 21, the system still purchases the same amount of energy, as the energy cost during those specific hours is being reduced, but focuses its production during photovoltaic available hours, which is in line with what would be expected.

Increasing the hydrogen capacity allows the system to store more of the photovoltaic energy produced to increase its profitability. However, energy is still purchased when the energy costs drop during night periods. The level of hydrogen, even with an increase in the hydrogen production, remains comparatively similar than in the previous case, proportional to the capacity increase.

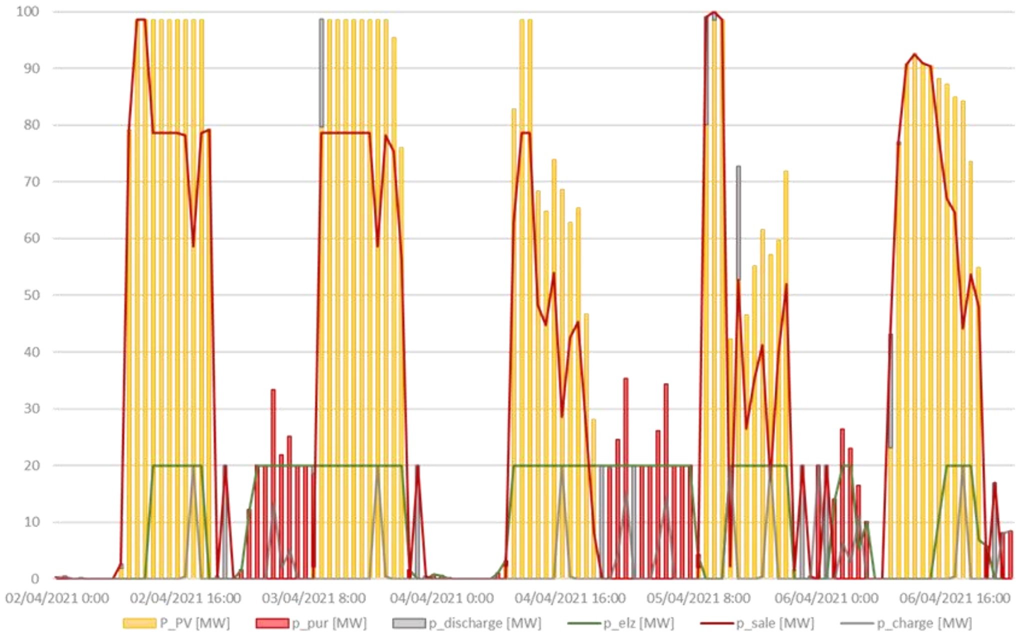

Figure 24. Energy balance for double hydrogen capacity.

6.2.2 AN INCREASE IN THE HYDROGEN DEMAND

Another main point to consider is the possibility of an increase in the hydrogen demand. Would the system be capable of satisfying an increase in the demand with the current hydrogen capacity and production? Hydrogen demand has been scaled up to 150% of the initial value.

As the electrolyser plant relies mainly on the photovoltaic power produced, an increase in the hourly power demanded may be a problem. For this reason, the system is being backed up with the possibility of a wind generation source that provides energy during low-light periods, when available. However, an increase in 50% of the hydrogen demanded is not being supported by the current system. Wind generation power isn't fully consistent to assume the nightly hydrogen production, and the established storage capacity does not allow the system to produce and store as much hydrogen as required using the photovoltaic generation power.

Finally, as the system relies heavily on the photovoltaic power generation, the plant is not capable of satisfying the increase in the demand. Other investments would be required for implementing this decision.

6.2.3 AN INCREASE IN THE HYDROGEN DEMAND & STORAGE

One possible solution for the increase in the demand is escalating the hydrogen storage. A feasible solution for a scale of 150% of the given demand could be satisfied by doubling its storage.

Figure 25 displays the behaviour of the hydrogen tanks with the increase in the demand. As shown, it doesn't differentiate as much from previous cases, even considering that the system requires more hydrogen production. The Level of Hydrogen behaves in a similar manner to the previously explained.

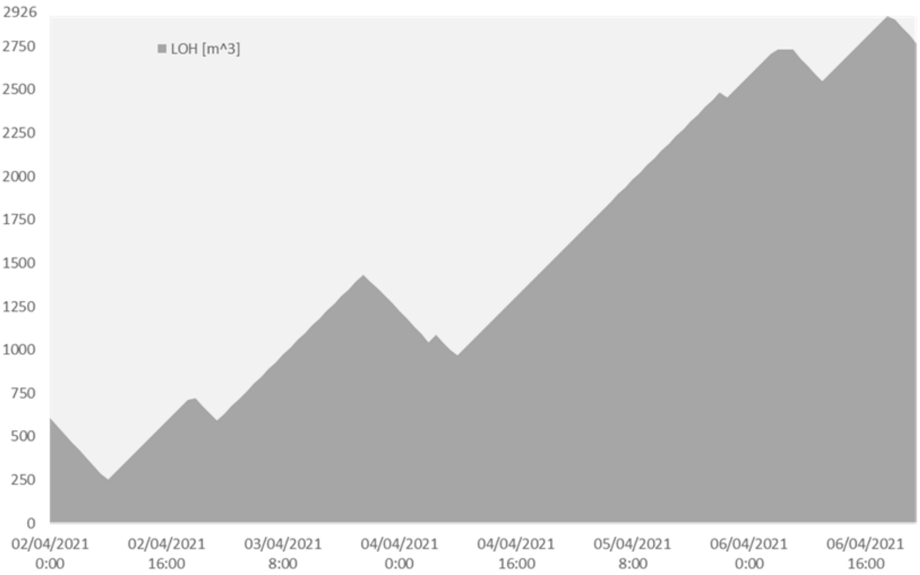

Figure 25. LOH for double capacity and 150% demand.

However, Figure 26 shows the increase in the hydrogen required and entering the electrolyser. Less photovoltaic energy is being sold to the market. Instead, hydrogen production becomes much more constant, as the demand is much higher. Nevertheless, the energy purchase periods and producing hours are very similar to the previous situation.

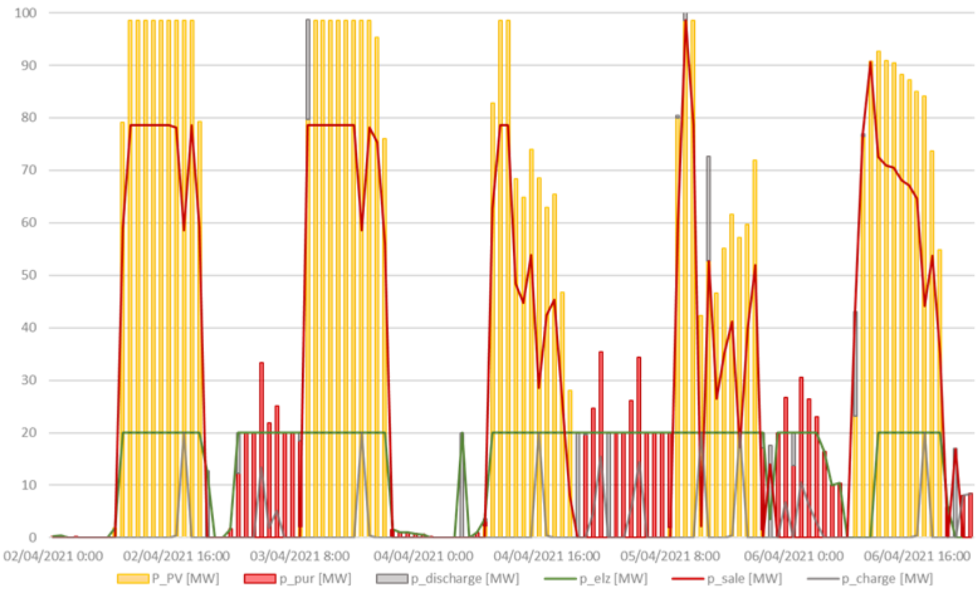

Figure 26. Energy balance for double capacity and 150% demand.

Increasing the hydrogen storage capacity may be one of the possible future decisions to implement when increasing the hydrogen demand, as it provides a feasible alternative to the increase in the production required.

6.2.4 AN INCREASE IN HYDROGEN DEMAND & PRODUCTION

Another possible solution for the increase in the hydrogen demanded is including more hydrogen production. For this reason, it has been considered that the system is now capable of producing twice as much hydrogen as it did in the initial case study, which could be associated with the purchase of a second electrolyser with the same characteristics. The following simulations are being studied for an increase in 50% of the demand and doubling its maximum available production, still using the original hydrogen storage.

Figure 27 displays the system behaviour when being able to produce higher quantities of hydrogen. The Level of Hydrogen appears to be less constant, and its storage varies considerably during the specific period.

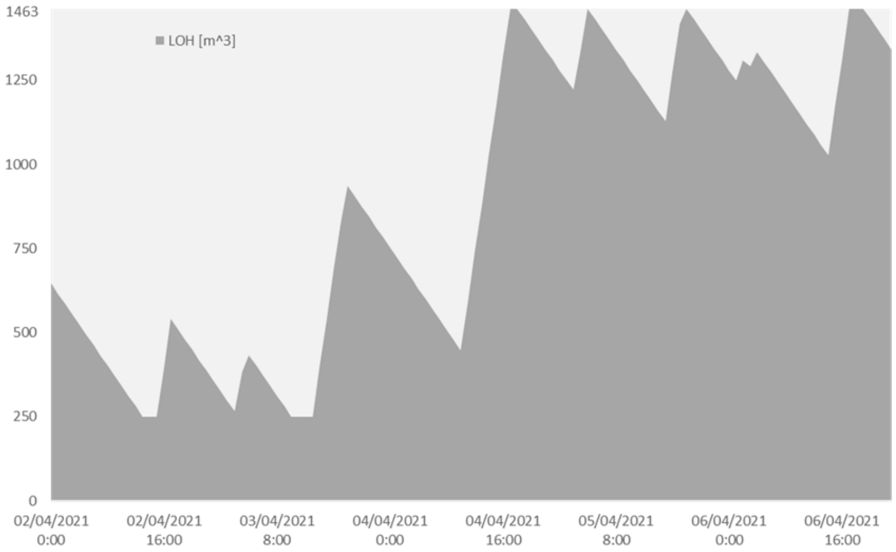

Figure 27. LOH for double production and 150% demand.

As described in Figure 28, most of the photovoltaic power is now being sold to the market. However, in highly productive hydrogen hours, the system focuses principally on its generation, and therefore produces hydrogen in a less consistent manner. Comparing it to the previous situation, where most hydrogen was almost constantly produced, the current model determines that it becomes more profitable when producing during short low-cost energy periods of time, by producing at its maximum.

Figure 28. Energy balance for double production and 150% demand.

Including more hydrogen production capacity satisfies the increase in the hydrogen demand. However, as shown, the production is developed in an inconsistent manner compared to the previous solution, which may lead to an under-utilization of the electrolyser plant in many situations.

Table 3, below, shows a summary of the different scenarios studied during the sensitivity analysis. On it, specific characteristics of each case are displayed, showing the feasibility of the modified plant, according to the optimization model.

Sensitibity Cases	H2 Production Capacity	H2 Storage Capacity	H2 Demand	Success
6.1 Base Case Study	100%	100%	100%	Feasible
6.2.1 Δ H2 Storage	100%	200%	100%	Feasible
6.2.2 Δ Demand	100%	100%	150%	Infeasible
6.2.3 Δ Demand & H2 Storage	100%	200%	150%	Feasible
6.2.4 Δ Demand & H2 Prod. Capacity	200%	100%	150%	Feasible

Table 3. Sensitivity analysis cases.

Chapter 7. CONCLUSIONS

Most of the energy produced by the photovoltaic plant is being sold to satisfy the energy balance established. Batteries are mostly charged with solar power and discharged when the energy cost rises. Hydrogen is mainly produced using photovoltaic power, unless the energy relative cost drops heavily and producing during night periods becomes more profitable. Under low-light photovoltaic situations, when the system is not capable of providing the sufficient energy to satisfy the demand, the plant relies on purchasing energy from the market.

Batteries, though, are not usually used for hydrogen production, as it would have been expected. They are mainly used for the energy sale when its cost is higher than expected. Nevertheless, there are specific situations where batteries may be used for hydrogen production.

It is worth noting, that the Level of Hydrogen has been proved not to be light-dependent. It could have been thought that high photovoltaic production time periods would lead to higher hydrogen production, and contrarily, low photovoltaic production would lead to low hydrogen production. Instead, the model determines that the Level of Hydrogen mainly depends on the specific relative energy costs of the period observed. This means that hydrogen will be highly produced in situations where the relative energy cost drops, independently of whether it is a high-light or a low-light period.

Future actions could be taken to develop this plant. Incrementing the hydrogen storage capacity would make the system more profitable. The purchase of hydrogen would be optimized, and the periods of hydrogen production would be restricted to the most profitable hours.

However, the system would not be capable of satisfying an increase in 50% of the demand with the basic specifications, as hydrogen production relies heavily on photovoltaic resources and large quantities of hydrogen cannot be stored. To cover that increase, an investment in order to modify the system should be undertaken.

One possible solution is incrementing the hydrogen storage capacity. The system would produce more hydrogen which would be stored at these larger tanks. The Level of Hydrogen status would be much consistent, being the hydrogen production more levelled.

Another possible solution is incrementing the hydrogen production by including another electrolyser. The system would be able to produce more hydrogen in an hourly basis. However, the hydrogen generation process would be more inconsistent, as the generation would only be restricted to exclusive high profitable periods in large-scale quantities. This solution would lead to an under-utilization of the electrolysers.

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ANNEX I – SOURCE CODE

```
import pyomo.environ as pyo
from pyomo.dataportal import DataPortal
from pyomo.environ import ConcreteModel, Set, Param, Var, Binary,
NonNegativeReals, Constraint, Objective, minimize, Suffix
from pyomo.opt import SolverFactory
import pandas        as pd
import matplotlib.pyplot as plt

mModel=ConcreteModel('Hydrogen Production Problem')

dictSets = DataPortal()

#SETS
dictSets.load(filename='mSets_Hours365.csv', set='h', format='set')
mModel.h=Set(initialize=dictSets['h'], ordered=True, doc='hours')

dictSets.load(filename='mSets_StorageSystem.csv', set='s', format='set')
mModel.s=Set(initialize=dictSets['s'], ordered=True, doc='Storage System')


#PARAMETERS

#dataframes
dfStorageParameters=pd.read_csv('mParam_StorageParam.csv', index_col=[0])
dfEnergyCost=pd.read_csv('mParam_EnergyCost365.csv', index_col=[0])
dfGeneration=pd.read_csv('mParam_Generation365.csv', index_col=[0])
dfWind=pd.read_csv('mParam_Wind.csv', index_col=[0])
dfDemand=pd.read_csv('mParam_Demand365.csv', index_col=[0])

#Link between parameters and dataframes
mModel.PtoH=Param(initialize=360/20)
mModel.LOH0=Param(initialize=1000)
mModel.BC=Param(initialize=0.00001)
mModel.C=Param(mModel.s,initialize=dfStorageParameters['Capacity'])
mModel.P=Param(mModel.s,initialize=dfStorageParameters['Performance'])
mModel.MINsto=Param(mModel.s,initialize=dfStorageParameters['Min Storage'])
mModel.MAXsto=Param(mModel.s,initialize=dfStorageParameters['Max Storage'])
mModel.EC=Param(mModel.h,initialize=dfEnergyCost)
mModel.P_PV=Param(mModel.h, initialize=dfGeneration['PV'])
mModel.P_WIND=Param(mModel.h, initialize=dfWind['Wind'])
mModel.D=Param(mModel.h, initialize=dfDemand['Demand'])


#VARIABLES

mModel.p_pur=Var(mModel.h,bounds=(0,100), doc='Power purchased',
within=NonNegativeReals)
```

```
mModel.p_sale=Var(mModel.h,bounds=(0,100),doc='Power in sale',
within=NonNegativeReals)
mModel.p_charge=Var(mModel.h,bounds=(0,20), doc='Charge of the BATT',
within=NonNegativeReals)
mModel.p_discharge=Var(mModel.h,bounds=(0,20), doc='Discharge of the BATT',
within=NonNegativeReals)
mModel.p_elz=Var(mModel.h,bounds=(0,20), doc='Power entering the electrolyser',
within=NonNegativeReals)
mModel.soc=Var(mModel.h, bounds=(mModel.MINsto['BATT'], mModel.MAXsto['BATT']),
doc= 'SOC of the BATT [p.u.]', within=NonNegativeReals)
mModel.loh=Var(mModel.h, bounds=(mModel.MINsto['ELZ'], mModel.MAXsto['ELZ']),
doc= 'Level of Hydrogen [m^3]', within=NonNegativeReals)
mModel.prodH2=Var(mModel.h, bounds=(0, None), doc='Producción de H2 (Conversión
de MW a kg H2) [kg H2]', within=NonNegativeReals)
mModel.sigma_pur_sale=Var(mModel.h, bounds=(0,1), doc='Binary variable for power
purchased', within=Binary)

#CONSTRAINTS

def ePurchase (mModel, h):
    return mModel.p_pur[h]<=mModel.P_WIND[h]
mModel.ePurchase = Constraint (mModel.h, rule=ePurchase, doc='Limitation of the
purchase')

def eProdH2 (mModel, h):
    return mModel.prodH2[h]==mModel.p_elz[h]*mModel.PtoH
mModel.eProdH2 = Constraint (mModel.h, rule=eProdH2, doc='Generation of
Hydrogen')

def eSOC(mModel, h):
    if h=='2021-01-01T00:00:00+01:00':
        return mModel.soc[h]==
+((mModel.P['BATT']*mModel.p_charge[h])/mModel.C['BATT'])-
((mModel.P['BATT']*mModel.p_discharge[h])/mModel.C['BATT'])
    return
mModel.soc[h]==mModel.soc[mModel.h.prev(h,1)]+((mModel.P['BATT']*mModel.p_charge[
h])/mModel.C['BATT'])-((mModel.P['BATT']*mModel.p_discharge[h])/mModel.C['BATT'])
mModel.eSOC = Constraint (mModel.h, rule=eSOC, doc='Balance equation for the
storage of the BATT [p.u.]')

def eLOH(mModel, h):
    if h=='2021-01-01T00:00:00+01:00':
        return mModel.loh[h]==     mModel.LOH0
+(mModel.P['ELZ']*mModel.prodH2[h]/mModel.C['ELZ'])-
((mModel.P['ELZ']*mModel.D[h])/mModel.C['ELZ'])
    return
mModel.loh[h]==mModel.loh[mModel.h.prev(h,1)]+(mModel.P['ELZ']*mModel.prodH2[h]/m
Model.C['ELZ'])-((mModel.P['ELZ']*mModel.D[h])/mModel.C['ELZ'])
mModel.eLOH = Constraint (mModel.h, rule=eLOH, doc='Balance equation for the
Level of Hydrogen [m^3]')

def eBalanceELZ(mModel):
```

```
    return sum(mModel.prodH2[h] for h in mModel.h)==sum(mModel.D[h] for h in 
mModel.h)
mModel.eBalanceELZ=Constraint(rule=eBalanceELZ, doc='Balance in the 
electrolyser')

def eEnergyBalance(mModel,h):
    return mModel.p_pur[h]+mModel.p_discharge[h]+mModel.P_PV[h]==mModel.p_sale[h]
+ mModel.p_charge[h] + mModel.p_elz[h]
mModel.eEnergyBalance=Constraint(mModel.h, rule=eEnergyBalance, doc='Energy 
Balance')

def ePurSaleConstraint1(mModel, h):
    return mModel.p_pur[h]<=100*mModel.sigma_pur_sale[h]
mModel.ePurSaleConstraint1=Constraint(mModel.h, rule=ePurSaleConstraint1, 
doc='Declaration of binary variable mModel.sigma_pur_sale')

def ePurSaleConstraint2(mModel, h):
    return mModel.p_sale[h]<=100*(1-mModel.sigma_pur_sale[h])
mModel.ePurSaleConstraint2=Constraint(mModel.h, rule=ePurSaleConstraint2, doc='If 
purchased, there is no sale')

def eBattLimitation(mModel, h):
    return 
(mModel.P['BATT']*mModel.p_charge[h]/mModel.C['BATT'])+(mModel.P['BATT']*mModel.p
_discharge[h]/mModel.C['BATT'])<=1
mModel.eBattLimitation=Constraint(mModel.h, rule=eBattLimitation, doc='The 
battery can not charge and dicharge more than it maximum in an specific time 
period')


#OBJECTIVE FUNCTION

def eCost(mModel):
    return sum(mModel.EC[h]*(mModel.p_pur[h]-mModel.p_sale[h]) + 
mModel.BC*mModel.p_charge[h] for h in mModel.h)
mModel.eCost = Objective(rule=eCost, sense=minimize, doc='Objective Function')


Solver = SolverFactory('gurobi')
Solver.options['LogFile'] = 'mModel.log'
SolverResults = Solver.solve(mModel, tee=True)
SolverResults.write()
mModel.pprint()
mModel.display()


#RESULTS OUTPUTTING

#mModel.p_pur
OutputResults = pd.Series(data=[mModel.p_pur[h]() for h in mModel.h], 
index=mModel.h)
OutputResults.to_frame(name='[MW]').rename_axis(['mModelo.p_pur'], 
axis=0).rename_axis([None], axis=1).to_csv('mModelo.p_pur.csv', sep=',')
```

```
#mModel.p_sale
OutputResults = pd.Series(data=[mModel.p_sale[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[MW]').rename_axis(['mModelo.p_sale'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.p_sale.csv', sep=',')

#mModel.soc
OutputResults = pd.Series(data=[mModel.soc[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[p.u.]').rename_axis(['mModelo.soc'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.soc.csv', sep=',')

#mModel.loh
OutputResults = pd.Series(data=[mModel.loh[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[m^3]').rename_axis(['mModelo.loh'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.loh.csv', sep=',')

#mModel.p_charge
OutputResults = pd.Series(data=[mModel.p_charge[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[MW]').rename_axis(['mModelo.p_charge'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.p_charge.csv', sep=',')

#mModel.p_discharge
OutputResults = pd.Series(data=[mModel.p_discharge[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[MW]').rename_axis(['mModelo.p_discharge'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.p_discharge.csv', sep=',')

#mModel.p_elz
OutputResults = pd.Series(data=[mModel.p_elz[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[MW]').rename_axis(['mModelo.p_elz'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.p_elz.csv', sep=',')

#mModel.prodH2
OutputResults = pd.Series(data=[mModel.prodH2[h]() for h in mModel.h],
index=mModel.h)
OutputResults.to_frame(name='[kg H2]').rename_axis(['mModelo.prodH2'],
axis=0).rename_axis([None], axis=1).to_csv('mModelo.prodH2.csv', sep=',')
```