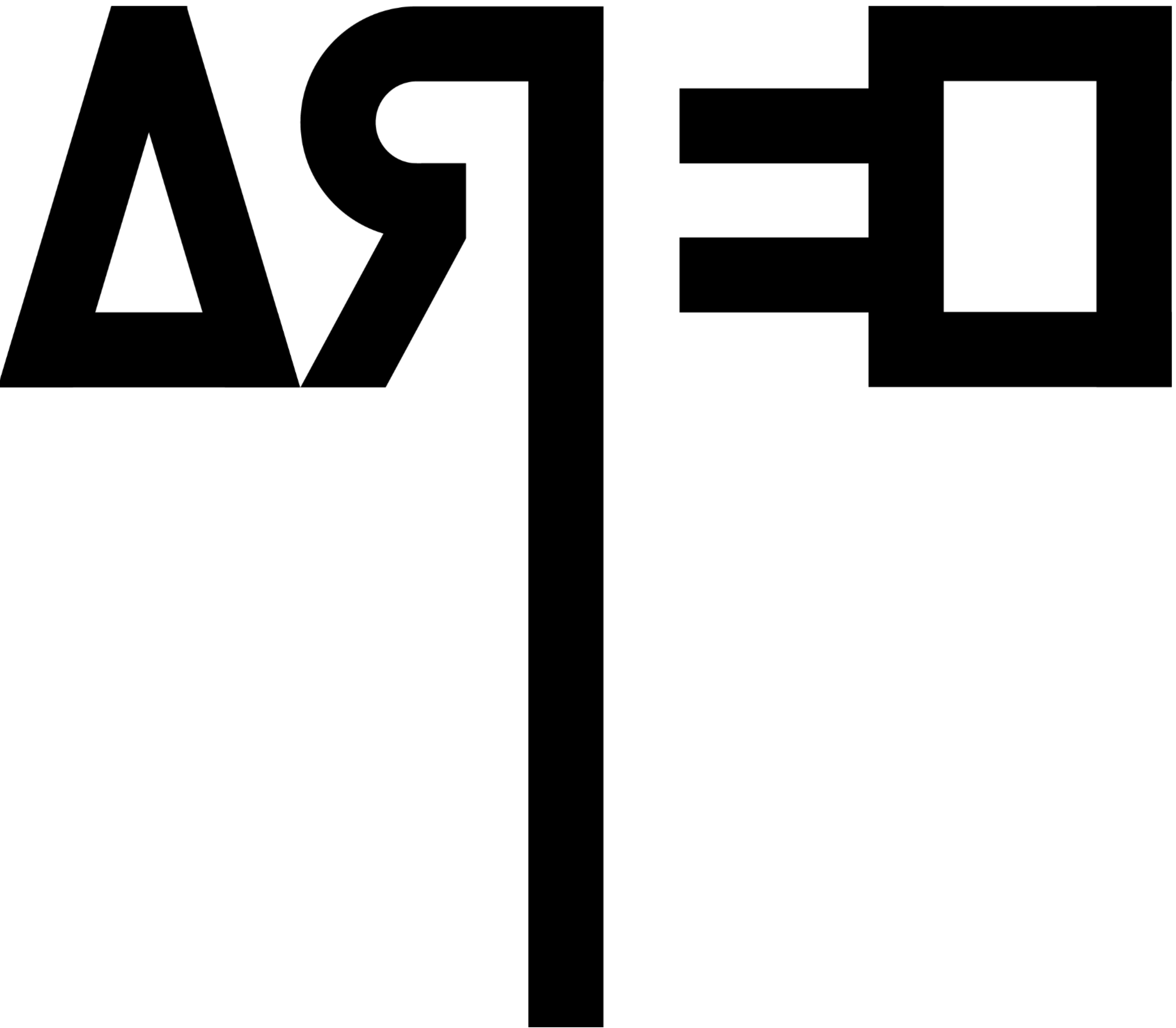

Table of Contents

Main objectives and initial considerations

This report is aimed to determine the optimal sizing of a hybrid power plant with a storage system (battery), considering that the customer:

1) Delivers 15 years of hourly discretised time series of wind and PV power production with a same length time series of wholesale energy market price forecast.
2) Gathers documentation about constructive and physical characteristics of the storage system, providing a specification sheet of the storage system.
3) Determines relevant economic parameters for the finance study as well as prices of components of every power system and their maintenance.

The customer agrees that the NPV (net present value of the whole project) is the function to be maximised. However, indices such as IRR will be given for completeness.

Model entries and preliminary analysis

Along this part, data that has been used for the calculation of this study will be presented and detailed. It will consist on a brief introduction describing the most general characteristics of the project, a data summary excel with main outputs and several excel sheets that gathers what the customer has delivered and serve as a data input for the model.

Location and general Project considerations

This Project for the renewable power plant is situated in La Solana (Albacete, Spain). The main points of this Project are shown in Table 1.

Project name	La Solana
Location coordinates (lat, lon)	(38.7763, -2.01417)
Power of interconection	100 MW
Project lifetime	25 years
Grid access	Yes
COD	2022

Table 1: general characteristics of the project

The storage system, in this case batteries, will be able to consume from grid. In this case taxes will be applied.

Renewable resource

The customer gives power series of wind and PV power from a renewable resource based on Fontedoso (Ourense). This time series are defined by the following parameters in Table 2.

Type of resource	Power	NEH (P50)	P50 variability	Anual degradation	Nº values	Δt
Wind	100 MW	2750 h	10.2 %	N.A.	131400	1 h
PV	50 MWp	2189 h	5.5 %	N.A.	131400	1 h

Table 2: Physical characteristics of renewable resource

The wind and PV series are then normalised and expressed in unitary power i.e. w = 2 and s=1 means that the installed wind and PV power coincide with twice and once the capacity of the point of interconnection (POI) respectively. Figure 1 shows the first complete year (8760 values) from the beginning of the available data of the 15-year time series:

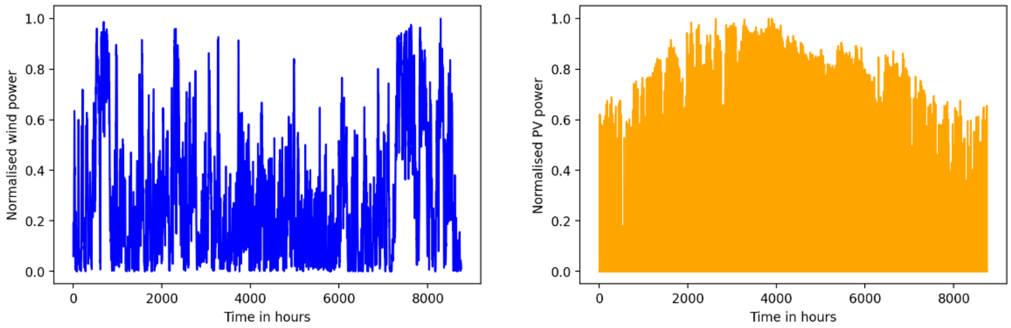

Figure 1: Normalised renewable resource. First year of each technology is shown. First data corresponds to 1st of Jan.

In general, both renewable resources are good enough for the zone they are located. The long-term correlation between both series is about -0.106 p.u. which indicates a good complementarity for their hybridisation.

For the shake of visual clarity in Figure 2 monthly averaged reference days are shown with a map of resource density for two technologies.

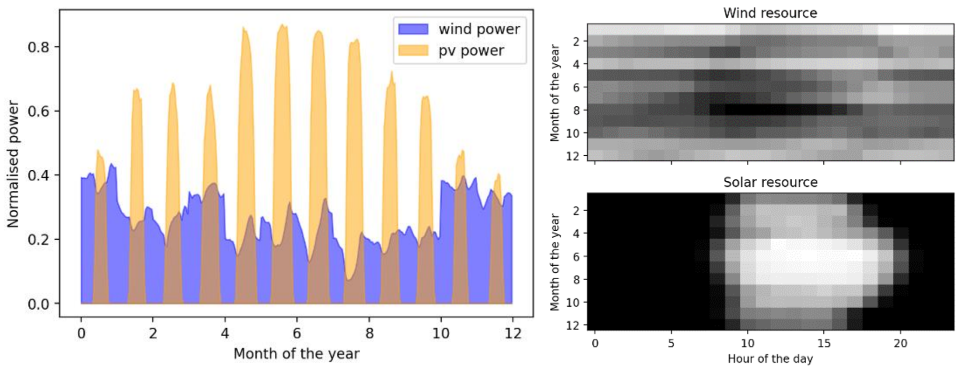

Figure 2: Wind and PV resources visually explained. Both pictures (left and right) contains same information: production curves along a monthly averaged day during a reference year.

The storage system

The considered storage system is a battery with characteristics shown in Table 3:

Nameplate storage power	65 MW
Approximate storage capacity	130 MWh
Cycle degradation	N.A.
Threshold degradation	35 %
Charge / discharge performance	92 % / 92 %
Lifetime	15 years
Minimum and máximum SOC	[10,90] %
Charge from grid	Yes
Maximum equivalent cycles per year	600

Table 3: Physical characteristics of the storage system

The storage system will be a fixed value in the optimization. The way the storage system degrades will be calculated according the following DOD (depth of discharge) degradation curve depicted in Figure 3

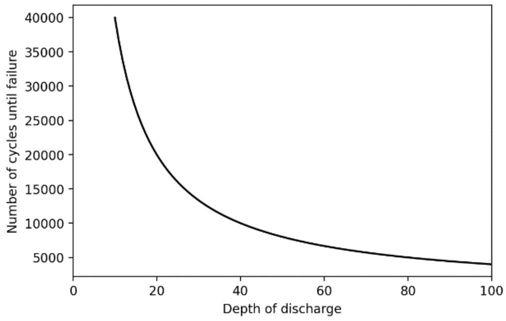

Figure 3: Degradation curve

For each year, the storage capacity is estimated using a *rainflow* algorithm that counts and classifies each cycle and calculates their damage through Figure 3. This damage per cycle is added until the storage system reaches the degradation limit. This threshold can be reached with an intensive use (how many cycles and their depth of discharge DOD) or by ageing (time variable t).

$$damage \propto f(DOD, t)$$

Other magnitude of interest is the number of equivalent cycles in a year y (NOC_y). They are defined as the ratio of the energy that enters the storage system (energy storage) and the maximum energy the system can storage at that time calculated through the multiplication of the current state of health (SOH) and the nameplate capacity (E_0):

$$NOC_y = \frac{\int_y \ Battery\ input\ power\ dt}{SOH * E_0}$$

It must be highlighted that damage calculated through this magnitude is not as accurate as with the result of a *rainflow* algorithm.

Energy markets

In this study the wholesale spot price market has been considered. For this purpose, 20 year forecast hourly discretised time series has been proposed. To meet customer's requirements this time series has been scaled to meet the mean prices from the most recent forecast given by an external company. When time series were not available last year has been repeated.

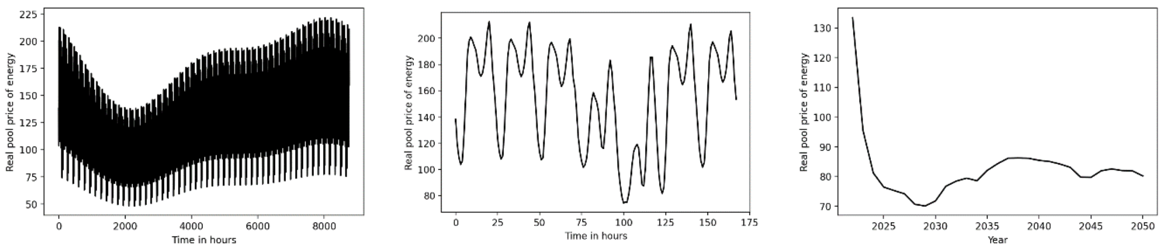

Figure 4: Considered price curves. From left to right: hourly time series for the first computed year, first week and mean price for the considered year set. First data corresponds to 1st Jan.

In the Figure 4 different representations of some data from real energy prices are shown. From left to right: hourly time series for the first year, first week of prices and mean price for the whole year set (20 years).

Inflation is set from 2022 to 2024 to 8 %, 4.1 % and 3 % respectively and a constant 2% for the rest. When for a year the price curve is not available, repetition of the previous year is assumed.

Model finance characteristics

Main finance parameters from each power source are gathered in the following Table 4

Technology	Unit	Fixed CapEx [€]	Variable CapEx [€ per unit]	Fixed OpEx [€/y]	Variable OpEx [€/y per unit]	Amortization (years)
Wind	MW	-	1000000	-	24000	15
PV	MWp	-	Curve Figure 5	-	Curve Figure 5	15
Energy Storage	MWh	-	318000	-	1000	5
Power storage	MW	-	202000	-	500	5

Table 4: Economic, constructive and operative data. (“Per unit” replaces MW of MWh when corresponds)

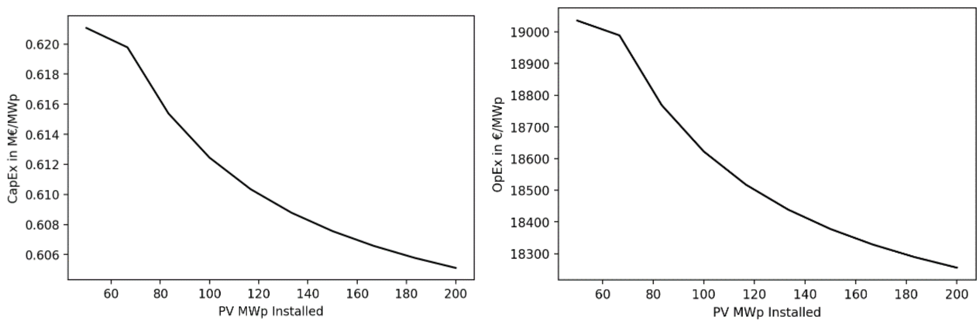

Figure 5: Normalised CapEx and OpEx of the PV system

Parameters related to electricity markets and its operation are shown in Table 5:

IVPEE	0 %
Energy grid taxes	13 €/MWh
Power grid taxes	12 €/MW
Taxes	25 %
WACC	7.15 %

Table 5: Finance parameters

Optimisation methodology

Time series treatment

Customer’s time series for wind, PV production as well as wholesale hourly energy market prices have been used along this study. Minor changes have been applied such as time series normalisation by the power they have been produced (100 MW for wind and 50 MWp for PV). Price series have been modified to meet latest Baringa’s forecast for mean prices according customer’s requirements: when available, time series predicted on the price series have been scaled with year-averaged prices from the external company by direct multiplication of the means ratio. Due to the fact that there are more forecasted mean year data than year hourly series, latest one has been replicated to meet the corresponding price average of that year. This does not produce a considerable error because latest years contribute the least to economic indices.

Production NEH have been correctly checked for the provided location (la Solana).

The optimiser

After the collection of the whole set of inputs, the optimiser solves a highly nonlinear optimisation problem in which finds the optimum behaviour of the proposed system. In this case customer sets the degrees of freedom of the system to be: wind, PV and storage output power as well as its storage capacity.

For this purpose, two economic indices will be optimised at once: NPV and IRR (LCOE is also defined), providing a clean image of how these vary when adding wind, PV and storage system. They are defined as follows.

The NPV (net present value) is, in the vast majority of possible scenarios, the magnitude that will determine the viability of a project. The greater NPV the more income the power plant produces. The IRR serves as an index

$$NPV(x) = \sum_{y=0}^{N-1} \frac{flux_y}{(1+x)^y} \ , \qquad NPV(IRR) = 0 \ , \ LCOE(x) = \sum_{y=0}^{N-1} \frac{C_y}{(1+x)^y} / \sum_{y=0}^{N-1} \frac{E_y}{(1+x)^y}$$

Where $flux_y$ is defined as the incomes minus the outcomes in monetary terms of the year y and the C_y and E_y coincide with the total cost and grid poured energy of the power plant in year y respectively. For calculating the NPV and the $LCOE$ for a project the variable x must be replaced by the company's WACC

The finance model

In each optimiser step, the algorithm calculates the maximum revenue for every generation mix, based on the given finance inputs. The revenues, as the customer claimed, are calculated by direct multiplication of the hourly curves: wind+PV generation, adding and subtracting storage power output/input respectively by hourly energy prices from pool. Taxes for the energy storage operation are considered when they apply.

Choosing the optimal sizing and preliminary analysis

For this project and characteristics, a successful addition of PV power has been reached. This adding maximises NPV (and therefore minimises LCOE) but decreases IRR.

Finance indices maps

In the Figure 6 normalised NPV and IRR are shown for a range of wind and PV installed power. The normalisation has been carried out by fixing a reference power of the corresponding access capacity (POI).

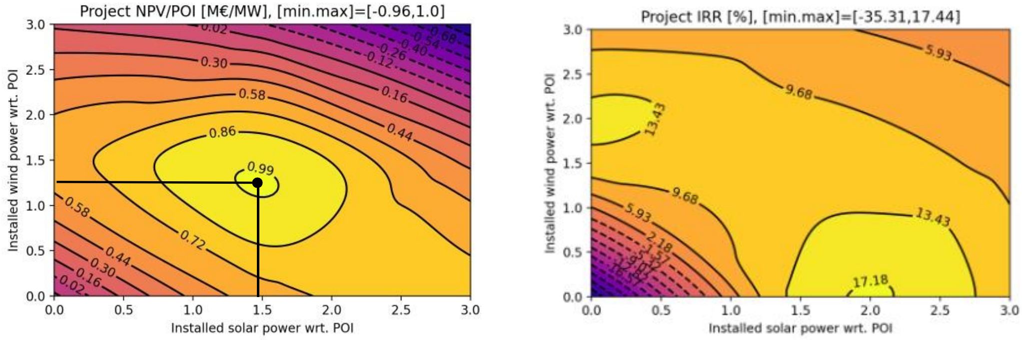

Figure 6: Indices maps for power plant optimisation

A maximum is clearly visible for the NPV of the project when w = 1.25 and s = 1.45. In this point the IRR loss is still acceptable due to the fact that the function slightly decreases. LCOE is not as relevant as NPV or IRR in this project because the main income source is the electricity market for this reason it is not shown. The turning point of NPV is produced due to the excessive wind and PV curtailment that cannot be used by the energy storage. At this point a change in slope of NPV and IRR is evident.

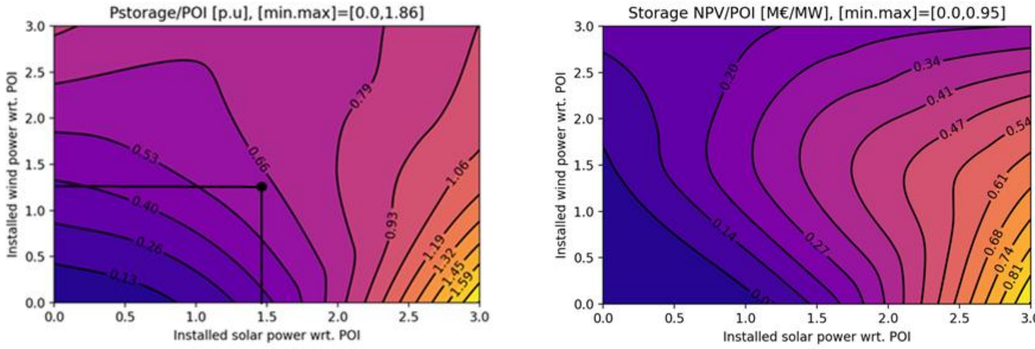

Figure 7: Optimal storage power and added NPV from storage.

In Figure 7 the optimal storage power is highlighted and equal to p = 0.65. This point adds a positive NPV shown in the right figure.

Conclusions

There is only one clear optimum sizing point when adding 100 MW of wind power, 150 MWp of PV power and a storage of 130 MWh 2h, yielding to an NPV of about 99 M€ and an IRR of 10.1 % for the whole project.

Operation of the optimised power plant

Once the power system has been sized, its optimal behaviour and operation is shown along the sections that follow

Example of a power system generation profile

Figure 8 shows how the optimal power system behaves during 10 days out of the 30 years of simulation. These days have been selected to include the operation of the battery storage system.

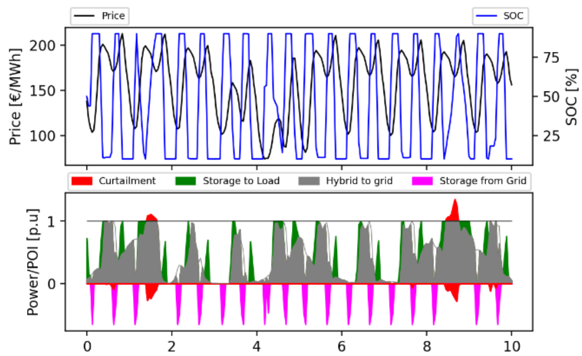

Figure 8: Example of power output of the system during the first 10 days

In this case, considering customer's requirements, operation of the battery storage system is limited by upper and lower limits of SOC, it can charge from grid when necessary and equivalent cycles per year are soft constrained (see Table 3). It can be noticed that due to the disparity between battery size, the magnitude of the curtailment and different applied prices to this energy, the energy storage system is likely to complete a cycle (or even two) a day.

The curtailment shape and the resource of the storage system can be appreciated in Figure 9.

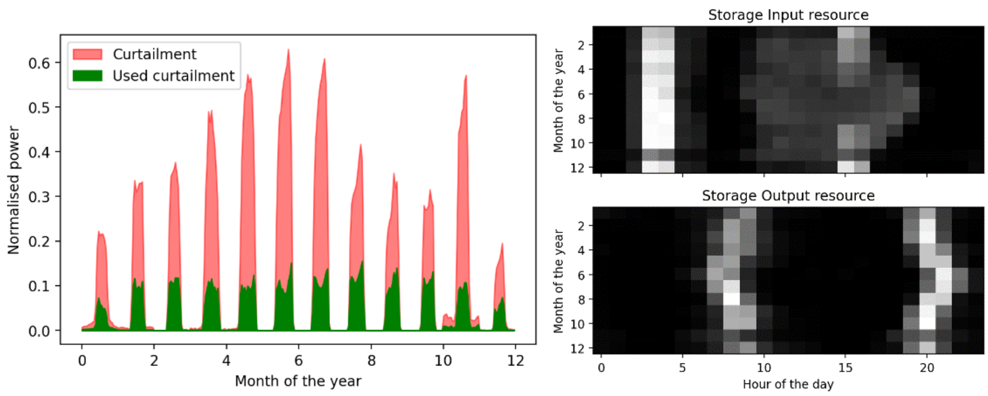

Figure 9: Curtailment shape and storage system resource.

Where in the left graph one can see the magnitude of the month averaged day curtailment compared to the used by the storage system. In the right plot the hours in which the storage system charges and discharges (cheap energy from market or curtailment and expensive hours in spot market respectively) are marked.

Statistical analysis of the energy storage system

This storage system with the selected operation constraints lasts for about 10-11 years doing 5000 equivalent cycles and around 9000 actual cycles, each one with different depth. This is shown in Figure 10, where battery cycles are analysed during the whole set of the years it operates indicating that the most common cycle is clearly a full one (between 10 % and 90 % SOC) but there are relevant shallow cycles too.

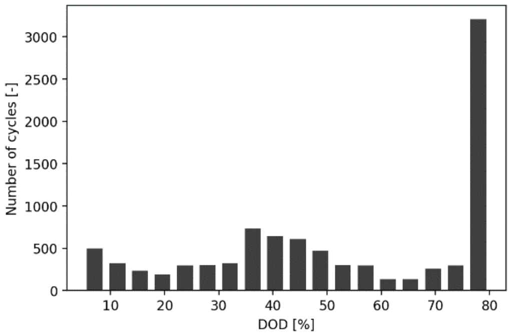

Figure 10: Cycling statistics for the battery storage system concerning depth of discharge and SOC

In Figure 11 the two relevant statistical analysis of the battery storage system when charging/discharging are displayed. Relevant modes of the curtailment are the ones that occur once per day (sun is maximum at midday and during this period curtailment is also maximum, for this reason there is a prominent spike at 24 h period), while for output modes relevant are what occur twice per day (price curve frequently shows maxima twice a day giving a spike at 12 h period).

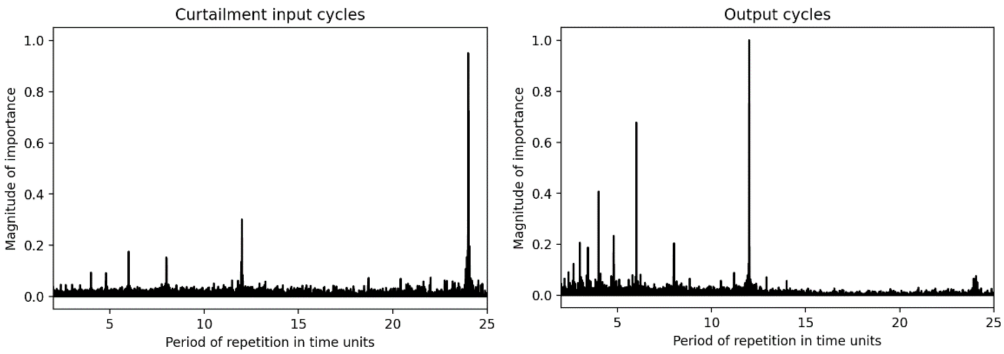

Figure 11: Cycle statistics concerning input power from curtailment only (left) and output power (right)

The rest of peaks can be explained due to interferences from other sources such as wind power output or the price curve itself.

General conclusions and recommendations

Along this study, a complete picture of different scenarios of PV added to a fixed power system composed by a wind farm and a battery storage system has been presented.

According to the requirements of the customer to size the whole power system in order to maximise NPV of the project, the following power proportions are advised in Table 6:

Power of interconection (POI)	100 MW
Installed wind power	125 MW
Installed PV power	150 MWp
Installed storage system power	65 MW
Installed storage system capacity	130 MWh

Table 6: Recommended power plant sizing for maximal NPV

These numbers can be modified according to customer’s strategic interests, once it is known that NPV may diminish as a consequence (see Figure 6).

Appendix I

Within this appendix, the way data is presented in the excel sheets that support this report is explained.

The excel file named: power_plant_data_series is structured in four sheets:

1) Project Technical Specs: This sheet gathers information about the installed power units in the power plant and the limit of the point of interconnection.
2) Economic inputs: CapEx, OpEx and economic indices of each power source are listed. For a storage system, capacity (storage) and power systems (converter) numbers are given separately.
3) Production and pricing: This sheet sums up the production (expressed in POI hours) of each power source. Additionally, when a storage system is at play, its state of health (SOH) and number of cycles (NOC) are also included.
4) Time series: In this sheet raw data is explicitly listed. This data is the minimum required data to verify all results given within this report.

For most cases, titles describe accurate enough what kind of number we are looking at, but some definitions are necessary to completely understand the results:

Hybrid	Related to the sum of all non-manageable resources (e.g. wind and PV) power generation, hours or whatever related concept that contains this word.
Project	Related to the whole powerplant. This includes each subsystem: wind, PV, storage system…
POI NEH	Net Equivalent Hours that are measured with respect to the limiting power of the Point Of Interconnection.
Price factor	This factor measures and adjusts how much the direct product of the mean price of a period of time multiplied by the NEH produced within that period deviates from the actual incomings value.

Table 7: Concepts

In the sheet of production and pricing:

- Hybrid grid poured POI NEH is the energy that the hybrid power plant (non-manageable power sources) sell to the grid.
- Hybrid curtailment POI NEH is the energy that the hybrid plant does not pour to the grid. The addition of this energy to the first one described must match the total produced energy by the hybrid power plant.
- The storage grid input POI NEH is the energy that the storage system buys from the grid. The energy that is bought to the hybrid power plant does not pay taxes as the other bought to the grid does.
- The storage curtailment input POI NEH is the energy that is used from curtailment NEH from the hybrid power plant.
- The stirage grid poured POI NEH is the energy sold to the grid by the storage system.
- The SOH (state of health) is measured with respect to the initial capacity of the battery.
- The NOC (net equivalent cycles) are yearly calculated with the beginning capacity that corresponds to the year that is being considered. To express it with respect to the initial capacity, it must be multiplied by the corresponding SOH.

The price factor of each energy is expressed in the following column.

In the sheet of time series:

- The Hybrid power production is the direct sum of the produced power of the non-manageable resources. This includes curtailment.

The rest of the time series are easily understood by its title name.