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Electricity price arbitrage in utility-scale PV-plus-battery systems

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Abstract. In this paper, we use MHOGA software for the optimization of an AC-coupled utility-scale PV-plus-battery system. Batteries are used for price arbitrage, being charged with the photovoltaic (PV) generation during hours of low electricity price and discharged during hours of high price. The correct estimation of the battery lifetime has great importance in the calculation of the net present value, to do this advanced models for estimating the Li-ion battery lifetime (considering cycle and calendar ageing) are used. With present components costs, considering the Spanish SPOT price of 2021 with an expected increase of 1% annual, the AC coupled utility-scale PV-plus-battery isn't economically viable comparing to the PV-only system. If electricity hourly price was multiplied by two, in certain cases adding battery to the PV system would be profitable.

Key words. PV, battery, utility-scale, price arbitrage, SPOT price.

1. Introduction

Photovoltaic (PV) generators sell electricity to the AC grid in the long term market through a power purchase agreement (PPA) or in the Daily / intraday market establishing the marginal cost of electricity (SPOT price, representing the cost of supplying an additional MWh to the grid) [1].

Energy storage can bring energy arbitrage and frequency support services. PV-plus-battery plants can be economically viable under certain scenarios, improving flexibility and performance [2].

For the European countries, considering the Li-ion battery wear cost (>0.073 €/kWh) [3] and the hourly electricity price of the daily market, energy arbitrage with Li-ion batteries would only have been suitable for less than 10% in 2019 and 2020. However, with different SPOT prices and battery cost and duration, the PV-plus-battery system could be profitable. In this paper we evaluate and optimize a utility-scale PV-plus-battery system, considering the 2021 SPOT prices in Spain and assuming an increase of 1% annual in these prices during the 25 years of the system lifetime, showing that it is not worth to add batteries to the PV system in this case.

2. System description

The AC-coupled PV-plus-battery system consists of a PV generator, a battery bank and an inverter/charger (Fig. 1). There is no load consumption and the benefits are obtained by selling electricity to the AC grid. The optimal system (which maximizes net present value, NPV) can be a PV-only or a PV-plus-battery system. PV-only systems inject all the electricity to the AC grid at the time when it is being generated. On the other hand, PV-plus-battery systems can inject electricity or charge batteries depending on the electricity price: during hours with low electricity prices batteries are charged with the PV generation and during hours with high electricity prices batteries are discharged, maximizing benefits (energy arbitrage). Also, when PV power is higher than the maximum power that can be injected to the AC grid, batteries are charged with the surplus power.

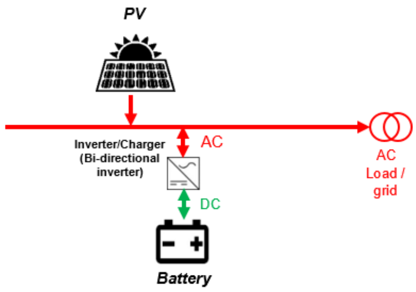

Fig. 1. PV-plus-battery system

The simulation and optimization of the system will be performed by MHOGA software (MegaWatt Hybrid Optimization by Genetic Algorithms) [4].

A. Location and irradiation

The system will be located near Zaragoza, Spain (latitude 41.66º N, longitude 0.86º W). The irradiation and temperature hourly data during one year can be directly downloaded by the software from different databases. In this case we will use the PVGIS [5] database, downloading hourly data for the year 2020, PV slope 35º, azimuth 0º (south faced), Fig. 2 and 3.

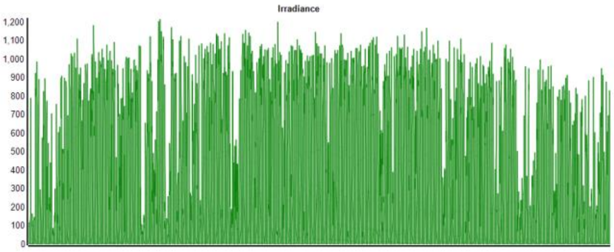

Fig. 2. Hourly Irradiance (W/m^2) near Zaragoza, PVGIS, year 2020, slope 35º, azimuth 0º

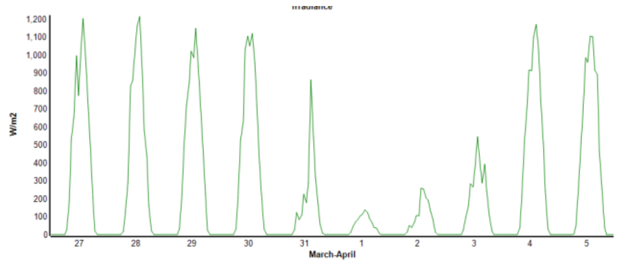

Fig. 3. Hourly Irradiance (W/m^2) near Zaragoza, PVGIS, 10 days of March-April 2020, slope 35º, azimuth 0º

B. Costs and sell electricity price

The assumptions of costs are the following: PV CAPEX cost (included its own inverter): 1.35 €/Wac [6]; AC battery CAPEX cost, including inverter-charger: 350 €/kWh (a wide range in the costs are shown in the literature, for example €321/kWh [2] or 575 €/kWh [7], assuming 1€=1$), we will consider 200 €/kWh for the battery bank and 150 €/kWh for the inverter-charger (75 €/kW considering 2 h discharge), these prices are slightly lower than the ones shown in ref. [8]. Batteries are expected to reduce their cost in a 2% annual rate, this value will be taking into account to calculate the replacement costs during the system lifetime (when batteries reach end of life and they must be replaced). O&M (OPEX) annual costs for PV are 1% of the PV CAPEX, similar to the values shown in ref. [2] and for the battery we consider the same 1% of the battery CAPEX.
Financial costs considered are the following: nominal discount rate 7%, general inflation rate 2%, installation and other costs 25% of CAPEX.
The electricity SPOT price of 2021 in Spain (Spanish electricity system operator [9], average 0.117, max.0.485 and min. 0.005 €/kWh) has been considered for the selling electricity price, Fig. 4. A 1% annual increase will be considered during the 25 years of the system lifetime.

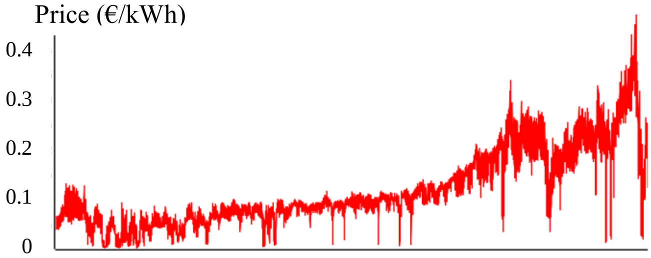

Fig. 4. SPOT price, Spain, year 2021

C. Components characteristics

In our case, the maximum power that can be injected in the HV AC grid will be limited to 30 MWac.
PV generators from 10 to 100 MWac are considered, in 10 MW steps, including MPPT but no sun tracking system in this case (fixed slope of 35º, south). NOCT is 43º and power temperature coefficient -0.4%/ºC. PV lifetime is expected to be the same as the system lifetime (25 years).
PV inverter efficiency is considered variable with output power, with a maximum of 97% (Fig. 5), and battery inverter-charger AC/DC efficiency is 98% while DC/AC maximum efficiency is 97% [2].

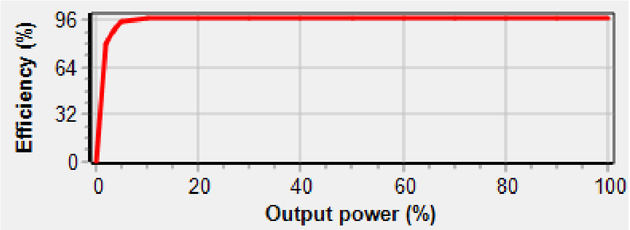

Fig. 5. Inverter efficiency

Battery type is Li-ion LiFePo4/graphite cell, commercial model Sony US26650FTC1, tested by Neumann et al. [10][11]. Battery bank possible capacities considered are from 0 to 50 MWh in steps of 5 MWh. The roundtrip efficiency is considered as a constant value of 95% and maximum power is limited to C/2 as usually recommended by the li-ion batteries manufacturers to maximize its lifespan. Advanced and accurate ageing battery models have been used. Neumann et al. models for the cycle ageing [10] (depending on full equivalent cycles, charge/discharge rates, C-rate, and depth of discharge, DOD) and for the calendar ageing [11] (depending on time, state of charge, SOC, and ambient temperature, T) are used to estimate the battery lifespan, used to estimate the replacement costs of the battery during the system lifetime. It will be considered that the battery must be replaced when the capacity loss is 20%, that is, when the remaining capacity is 80%, what can happen in few years or in many years, depending on the operating conditions (number of full equivalent cycles per day, C-rate, DOD, SOC and T). Fig. 6 and 7 show the capacity loss under certain conditions, due to cycle ageing and to calendar ageing, respectively. Maximum battery lifetime considered is 15 years.

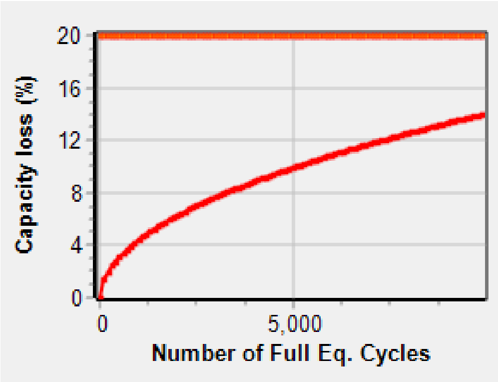

Fig. 6. Cycle ageing: Naumann et al. model of capacity loss vs. full equivalent cycles for C-rate = 1, DOD = 60% [10].

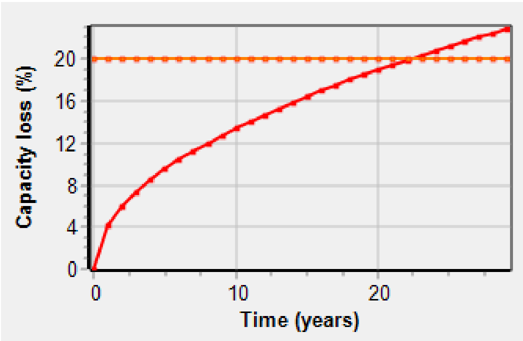

Fig. 7. Calendar ageing: Naumann et al. model of capacity loss vs. time (years) for SOC = 50%, T = 25ºC [11].

From 0 to 20 MWac are considered for the inverter-charger, in steps of 5 MWac. Inverter/charger lifespan considered is 15 years, this means that at the beginning of the 16th year this component will have to be replaced.

2. Battery management strategy for price arbitrage

When the difference between the maximum and minimum electricity price of a day is higher than X (€/kWh), batteries are ready to work this day, otherwise they will not be charged neither discharged.

- Charge: batteries will be charged when the electricity price is lower than the day minimum price + Y%.
- Discharge: batteries will be discharged when the electricity price is higher than the day maximum price - Y%.

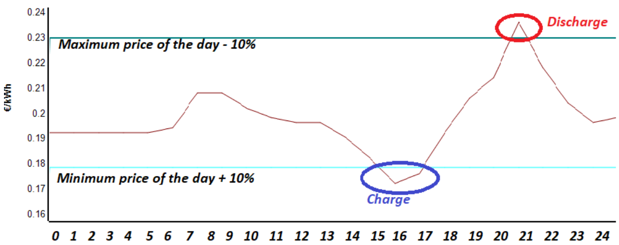

Fig. 8. Battery management for a specific day with X = 0.05 €/kWh and Y = 10%.

Fig. 8 shows the hourly price of a specific day with X=0.05 €/kWh and Y=10%, where batteries will be charged during two hours and discharged during one hour.

X value is for the first year of the simulation, next years (up to the system lifetime) X is increased in the same 1% annual as the SPOT electricity price.
Also, batteries are charged whenever the PV output power is higher than the maximum allowed to inject to the AC grid (30 MWac), with the surplus power that cannot be injected to the grid.

3. System optimization

Although MHOGA software allows efficient optimization by genetic algorithms, obtaining the optimal or a solution near the optimal evaluating just a low percentage of the possible combinations, in this case the enumerative method will be used (evaluating all the possible combinations of PV, battery and inverter-charger), because in this case the number of possible combinations is low. Therefore, all the combinations of components will be evaluated, simulating each of them in hourly steps during a typical year (the software can use lower time steps, up to 1 minute, and can simulate the performance of the system during all the years of the system lifetime).
The net present value (NPV) will be calculated for each combination, accounting all the incomes for the energy selling and costs (including CAPEX, OPEX for the different years, components replacement during the system lifetime and residual value of the components at the end of the system lifetime), converting all the incomes and costs to the initial time of the inversion. After evaluating all the combinations, they are sorted from best to worst NPV. Also other economical parameters are calculated, as internal rate of return (IRR), capacity factor, levelized cost of energy (LCOE), etc.

4. Results

A. 2021 SPOT prices.

Three cases have been considered for the optimization, depending on the control variables X and Y (section 2):

- Case 1: X=0.05 €/kWh, Y=10%
- Case 2: X=0.1 €/kWh, Y=10%
- Case 3: X=0.15 €/kWh, Y=10%

For each case, the optimization has been carried out, evaluating all the possible combinations of components.
The optimal system (system with maximum NPV) obtained for each case is shown in Table I.
In all the cases the optimal system includes a PV generator of 40 MW. We can see that for all the cases the optimal PV-plus-battery system is worse (lower NPV) than the PV-only system, therefore adding battery storage is not economically viable.
Comparing the optimal PV-plus-battery systems of cases 1, 2 and 3, we can see that NPV and capacity factor (defined as annual energy sold to the grid divided the peak power of the PV x 8760 h) is almost the same (two decimal places), and almost the same as for the PV-only system, as energy injected to the AC grid is (sell energy) is almost the same.

Table I. – Optimal system for cases A) 1, 2 and 3

	PV-only	Case 1	Case 2	Case 3
PV (MW)	40	40	40	40
Battery (MWh)	-	5	5	5
Inverter-charger (MW)	-	5	5	5
NPV (M€)	17.26	15.44	15.24	15.12
Investment cost (M€)	67.5	69.22	69.22	69.22
IRR (%)	9.59	9.28	9.25	9.23
Capacity factor (%)	25.79	25.79	25.79	25.79
LCOE (€/kWh)	0.078	0.08	0.08	0.08
PV generation (GWh/yr)	69.21	69.21	69.21	69.21
Bat. charge energy (GWh/yr)	-	0.39	0.09	0.03
Bat. disch. energy (GWh/yr)	-	0.36	0.09	0.03
Hours of bat. charge per year	-	135	20	6
Hours of bat. disch. per year	-	181	43	15
Battery lifetime (years)	-	12.07	15	15
Sell energy (GWh/yr)	67.76	67.93	67.82	67.78
Sell incomes, 1st year (M€)	7.19	7.23	7.21	7.19
Sell incomes, NPV (M€)	92.45	93.00	92.67	92.54
PV costs, NPC (M€)	61.86	61.86	61.86	61.86
Batt. costs, NPC (M€)	-	1.37	1.37	1.37
Inv-ch costs, NPC (M€)	-	0.52	0.52	0.52

Each system is simulated during a whole year, but, in order to show the performance of the system, in Fig. 9 we can see the simulation of 3 consecutive days (18th-20th September) for the optimal combination of case 1.
We can see that for the three days the difference between the maximum and minimum electricity price of the day is higher than X = 0.05 €/kWh, therefore the batteries will be charged if price is lower than the minimum of the day plus Y=10% and they will be discharged if the price is higher than the maximum of the day minus Y. We can see the hourly electricity price in the upper graph, this in the lower graph (brown) and the limits to charge / discharge. In the lower graph we can see the PV generation (yellow), battery charge (light brown), battery discharge (blue) and injection to the grid (thin purple), referred to the left axis. We can see also the battery energy (state of charge) in red, referred to right axis (limit in 5 MWh).
Fig. 10 and 11 show the annual simulation of the optimal system of case 1.

B. 2021 SPOT prices x 2.

In this case, the SPOT hourly price of 2021 is multiplied by 2, and the same optimizations are carried out again:

- Case 1: X=0.05 €/kWh, Y=10%
- Case 2: X=0.1 €/kWh, Y=10%
- Case 3: X=0.15 €/kWh, Y=10%

The optimal system (system with maximum NPV) obtained for each case is shown in Table II.
In all the cases the optimal system includes a PV generator of 60 MW. We can see that for cases 1 and 2 the optimal PV-plus-battery system has higher NPV than the PV-only system.
We can see that the battery capacity of the optimal system decreases with the increase of parameter X. The reason is because with high values of X, only few days are ready for the charge/discharge, therefore the investment in battery and inverter-charger is not compensated by the incomes.

Table II. – Optimal system for cases B) 1, 2 and 3

	PV-only	Case 1	Case 2	Case 3
PV (MW)	60	60	60	60
Battery (MWh)	-	45	25	0
Inverter-charger (MW)	-	20	10	0
NPV (M€)	121.04	127.04	121.27	120.41
Investment cost (M€)	101.25	113.9	108.44	101.97
IRR (%)	17.92	17.28	16.36	17.72
LCOE (€/kWh)	0.094	0.103	0.100	0.096
PV generation (GWh/yr)	103.82	103.82	103.82	103.82
Bat. charge energy (GWh/yr)	-	9.29	2.44	0.29
Bat. disch. energy (GWh/yr)	-	8.59	2.27	0.27
Hours of bat. charge per year	-	224	106	38
Hours of bat. disch. per year	-	511	283	134
Battery lifetime (years)	-	8.27	12.21	15
Sell energy (GWh/yr)	84.21	90.84	86.01	84.45
Sell incomes, 1st year (M€)	18.19	20.30	18.98	18.31
Sell incomes, NPV (M€)	233.82	260.97	244.06	235.42
PV costs, NPC (M€)	92.53	92.53	92.53	92.53
Batt. costs, NPC (M€)	-	17.06	7.53	1.37
Inv-ch costs, NPC (M€)	-	1.56	1.04	0.52

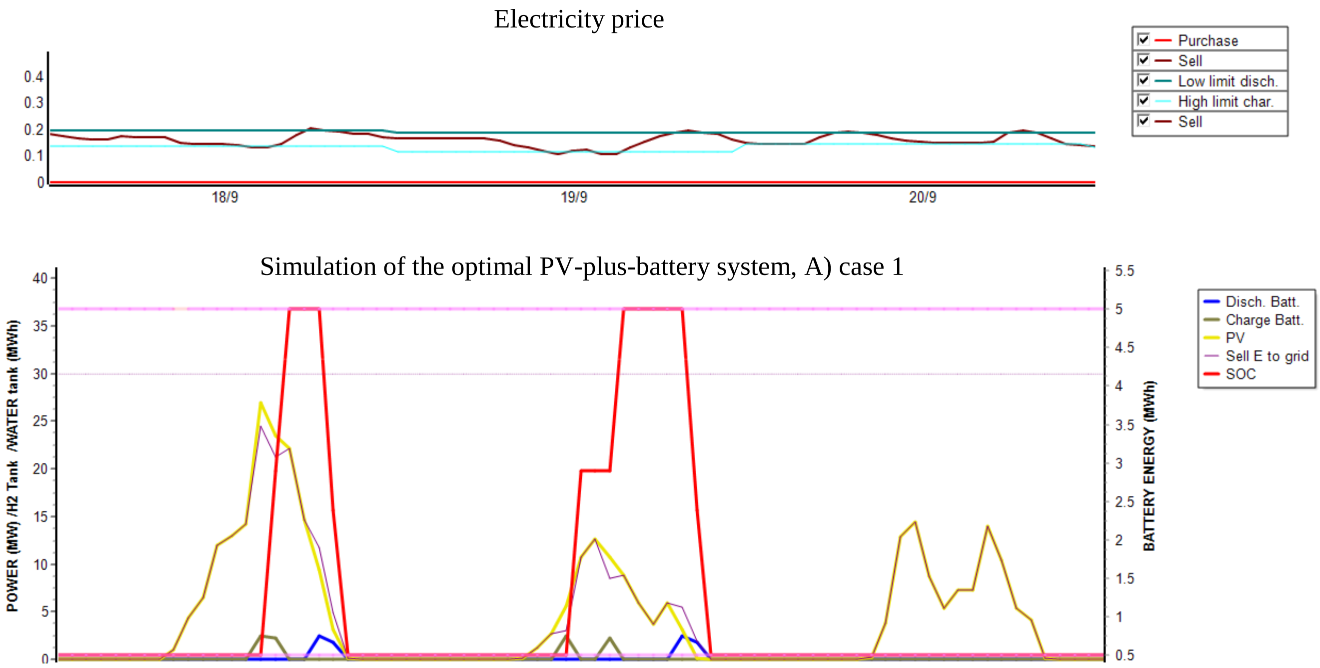

Fig. 9. Electricity price with charge and discharge limits (up) and simulation of the optimal system for case 1 for three consecutive days (18th to 20th September). Optimal PV-plus-battery system, A) case 1.

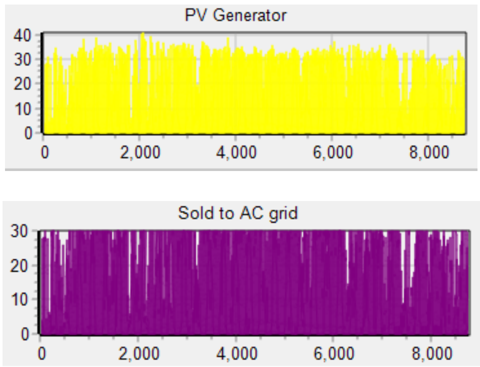

Fig. 10. Horly PV generation and energy injected to the grid during a full year (MW), optimal PV-plus-battery system, A) case 1.

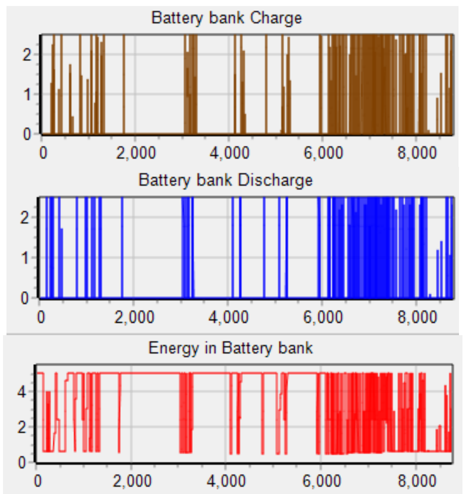

Fig. 11. Optimal system for case 1. Horly charge and discharge battery power (MW) and SOC (MWh) during a full year. Optimal PV-plus-battery system, A) case 1.

In Fig. 12 we can see the simulation of 3 consecutive days for the optimal combination of case 1. We can see that in the first two days (16th and 17th June) the difference between the maximum and minimum electricity price of the day is higher than X = 0.05 €/kWh, therefore the batteries will be charged if price is lower than the minimum of the day plus Y=10% and they will be discharged if the price is higher than the maximum of the day minus Y. The first day shown, during the hours of charge strategy, batteries cannot be charged because they are already at 100% SOC (see red curve, right axis); there is only one hour with discharge strategy, in the evening, when the battery is discharged at its maximum power (C/2, that is, 22.5 MW but the inverter efficiency implies that the power injected to the grid is a bit lower, added to the PV power). The second day, during several hours in the morning there is PV power that cannot be injected in the grid (as it is higher than 30 MW), so the rest is used to charge the battery, and during the hours of charge strategy, batteries cannot be charged because they are already at 100% SOC; for the discharge strategy hour, the battery power is lower than C/2 because PV + battery cannot exceed the maximum output power of 30 MW.

In the third day (18th June) the difference between the maximum and minimum electricity price of the day is lower than X = 0.05 €/kWh, therefore the batteries management strategy will not be used that day; however, if there is surplus power that cannot be injected to the grid, it will be used to charge the batteries, as it occurs during two hours.

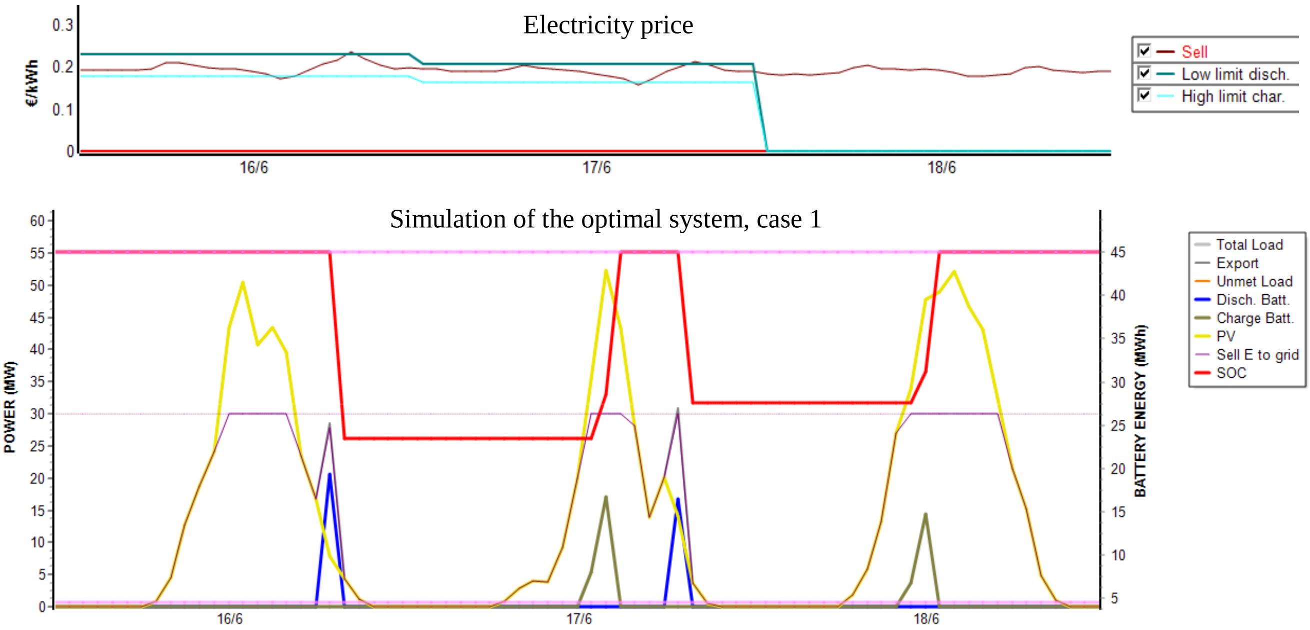

Fig. 12. Electricity price with charge and discharge limits (up) and simulation of the optimal system for case 1 for three consecutive days (16th to 18th June). Optimal PV-plus-battery system, B) case 1.

5. Conclusion

In this paper, we have used MHOGA software for the optimization of an AC-coupled utility-scale PV-plus-battery system, using the battery for energy arbitrage to maximize the benefits. The software uses advanced models for estimating the battery lifetime (considering cycle and calendar ageing), which has great influence in the net present cost of the system (which includes components CAPEX, OPEX and replacements during the system lifetime) and also in the NPV. The hourly price at which the electricity is sold to the AC grid, and its expected annual inflation have also great importance in the economical evaluation of the PV-plus-battery system. The battery and inverter/charger costs and the control strategy for the battery management also has great influence in the incomes and therefore in the NPV.
With present components costs, considering the Spanish SPOT price of 2021 with an expected increase of 1% annual, it is not worth to add batteries to the PV-only system. However, with prices twice of those, AC coupled utility-scale PV-plus-battery can be economically viable comparing to the PV-only system.

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