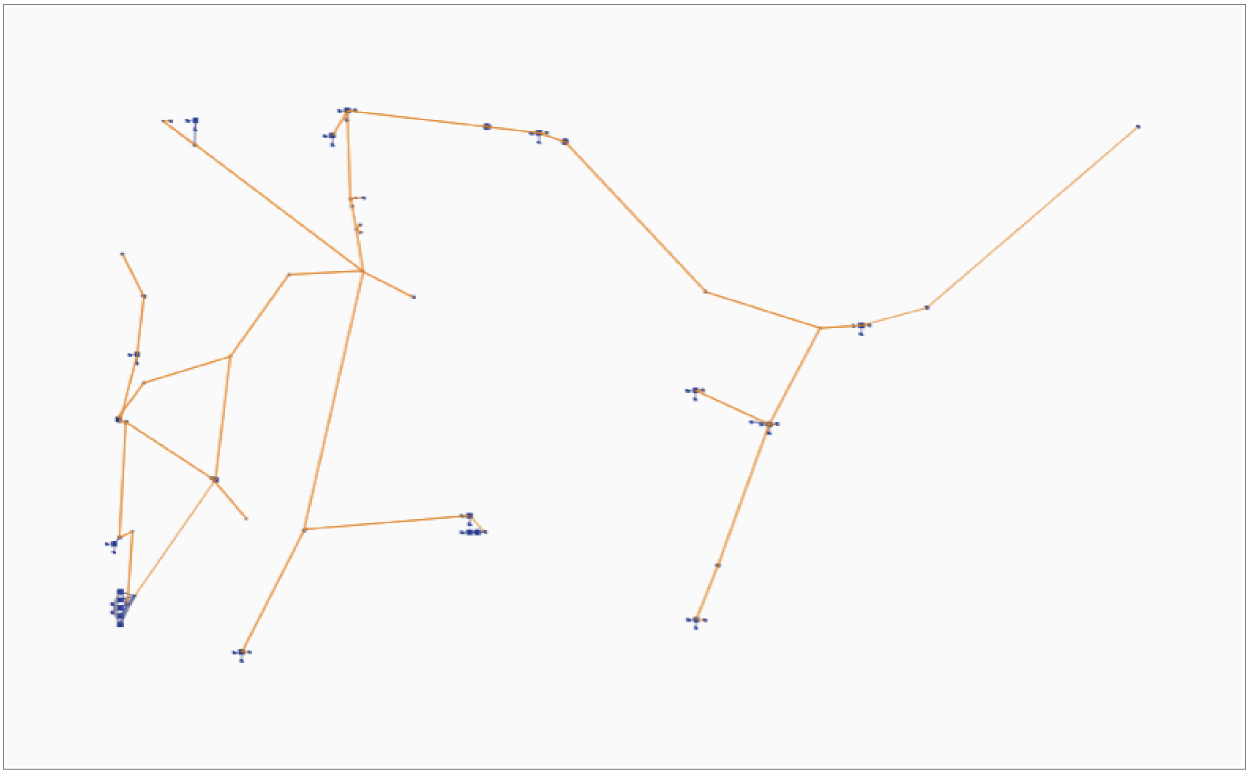
Green Hydrogen on the Iberian Peninsula

An example study, Jan 2025



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Executive Summary

This example study is the first of its kind to investigate the availability of green hydrogen supplies and the expected curtailment of solar parks and wind farms, as two sides of the same coin.

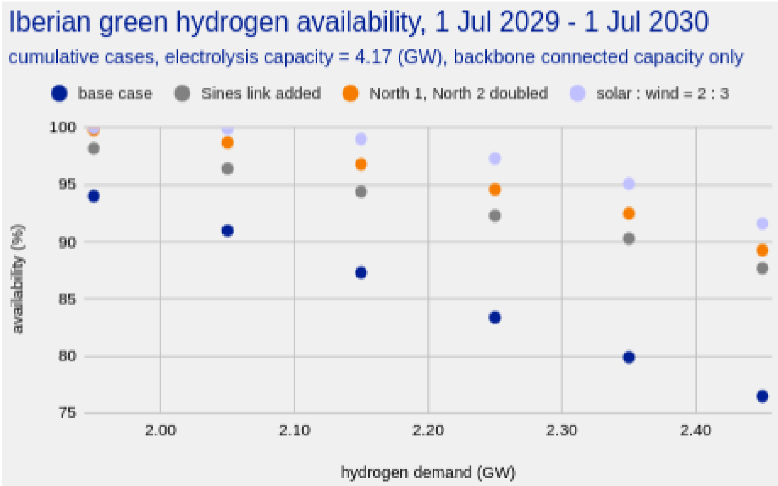
This study of green hydrogen on the Iberian Peninsula in 2030 is based on data from the websites of the EU government, banks, and subsidy organisations, and of the respective project owners, as of 1 October 2024.

It investigates the integrated performance of the green power generation, hydrogen production, storage, and pipeline transport elements of the value chain to meet the demand of the green hydrogen consumers, based on the published data, complemented with weather risk data and own assumptions. Experience in the oil, gas, and petrochemicals industries has shown the indispensable value of stochastic modelling, covering a wide spectrum of risks, to assess the robustness of development plans in meeting supply availability requirements.

This study aims to set an example on how the same stochastic modelling approach can be successfully applied to the renewable power and nascent green hydrogen industries.

The study uses the ARTIS® modelling platform, developed by and commercially available from SecuoS BV.

For given capacities, relatively small changes in the demand lead to large changes in the availability of the green hydrogen supplies. Several opportunities to increase the stable hydrogen supplies are suggested and evaluated. This shows that significant improvements over the base case can be achieved.



For the base case, the expected curtailment is constant, at about 920 MW, on the demand range from 2.05 to 2.45 GW. The first cumulative change, that is connecting Sines and Portalegre, leads to significant improvements, at the maximum demand of 2.45 GW, the expected curtailment reduces by 390 MW from 920 MW down to 530 MW. However, the second change makes little difference.

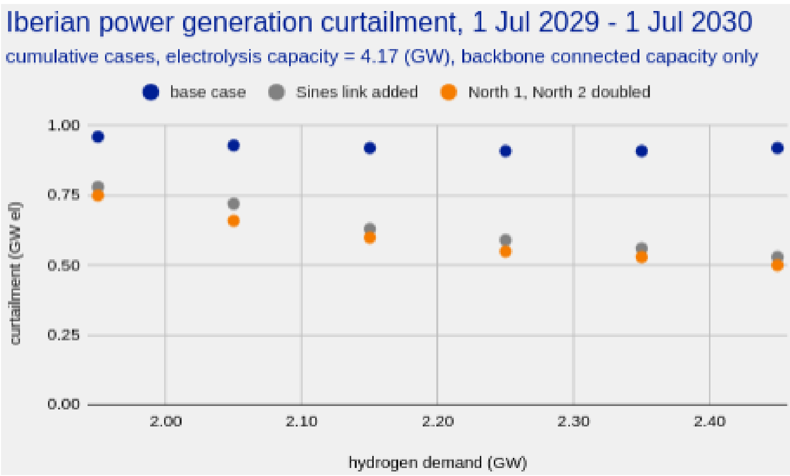


Table of Contents

1 Scope

1.1 Background

This example study of green hydrogen on the Iberian Peninsula in 2030 is based on data from the websites of he EU government, banks, and subsidy organisations, and of the respective project owners. All input data is as of 1 October 2024.

SecuoS and Geostock (an International Energy Storage Specialist Company) had carried out a joint study [1] on Sustainable Hydrogen Project Development, as an example of integrated project optimisation. That study, updated in March 2023, shows how to optimise a single integrated hydrogen project, taking account of the weather variability and other risks, under the condition of near 100% availability of the green hydrogen supply to the consumers.

All hydrogen network studies reported by others in the nascent hydrogen industry are deterministic. These deterministic models do not include any risks themselves; but often a number of different scenarios and possible 'N-1' cases are presented, each of which is also deterministic. This common approach does not sufficiently take into account the dominating factors that the capacity of the solar plants and wind farms is unpredictable, and only partly correlated.

Experience in the oil, gas, and petrochemicals industries [2] has shown the indispensable value of stochastic modelling, covering a wide spectrum of risks, to assess the robustness of development plans in meeting supply availability requirements.

This study aims to set an example of the stochastic modelling approach, based on data from EU government sources, EU industry sources, and project owners' websites, for the nascent hydrogen industry.

The main benefits of this approach are that it allows the effects of generating capacity, the ratio between solar/wind sources and the size and location of hydrogen storage in the network to be evaluated. These effects are quantified and can be used to instruct and support risk based business decisions. This is especially important in making the case for hydrogen storage which has been identified as an essential element in establishing the hydrogen ecosystem [26].

1.2 System description

This study investigates the hydrogen production, storage and pipeline transport to end consumers on the Iberian Peninsula in 2030, based on the data from publicly accessible sources, as on 1 October 2024, cross-checked with input data of ENTSOG's TYNDP 2024 study [27] (at the stage of public consultation), and complemented with weather variability and own assumptions.

Electrical power is generated by a mix of wind and solar facilities. It is supplied via substations to electrolysis plants to produce hydrogen. The hydrogen is then compressed for local consumption and for transport through the Spanish and Portuguese hydrogen network. From there, it is transported to assumed consumption locations. Excess hydrogen is compressed further and injected into salt caverns for storage, in North Spain and in West Portugal. The stored hydrogen is available to make up for any shortfall arising from variations in wind and solar power and equipment downtime. Line-pack has not been taken into account [37].

Figure 1.1 shows the green hydrogen projects, the Iberian hydrogen network, the REN natural gas network, and connecting pipelines, as projected in 2030. Only the connected projects are considered; the projects that have no connection to the hydrogen network have been left out of this study.

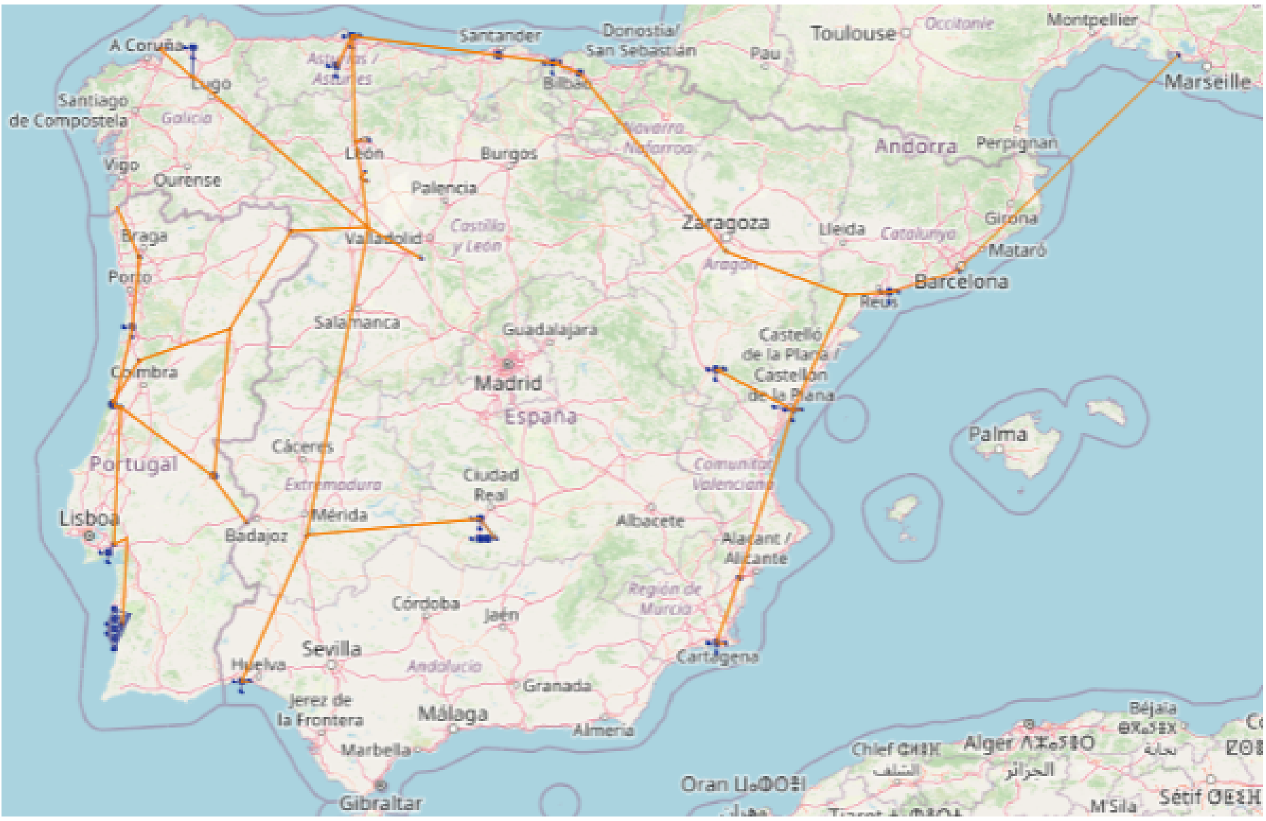


Figure 1.1: Integrated system overview showing hydrogen production, storage and transport

The base layer of this map has [openstreetmap.org]() copyright.

Potential export to France from the Iberian Peninsula via BarMar is part of the system and considered; possible imports from North Africa or France are ignored as these are not foreseen before 2030. The time period selected is from 1 July 2029 until 1 July 3030; around that time the EU rules for renewable hydrogen [28] will no longer allow any possible grey backup power supply on the peninsula, apart from short periods of imbalance.

1.3 System boundaries

The system boundaries cover all production-critical facilities from the green energy production at the solar parks and wind farms until the front gate of the hydrogen consumers. This includes the electrolysis, storage, treating, and hydrogen transport.

The system is modelled with no connection to the public electric power grid, batteries, or other electric storage. This is aligned with the EU directive that restricts the use of grid supply for green hydrogen production, from 2030 onwards. However, it would be straightforward to include this in the model to match any future changes in the directive.

The study evaluates the performance of the system, once fully operational; it does not include project delay, phasing, or commissioning risks.

The modelling scope encompasses all identified factors that might influence performance either positively, through opportunities, or negatively, through risks. This includes the market parameters such as supply and demand fluctuations, capacity profiles, and any contractual requirements. A key factor that affects system performance is equipment reliability resulting from degradation, failure, human error, other unplanned events, and the associated repair times. In addition, there are operational requirements for flushing, cleaning, regeneration, planned maintenance, inspections and other scheduled outages.

The impact of the surrounding natural environment is also included. This may arise for example from the impact of seasonal and daily weather variability on renewable power generation, the impact of ambient temperature on equipment capacity, and any effects on repair times which may be linked to the time of day and year, and the manning strategy of the facility.

Data on the above are sourced from a number of different industry and public sources. One of the benefits of this type of study is that it allows uncertainties in data to be investigated via sensitivity analyses to understand the impact on overall system performance, so that the relative importance of data quality can be assessed.

1.4 Approach

The study aims to establish a base case and assess three possible network design changes that have a positive impact on the availability of the hydrogen supplies to the consumers. The base case includes the electrolysis projects that are planned to be connected to the hydrogen network, by 2030.

As sensitivities to the base case, the following three cumulative changes are examined:

- adding a hydrogen pipeline between Sines and Portalegre, connecting the Sines projects to the Portuguese hydrogen backbone
- doubling the Spanish North 1 and North 2 storage capacities, without changing their injection and withdrawal capacities
- swapping the ratio of the solar parks and the wind farms peak capacities in each location from 1.5 : 1 to 1 : 1.5

In each case, the sensitivities show how much demand can be met on a range of availability conditions, up to 100%.

For each case, a second series of sensitivities assesses the utilisation of the solar parks and wind farms, showing the power generation curtailment at different times of the day and the year.

The study models the hydrogen network inside the system boundaries and evaluates and reports the availability of the hydrogen supplies. All results are reported in terms of standard industry metrics, both as functions of time and as averages over the study period.

1.5 Study limitations

The present model has been prepared using publicly available data and with limited funding. Therefore, a number of assumptions and simplifications had to be made:

- this study does not include any electric grid details; it is not a load flow or power flow study

- as an independent study, it is based on publicly available data only
- spatial correlation of the power generation capacity of the solar park sand wind farms has been modelled to a reasonable but limited extent
- ageing effects on solar generation e.g. due to panel contamination, cleaning and long term degradation are not modelled
- modelling of wind speed distribution does not accurately reflect transition frequencies between different wind speed states
- some extreme weather events are not accounted for e.g. prolonged cloud cover events

In general the effects of these are small, however specific applications with input from the system owners/operators, and use of the EU meteorological databases, would allow these limitations to be removed, as demonstrated in a previous joint study [1].

This study does not address economic value, for the sake of simplicity and the lack of firm data on the demand. Hence, the study does not aim to optimise the capacity balance of the hydrogen network.

This example study has been developed without any discussion with third parties.

1.6 Value - how the model can be applied

The present study shows that a stochastic model of a large country-wide green hydrogen network can provide key insights. There are several other ways in which such a model has been used previously in the oil, gas, and petrochemicals industries. Some of these are included here for information.

1.6.1 Network optimisation

It is challenging to optimise large energy supply networks under constraints on the availability of the hydrogen supplies, because of network complexities, the large number of assumptions to be made, input data quality limitations, and the required computing resources.

This study, together with the previous study [1], suggests how some of these challenges can be addressed in a 3-step approach. The first step optimises the individual green hydrogen projects, under their respective availability conditions, as if they were all operating in island mode, under the assumption of unlimited hydrogen storage. The second step optimises the network connectivity, the booster compression locations and capacities, and the hydrogen storage injection and withdrawal capacities. The third step minimises the respective storage capacities.

1.6.2 Power generation curtailment

The output from the ARTIS model shows when power generation curtailment occurs and its magnitude. The curtailment results can be used to quantify the scope for additional flexible power demand, for example with batteries, crypto mining, and electrolysis. On the other hand, they can be used to identify the root causes, allowing sensitivity cases to be run investigating the benefit of alleviating the constraints.

1.6.3 Criticality analysis and de-bottlenecking

The model is populated with equipment reliability data. This allows the effects of planned and breakdown maintenance to be identified. Moreover, the criticality of individual units and connections within the system and the benefits of improvements such as adding redundancy, increasing flexibility by installing headers to allow cross-feeding within units or even the benefit of additional pipelines between locations can all be quantified.

1.6.4 Operating strategy development

In actual operations, there are a number of decisions to be made which are directed by the operational strategy of the system. The model can be used to investigate the impact of alternative strategies such as:

- scheduling of preventive maintenance work – this applies across different timescales (diurnal, weekly, seasonal)
- stock level management of storage across the system to minimise both empty and full periods which can both lead to curtailment in production
- maintenance response times e.g. minimising response time by holding local spares, providing 24/7 cover

The model increases understanding of how the strategy affects overall production and identifies opportunities to improve this or reduce costs.

1.6.5 Economic modelling

The output of the model for any specific case is a probabilistic forecast of production over time. This allows the risk to be quantified and supports decisions to be taken in the context of whatever contractual, reputational or other considerations exist. Moreover, the output shows the variation over time due to seasonal variations in generating capacity and as new projects are commissioned.

For example, if a supply contract specifies a required availability in terms of maximum frequency and/or duration of supply interruptions the model can be used to assess how likely this will be achieved. Where this is not acceptable alternatives can be explored to address this for example uncertainty arising from weather patterns or equipment failure can be reduced by increasing production capacity and storage to cover periods of undersupply. Conversely, it may be that the system oversupplies and can be simplified to reduce cost.

1.6.6 Live applications

One of the more advanced applications of stochastic modelling is for existing operating facilities and systems where the model is continuously updated to represent the live condition. This allows real time modelling of production risk which can help with planning of maintenance activities, stock control and with a clear understanding of the live production risk. An additional feature of such live systems is the capture of location specific equipment reliability data that both increases accuracy of the model over time as well as creating a data resource for use in modelling future projects. This is particularly important in areas where technology is developing and industry data is limited such as the green hydrogen business.

1.7 Tools and data sources

1.7.1 ARTIS®

The study uses the ARTIS modelling platform, the in-house tool of SecuoS [29]. ARTIS is a web based application for calculating the available capacity of complex interrelated production systems, consisting of many process elements, each of which is subject to inspection, testing, failure, repair and maintenance. ARTIS is capable of handling time-varying production capacity profiles to give a period-by-period analysis of the reliability, production availability and system capacity. For instance, ARTIS can be applied to oil and gas projects, gas liquefaction plants and oil refineries.

ARTIS is web-based and fully transparent; no special software or detailed expertise is required for reviewing the models.

1.7.2 Ownership

Ownership of the tool (comprising the ARTIS model, ARTIS platform and any dedicated interface software) related to this study remains with SecuoS BV.

1.7.3 Input data

The input data taken from the sources listed in section 6 are used without verification of their accuracy.

All input data are preliminary assumptions and can be adjusted when new information becomes available.

2 System configuration

2.1 Introduction

A production availability model describes whether a system is able to operate at maximum capacity, able to operate at a reduced capacity, or unable to operate, depending on the status of its facilities. Rather than modelling the physical flow in a process flow scheme, the model reflects the time-dependent ability to produce, while respecting the mass and energy balances.

The system can comprise of many facilities, each with any number of equipment items. In the two most common and simple cases, the items are arranged in series, in a single train, or as a number of parallel trains. This arrangement reflects the impact on the system when an item downtime event happens, such as an inspection or a failure [30] and [31]:

- Items that are arranged in series are critical to the train. That is, when such an item fails, the train can no longer operate.
- Items are arranged in parallel if, upon failure of one item, the parallel items and trains can continue production, and the whole system can continue to operate, possibly at a lower capacity.
- In general, systems cannot be modelled by serial and parallel nesting only; they must be modelled as a network of chains, each with individual nodes. In that case, each node is still critical to the performance of its chain, and the above two principles still apply.

The model includes both supply and demand.

The utilities, like power generation and biological treatment of process water, are just as much part of the model as are the generation, conversion, transport, and storage facilities. This implies that the model has a single unit of capacity for the whole system. In this study, the unit of power for all energy carriers is megawatt (MW) or gigawatt (GW). The unit of energy is megawatt-hour (MWh) or gigawatt-hour (GWh). The unit of pressure is bar.

In this study, a clear distinction is made between the terms 'curtailment' and 'losses', depending on where the root cause of a shortfall is. The term 'curtailment' strictly refers to shortfalls that have their root causes downstream of the power generation facilities. All other shortfalls are referred as 'losses'. Curtailment is defined as the need to cut back power generation due to root causes that are downstream of the power generation facilities. It can occur for a number of reasons including hydrogen network capacity bottlenecks, storage restrictions, and equipment failures.

2.2 Project integration

The model includes the hydrogen network and the underground storage facilities, 18 PEM electrolysis plants, of which 11 in Spain and 7 in Portugal. Each electrolysis plant is powered by a local solar park and a local wind farm, but the existing project Puertollano I only has a solar park. The electrolysers in Sines get their power from the same solar park and wind farm. The 1 GW projects at Cadiz, the 35 MW HYSENCIA project, and all other projects that have no connection to the hydrogen network, by 2030, are not modelled.

For each electrolysis plant, its wind farm and solar park are in the same area and they are connected to a single substation. The substation transforms the voltage from 33 kV to a lower level suitable for supplying the rectifiers of the electrolyser stack modules. The power transmission cables that connect the substation to the electrolysis plant are assumed to have sufficient capacity and no downtime. The hydrogen network is bi-directional.

The day of the year, the time of the day, the local weather, and the planned and unplanned downtime determine the available capacity of the hydrogen supplies .

2.3 Solar parks

Each solar park is modelled as a single block, with an hourly capacity profile that captures the daily and seasonal cycles. The profiles are based on the solar cycle in Madrid and the possible capacity levels are arranged in 1%-wide bins.

2.4 Wind farms

Each wind farm is modelled as a single block. For each location, the possible capacity levels are arranged in 10%-wide bins.

2.5 Electrolysis

The location, capacity, and start-up date of the electrolysis plants are taken from the respective sources listed in section 6. The electrolysis processes are assumed to have an efficiency of 70%. The balance of plant includes treating and compression to 100 bar for pipeline transport.

2.6 Booster compression

The model includes six booster compression stations, for maintaining the hydrogen in the hydrogen network at 100 bar, at intervals of about 200 km [33].

2.7 Underground storage

The model includes the salt cavern storage facilities North-1 and North-2 in Spain and the salt caverns at Carriço in Portugal. The Carriço location has 2 salt caverns that are repurposed to store pure hydrogen, hence blending with natural gas is assumed to occur downstream of the withdrawal. Each storage includes injection and withdrawal facilities.

2.8 Demand

Because firm data on the future demand is still lacking, the model assumes that the green hydrogen is consumed near the locations of the electrolysis plants in Spain and in four different locations in Portugal.

In Portugal, the hydrogen in commingled with natural gas, with a maximum hydrogen content of 10%, and transported through and stored in the existing REN facilities. It is assumed that this amounts to a final demand of 400 MW of hydrogen.

For all locations, the demand is assumed to be constant, with no downtime and no flexibility.

3 Assumptions

3.1 Input data

The input parameters for the surface and subsurface facilities include:

- probability distributions of the wind farm and solar park generating capacity
- the maximum operating capacities of all surface and subsurface assets
- conversion efficiencies
- the planned downtime events (maintenance, inspection, projects, withdrawals, ...) of all surface and subsurface assets
- parameters for the stochastic life- and downtime of all surface and subsurface facilities
- the hydrogen demand is constant at leach location

The study uses the standard definitions from relevant ISO standards.

3.2 Planned downtime

The seven electrolysis plants are down 1 day, for planned inspections, every 4 years. Module change-out is done every 6 months, on a rotating schedule, lasting 1 day, with a remaining plant capacity of 95%.

The six booster compression stations have an inspection schedule, with change-out of the valves on the reciprocating compressors, of 8 hours, every year. During these inspections, the remaining station capacity is 50%.

The North-1 and North-2 injection facilities are down for 1 week, every 4 years, on a rotating schedule. Upon completion, the withdrawal facilities are down for 1 week. In addition, well service of 8 hours is scheduled every year.

The annual planned inspections of the Carriço underground storage is based on the REN Annual Maintenance Programme and Restrictions Forecast [36]. The Carriço injection facilities are down for 4 weeks, every 2 years, with a remaining capacity of 50%. The Carriço withdrawal facilities are down for inspections for a period of 2 weeks, every year.

No planned downtime is assumed for the solar parks and the wind farms, because their production availability is dominated by the time of the day and the weather. For the wind farm, it is assumed that the turbines' condition monitoring systems enable all repairs to be scheduled on an opportunity basis.

3.3 Unplanned downtime

For each location, the wind speed has a Rayleigh distribution. Because most projects, except the ones at Sines, are more than 250 km apart, the probability distributions of the wind speeds are assumed to be mutually independent. The 5 electrolyser projects at Sines get their power from a single single shared solar park and a single shared wind farm, hence the power supplies to those 5 projects are fully correlated.

For each solar park, cloud cover is modelled as an independent random process, with clear mornings and cloud cover, if any, starting at 14:00, on average [34]. Hence, across the whole Iberian Peninsula, all solar park power supplies have a degree of mutual correlation in time. Persistent clouds, over a time span of more than a few days, are not modelled, although they are known to occur sometimes. Cloud cover reduces the solar park capacity by 50%.

This example study uses reliability data that has been collected by the Oil & Gas industry, some of which under the OREDA Joint Industry Project [35]. Although the OREDA project does not consider hydrogen, no adjustments have been made for possible different failure modes, failure frequencies and repair times. The active repair times of OREDA have been used.

3.4 Operating flexibility

This study makes a number of assumptions on the operating flexibility.

- At any time, the project uses the full available capacity first to satisfy the full 1.14 GW hydrogen demand ,and then to inject all remaining hydrogen into the underground storage facilities.
- The hydrogen network is assumed to have enough line-pack only for limited operational use [37].
- For each underground storage, the initial volume of working gas is zero, but the cushion gas is in place.
- The turndown capacity of the electrolyser plants is zero, that is they can operate at any level up to their maximum capacity.

3.5 Unknowns

As in any long-term planning context, assumptions on the timing of hydrogen project development are uncertain. In addition, there are large uncertainties around the future market developments and, in particular, future peak demand.

Access to data on the capacity and the historically achieved reliability of existing assets is limited by lack of experience, confidentiality, consistency of definitions, and data quality. In many cases, data that were collected for natural gas facilities are taken to apply for hydrogen as well. At the present, these assumptions cannot be validated.

4 Results

In the base case, the total electrolysis capacity is 4.17 GW, the ratio of solar to wind peak capacity is 3 : 2, and the total demand ranges from 1.95 to 2.45 GW.

The cumulative changes to the base case are:

- adding a pipeline between Sines and Portalegre, connecting the Sines projects to the Portuguese hydrogen backbone,
- doubling the Spanish North 1 and North 2 storage capacities, without changing their injection and withdrawal capacities,
- swapping the ratio of the solar parks and the wind farms peak capacities in each location from 3 : 2 to 2 : 3.

All results are based on 100 Monte Carlo simulations, on the 1-year period from 1 July 2029 till 1 July 2030.

With the model and data outlined above, section 4.1 presents the results for the availability of the hydrogen supplies and section 4.2 presents the expected curtailment of the solar parks and wind farms.

4.1 Hydrogen supply availability

For the hydrogen supply availability runs, the 15 assumed hydrogen consumption nodes set the demand for the green hydrogen. The total demand for green hydrogen, summed over all locations, is met through direct supplies from the respective local electrolysis plants, or by transport via the hydrogen network from the other plants and from the underground storages. The Portuguese demand, that is 400 MW, is blended with natural gas and supplied through the existing REN network. Figure 4.1 shows that, for the given capacities, relatively small

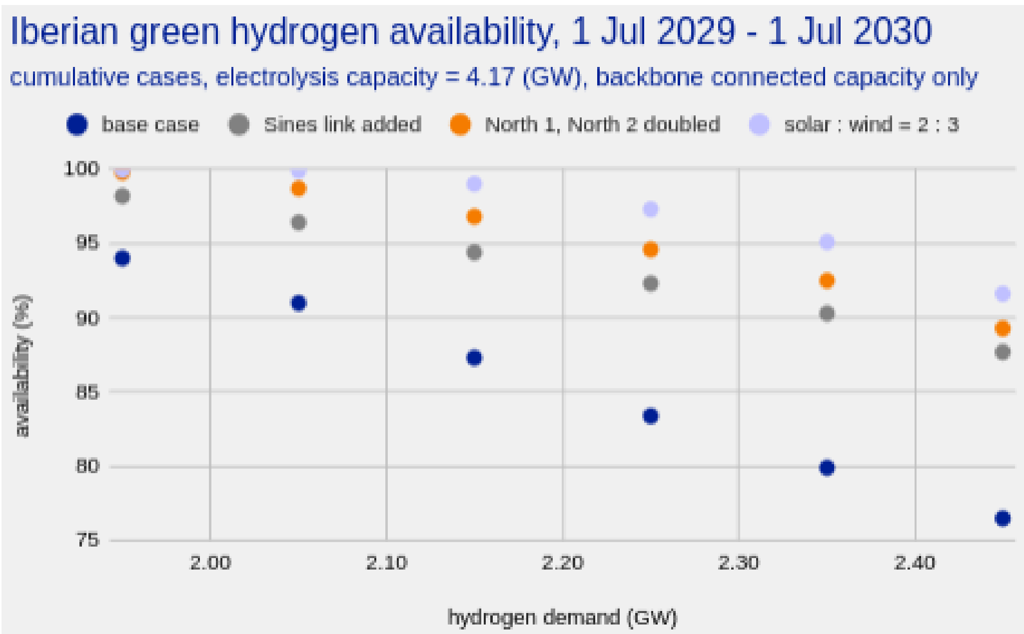


Figure 4.1: supply availability as a function of demand

changes in the demand, with steps of 100 MW, lead to large changes in the availability. For the base case, the availability drops off rapidly, from close to 100% down to about 75%, on the demand range from 1.95 to 2.45 GW.

The cumulative changes to the base case all lead to significant improvements. At the maximum demand of 2.45 GW,

- connecting Sines and Portalegre increases the availability by 11.2% from 76.5% up to 87.7%
- doubling the North 1 and North 2 storage capacities increases the availability by 1.6% from 87.7% up to 89.3%
- swapping the solar:wind peak capacity ratio increases the availability by 2.3% from 89.3% to 91.6%

Three weeks after the input data for the study had been frozen, on 21 Oct 2024, Repsol announced the delay of their electrolyser projects in Spain [5], with a total capacity of 350 MW. When making no other change, the impact of this delay is to reduce the base case availability at 1.95 MW demand by 6.8% from 94.0% down to 87.2%.

4.2 Curtailment of the solar parks and wind farms

For the curtailment runs, the 14 solar parks and 13 wind farms set the demand for power consumption by the 18 electrolysis plants. For the same base case and cumulative changes as in section 4.1, Figure 4.2 shows the expected power generation curtailment, in GW el. For the

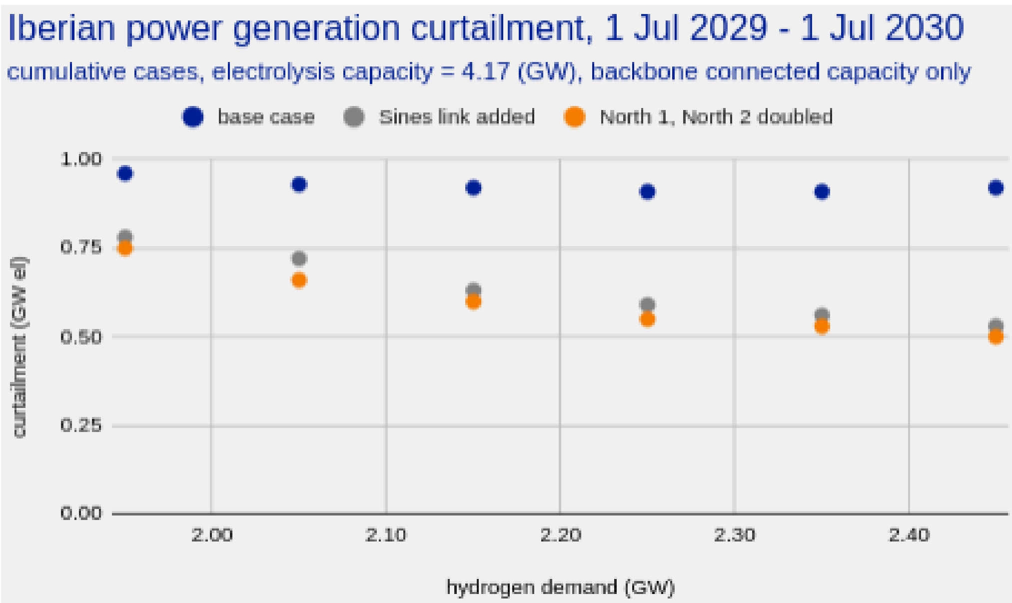


Figure 4.2: Power generation curtailment

base case, the expected curtailment is constant, at about 920 MW, on the demand range from 2.05 to 2.45 GW.

The first cumulative change, that is connecting Sines and Portalegre, leads to significant improvements, at the maximum demand of 2.45 GW, the expected curtailment reduces by 390

MW from 920 MW down to 530 MW. However, the second change makes little difference, with a further improvement of only 30 MW.

Curtailment changes significantly during the year and during the day. For the case with the Sines pipeline added, the North1 and North 2 capacity doubled, and the total hydrogen demand

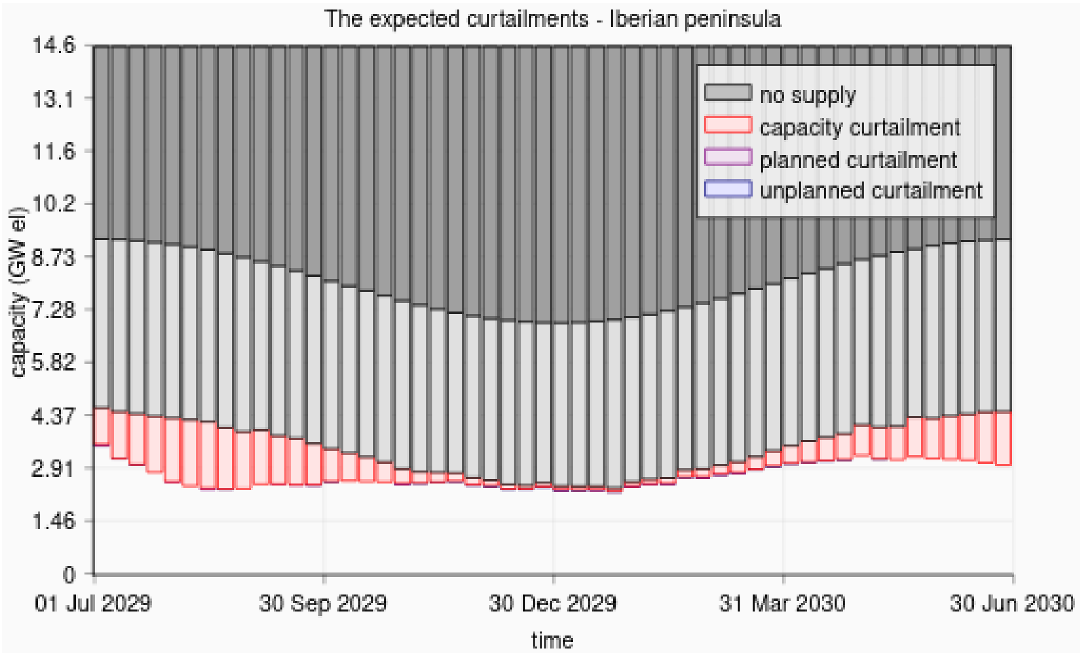


Figure 4.3: weekly power generation curtailment

at 1.95 GW, Figure 4.3 shows the weekly curtailment over the 1-year period from 1 Jul 2029 till 30 Jun 2030, based on 100 simulations. After the Portuguese demand has built up, in September 2029, the expected curtailment follows the annual solar cycle:

- 1000 MW curtailment in June and July,
- 500 MW curtailment in March and October,
- almost no curtailment in December and January.

For the same case, Figure 4.4 shows the curtailment duration curve. On 1 Jul 2029 – 30 Jun

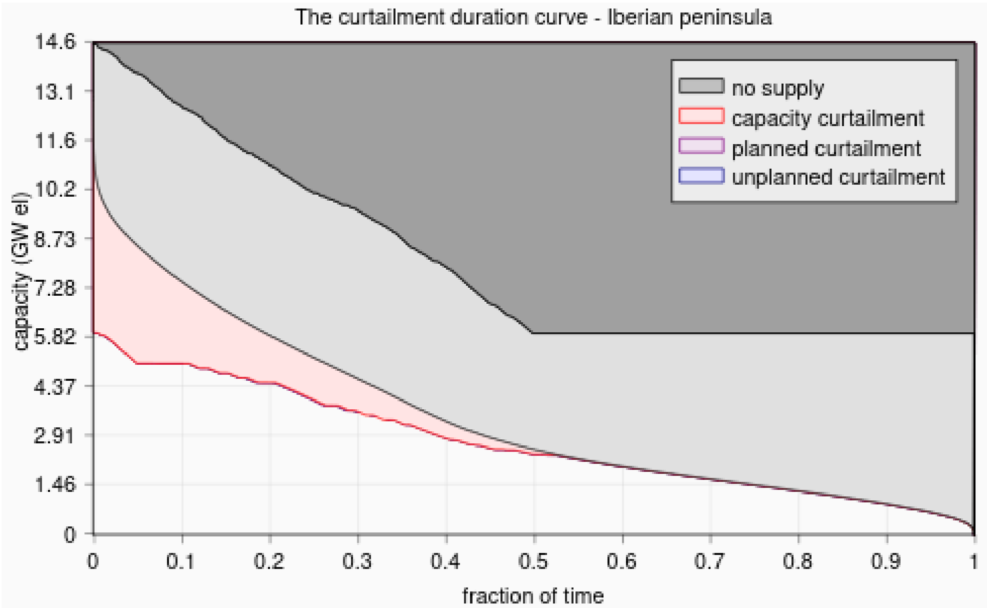


Figure 4.4: The curtailment duration curve

2030, the curtailment, shown in red, is 500 MW. It is based on the same 100 simulations. Curtailment only arises during the day, and is due to:

- available power above the electrolyser capacity, and/or
- hydrogen demand variations, and /or
- full hydrogen storage facilities.

The short plateaus of the capacity curtailment duration curve, in red. reflect the different system states:

- on the interval [0, 0.05], it is around noon and all electrolyser capacities are limiting
- on [0.05, 0.18], North 1 is full, the injection capacities are limiting, and the small steps reflect the demand build-up
- on [0.23, 0.34], North 1 and North 2 are full, the Carriço and Puertollano I injection capacities are limiting, and the small steps again reflect the demand build-up
- outside those intervals, the local power supplies determine which electrolyser capacities are limiting, if any
- there is no curtailment at night, between 21:00 and 06:00, because all electrolysers are capable of handling full peak wind power supplies.

Again for the same case, Figure 4.5 shows an example of a single 2-day simulation, hour by

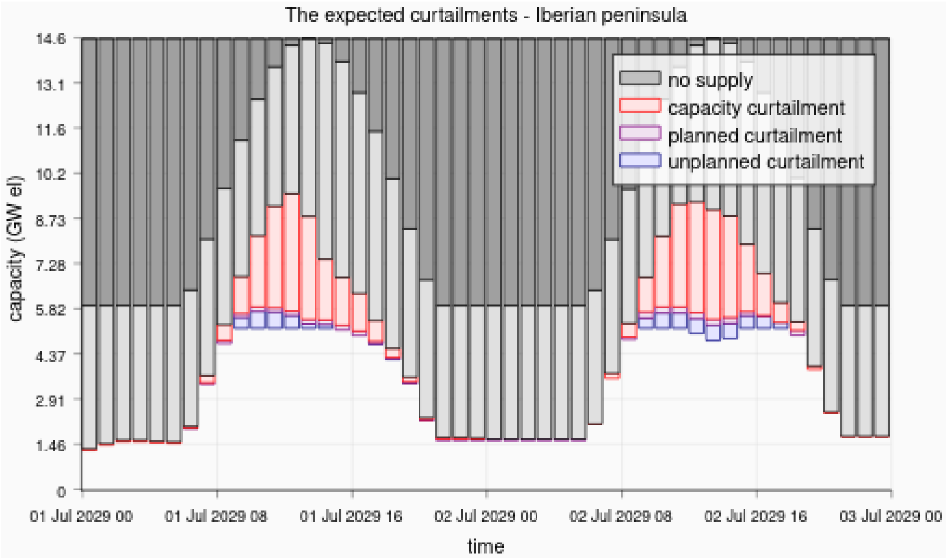


Figure 4.5: Hourly power generation curtailment

hour, with the diurnal cycle: peak curtailment is 3.8 GW around noon, due to hydrogen network constraints:

- in the afternoon, clouds reduce solar generation and hence curtailment,
- planned electrolyser downtime causes 70 MW curtailment,
- unplanned electrolyser and injection downtime causes 120 MW curtailment.

4.3 Storage facilities

Section 4.1 includes the case that adds the pipeline between Sines and Portalegre. This section provides an overview of the storage utilisation for that case, at the demand level of 1.95 GW.

The storage capacities represent the working volumes, excluding the cushion gas.

Figure 4.6 shows the weekly expected content and the expected ullage of North-1. In the

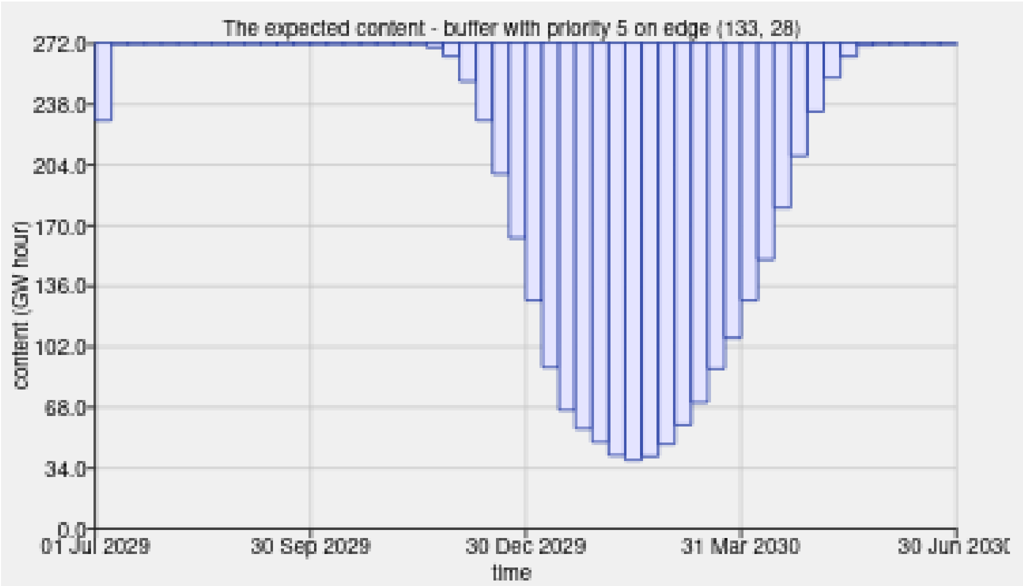


Figure 4.6: the expected content of the North-1 salt cavern

model, North-1 is on the edge from its injection facility, node 133, to its withdrawal facility, node 28, and it has priority 5, that is the highest. The blue bars represent the ullage.

On 1 July 2029, the storage starts half full. Injection starts immediately, and within one week, the storage is full. Until late November it remains full and only then withdrawal starts, as necessary to meet the demand.

Although the weekly averages don't show North-1 to become empty, this does happen on shorter time scales. As Figure 4.7 shows, on the continuous time scale, about 63% of the time the storage is full and 3% of the time it is empty. The expected duration of the tank bottom events is about 9 hours.

Statistics - buffer with priority 5 on edge (133, 28)

result	**frequency (1/year)**	**duration (hour)**	**expected time %**
bottom	28.1	8.87	2.84
top	63.1	77.4	55.7
injection	209	7.02	16.7
withdrawal	213	10.1	24.6
idle	0.301	17.8	0.0611
total	**513**	**-**	**100**

Figure 4.7: North-1 statistics

Although North-1 has a higher priority than North-2, North-1 injection and withdrawal still alternate when North-2 is operating at its maximum withdrawal capacity and when it's empty. The frequency of alternation is about 200 times per year.

In the idle state, the storage is not full, not empty, and there is neither injection nor withdrawal. Because of their limited injection and withdrawal capacities, North-1 and North-2 can be at an intermediate content level at the same time.

Figure 4.8 shows the weekly expected content and expected ullage of North-2. In the model,

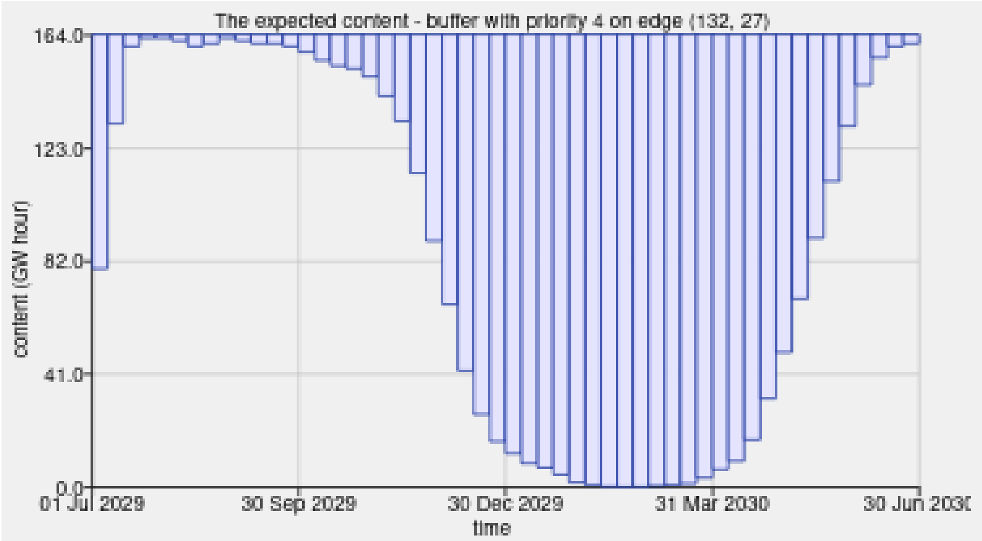


Figure 4.8: the expected content of the North-2 salt cavern

North-2 is on the edge from its injection facility, node 132, to its withdrawal facility, node 27, and it has priority 4.

As for North-1, the North-2 storage starts half full on on 1 July 2029. Injection only starts after one week, when North-1 is full. About one week later, North-2 is mostly full, but injection and withdrawal continue to alternate. From October until January, withdrawal exceeds injection, and the storage stays mostly empty during February and March. Injection restarts in early April and the storage is mostly full again towards end June 2030.

Figure 4.9 shows the statistics of the North-2 injection and withdrawal. As opposed to North-1, North-2 never stays full for extended periods. Only about 18% of the time the storage is full and 30% of the time it is empty.

Because North-2 has a lower priority than North-1, North-2 injection and withdrawal alternate almost daily, with an injection frequency of 340 times per year. As for North-1, the idle time is low, because the hydrogen production is almost never exactly equal to the demand.

Statistics - buffer with priority 4 on edge (132, 27)

result	frequency (1/year)	duration (hour)	expected time %
bottom	96.2	27.3	30
top	99.1	15.6	17.7
injection	340	6.21	24.1
withdrawal	333	7.43	28.2
idle	0.763	5.85	0.0509
total	**869**	**-**	**100**

Figure 4.9: North-2 statistics

5 Discussion

This exercise shows that the stochastic modelling techniques that have been developed and used previously by SecuoS on many supply and demand networks in the oil, gas, and petrochemical industries can be applied equally well to green hydrogen networks, yielding results that assist in understanding the system performance and the associated project risks. This includes an analysis of the expected curtailment of the power generation by the solar parks and wind farms. Based on the ARTIS platform, a single model is developed that addresses both green hydrogen availability and power generation curtailment questions.

This study highlights the versatility and power of the stochastic modelling approach for the future European hydrogen infrastructure, under the constraint of reliable hydrogen supplies.

Consumers who are unable to offer demand flexibility are likely to seek reassurance of the continuity of their planned future hydrogen supply, and the best way to achieve that is by carrying out studies along the lines of this example. Ideally, this can be timed no later than during the project design phase, in preparation for the final investment decision.

The demand sensitivities in section 4.1 suggests that care must be taken not to overcommit in the hydrogen sales and purchase agreements.

The turndown capacity of the electrolyses plant is assumed to be zero, but operating experience with different technologies and designs must show if that is achievable.

The system boundaries of this example study include Portugal and Spain only, until 2030. This area and time period can be widened, to include proposed import and export projects. On the other hand, the same approach can be used on a smaller scale as well, for example to quantify the hydrogen network transport and storage requirements for an individual hydrogen valley.

Network optimisation, with a focus on the capacity balance of all facilities, can minimise the Levelised Cost of Energy (LCoE) of the hydrogen supplies, along the lines of the previous study [1]. Under the cost assumption made in that study, the sharing of the weather risk over a large geographical area, the use of shared hydrogen pipeline and storage facilities, and contract optimisation opportunities will reduce the Levelised Cost of Energy.

For the proposed green hydrogen projects, the integrated network optimisation must happen now, prior to the final investment decisions. Optimising the reliability, production availability ,and the effect of storage on the supply chain will be necessary to ensure that contractual delivery criteria can be met, both before and after 2030, for the lifetime of the project.

Although not assessed here, the approach can identify the criticality of the individual facilities, thereby providing directions for possible design improvements. The alignment with the green supply requirements of the hydrogen consumers can already start during the concept development phase of the projects.

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