Impact analysis of large-scale electrolyzer deployment on the electrical grid in Andalusia

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Abstract

This study investigates the impact of large-scale electrolyzer deployment on the electrical grid of the Andalusia region, aligning with Spain's ambitious hydrogen production targets for 2030. Using a custom-developed operational model, the research explores various case studies, including a baseline scenario and more ambitious electrolysis capacity deployments. These case studies assess different strategies for the placement of electrolyzers, such as concentrating capacity near renewable energy sources versus near hydrogen demand centers.

The results indicate that the baseline scenario, which aligns with current infrastructure plans for 2030, does not significantly stress the electrical grid, suggesting that the planned projects are feasible within the existing and anticipated energy system for 2030. However, achieving a more ambitious hydrogen production scenario, such as the Spanish government's revised target of 11 GW of electrolyzer capacity, will require strategic planning. The study highlights the importance of positioning additional electrolyzer capacity near renewable energy sources to minimize grid congestion and operational costs while ensuring that the production process operates at full capacity. Additionally, it emphasizes that placing electrolyzers near hydrogen demand centers requires additional management of grid congestion.

The operational model has been proven effective in simulating the interactions within the energy system and quantifying the potential impacts of different case studies. However, aspects such as investment costs, detailed technological representation, and energy storage were not included in the model and should be addressed in future research for a more comprehensive analysis.

This research offers a set of recommendations for the deployment of electrolyzers in Andalusia, emphasizing the importance of strategic placement to achieve the right balance between grid reinforcement and operational efficiency for developing a cost-optimal hydrogen economy as the region moves towards its 2030 hydrogen targets.

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Contents

1 Introduction

1.1 Motivations and context

The energy transition is accelerating as countries intensify their efforts to reduce greenhouse gas emissions and shift towards sustainable energy systems. Hydrogen produced from renewable energy sources via electrolysis, is becoming a key vector of this transition. Europe has set an ambitious roadmap to establish a robust hydrogen ecosystem by 2030 [1], with the goal of producing 10 million tons of renewable hydrogen annually. This initiative positions hydrogen as an important element for decarbonizing sectors such as heavy industry, transportation, and energy storage.

Several countries have developed their own roadmaps to align with this broader strategy. Spain, capitalizing on its abundant renewable energy resources, has launched a significant initiative within this European framework. The Spanish government adopted a roadmap in 2020, announcing the installation of 4 GW of electrolyzer capacity by 2030. [2]. However, in 2023, a revision of the National Integrated Energy and Climate Plan (NECP) revealed an even more ambitious target of 11 GW of electrolyzer capacity by 2030, positioning Spain as a major player in the EU's hydrogen strategy.

The Andalusian region, with its favorable geographic conditions and renewable energy potential, stands at the front of Spain's hydrogen ambitions and is set to host several electrolysis projects by 2030.

Counting over 8.4 million people, Andalusia is the most populated region of Spain, and drives therefore a significant demand for energy. The region's electricity consumption reached approximately 38 TWh in recent years [3], emphasizing the importance of a reliable energy infrastructure. In this context, hydrogen stands as a key vector to decarbonize energy demanding sectors such as industry and mobility.

In 2024, renewable energy sources contribute to about 60% of the region's generation capacity, with important capacities in solar and wind energy that are expected to increase in the incoming years. Deploying large-scale electrolyzers is a strategic move to capitalize on this renewable energy potential, converting it into green hydrogen in order to decarbonizing several sectors with hydrogen such as industry and mobility. However, this also introduces significant challenges in integrating these systems into the existing electrical grid. Electrolyzers draw considerable electricity as input, adding load to the grid and potentially causing additional stress.

1.2 Objective of the study

This study aims to explore the impact of large-scale electrolyzer deployment on the electrical grid in the Andalusia region. Specifically, it seeks to assess the feasibility of integrating significant hydrogen production capacity into the existing power network and to identify the strategic locations for electrolyzers that would optimize their operation within the grid's constraints.

The investigation will focus on analyzing various hydrogen production scenarios, varying the number and location of electrolyzers. These case studies will be evaluated to understand their impact on grid congestion, renewable energy utilization, and the overall feasibility of Spain's hydrogen strategy for 2030. Additionally, the study will assess the potential need for grid reinforcement or expansion to accommodate the increased electricity demand associated with large-scale hydrogen production.

To achieve these objectives, the energy system of Andalusia of 2030 including the transmission network and the electrolyzers are modeled. This model will be used within a simplified operational version of the TIMES (The Integrated MARKAL-EFOM System) [4] framework, developed specifically for this analysis. This modeling approach enables a comprehensive evaluation of different case studies, providing quantifiable insights into the most effective strategies for deploying electrolyzers in Andalusia.

1.3 Research questions

This study is structured around two central research questions that will guide the analysis:

- *Is the Andalusian power network capable of sustaining the planned electrolysis projects for 2030?* This question addresses whether the baseline of current infrastructure planned by 2030 can be integrated into the electrical grid.
- *What are the optimal strategic locations for electrolyzers to achieve an ambitious hydrogen production scenario by 2030?* This question explores whether Spain's revised ambitious target of 11 GW of electrolysis capacity can be achieved and identifies the best geographical distribution for these additional projects.

2 Methodology

2.1 Methodology overview

Figure 1 presents an overview of the methodology used in the analysis. The process starts with the definition of the scenarios and study cases describing the energy system and the hydrogen strategy for 2030. These scenarios serve as an input for constructing the model's structure and for gathering the necessary data.

The model structure is made to incorporate various elements, including the localization of power plants' capacities, the distribution of electrical demand, and the location of electrolyzers within the grid. The transmission network is modeled to accurately incorporate these elements. Finally, this model structure, complemented with the data from the technologies, is integrated into the simplified version of the TIMES framework, a tool developed by the IEA-ETSAP (International Energy Agency - Energy Systems Analysis Program) for energy systems analysis [4], The developed framework relies on a Direct Current Optimal Power Flow (DC-OPF) module for cost optimization, and include the network and energy system constraints, therefore allowing for the analysis of different case studies under the defined conditions.

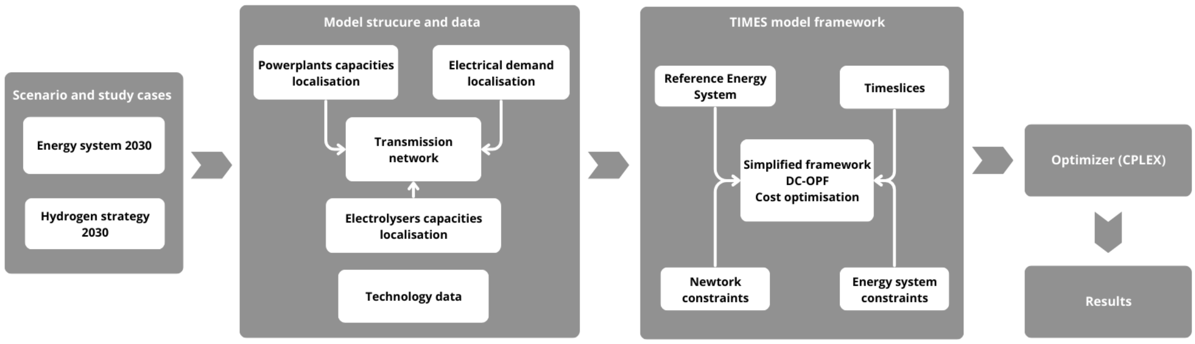


Figure 1: Methodology overview

2.2 Scenario for the 2030 energy system

This study assesses the development of electrolyzer capacity for the year 2030 in the region of Andalusia. To evaluate their integration into the energy system, the 2030 energy system must be accurately represented. The system is modeled using data from the recently updated Integrated National Energy and Climate Plan (NECP) for Spain [5]. This document, developed by the Spanish Government, establishes strategic guidelines and measures to achieve national energy transition targets by 2030. Notably, the NECP sets goals for the deployment of renewable energy sources and outlines their expected contributions to the national energy mix. It also includes projections for electricity demand growth by 2030. Using the NECP as a basis for the model's data ensures that the model accurately reflects Spain's energy landscape in 2030.

The target scenario of the NECP for the year 2030 includes the following forecasts:

- The electricity generation park which details the installed capacity [MW] at the country level for each technology, including both renewable and non-renewable sources. The detailed table can be found in Appendix 1
- A projected final electricity demand of **238 TWh** in Spain for 2030.
- A share of **81%** of renewable energy in the electricity generation sector by 2030.
- The projected electricity trade volumes with neighboring countries.
- A forecast of **11 GW** of electrolyzer capacity to be installed in Spain by 2030.

2.2.1 Adaptation to Andalusia level

The targets of the NECP previously mentioned are set at the country level, it is therefore necessary to downscale the national-level projections to the regional level of Andalusia in order to incorporate them in the study. This gives the following data for Andalusia regarding the 2030 energy system:

- The electricity generation park which details the installed capacity [MW] at the region's level for each technology. This is adapted at the region's level by taking the actual share of each technology in the region regarding the whole country.
- A share of more than **81%** of renewable energy in electricity generation sector by 2030.
- A projected final electricity demand of **40.35 TWh** in Andalusia for 2030.
- An installed capacity of **4 GW** of electrolyzers in the region. The definition of the different study cases that define the electrolyzers placement are described later in 2.3.4.

2.3 Model structure and data

Based on the data and shares established by the NECP for the 2030, the energy system and the grid of Andalusia must be modeled, including the transmission grid, power plants, electricity demand, and electrolyzers.

The electricity system is composed of three primary components: generation, transmission, and distribution as represented in figure 2.

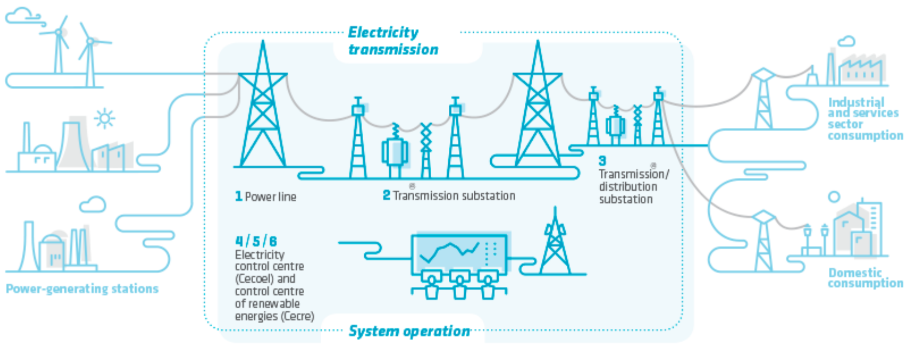


Figure 2: Structure of the electricity system
Source: Red Eléctrica de España (REE)

1. **Generation**: Electricity generation involves a mix of energy sources. Figure 3 shows the actual generation park of Andalusia with the capacity of each technology.

Hydro	623
Pumped storage	585
Coal	570
Combined cycle	5,952
Wind	3,642
Solar photovoltaic	6,012
Thermal solar	1,000
Other renewables	451
Cogeneration	654
Non-renewable waste	51
Total capacity	**19,541**

Figure 3: Andalusia: Installed capacity by technology [MW] in 2024
Source: Red Eléctrica de España (REE)

2. **Transmission**: The transmission network allows the transportation of electricity from power plants to the distribution network. The high-voltage transmission network operates at voltage levels between 110kV to 400 kV and is managed by Red Eléctrica de España (REE), the Spanish transmission system operator, which oversees the integration of various energy sources, grid maintenance, and the balance between supply and demand.

3. **Distribution**: After transmission, high-voltage electricity is transformed at the different sub-stations to lower voltages ($<$ 66kV) suitable for distribution. The distribution network is then responsible for delivering electricity to the end users.

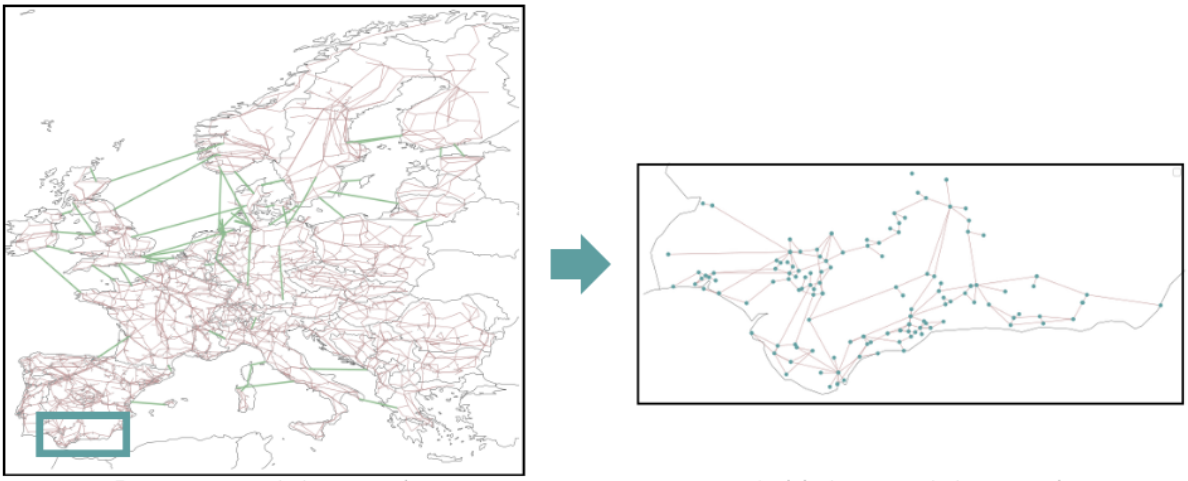
While this study primarily focuses on the transmission network, the generation and distribution aspects are also incorporated in a simplified manner. In this model, generation and demand are represented as aggregated values at each node of the transmission network. The following subsections details how every components of the electrical system are modelled.

2.3.1 Transmission network modelling

The model must incorporate data on the transmission infrastructure, including the transmission lines, their parameters, as well as the location and capacity of the substations. The regional grid of Andalusia must be accurately represented to integrate the projected deployment of electrolyzers.

The transmission network composes the base structure of the model. Transmission lines connect nodes together. Each node has a corresponding load and generation. Moreover, electrolyzers could be assigned to some nodes and will create an additional load. It is therefore important that the network is represented as accurately as possible, with the necessary parameters for the modeling. The data of the region's transmission grid is sourced from a pre-built model of PyPSA-EUR [6]. Pypsa-EUR is a open model dataset of the European power system at the transmission network level, which is based on the ENTSO-E grid model [7].

The geographical boundaries of the region were used to filter the relevant buses.



European transmission network

Andalusian transmission network

For each transmission line, the necessary parameters for modeling are retrieved:

Table 1: Transmission line parameters

Parameter	**Description**
Start and end Bus	The starting and ending buses of a transmission line, representing the nodes between which the electricity is transmitted.
Maximum transmission capacity $S_{\max}$ (MW)	The limit of apparent power that can pass through a line. Under the DC assumption, the power (MW) is considered equal to the apparent power (MVA).
Line susceptance B (pu)	The measure of a line's ability to allow the flow of electric power, calculated using the line reactance X. Under the DC assumption, susceptance B is given by $B = -\frac{1}{X}$.

To ensure an accurate representation of inter-regional and international connectivity within Andalusia's energy model, it is essential to account for the transmission lines connecting Andalusia to neighboring regions. These lines have specific capacity limits [MW], which restrict the amount of power that can flow through them. Each external region or country is modeled as a fictive bus, to which all corresponding transmission lines converge. These buses are assigned annual generation capacities and annual loads based on data from the NECP scenario. This approach accurately represents the dynamics of power importation and exportation, ensuring that the model can simulate the flow of electricity across borders and regional boundaries, while respecting the limitations imposed by the transmission capacities.

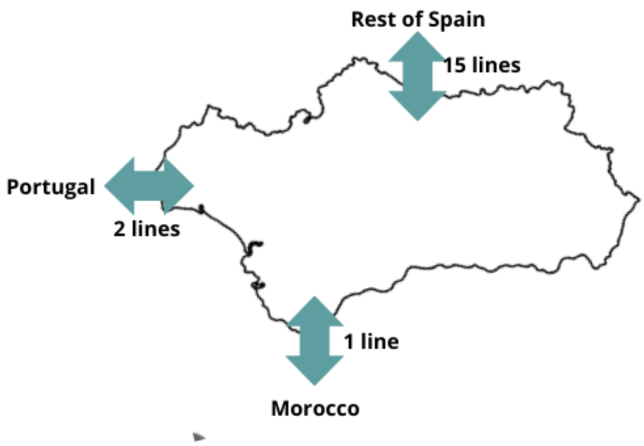


Figure 4: Connection with the surrounding regions

The final transmission grid used in the model consists of a network of high-voltage lines and sub-stations, as well as connections to the surroundings regions. The key components include:

- **Transmission lines**: The region has **177** high-voltage transmission lines with capacities ranging from 220 kV to 400 kV. Moreover, **18** lines connects the region to the outside countries and the rest of Spain.
- **Buses and sub-stations**: There are **138** buses, including **79** sub-stations where voltage can be lowered. These are nodes were demand and generation are allocated.
- **Generators and loads**: Each sub-station has corresponding hourly load profile [MW/h] and a generation capacity per technology type [MW]. These are detailed in the following sections 2.3.2, 2.3.3.

Figure 5 presents a visual representation the final transmission grid.

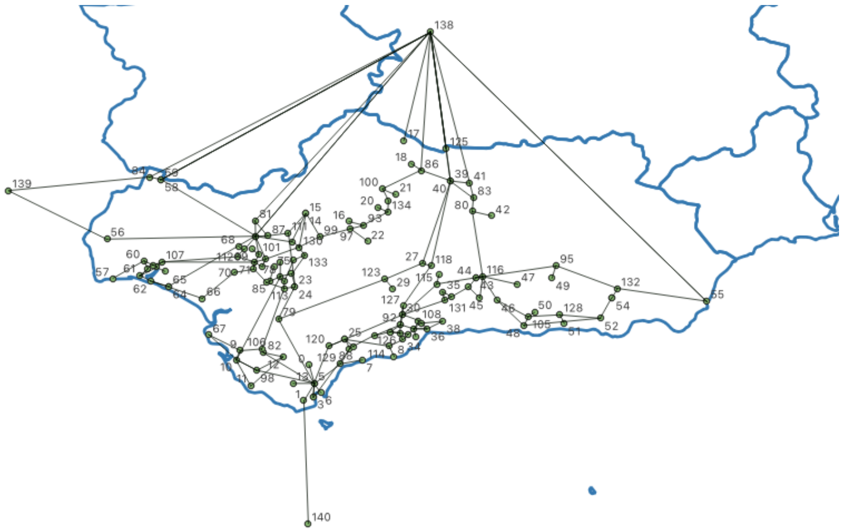


Figure 5: Transmission grid model with buses and transmission lines

2.3.2 Electricity generation: Allocation of existing and new capacities

The PyPSA-EUR dataset provides information on existing power plant capacities. The challenge lies in adapting this network to incorporate the power plants that will be installed in the incoming years and therefore reflect the projected generation capacities for the year 2030.

Data on electricity generation capacities are sourced from the Global Energy Monitor database [8]. This database offers information on both existing and planned power plant projects, including the following parameters:

Table 2: Power Plant Data

Parameter	**Description**
Technology Type	solar, wind, hydro, biomass, gas, and coal.
Installed Capacity (MW)	The maximum output capacity of each power plant.
Coordinates (x, y)	The geographical location of each power plant.
Status	The operational status of each power plant (operational, pre-construction, under construction, or announced).

The methodology for allocating both existing and new electricity generation capacities to each node involves the following steps:

1. **Aligning with NECP targets:** The data from the Global Energy Monitor database are cross-referenced with the projected installed capacities for each generation technology as set by the NECP for 2030 (see Section 2.2.1). This ensures that the allocated capacities align with the targets established in the NECP scenario.

2. **Allocating to sub-stations:** The predicted capacities are then assigned to the nearest sub-stations. This process differs for gas and coal plants versus renewable energy plants:

   - **Gas and coal plants:** These are matched with the existing entries in the PyPSA-EUR data, ensuring they are correctly allocated to the sub-stations they are already connected to. Since no new projects are planned for gas and coal plants, their allocation remains as in the current dataset.
   - **Renewable energy plants:** As most of these are new projects and not yet present in the PyPSA dataset, they are allocated to the nearest sub-station available using geographic information system (GIS) tools.

Figure 6 illustrates the process of allocation of power plant capacities in the region.

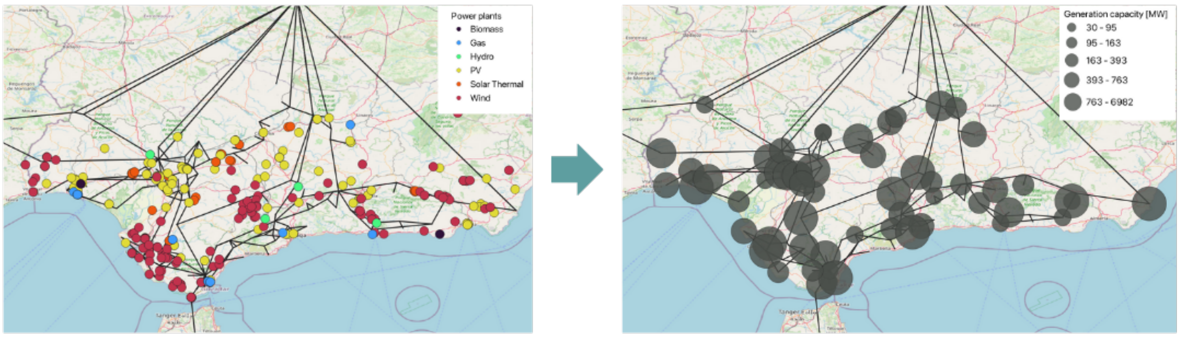


Figure 6: Allocation of power plant capacities

2.3.3 Electricity demand allocation

Similar to electricity generation, the electricity loads in the network obtained from PyPSA-EUR do not reflect the year 2030 and thus require adaptation. The electricity demand allocation process for Andalusia is based on the projected electricity demand for 2030, in accordance with the growth rates anticipated by the NECP.

The initial demand data for Andalusia is sourced from the PyPSA-EUR database, which provides an hourly demand profile $[MW/h]$ at each sub-station over a complete year. To adjust for 2030, the hourly demand profile at each node is incremented to align with the annual consumption predicted by the NECP. This ensures that each sub-station's demand profile accurately reflects the anticipated electricity consumption for the year 2030.

Figure 7, illustrates the distribution of annual electricity loads across Andalusia for 2030. Each circle represents a sub-station and its corresponding annual load in MWh.

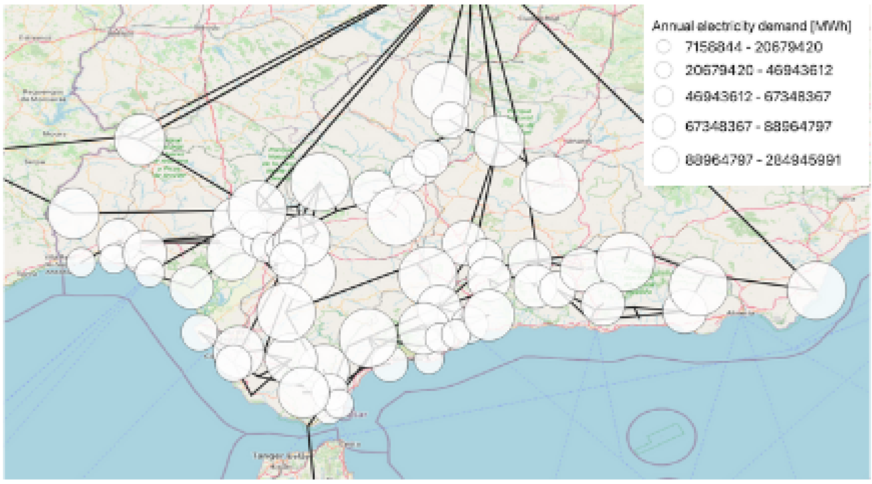


Figure 7: Electricity demand allocation in Andalusia.

2.3.4 Electrolysis allocation: planned projects

At this stage, the model for the energy system and transmission network has been built. Electrolyzers are added to this electricity system as an additional load, to reflect their integration into the grid by 2030.

The allocation of electrolysis capacity in Andalusia for 2030 is based on projections and studies from the International Energy Agency (IEA) [9]. The data include hydrogen production projects planned for 2030, with details on the electrolyzer capacities, geographical locations, and projects statuses. Considering only projects that have reached at least the feasibility study stage and are set to be commissioned by 2030, the total electrolyzer capacity in Andalusia is projected to reach 1.85 GW. Figure 8 illustrates the planned distribution of electrolyzer capacities across Andalusia. The map highlights the locations of these projects, with the size of each circle representing the magnitude of the electrolyzer capacity in MW.

The projects are characterized by a specific capacity [MW], which determines their potential energy output. The annual electricity demand for each electrolysis facility is calculated using the following equation:

$$\text{Annual Energy Demand [MWh]} = \text{Capacity [MW]} \times 8760 \text{ [hours/year]} \times 0.7 \qquad (1)$$

In this equation, the factor 0.7 accounts for the operational availability of the electrolyzers, meaning they are expected to be active and producing hydrogen 70% of the time throughout the year. This corresponds to the assumption take by IEA in their database of electrolyzers projects, for a mix of grid electricity and renewable input. [9] The efficiency of the electrolysis production process is equal to 50 kWh/kgH_2.

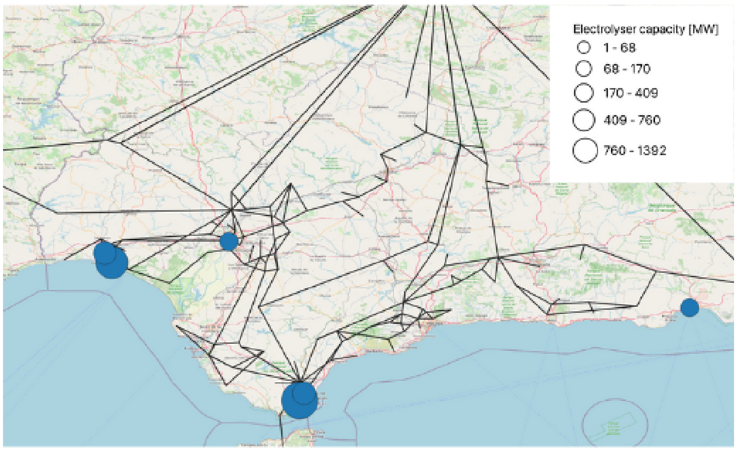


Figure 8: Planned electrolyzers projects for 2030 according to IEA - 1.85 GW.

2.3.5 Electrolysis allocation: Definition of study cases

This map forms the baseline case. Building on this foundation, additional study cases are developed to achieve a target electrolyzer capacity of 4 GW at the regional level, reflecting the 11 GW target of the country. The planned projects are preserved as they are, and the necessary capacity to reach the 4 GW target is used to construct the different cases. The study evaluates the following cases:

Capacity expansion at planned sites: The first case focuses on keeping the current hydrogen production sites and scaling up their capacities to achieve a total installed capacity of 4 GW.

Proximity to renewable generation: In the second study case, electrolyzers are allocated to sub-stations with the highest renewable energy generation capacity.

Two configurations are tested:

- **Centralized configuration:** electrolyzers are concentrated in three locations with the highest renewable generation.
- **Decentralized configuration:** electrolyzers are distributed across 15 locations, increasing the geographic spread.

Figure 9 illustrates the additional locations for electrolyzers capacity in this case study, with the centralized configuration shown on the left and the decentralized configuration on the right.

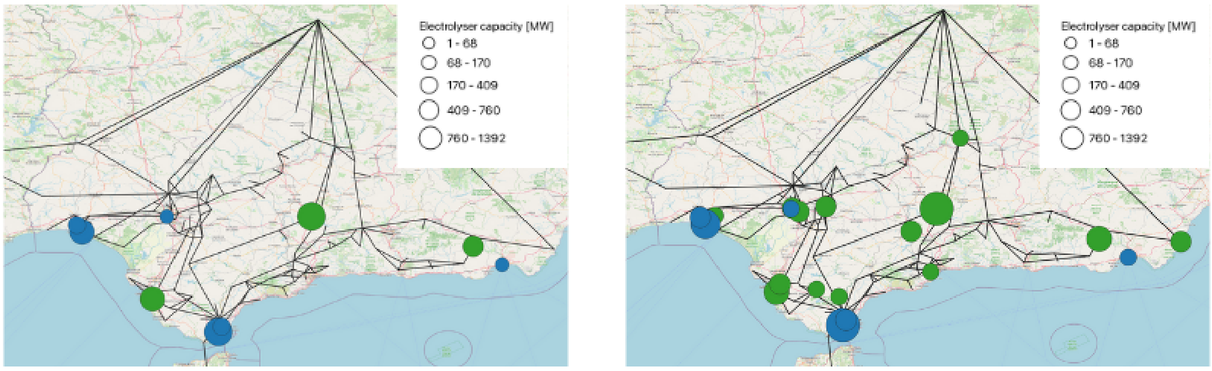


Figure 9: Production-oriented electrolyzers allocation - Left: Centralized; Right: Decentralized. In blue : IEA sites; In green: additional sites

Proximity to hydrogen demand: The third case evaluates the impact of allocating electrolyzers close to areas where hydrogen demand is expected to be high, such as industrial zones and transportation hubs. In constructing this case study, it is assumed that demand will be primarily concentrated near industrial areas and regions with high population density.

Two configurations are also tested in this case study:

- **Centralized configuration:** electrolyzers are concentrated in five strategic locations near high-demand areas.
- **Decentralized configuration:** electrolyzers are distributed across 15 locations, reflecting a more distributed demand pattern.

Figure 10 shows the planned electrolyzer locations for this case study, with the centralized configuration on the left and the decentralized configuration on the right.

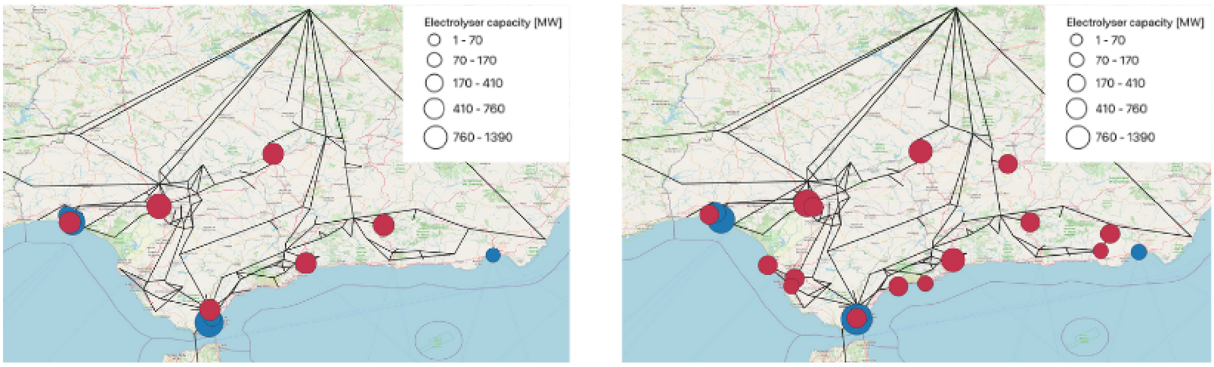


Figure 10: Demand-oriented electrolyzers allocation - Left: Centralized; Right: Decentralized. In blue: IEA sites; In red: Additional sites

In total, six different study cases are implemented and analyzed within the model (see 11). These case studies provide insights into the trade-offs between different strategies, such as concentrating capacity near renewable resources versus aligning capacity with demand centers.

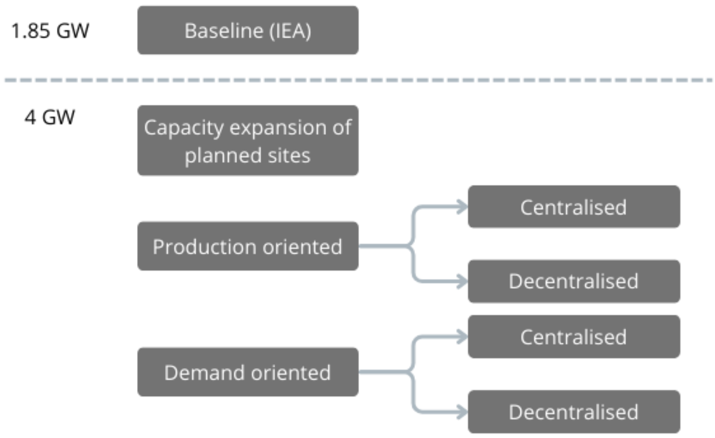


Figure 11: Study cases summary

2.4 Simplified TIMES model

The Andalusian energy system for the year 2030 is modeled using a framework based on the TIMES model, a tool developed by the IEA-ETSAP for energy systems analysis [4]. TIMES employs linear programming to optimize energy systems by minimizing costs, supporting decision-making in energy policy and planning.

For this study, a simplified model is developped based on the TIMES framework, focusing only on operational optimization. This model optimizes the system based on operational costs without considering new investments.

The following sections provide detailed descriptions of the model's components.

2.4.1 Reference Energy System

The Reference Energy System (RES) serves as the fundamental framework, representing the key components and interactions within the energy network. It forms the basis for the TIMES model, which simulates and analyzes Andalusia's energy system for the year 2030.

The RES provides a comprehensive schematic of energy flows within the region, including energy generation, transmission, and consumption. It includes various energy sources, conversion processes, and end-use sectors, ensuring an accurate representation of the regional energy system. Figure 12 illustrates the reference energy system for Andalusia. The boxes depict the **Processes**, while the arrows indicate the flow of **Commodities** through these processes within the system.

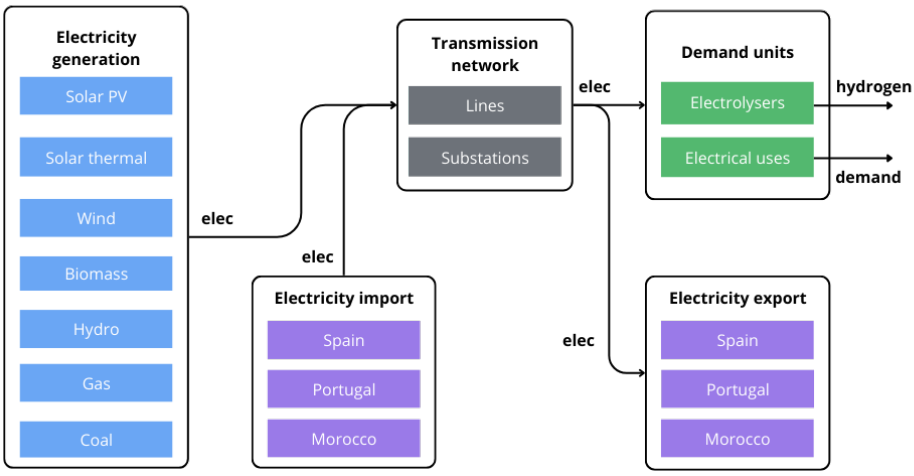


Figure 12: Reference Energy System for Andalusia; Lines: Commodities; Boxes: Processes

The processes include electricity generation technologies, the transmission network, demand units, and electricity import and export. These processes are characterized by specific technological data such as efficiency, availability factors, capacity limits, and operational costs. Detailed data on these technologies can be found in Appendix 2.1.

2.4.2 Timeslices

In the TIMES framework, timeslices are used to capture the variations in energy demand and supply throughout the year. These timeslices allow the model to reflect seasonal and hourly patterns of energy consumption and generation, providing a detailed analysis of the energy system.

The year is divided into three main seasons: winter, summer, and an intermediate season. Each season is further subdivided into 24 hourly timeslices, enabling the model to account for hourly variations within a seasonal representative day. In total, the model contains 72 timeslices ($3 \times 24h$).

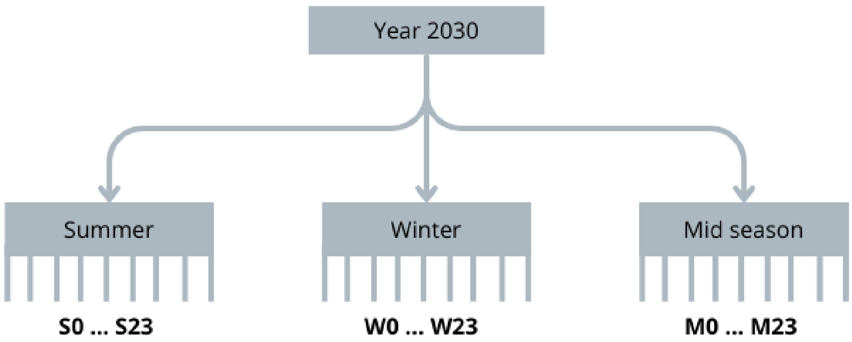


Figure 13: Yearly division and hourly timeslices in the model

This division into timeslices affects several key components:

Electricity demand: The model includes hourly electricity demand profiles, which represent the fluctuations in electricity consumption throughout the day. These profiles are essential for accurately modeling energy demand. Figure 14 shows an example of hourly demand profiles for summer and winter.

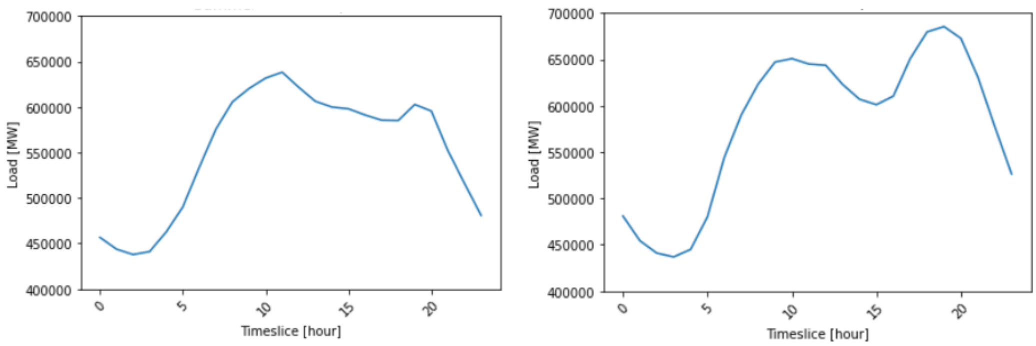


Figure 14: Summer and winter hourly electricity demand profiles

Hourly availability factors: Hourly availability factors for power plants are incorporated to account for hourly variability in generation capacity. These factors, based on historical data and technological characteristics, ensure that the model accurately simulates the operation of different generation technologies throughout the day. They are particularly relevant for solar and wind generation which can be found in the appendix 2.2.

Electrolysis demand: Unlike electricity demand, hydrogen demand is modeled without predefined hourly profiles for electrolyzers. The model optimizes hydrogen production based on the overall system's efficiency rather than following a strict hourly schedule. However, to distribute demand appropriately, a seasonal demand is defined for each of the three seasons, and the model optimizes the production schedule accordingly.

2.4.3 Simplified TIMES framework

The simplified TIMES framework developed for this study focuses on the operational aspects of the energy system, excluding capacity investments. It models the andalusian energy system for the year 2030, optimizing operation costs while adhering to various operational constraints. The Reference Energy System (RES) and the transmission network are integrated into this framework, which is implemented using GAMS language.

The primary objective of the simplified TIMES framework is to minimize the generation cost while ensuring the feasibility of the energy system across all timeslices. The model achieves this through linear programming, optimizing the operation of the system within the defined constraints. The following section describes the main components of the model that is available in Appendix 3.

To maintain system feasibility at every timestep, dummy loads are added at each node. These loads, assigned at high cost, provide generation backup when the standard generation system is insufficient. Importing the missing power would not ensure the feasibility of the model as the limits in lines' transfer capacities could prevent the power to go to the target node.

The model operates in the Andalusia region (AN) for the year 2030 (t), dividing the year into three seasonal periods, summer, winter and the rest, each with 24 hourly timeslices (s) to capture temporal variations. The electricity network is represented with nodes (n) and transmission lines (l), mapping their start and end nodes (n). The import/export (ie) parameter describes direction of the fluxes in the lines. The process (p) are the different energy conversion technologies and the commodities (c) that represent the flow between the processes as it is described in the REF (see 12). Finally, the set In/Out (io) describes whether the commodity at a process/node is produced (Out) or consumed (In). These sets are summarized in Table 3:

Table 3: Model Sets

Set	Description
r	Region (AN)
t	Year (2030)
s	Timeslice ([SH0,SH23] ∪ [WH0,WH23] ∪ [MH0,MH23])
ie	Import Export (IMP, EXP)
io	In Out (IN, OUT)
p	Process (GAS, BIO, SOLAR, WIND, ELECTROLYSIS...)
c	Commodity (gas, elec, wind, hydrogen, etc.)
l	Lines ([L0,L196])
n	Nodes ([B0,B141])

The parameters are defined over one or more sets, with technology data sourced from the document [10] and available in appendix 2.1. The key parameters are summarized in Table 4.

Table 4: Main Parameters

Parameter	Description
`ACT_COST(r,p,t)`	Activity cost [EUR/GJ]
`ACT_EFF(r,p,t)`	Activity efficiency [%]
`CAP_BND(r,t,p)`	Process capacity bound [MW]
`NCAP_AF(r,p,t,s)`	Availability factor [%]
`COM_PROJ(r,c,t,s)`	Demand projection [PJ]
`H2_DEM_SUMMER(r,c,t)`	Hydrogen demand in summer [PJ]
`H2_DEM_WINTER(r,c,t)`	Hydrogen demand in winter [PJ]
`b(r,l,t)`	Susceptance of line l [pu]
`CAP_GR_BND(r,t,l)`	Line capacity bound [MW]

The model optimizes several variables to minimize the overall system cost. The key variables are listed in Table 5:

Table 5: Main variables

Variable	Description
cost	Objective function cost [EUR]
var_comaux(r,t,n,s)	Voltage angle at node n [rad]
var_ncap(r,p,t)	New capacity [MW]
var_act(r,p,t,s)	Activity level of process p [PJ]
var_gr_act(r,t,l,s)	Activity level of grid line l [MW]
var_gr_ncap(r,t,l)	New grid line capacity [MW]
var_ire(r,t,l,s,ie)	Exchange of commodity on line l [MW]
var_flo(r,p,c,t,s)	Flow of commodity c in process p [PJ]
var_gridelc(r,t,c,n,s,io)	Electricity flow at node n [MW]

The model's objective is to minimize the total system operational cost, which includes both the generation costs (defined by the activity cost of each technology) and the costs associated with commodity flows. The activity cost for each technology corresponds to the variable operation and maintenance (O&M) costs in EUR/GJ. These costs include expenses directly tied to the operation of power plants, such as maintenance and other operational costs that vary with the level of output.

The objective function is defined as:

$$\begin{aligned} cost = \sum_{(r,p,c,t,s)} & ACT\_COST(r,p,t) \times var\_act(r,p,t,s) \\ & + FLOW\_COST(r,p,c,t) \times var\_flo(r,p,c,t,s) \end{aligned} \tag{2}$$

The model incorporates several types of constraints to accurately represent the Andalusian network and energy system. All the constraints are available in Appendix 3 and the most important ones are presented below:

1. **Generation and demand constraints**: These constraints ensure that generation meets demand at all times, accounting for resource availability and projected demand profiles. The primary constraint is formulated as:

$$\begin{aligned} \sum_{p \in \mathrm{top}(p,c,\text{'OUT'})} var\_flo(r,p,c,t,s) \geq \sum_{p \in \mathrm{top}(p,c,\text{'IN'})} & var\_flo(r,p,c,t,s) \\ & + COM\_PROJ(r,c,t,s) \end{aligned} \tag{3}$$

2. **Hydrogen demand constraints:** These constraints ensure that hydrogen demand is met during both winter and summer seasons. The demand is not defined

for each timeslice but for each season, allowing flexibility in production. The following equations ensure that the cumulative flow of electricity into electrolysis processes meets seasonal hydrogen demand:

$$\sum_{s \in winter} var\_flo(r, \text{'Electrolysis'}, \text{'h2'}, t, s) \geq H2\_dem\_winter(r, \text{'h2'}, t) \tag{4}$$

$$\sum_{s \in summer} var\_flo(r, \text{'Electrolysis'}, \text{'h2'}, t, s) \geq H2\_dem\_summer(r, \text{'h2'}, t) \tag{5}$$

A constraint also limits the capacity [MW] for the electrolysis process. Ensuring that the electrolyzers' power do not overcome their maximum capacity.

3. **Exportation and importation constraints**: These constraints limit the annual energy that can be imported from Portugal and Morocco, and require the region to export a specified amount of electricity annually. Additionally, the transmission lines connecting the region to other countries have defined capacity limits [MW].

4. **Network constraints**: These constraints include the limitations of the transmission network, ensuring that the electricity flow does not exceed the capacities of the grid lines while balancing what is produced and consumed at each node in the network. The **Voltage Angle Formulation** method models the flow of electricity based on the voltage angles at different nodes. The power flow equation is defined as:

$$\begin{aligned} var\_ire(r, t, l, n, s, \text{'EXP'}) - var\_ire(r, t, l, n, s, \text{'IMP'}) = \\ -b(r, l, t) \times var\_comaux(r, t, n, s) - var\_comaux(r, t, nn, s)) \end{aligned} \tag{6}$$

Line capacity constraints ensure flows do not exceed maximum capacities:

$$var\_gr\_ncap(r, t, l) \leq CAP\_GR\_BND(r, t, l) \tag{7}$$

The simplified model provides several key outputs, at every timeslice of the year 2030:

- **Activity level of processes**: This includes the operational levels of the processes, such as electricity generation and electrolysis.
- **Flows of commodities**: The model outputs the flows of commodities, such as electricity and hydrogen, throughout the energy system.
- **Activity level of each grid line**: The operational levels of each transmission line are calculated, indicating how much electricity is being transmitted through each line.
- **Electricity flow at each node (In and Out)**: The model determines the electricity flow into and out of each node in the network, ensuring that all demand constraints are satisfied.

3 Results

This section presents the results for the baseline case and the study cases, focusing only on the summer and winter seasons, which represent the extreme conditions. It is important to note that, due to Andalusia's mild winter climate and significant solar potential throughout the year, the differences between summer and winter are moderate. These seasonal variations would likely be more pronounced in regions with more extreme weather differences between summer and winter.

3.1 Baseline case: Planned facilities (1.85 GW)

The baseline case models the planned facilities as outlined by the International Energy Agency (IEA), projecting a total of **1.85 GW** of electrolysis capacity for the region. This case serves as a reference point for evaluating the performance and challenges associated with the integration of electrolyzers into the existing energy system.

Line congestion: Line congestion level is a critical factor in assessing the ability of the transmission network to handle electricity flows without exceeding its capacity. The congestion level for each line and for each time of the year, is calculated using the following equation:

$$\text{Congestion level [\%]} = \frac{\text{Activity level of grid line l [MW]}}{\text{Line capacity bound [MW]}} = \frac{var\_gr\_act(r,t,l,s)}{CAP\_GR\_BND(r,t,l)} \tag{8}$$

The number of transmission lines over 24h that reaches the different congestion levels for the summer and winter seasons are summarized in Table 6. The results indicate that the majority of transmission lines operate below 50% congestion during both seasons, suggesting that the current grid infrastructure is capable of accommodating the planned electrolysis capacity without significant problems.

Table 6: Congestion levels during summer and winter for the baseline case. The numbers represent the quantity of transmission lines within each congestion range.

Congestion [%]	**Summer**	**Winter**
<50%	187	177
50-70%	5	12
70-80%	3	6
>80%	2	2

These findings suggest that, under the baseline case, the grid remains robust with sufficient capacity to manage the projected electricity flows from electrolysis activities. Nevertheless, the few lines experiencing higher congestion could become critical points as electrolysis capacity expands.

Hydrogen production: Power for hydrogen production can be extracted from the results and the contribution of each process can be computed. Figure 15 illustrates the power used for electrolysis, categorized by energy source, during the summer and winter seasons. The red line indicates the total electrolysis capacity at the regional level (1850 MW).

The hydrogen production relies on average over the year at 80% on renewable energy sources, reaching peak values at 90%. Moreover, the electrolysis capacity is used at is full potential (1850 MW) during peak hours.

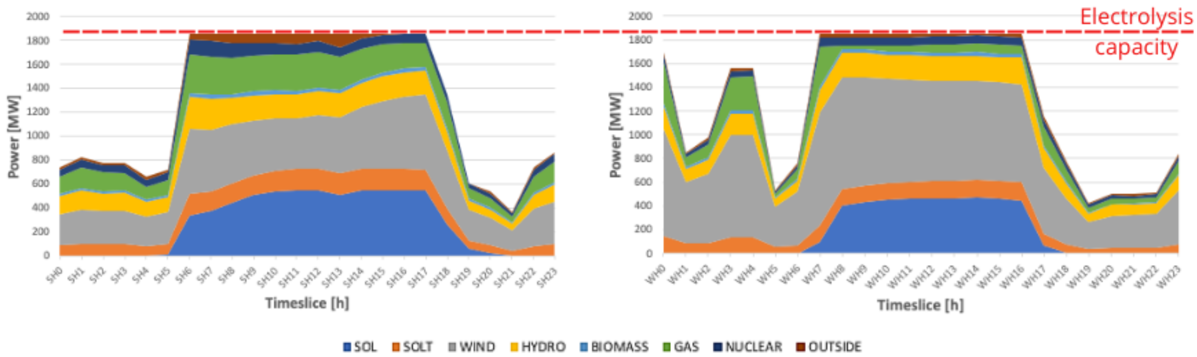


Figure 15: Electricity used for electrolysis decomposed by energy sources. Left: Summer; Right: Winter.

3.2 Case Study 1: Capacity expansion at planned sites

This case study explores the effects of increasing the electrolysis capacity of planned sites to a total of 4 GW.

Lines congestion: The results indicate that this expansion leads to a significant rise in high congestion levels across the transmission network, as shown in Table 7.

Table 7: Congestion levels during summer and winter periods for case 1. The numbers represent the quantity of transmission lines within each congestion range.

Congestion [%]	Summer	Winter
< 50%	183	171
50-70%	8	16
70-80%	2	6
> 80%	4	4

Hydrogen production: Figure 16 illustrates the power used for electrolysis, categorized by the energy source, for both summer and winter periods. The red line indicates the total electrolysis capacity at the regional level (4000 MW). The data reveal that hydrogen production is less reliant on renewable energy sources, with only **66.61%** of renewable sources in the electricity mix.

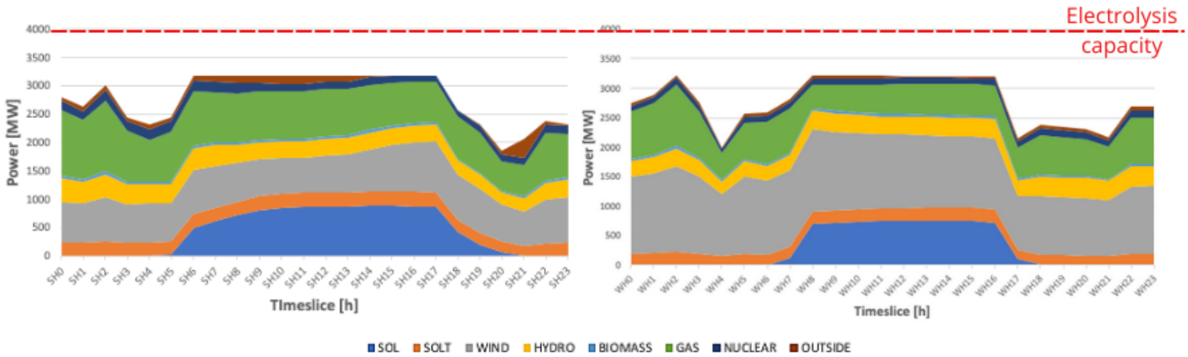


Figure 16: Electricity used for electrolysis decomposed by energy sources. Left: Summer; Right: Winter.

In every configuration, the electrolyzers are expected to operate at 70% of their total capacity on an annual average, based on the assumptions for hydrogen demand (see 1). However, the model shows that under actual conditions, the system achieves an instantaneous peak utilization of only **80.46%** of the total electrolysis capacity. This under-performance may be due to the limitations of the current grid infrastructure. Indeed, these locations seem to lack sufficient nearby generation to reach maximum capacity without exceeding the transfer limits of the transmission lines.

3.3 Case Study 2: Production oriented

This case study evaluates the impact of optimizing electrolyzer locations based on proximity to renewable energy production. Two placement strategies are tested: one centralized with 3 facilities, and one decentralized with 15 facilities.

Line congestion: In the centralized case (Table 8, left), the system experiences very low congestion, with most transmission lines operating below 50% capacity. On the other side, the decentralized case (Table 8, right) results in slightly higher congestion levels.

Table 8: Congestion levels for summer and winter in both centralized (left) and decentralized (right) cases. The numbers represent the quantity of transmission lines within each congestion range.

Congestion[%]	Summer	Winter
$< 50\%$	187	187
50-70%	7	7
70-80%	2	2
$> 80\%$	1	1

Congestion[%]	Summer	Winter
$< 50\%$	187	183
50-70%	5	8
70-80%	1	4
$> 80\%$	4	2

Hydrogen production: Figure 17 presents the power used for electrolysis in the centralized case, categorized by energy source. The red line indicates the total electrolysis capacity at the regional level (4000 MW). This case study demonstrates a significant utilization peak during periods of high renewable energy availability, particularly in summer. The electrolysis capacity is used at his full potential for approximately 9 hours daily during summer and 7 hours daily during winter.

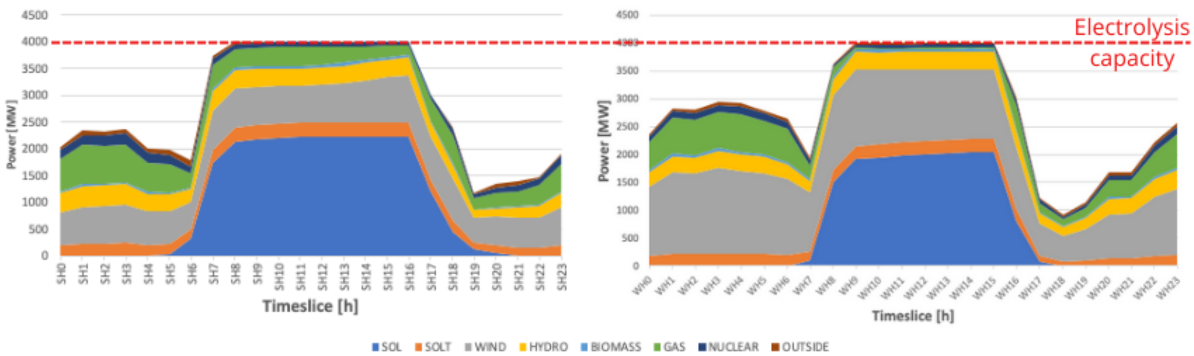


Figure 17: Electricity used for electrolysis by energy source. Left: Summer. Right: Winter.

On average, the hydrogen produced annually is coming at 78.5% from renewable sources, reaching 95% during peak production hours. This operation pattern suggests that placing electrolyzers sites close to renewable energy sources allows for more efficient grid management, and better utilization of available renewable energy and capacity potential in the electrolysis process.

The decentralized case shows very similar curves and results, with slightly poorer renewable shares.

Marginal cost of electrolysis: Figure 18 shows the marginal cost of electricity used for electrolysis. It represents the cost to produce one more unit of hydrogen (1 PJ = 2.778e8 kWh). These costs are relatively lower than typical electricity prices in Spain. This is explained by the fact that the marginal costs calculated by the model only rely on the variable O&M costs, while the electricity price also account for fixed costs, market dynamics, taxes, and other regulatory factors not included in the model. However, these marginal costs are still insightful for understanding the incremental cost of generating an additional unit of electricity under the model's assumptions.

In the decentralized case, higher marginal costs are observed during the early hours of the day, likely due to the variability in renewable energy availability across different locations. However, during periods of peak renewable energy production, both cases exhibit a significant reduction in marginal costs, demonstrating the benefits of aligning electrolysis operations with renewable energy peaks and placements.

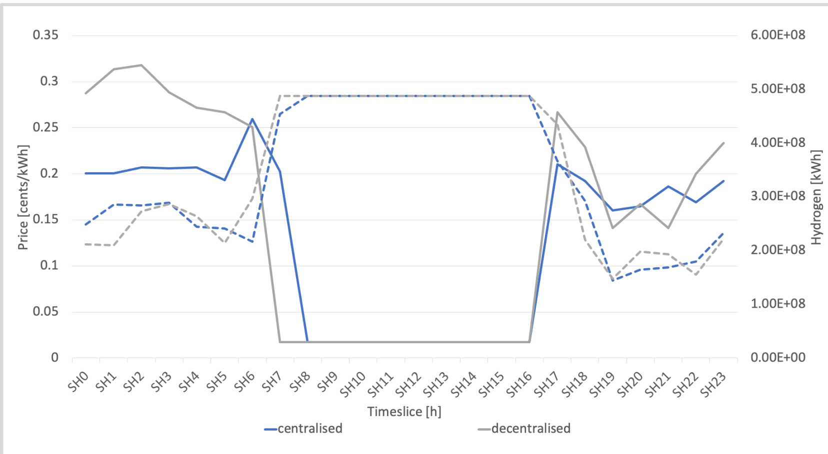


Figure 18: Marginal cost of electricity for electrolysis over a summer day

3.4 Case Study 3: Demand oriented

This case study evaluates the impact of localizing electrolyzers based on their proximity to hydrogen demand centers. This approach is strategic for minimizing transportation costs and emissions while maximizing the efficiency of hydrogen distribution.

Line congestion: The congestion data in Table 9 reveals a significant increase in the number of lines operating above 80% capacity. This suggests that a demand-oriented allocations induce considerable stress on the grid. The winter season, with its higher energy demands, particularly exacerbates this issue.

Table 9: Congestion levels for summer and winter - Centralized (left) and decentralized (right) case. The numbers represent the quantity of transmission lines within each congestion range.

Congestion	Summer	Winter
< 50%	170	161
50-70%	14	22
70-80%	1	1
>80%	12	13

Congestion	Summer	Winter
< 50%	175	168
50-70%	10	16
70-80%	2	2
> 80%	10	11

Since this case study generates congestion, identifying the problematic lines, that have high congestion level over a long duration is strategic. Figure 19 shows the percentage of the year where line utilization reaches 50% or more. It allows to identify and localize the potential lines that would require a capacity upgrade.

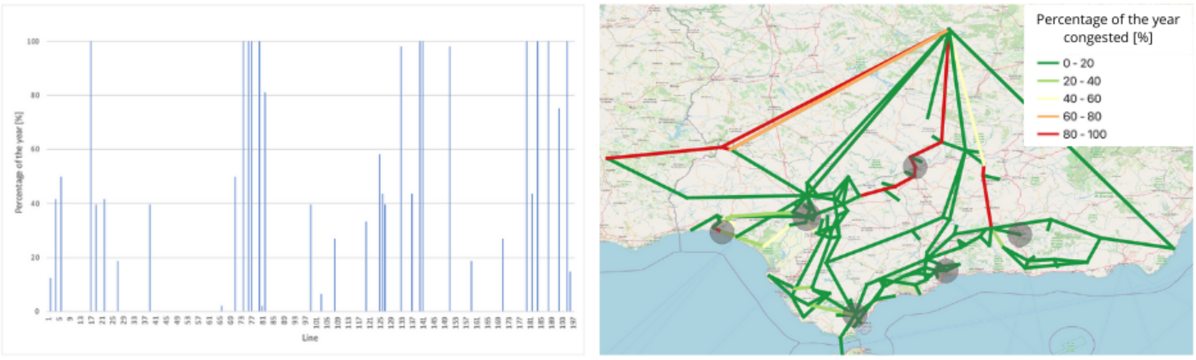


Figure 19: Percentage of the year where line congestion reaches 50% or more with a spatial representation (right). The circles represents the electrolyzers' placements

This case study leads to the use of dummy loads to ensure the model's feasibility. This means that some lines have reached a 100% congestion rate and that the model can not ensure that the demand is met. Figure 20 allows to visualize the placement of the sub-stations where shortages occur and their maximum magnitude over the year.

They are localised in the sub-stations along the lines that often reach congestion (in red). This reflects the complexities introduced by aligning electrolyzers' geographical deployment with hydrogen demand sites.

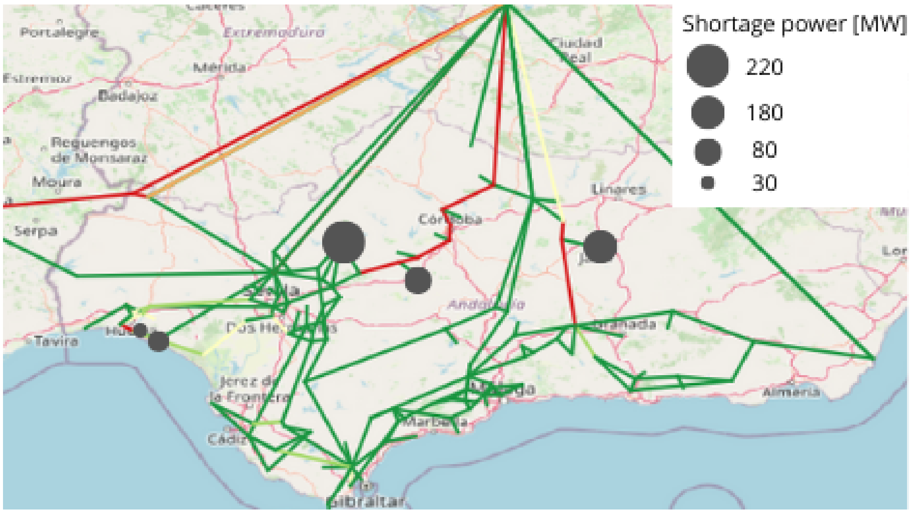


Figure 20: Maximum instantaneous shortage power over the year

Hydrogen production: Figure 21 illustrates the power used for electrolysis in the centralized case, categorized by energy source. This case study exhibits greater variability and occasional under-utilization of the electrolysis capacity, particularly during the winter months. The data indicate that the maximum electrolysis capacity is never reached for extended periods. This is due to the transmission lines reaching their maximum capacities, preventing the system from meeting the demand without causing shortages.

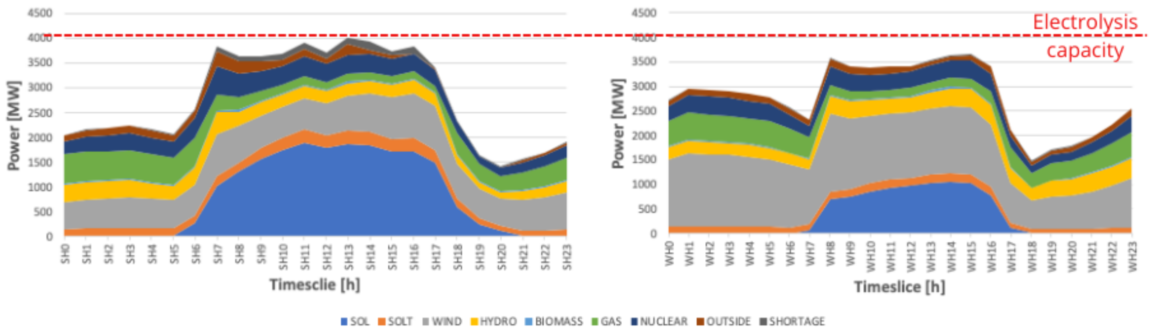


Figure 21: Power used for electrolysis by energy source. Left: Summer. Right: Winter.

This case study results in hydrogen production being sourced from 68.78% on renewable energy on average throughout the year. This is a lower percentage compared to the production-oriented case, reflecting the trade-offs between proximity to demand sites and renewable energy utilization.

Marginal cost of electrolysis: Figure 22 shows the marginal cost of electricity used for electrolysis throughout the day. The centralized placement strategy results in lower marginal costs during periods of peak renewable energy availability, while the decentralized approach offers lower costs during periods of high demand, particularly at the end of the day. However, overall marginal costs in this case study are significantly higher than in Case Study 2, indicating the economic challenges of a demand-oriented strategy.

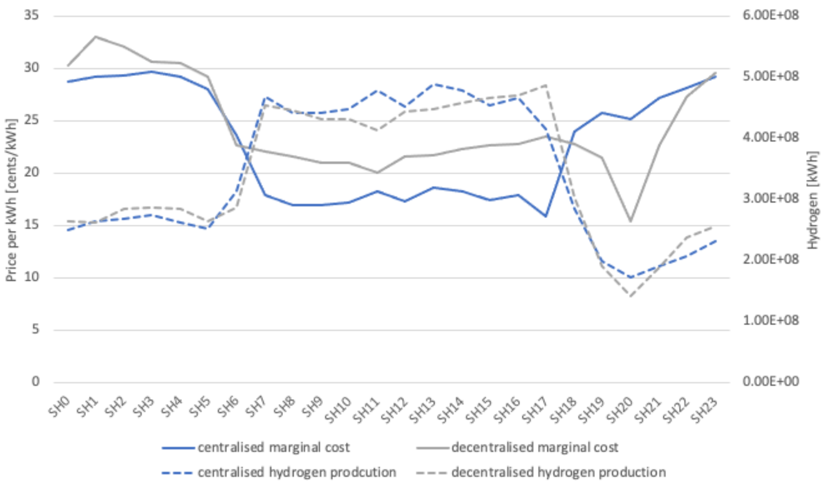


Figure 22: Marginal cost of electricity for electrolysis over a summer day

4 Discussion

4.1 Comparative analysis of cases studies

The different case studies can be compared across relevant metrics. First, figure 23 shows the number of transmission lines that reach 80% utilization over a day in both summer and winter. Each bar indicates the percentage increase relative to the baseline case, highlighting the differences in grid congestion across the cases.

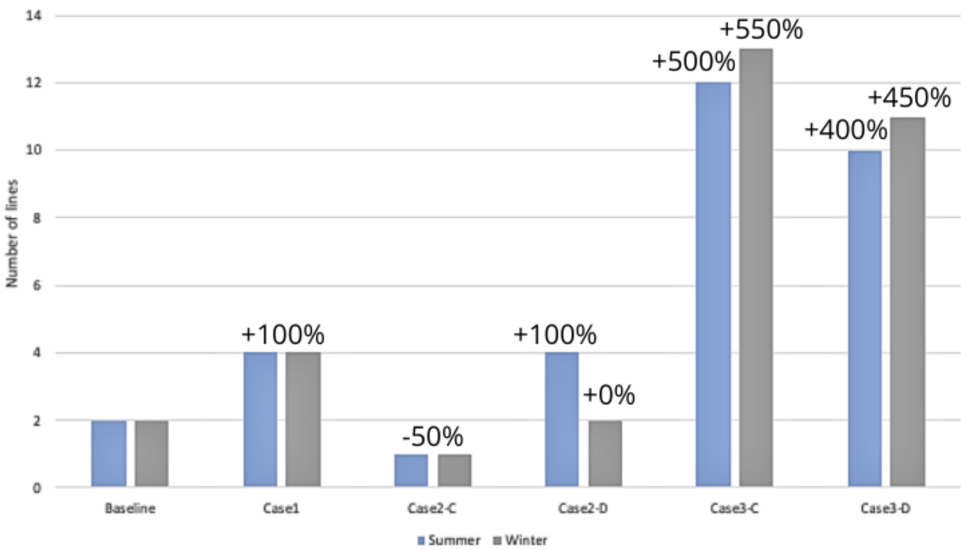


Figure 23: Number of lines reaching or surpassing 80% congestion level over a 24h period.- C (Centralized) and D (Decentralized).

This figure highlights the significant variation in grid congestion across the each case. Case 2, which involves placing electrolyzers close to renewable energy production, shows the most favorable results in terms of grid congestion. Specifically, the centralized approach reduces congestion by 50% compared to the baseline . This finding is important, as it indicates that strategically placing electrolyzers near renewable energy sources can enhance grid efficiency and remove stress on the transmission network. On the contrary, Case 3, which focuses on proximity to hydrogen demand centers, leads to higher congestion levels, particularly in winter. This suggests that while demand-oriented placement may reduce transportation costs and emissions, it also imposes significant stress on the grid. Notably, unlike Case 2, the centralized placement in Case 3 slightly increases congestion levels.

Table 10 provides a detailed comparison of key metrics across the case studies.

Table 10: Comparison of key metrics across study cases

Study case	**Average renewable energy [%]**	**Maximum utilization of electrolyzers [%] over consecutive hours [h]**	**Average marginal cost of electrolysis [cents/kWh]**
Baseline (1.85 GW)	79.9	100 (12h)	0.0633
Case 1: Capacity Expansion (4 GW)	66.61 (-16.75%)	80.46 (-19.54%) (9h)	7.013 (+10979%)
Case 2: Centralized (4GW)	78.47 (-1.79%)	100 (-0%) (9h)	0.1295 (+104%)
Case 2: Decentralized (4GW)	77.9 (-2.5%)	100 (-0%) (10h)	0.1479 (+133%)
Case 3: Centralized (4GW)	68.78 (-13.9%)	100 (-0%) (1h)	22.67 (+35713 %)
Case 3: Decentralized (4GW)	67.77 (-15.18%)	99 (-0.01%) (1h)	24.53 (+38651 %)

When evaluating the mix of electricity used for hydrogen production, Case 2 again stands out, achieving a mix at 78.47% of renewable energies, although it does not surpass the baseline. This result may be due to the increased demand (4 GW), necessitating a greater reliance on non-renewable sources despite the proximity to renewables. Case 1, involving capacity expansion at existing sites, shows a 16.75% reduction in renewable energy utilization. This reduction suggests that the current placements (baseline) are optimal only up to a certain capacity; beyond that, the reliance on non-renewable sources increases. In Case 3, the use of renewable energies decreases slightly, particularly in the decentralized approach, which sees a 15.18% reduction compared to the baseline.

Regarding the maximum utilization of electrolysis capacity, Case 2 demonstrates a full potential utilization (100%) during peak periods. This pattern highlights the efficiency of this approach, justifying the investment in such facilities. In contrast, Case 1 and Case 3 show lower maximum utilization rates. In Case 1, the utilization drops to 80.46%, indicating that the existing placements cannot efficiently support higher capacities. Case 3, despite achieving a high utilization rate of 100%, sustains this level only briefly (1h), suggesting that demand-oriented placement may lead to occasional under-utilization.

The increase in marginal cost of electrolysis relative to the baseline is the lowest in Case 2, particularly in the centralized case, where alignment with renewable energy availability reduces operational costs. This outcome highlights the economic benefits of placing electrolyzers near renewable energy sources, facilitating more cost-effective hydrogen production. On the contrary, Case 1, due to a simple capacity expansion on existing sites without strategic planning, experiences a significant increase in marginal costs by over 10,000%, likely due to a higher reliance on non-renewable energy sources. Case 3 shows the highest marginal costs, with the decentralized approach being particularly expensive. These significant costs are attributed to the use of dummy loads in the model when the generation system and line capacities are insufficient to meet the demand. These really high marginal costs do not reflect reality as the cost of dummy loads is set arbitrarily high to discourage their use. However, this increase still reflects the economic challenges of meeting hydrogen demand, where electricity costs rise during high-demand periods.

In summary, the comparative analysis highlights the trade-offs inherent in each case study. Case 2, especially the centralized approach, offers the most balanced performance across all metrics, optimizing grid efficiency and economic viability while maintaining mix high in renewable energy. In contrast, Case 1 highlights the limitations of expanding capacity without considering grid impacts, while Case 3 presents significant challenges in terms of grid congestion and operational costs. Although Case 3 performs worse than the other cases across the analyzed metrics, it has the potential to reduce costs and energy consumption associated with hydrogen transportation. However, these benefits are not quantified in this analysis, indicating the need for further investigation to provide a more balanced overall assessment.

4.2 Recommendations for electrolyzers deployment

These findings highlight the importance of strategic planning in the deployment of large electrolysis capacity, indicating that an optimal hydrogen economy relies on balancing proximity to renewable energy sources with careful grid management. Based on the case studies results, the following recommendations are proposed:

Prioritization of electrolyzers near renewable energy sources: Placing electrolyzers close to large renewable energy producers significantly improves grid efficiency and reduces operational costs. The analysis demonstrates that centralized facilities, particularly those located in areas with high renewable potential, contribute to lower grid congestion. Therefore, it is advisable to prioritize these areas. This strategy ensures a stable, efficient, and cost-effective supply of hydrogen, leveraging the availability of renewable resources to maximize the utilization of electrolysis capacity.

Grid congestion solutions when considering demand-oriented placement: While proximity to renewable energy is recommended, the placement of electrolyzers near hydrogen demand centers, such as industrial hubs, refineries, and transportation hubs, must be approached with caution. Indeed, Case 3 reveals that this strategy can increase grid congestion and operational costs, particularly during peak demand periods. To mitigate these challenges, it is essential to plan for grid reinforcements in specific areas where line capacity is likely to be exceeded. Grid updates, such as increasing line capacity, are necessary to support the additional load, therefore identifying the stressed lines is necessary, as it is done in Figure 22. Achieving the right balance between grid reinforcement and operational efficiency is important for developing a cost-optimal hydrogen economy that can meet demand while minimizing hydrogen transportation costs and emissions.

Integrated planning for hydrogen infrastructure: Considering a complete approach to hydrogen infrastructure development, incorporating both hydrogen production and hydrogen distribution networks, is essential. This includes not only the strategic placement of electrolyzers but also the development of pipelines and storage facilities to support hydrogen transport from production sites to demand sites. By integrating all these elements, the region can minimize the need for expensive grid upgrades while ensuring that hydrogen is delivered efficiently and sustainably to where it is needed.

Grid upgrades for renewable integration: Given the increased reliance on renewable energy, it is necessary to ensure that grid upgrades are aligned with renewable integration strategies. This involves not only reinforcing the grid to accommodate new electrolyzers but also improving the grid's ability to handle the variability of renewable generation. Some gird management technologies, such as smart grids and demand-response systems, should be considered to optimize the balance between supply and demand.

In summary, the model-based approach used in this analysis has provided quantitative insights by allowing the evaluation of different case studies, leading to valuable recommendations. The deployment of electrolyzers should be guided by a strategy that prioritizes renewable energy integration, minimizes grid congestion, and balances the costs and benefits of grid upgrades. By adopting these recommendations, regions can develop an efficient hydrogen ecosystem.

4.3 Limitations of the model

While the model developed for this study offers a representation of the Andalusian energy system, it does have some limitations that need to be pointed out.

Electricity storage: The model does not include electricity storage solutions such as batteries or pumped hydro storage. Storage systems could help with the variability of renewable energy sources by storing excess energy during periods of low demand and releasing it when demand is high. Without these systems, the model may overestimate grid congestion and under-utilize available renewable resources.

Demand-response: The model assumes a fixed hourly electricity demand without incorporating demand-response behaviors. Incorporating it in the model, would allow the system to adjust demand in response to electricity prices and grid conditions.

Hydrogen storage: Hydrogen storage is also not considered in the model. Including hydrogen storage would allow better management of hydrogen supply and demand, particularly with variable renewable energy inputs. Hydrogen storage can absorb surplus production during low-demand periods and supply hydrogen when demand peaks, potentially reducing operational costs and improving system efficiency.

Technology representation: The model simplifies the representation of various process technologies, including power plants and electrolyzers. It does not account for operational parameters such as ramping rates, startup times, minimum operating levels, part-load efficiency losses, and shutdown times. Including these parameters would provide a more accurate and realistic representation of the system's operations.

Consideration of investments: The model is purely operational, focusing on the hourly operation of the energy system without addressing investment in new infrastructures. It does not consider the costs for building new electrolyzers, power plants, or expanding transmission networks. This limitation restricts the model's ability to assess the long-term financial viability and strategic implications for the different case studies. Adding this dimension to the model could allow, for example, for an accurate assessment of the differences in impact between investing in the construction of centralized and decentralized sites.

Grid expansion model: The model assumes that transmission line capacities are fixed, without considering potential expansions or new line constructions. As discussed in 4.2, quantifying the costs and impact of this expansion would be important when considering placements that requires grid expansion. It would allow to find the right balance of electricity grid reinforcement to operate at the most optimal cost.

5 Conclusion

The operational model developed for this study has successfully quantified the impacts on the transmission grid and provided answers to the research questions. Designed specifically for the Andalusian region, the model integrates various aspects of the energy system, including generation, transmission, and electrolysis. It allows for the analysis of different case studies by simulating interactions between these components under the conditions expected for 2030. The flexibility of this modeling method enabled the evaluation of various configurations and their impacts on the grid.

The analysis has effectively addressed the initial research questions:

1. Is the Andalusian power network capable of sustaining the planned electrolysis projects for 2030?
2. What are the optimal strategic locations for electrolyzers to achieve an ambitious hydrogen production scenario by 2030?

Firstly, it appears that the baseline case, which includes the planned infrastructure for 2030, does not impose excessive stress on the electrical grid. The projects planned within this scenario seem feasible with the existing grid infrastructure and the energy system forecasted for 2030.

However, for a more ambitious hydrogen production scenario, it will be important to strategically position the additional electrolysis capacity. This will require finding an optimal balance between proximity to renewable energy sources and managing grid congestion. While locating electrolyzers near consumption centers could increase operational costs and congestion risks, placing them closer to renewable sources could minimize these impacts and reduce operational costs.

In summary, this study demonstrates that integrating large-scale electrolyzer capacity in the Andalusian region is feasible but requires careful strategic planning. The use of an operational model proved to be a valuable tool for informing this planning process, allowing for the simulation of different case studies and the development of optimized solutions for Andalusia's future energy landscape. However, the model has limitations, including the exclusion of investment costs, simplified technology representation, and the absence of energy storage considerations, which should be addressed in future studies for a more comprehensive analysis.

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Appendix A

Appendix

1 NECP

Table A.17. Electricity generation park in the PNIEC 2023-2030 scenario

Scenario generation park. Gross power (MW)				
Years	**2019**	**2020**	**2025**	**2030**
Wind *	25.083	26.754	42.144	62.044
Solar photovoltaic * *	8.306	11.004	56.737	76.387
Solar thermoelectric	2.300	2.300	2.300	4.800
Hydraulic	14.006	14.011	14.261	14.511
Biogas	203	210	240	440
Other renewables	0	0	25	80
Biomass	413	609	1.009	1.409
Coal	10.159	10.159	0	0
Combined cycle	26.612	26.612	26.612	26.612
Cogeneration	5.446	5.276	4.068	3.784
Fuel and Fuel/Gas (Non-Peninsular Territories)	3.660	3.660	2.847	1.830
Waste and other	600	609	470	342
Nuclear	7.399	7.399	7.399	3.181
Storage *	6.413	6.413	8.828	18.543
Total	**111.101**	**115.015**	**166.939**	**213.963**

** Including the storage of the thermoelectric solar is as high as 22 GW.*
Source: Ministry of Ecological Transition and the Demographic Challenge, 2023

Figure 24: Source:[5]

2 Technology data

2.1 Annual technology data

Table 11: Process efficiency [10] and capacity bounds

Process	Efficiency (-)	Capacity Bound (MW)
GAS	0.600	6384.465
HYDRO	0.900	1017.000
SOLAR	1.000	18812.000
SOLAR THERMAL	1.000	1140.600
WIND	1.000	5867.900
BIOMASS	0.468	169.000
COAL	0.500	0.000
SPAIN	1.000	+inf
PORT	1.000	+inf
MAROC	1.000	+inf
SHORTAGE	1.000	+inf
ELEC DEMAND	1.000	+inf
ELECTROLYSIS	1.000	4000.000

Table 12: Variable O&M costs for each technology (EUR/GJ) [10]

Process	Activity cost (EUR/GJ)
GAS	2.00
HYDRO	1.25
SOLAR	0.00
SOLAR THERMAL	0.00
WIND	0.00
BIOMASS	3.13
COAL	2.08
SPAIN	100.00
PORT	100.00
MAROC	100.00
SHORTAGE	10000.00

Table 13: Capacity factors

Process	**Availability factor (-)**
GAS	0.9
HYDRO	0.7
SOLAR	See 2.2
SOLAR THERMAL	0.5
COAL	0.9
BIO	0.7
WIND	See 2.2
SPAIN	1.0
PORT	1.0
MAROC	1.0
SHORTAGE	1.0
ELEC DEMAND	1.0
ELECTROLYSIS	1.0

2.2 Hourly availability factors

Table 14: Seasonal hourly availability factors for photovoltaic [11]

Hour	**Winter**	**Middle**	**Summer**
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0.00440255	0.004437525
6	0	0.0267902	0.0603395
7	0.0205605	0.1698656	0.21011875
8	0.2119375	0.355894	0.3898035
9	0.394231	0.5005874	0.53902
10	0.513491	0.6091904	0.64351375
11	0.58187625	0.671824	0.7044575
12	0.5896835	0.6771026	0.71734975
13	0.54066	0.6263594	0.6797745
14	0.45644225	0.5375394	0.6006505
15	0.335278	0.417066	0.48032325
16	0.11642675	0.2549866	0.3230615
17	0.016898	0.0800124	0.14886425
18	0	0.00888175	0.0313065
19	0	0.000135	0.001622333
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0

Table 15: Seasonal hourly availability factors for wind generation [12]

Hour	Winter	Middle	Summer
0	0.54803951	0.39660135	0.24109797
1	0.55189566	0.40342366	0.24470488
2	0.55570584	0.41109017	0.25019086
3	0.56025762	0.41841543	0.25502856
4	0.56421645	0.42556904	0.25968496
5	0.56718988	0.43233197	0.26188305
6	0.57023365	0.43516958	0.25763834
7	0.5722862	0.42887023	0.25774785
8	0.56422965	0.42025591	0.25815585
9	0.54482082	0.4114773	0.25459094
10	0.52632327	0.39827495	0.24801767
11	0.50982558	0.38359082	0.24545855
12	0.49438919	0.37265604	0.25025914
13	0.48127519	0.36917707	0.26247236
14	0.47154798	0.3733536	0.27972997
15	0.46918567	0.38281654	0.30097087
16	0.47996406	0.39464423	0.32174948
17	0.49500973	0.40796413	0.33570545
18	0.50825745	0.41199828	0.33761308
19	0.51977004	0.40356236	0.32021739
20	0.52879375	0.3938281	0.28901838
21	0.53491555	0.38738146	0.26136307
22	0.53933601	0.3863701	0.24649779
23	0.54363333	0.39061035	0.2405575

3 GAMS Model

Symbols

Sets

Name	Domains	Description
r	*	region
t	*	years
s	*	timeslice
WHS	s	winter
SHS	s	summer
MHS	s	middle
ie	*	import export
io	*	in out
p	*	process
l	*	lines
c	*	commodity
n, nn	*	nodes
TOP	p, c, io	link between processes and comotities (REF)
line_nodes	l, n, nn	mapping of lines to their start and end nodes
bilateral	l, n, nn	indicator if the lines are bilateral or not
link	l, n	link nodes and lines

Parameters

Name	Domains	Description
ACT_EFF	r, p, t	Activity efficiency
CAP_BND	r, t, p	Process Capacity bound
NCAP_AF	r, p, t, s	Process availability
FLO_COST	r, p, c, t	Cost of commodity produced by process
COM_PROJ	r, c, t, s	Demand projection
DEM_PT	r, c, t	Portugal export
DEM_MA	r, c, t	Morocco export
H2_DEM_SUMMER	r, c, t	H2 demand for summer
H2_DEM_WINTER	r, c, t	H2 demand for winter
H2_DEM_MID	r, c, t	H2 demand for middle season
ACT_COST	r, p, t	Activity cost EUR per GJ
coeff	p	Demand -1 / Production 1
b	r, l, t	Susceptance of line l
GR_GENFR	r, n, p, t	Repartition of generation capacities
GR_ENDFR	r, n, p, t	Repartion of demand

Name	Domains	Description
CAP_GR_BND	r, t, l	Lines capacity bound in MW
G_CONV		Conversion factor
PRC_CAPACT		Conversion MWh to PJ
TIME	s	Conversion factor for timeslices

Variables

Name	Domains	Description
cost		Objective function cost
var_comaux	r, t, n, s	Voltage angle at node n
var_ncap	r, p, t	New capacity in MW
var_act	r, p, t, s	Activity level of process p PJ
var_gr_act	r, t, l, s	Activity level of grid line l MW
var_gr_ncap	r, t, l	New grid line capacity MW
var_ire	r, t, l, n, s, ie	Exchange of commodity on line l
var_flo	r, p, c, t, s	Flow of commodity c in process p in PJ
var_gridelc	r, t, c, n, s, io	Electricity flow at node n MW

Equations

Name	Domains	Description
obj		objective function
eq_capact	*, *, *, *	capacity to activity
eq_actflo	*, *, *, *	activity to flow
eq_combal	*, *, *, *	commodity balance
eq_acteff	*, *, *, *	activity efficiency
eq_capbnd	*, *, *	capacity bound
eq_h2_winter	*, *, *, *	h2 demand winter
eq_h2_summer	*, *, *, *	h2 demand summer
eq_h2_mid	*, *, *, *	h2 demand middle
eq_h2_bis_winter	*, *, *, *	h2 additional demand
eq_h2_bis_summer	*, *, *, *	h2 additional demand
eq_h2_bis_mid	*, *, *, *	h2 additional demand
eq_gr_capact	*, *, *, *	capacity to activity
eq_gr_actflo	*, *, *, *	activity to flow
eqe_combal	*, *, *, *	flow balance at the nodes
eqe_gr_combal	*, *, *, *	commodity balance for the grid
eq_gr_ire	*, *, *, *, *, *, *	line flow
eq_slack_bus	*, *, *, *	slack bus definition
eq_gr_powflo	*, *, *, *, *, *	power flow
eq_gr_genall	*, *, *, *	generation balance at nodes

Name	Domains	Description
eq_gr_demall	*, *, *, *	demand balance at nodes
eq_gr_bnd	*, *, *, *	line capacity bound
eq_export_s	*, *, *, *, *, *	export to Spain
eq_export_p	*, *, *, *	export to Portugal
eq_export_m	*, *, *, *	export to Morocco
eq_marocco	*, *, *	limit import from Morocco
eq_portugal	*, *, *	limit import from Portugal

Equation Definitions

obj

$$\text{cost} = \sum_{r,p,c,t,s} (\text{G\_CONV} \cdot \text{ACT\_COST}_{r,p,t} \cdot \text{var\_act}_{r,p,t,s} + \text{FLO\_COST}_{r,p,c,t} \cdot \text{var\_flo}_{r,p,c,t,s})$$

---

eq_capact$_{r,p,t,s}$

$$\text{var\_act}_{r,p,t,s} \leq \text{var\_ncap}_{r,p,t} \cdot \text{PRC\_CAPACT} \cdot \text{TIME}_s \cdot \text{NCAP\_AF}_{r,p,t,s} \qquad \forall r,p,t,s$$

---

eq_actflo$_{r,p,t,s}$

$$\text{var\_act}_{r,p,t,s} = \sum_{c|\text{TOP}_{p,c,\texttt{OUT}}} \text{var\_flo}_{r,p,c,t,s} \qquad \forall r,p,t,s$$

---

eq_acteff$_{r,p,t,s}$

$$\text{var\_act}_{r,p,t,s} = \text{ACT\_EFF}_{r,p,t} \cdot \sum_{c|\text{TOP}_{p,c,\texttt{IN}}} \text{var\_flo}_{r,p,c,t,s} \qquad \forall r,p,t,s \mid \sum_{c|\text{TOP}_{p,c,\texttt{IN}}} 1$$

---

eq_combal$_{r,c,t,s}$

$$\sum_{p|\text{TOP}_{p,c,\texttt{OUT}}} \text{var\_flo}_{r,p,c,t,s} \geq \sum_{p|\text{TOP}_{p,c,\texttt{IN}}} \text{var\_flo}_{r,p,c,t,s} + \text{COM\_PROJ}_{r,c,t,s} \qquad \forall r,c,t,s$$

---

eq_h2_winter$_{r,'HDMD','hdem',t}$

$$\sum_{s,WHS_s} \text{var\_flo}_{r,\texttt{HDMD},\texttt{hdem},t,s} \geq \text{H2\_DEM\_WINTER}_{r,\texttt{hdem},t} \qquad \forall r,'HDMD','hdem',t$$

---

eq_h2_summer$_{r,'HDMD','hdem',t}$

$$\sum_{s,SHS_s} \text{var\_flo}_{r,\texttt{HDMD},\texttt{hdem},t,s} \geq \text{H2\_DEM\_SUMMER}_{r,\texttt{hdem},t} \qquad \forall r,'HDMD','hdem',t$$

eq_h2_mid$_{r,'HDMD','hdem',t}$

$$\sum_{s,MHS_s} \text{var\_flo}_{r,\texttt{HDMD},\texttt{hdem},t,s} \geq \text{H2\_DEM\_MID}_{r,\texttt{hdem},t} \qquad \forall r,'HDMD','hdem',t$$

eq_h2_bis_winter$_{r,'HDMDBIS','hdembis',t}$

$$\sum_{s,WHS_s} \text{var\_flo}_{r,\texttt{HDMDBIS},\texttt{hdembis},t,s} \geq \text{H2\_DEM\_WINTER}_{r,\texttt{hdembis},t} \; \forall r,'HDMDBIS','hdembis',t$$

eq_h2_bis_summer$_{r,'HDMDBIS','hdembis',t}$

$$\sum_{s,SHS_s} \text{var\_flo}_{r,\texttt{HDMDBIS},\texttt{hdembis},t,s} \geq \text{H2\_DEM\_SUMMER}_{r,\texttt{hdembis},t} \; \forall r,'HDMDBIS','hdembis',t$$

eq_h2_bis_mid$_{r,'HDMDBIS','hdembis',t}$

$$\sum_{s,MHS_s} \text{var\_flo}_{r,\texttt{HDMDBIS},\texttt{hdembis},t,s} \geq \text{H2\_DEM\_MID}_{r,\texttt{hdembis},t} \quad \forall r,'HDMDBIS','hdembis',t$$

eq_export_p$_{r,'EXPORT\_PT','port\_dem',t}$

$$\sum_{s} \text{var\_flo}_{r,\texttt{EXPORT\_PT},\texttt{port\_dem},t,s} \geq \text{DEM\_PT}_{r,\texttt{port\_dem},t} \qquad \forall r,'EXPORT\_PT','port\_dem',t$$

eq_export_m$_{r,'EXPORT\_MA','maroc\_dem',t}$

$$\sum_{s} \text{var\_flo}_{r,\texttt{EXPORT\_MA},\texttt{maroc\_dem},t,s} \geq \text{DEM\_MA}_{r,\texttt{maroc\_dem},t} \; \forall r,'EXPORT\_MA','maroc\_dem',t$$

eq_capbnd$_{r,p,t}$

$$\text{var\_ncap}_{r,p,t} \leq \text{CAP\_BND}_{r,t,p} \qquad \forall r,p,t$$

eqe_combal$_{r,t,'elec',s}$

$$\sum_p(\text{coeff}_p \cdot \text{var\_act}_{r,p,t,s}) + \sum_n(\text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{IN}} - \text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{OUT}}) \cdot \text{PRC\_CAPACT} \cdot \text{TIME}_s = 0 \qquad \forall r,t,'elec',s$$

eq_gr_capact$_{r,t,l,s}$

$$\text{var\_gr\_act}_{r,t,l,s} - \text{var\_gr\_ncap}_{r,t,l} \leq 0 \qquad \forall r,t,l,s$$

eq_gr_actflo$_{r,t,l,s}$

$$\text{var\_gr\_act}_{r,t,l,s} = \sum_n(\text{link}_{l,n} \cdot \text{var\_ire}_{r,t,l,n,s,\texttt{IMP}}) \qquad \forall r,t,l,s$$

eqe_gr_combal$_{r,t,n,s}$

$$\sum_l(\text{link}_{l,n} \cdot (\text{var\_ire}_{r,t,l,n,s,\texttt{IMP}} - \text{var\_ire}_{r,t,l,n,s,\texttt{EXP}})) - \text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{IN}} + \text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{OUT}} = 0 \qquad \forall r,t,n,s$$

eq_gr_ire$_{r,t,l,n,nn,'IMP',s}$

$$\text{var\_ire}_{r,t,l,n,s,\texttt{IMP}} = \text{var\_ire}_{r,t,l,nn,s,\texttt{EXP}} \qquad \forall r,t,l,n,nn,'IMP',s \mid \text{bilateral}_{l,n,nn}$$

eq_slack_bus$_{'AN','2030','B100',s}$

$$\text{var\_comaux}_{\texttt{AN,2030,B100},s} = 0 \qquad \forall 'AN','2030','B100',s$$

eq_gr_powflo$_{r,t,l,n,s,nn}$

$$\text{var\_ire}_{r,t,l,n,s,\texttt{EXP}} - \text{var\_ire}_{r,t,l,n,s,\texttt{IMP}} = -(\text{b}_{r,l,t} \cdot (\text{var\_comaux}_{r,t,n,s} - \text{var\_comaux}_{r,t,nn,s})) \; \forall r,t,l,n,s,nn \mid \text{line\_r}$$

eq_gr_genall$_{r,t,n,s}$

$$\text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{OUT}} \cdot \text{PRC\_CAPACT} \cdot \text{TIME}_s = \sum_p(\text{GR\_GENFR}_{r,n,p,t} \cdot \text{var\_act}_{r,p,t,s}) \qquad \forall r,t,n,s$$

eq_gr_demall$_{r,t,n,s}$

$$\text{var\_gridelc}_{r,t,\texttt{elec},n,s,\texttt{IN}} \cdot \text{PRC\_CAPACT} \cdot \text{TIME}_s = \text{GR\_ENDFR}_{r,n,\texttt{EDMD},t} \cdot \text{var\_act}_{r,\texttt{EDMD},t,s} + \text{GR\_ENDFR}_{r,n,\texttt{EXPORT\_PT},t} \cdot \text{var\_act}_{r,\texttt{EXPORT\_PT},t,s} + \text{GR\_ENDFR}_{r,n,\texttt{EXPORT\_MA},t} \cdot \text{var\_act}_{r,\texttt{EXPORT\_MA},t,s} +$$

$$\text{GR\_ENDFR}_{r,n,\texttt{HDMD},t} \cdot \text{var\_act}_{r,\texttt{HDMD},t,s} + \text{GR\_ENDFR}_{r,n,\texttt{HDMDBIS},t} \cdot \text{var\_act}_{r,\texttt{HDMDBIS},t,s} \quad \forall r,t,n,s$$

eq_gr_bnd$_{r,t,l,s}$

$$\text{var\_gr\_ncap}_{r,t,l} \leq \text{CAP\_GR\_BND}_{r,t,l} \qquad \forall r,t,l,s$$

eq_export_s$_{r,t,l,n,s,ie}$

$$\text{var\_ire}_{r,t,l,\texttt{B138},s,\texttt{IMP}} = 0 \qquad \forall r,t,l,n,s,ie$$

eq_marocco$_{r,p,t}$

$$\sum_s \text{var\_act}_{r,\texttt{GMAROC},t,s} \leq 1.4256 \qquad \forall r,p,t$$

eq_portugal$_{r,p,t}$

$$\sum_s \text{var\_act}_{r,\texttt{GPORT},t,s} \leq 6.352 \qquad \forall r,p,t$$

$\text{var\_act}_{r,p,t,s} \geq 0 \ \forall r,p,t,s$
$\text{var\_flo}_{r,p,c,t,s} \geq 0 \ \forall r,p,c,t,s$
$\text{var\_ncap}_{r,p,t} \geq 0 \ \forall r,p,t$
$\text{var\_gridelc}_{r,t,c,n,s,io} \geq 0 \ \forall r,t,c,n,s,io$
$\text{var\_gr\_act}_{r,t,l,s} \geq 0 \ \forall r,t,l,s$
$\text{var\_gr\_ncap}_{r,t,l} \geq 0 \ \forall r,t,l$
$\text{var\_ire}_{r,t,l,n,s,ie} \geq 0 \ \forall r,t,l,n,s,ie$