

On the Value Proposition of Battery Energy Storage in Self-Consumption Only Scenarios: A Case-Study in Madeira Island

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Abstract—This paper presents a **Techno-Economic assessment of the value proposition of introducing battery energy storage in the Madeira Island electric grid, where only micro-production for self-consumption is currently allowed. The evaluation was conducted against two local micro-producers using one year of energy consumption and solar PV production measurements. The assessments considered three different pairs of battery capacity/inverter size, and the outputs analyzed considering self-consumption, self-sufficiency, and energy costs. The results show that despite the increase in self-consumption and self-sufficiency, the value proposition of battery energy storage is still considerably low even considering a massive decrease in the costs of storage. Furthermore, the results also suggest that given the small size of the solar PV installations, inverters with half the size of the installed PV capacity represent the best value for money.**

I. INTRODUCTION

This paper considers the case of Madeira Island, where since 2014 utilities promotes the inclusion of distributed generation (DG) only for self-consumption purposes. This restriction happens in part due to the isolated nature of the electric grid, which can be greatly affected by the intermittent and uncertain nature of renewable production [1].

Yet, while this technical restriction helps to maintain grid stability, it is surely not helping to increase the number of renewable energy sources (RES) in the electricity mix. Furthermore, since in most cases of domestic micro-production of solar energy does not match the demand, it is very unlikely that the self-consumption share will be higher than 50% [2].

Under the case where DG owners are not allowed to supply power back to the grid, the main value proposition of energy storage is its ability to promote and increase in self-consumption, which refers to the amount of production that is consumed on-site relative to the total production [3]. As a consequence of increased self-consumption, one should expect an increase in self-sufficiency (i.e., the degree to which the on-site generation is sufficient to fill the energy needs of the building) [3], and reduced electric energy bills.

The objective of this work is to study the effects of introducing energy storage devices in solar PV installations in Madeira Island, where grid-injection is currently not an option. To this end, it relies on year-long energy consumption and solar PV production data from two local domestic micro-producers. The simulations were conducted considering three different pairs of battery capacity/inverter size, and the obtained results analyzed with respect to self-consumption (SC), self-sufficiency (SS), and energy costs.

A. Related Works

In [3] a 2015 review on research on PV self-consumption and options to improve it was conducted. Energy storage and load management also called demand-side management (DSM) were two of the options for increased self-consumption. Overall, the results showed that it was possible to increase the relative self-consumption by 13-24% with a battery storage capacity of 0.5-1 kWh per installed kW PV power and between 2% and 15% with DSM.

In 2016, the authors of [4] conducted an economic analysis of the benefits of Tesla’s Powerwall battery for the end-user of the German market. Simulations were conducted with a scaled annual consumption from 1 MWh to 10 MWh, and the PV system size ranged from 1 kWp to 10 kWp. A “greedy” strategy was used to control the battery operation. Overall, the results showed that Tesla’s Powerwall could be, at the time, an economically viable purchase with a return on investment over 25% in some cases with a rising electricity price. This work also showed that stricter limits of grid feed-in power would lead to larger energy waste in cases where simple “greedy” control algorithms are used, requiring a more advanced, predictive operation strategies that prevent curtailment losses.

In 2017, in [5] an energy storage system was modeled in the context of residential buildings with PV generation and simulated using real data from a typical residential household in Coimbra (Portugal) with the objective of increasing the match between the local generation and consumption. The control of the battery charging and discharging process was done considering as main objective the minimization of the power flows between the

household and the grid by increasing self-consumption of the generated energy and storing the surplus generation. The second objective was the minimization of the energy bill and therefore when consumption of energy from the grid was inevitable, the energy would be consumed in the period with lower costs, being such energy stored in the battery for later use. The results showed that the designed system was able to reduce the energy sent to and consumed from the grid in 76% and in 78.3% respectively, as well as the energy bill in 87.2%. An economic assessment was also conducted, showing that despite the financial benefits, due to the high costs of storage devices at the time, about 550 €/kWh, the investment was not cost-effective.

B. Document Organization

The remaining of this paper is organized as follows: An overview of the Madeira Island electric grid is given in Section II. The research design is presented in Section III. The simulation results are presented and discussed in Section IV, before the paper is concluded in Section V.

II. OVERVIEW OF THE MADEIRA ISLAND ELECTRIC GRID

Madeira is an archipelago in the North Atlantic Ocean, located about 1000 km southwest of mainland Portugal. It has a population of almost 270,000. 111,000 of which live in the capital city of Funchal.

As of the writing of this document, there are 118543 domestic consumers in Madeira. Overall, these consumers are responsible to 30% of the total yearly consumption, that in 2016 was 798 GWh (about 15 GWh per week) [6].

Madeira is a total energy island, and all the energy is generated locally by a single DSO/TSO. The DSO/TSO is responsible for the activities related to production, transport, distribution, and commercialization of electric energy. It is also the entity that acquires the electric energy that is produced by private micro- and mini-producers.

The electric grid in Madeira island is fed by five sources of energy, namely: hydro, wind, photovoltaic, solid waste incineration, and thermal energy from burning fossil fuels like diesel and natural gas. As of this writing, the electric energy production in Madeira island is guaranteed by two thermal plants, 10 hydro plants, eight wind farms, one solid waste plant, three solar farms with 7 MW, 2 MW and 6 MW respectively, and 785 distributed solar micro and mini-producers, with full injection to the grid [6].

A. Regulation for Mini / Micro-Production and Self-Consumption

The Decree-Law no 153/2014 of October 20th of 2014 defines the current legislation for micro-production and self-consumption of energy. This Decree-Law defines two types of Units of Production, the UPP (Unit of Small Production), and the UPAC (Unit Production for Self-Consumption).

UPPs are units of production, based on a single technology (e.g., solar or wind). All the energy produced by

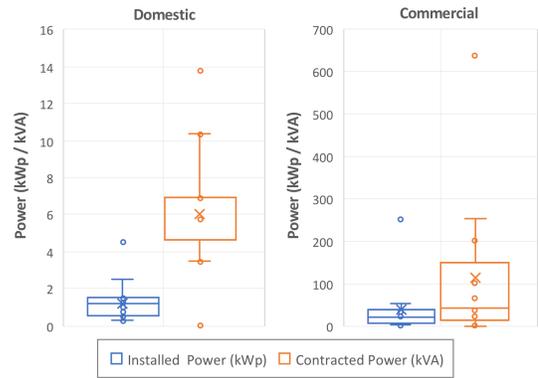


Fig. 1. Distribution of the installed and contracted power across the 49 registered UPACs: domestic (left), commercial (right).

a UPP must be injected to in the Public Service Electric Grid (RESP). UPACs, are units of production that can be either off-grid or grid-connected. The energy produced by a UPAC, must be first used for self-consumption, and only then injected to the grid.

In Madeira, since 2014, the local DSO/TSO does not accept new UPPs, and UPACs are not allowed to inject the excess energy to the RESP (i.e., excess production must be curtailed). This imposition is owing to the isolated nature of the Madeira electric grid that is very sensitive to variations in the energy produced by RES. Hence the need to avoid direct injection to the grid. Nevertheless, the DSO/TSO still maintains the 785 installations contracted before this decision [7].

B. Self-consumption in Madeira

As of this writing, there were 49 UPACs registered in Madeira Island, 36 of which are domestic installations and 12 commercial installations. Figure 1 shows the distribution of the UPAC installations in terms of the installed and contracted power. An immediate observation is that despite having the possibility of installing solar PV power up to 200% of the contracted power, the average installed solar PV power is about 18% of this value in domestic installations, and 30% in commercial. There are several reasons for this, including the lack of space or the long pay-back time. However, in Madeira, the main reason is the need to dimension the UPAC to approximate the electricity produced with the energy consumed, to minimize grid injection. Also noteworthy is the fact that 25% of the commercial installations have over 150 kWp installed. These installations, however, belong to hotels and self-consume all the energy that is produce. Thus are not of interest for this work.

III. RESEARCH DESIGN

A. Consumption and Solar PV Production Data

This paper uses one year of data from two local UPACs. The time-series measurements for solar PV production (P_{PV}) and power consumption (P_{Loads}) were taken from

TABLE I
INSTALLATION DETAILS OF THE UPACS CONSIDERED IN THIS WORK.

ID	Contracted Power (kVA)	Installed PV (kWp)	Consumption (MWh)	Year Totals Production (MWh)	Possible SS (%)
A	6.9	1.5	4.92	2.133	43.36
B	6.9	3	3.709	3.029	81.65

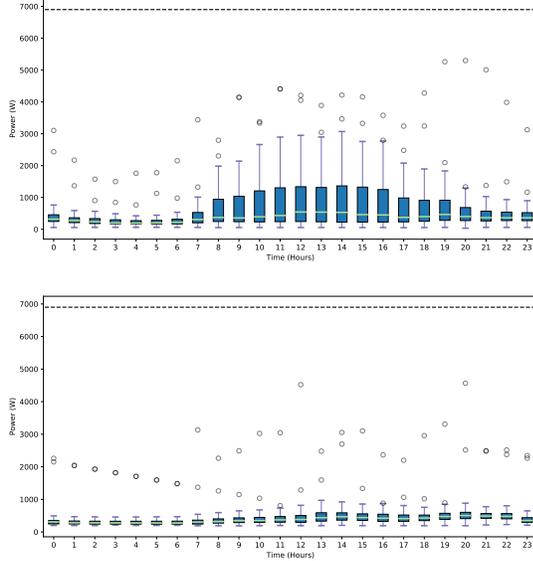


Fig. 2. Hourly distribution of active power. UPAC A (top), and UPAC B (bottom). The dashed lines represent the 6.9 kVA PPC.

the metering infrastructure of each UPAC at the maximum sampling rate allowed by the installed smart-meters and averaged at the rate of 1 sample per minute (1/60 Hz). Table I shows the Peak Power Contract (PPC), installed solar PV capacity, yearly totals, and best possible SS (i.e., with 100% SC) for each UPAC. Figure 2 shows the hourly distribution of the active power in each UPAC.

The following metrics were computed from the yearly consumption and production data:

a) P_{PV_Loads} : This is the power from the PV that is being consumed in real-time by the loads. It is given by equation 1:

$$P_{PV_Loads}(t) = \min(P_{PV}(t), P_{Loads}(t)) \quad (1)$$

b) P_{PV_Grid} : This is the surplus power from the PV that is injected in the grid in real-time. Since there is no feed-in tariff for grid injection, this is considered wasted power. It is given by equation 2:

$$P_{PV_Grid}(t) = P_{PV}(t) - P_{PV_Loads}(t) \quad (2)$$

c) P_{Grid_Load} : This is the power from the grid that is being consumed by the loads. It is given by equation 3

$$P_{Grid_Load}(t) = P_{Loads}(t) - P_{PV_Loads}(t) \quad (3)$$

d) *Self Consumption (SC)*: Is given by equation 4:

$$SC = \frac{\sum_{t=1}^T P_{PV_Loads}(t)}{\sum_{t=1}^T P_{PV}(t)} \times 100 \quad (4)$$

e) *Self Sufficiency (SS)*: Is given by equation 5:

$$SS = \frac{\sum_{t=1}^T P_{PV_Loads}(t)}{\sum_{t=1}^T P_{Loads}(t)} \times 100 \quad (5)$$

f) *Cost*: The total energy cost (after one year) was calculated assuming the current price of 0.16 €/kWh.

At this point, it is important to remark that UPAC A is equipped with specialized hardware to curtail the solar PV generation before it exceeds the actual demand. While conforming with the DSO/TSO norms, this practice prevents the measurement of the total PV production unless everything is consumed by the UPAC loads (i.e., it is not possible to quantify the amount of solar PV that would be injected in the grid).

As such, this work uses simulated (hourly) solar PV production data, from the PVWatts Calculator¹ application of the National Renewable Energy Laboratory (NREL).

B. Simulation Software

SimSES (Simulation of stationary energy storage systems) [8] is an open-source modeling framework for simulating stationary energy storage systems developed at the Institute for Electrical Energy Storage Technology of the Technical University of Munich. SimSES was developed in MATLAB, and the software provides a detailed simulation and evaluation of stationary energy storage systems, mainly focusing on lithium-ion batteries.

Altogether, taking as input parameters the time series of energy consumption and production data, it is possible to simulate and evaluate stationary energy storage operation from a techno-economic perspective. The simulation time was set to 365 days, and the granularity of the consumption and solar PV production data to 1/60 Hz (i.e., 1 sample per minute). As for the different simulation parameters, it was decided to leave some unchanged, while tweaking the others. The following parameters were considered in the simulations:

1) *Battery characteristics*: The parameters left unchanged were: nominal voltage (51.2 V), the ambient temperature (25°C), the end of life (80% SOH). The type of battery and aging model were both set to the default Tesla Daily Cycle PowerWall. All the remaining parameters were changed as follows:

a) *Capacity (kWh)*: Set to 1kWh, 2kWh, 5kWh, and 10 kWh.

b) *State of Charge (SOC - %) lower and upper limits*: Set to 20% and 80% respectively.

c) *Initial SOC (%)*: Set to 20%, meaning that the battery is discharged when the simulation starts.

¹ PVWatts Calculator, <https://pvwatts.nrel.gov/>

d) *Initial State of Health (SOH - %)*: Set to 100%, thus assuming the battery is brand new.

2) *Power electronics*: Three different inverter sizes were considered based on the installed solar PV in each house. More precisely, House A: 0.75kW, 1kW, and 2 kW; House B: 1kW, 1.5 kW, and 3kW. Each inverted was combined with each battery, for a total of 12 battery/inverter pairs.

As for the inverter efficiency, it was set to the default equation used in SimSES [8], where the efficiency is affected by both the inverter size and the amount of power to be transferred. Figure 3 shows the efficiency in function of the inverter size and the amount of power to be transferred.

3) *Battery Operation Strategy*: In this work, the *greedy* strategy was adopted. This is a standard operation strategy in self-consumption scenarios, being adopted by many other authors (e.g., [4], [5]). It works by determining the residual load (i.e., the difference between production and consumption) and actuating the battery accordingly, either by storing excess production unless the upper SOC limit is reached, or supplying the excess demand from the battery unless the lower SOC is reached.

C. Simulation Outputs

The SimSES simulator produces several outputs at a granularity of one sample every 15 minutes (1/900 Hz). The following were considered:

- $P_{Loads}(t)$, referring to the total consumption of the loads over time t .
- $P_{PV}(t)$, referring to the amount of power being produced by the solar PV system over time t .
- $Grid(t)$, referring to the amount of power requested/injected from/to the grid over time t . If power is requested, $Grid(t)$ will have a positive value. Otherwise, if excess P_{PV} is injected, $Grid(t)$ will have a negative value.
- $BESS(t)$, referring to the amount of power requested/injected from/to the battery over time t . If power is requested, $BESS(t)$ will have a negative value. Otherwise, if P_{PV} is injected, $BESS(t)$ will have a positive value.

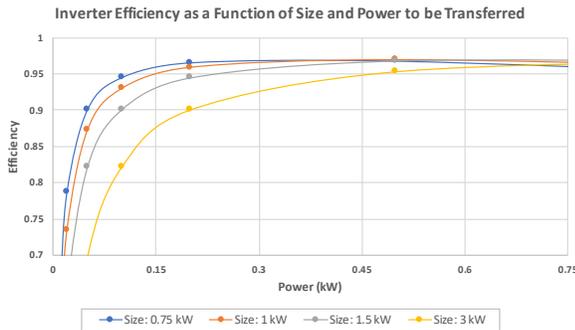


Fig. 3. Inverter efficiency as a function of its size and the amount of power to be transferred.

From the selected outputs, the following metrics were calculated:

a) $P_{PV_Grid}(t)$: Power from PV going to the Grid over time t . This is the negative part of $Grid(t)$. It is given by equation 6:

$$P_{PV_Grid}(t) = |min(0, Grid(t))| \quad (6)$$

b) $P_{PV_BESS}(t)$: Power from PV going to the BESS over time t . This is the positive part of $BESS(t)$. It is given by equation 7:

$$P_{PV_BESS}(t) = max(0, BESS(t)) \quad (7)$$

c) P_{PV_Load} : Power from PV going to the Loads (W) This is the amount of solar PV production being consumed by the loads. It is given by equation 8:

$$P_{PV_Loads}(t) = P_{PV}(t) - P_{PV_Grid}(t) - P_{PV_BESS}(t) \quad (8)$$

d) P_{Grid_Loads} : Power from the Grid going to the Loads. This is the positive part of $Grid(t)$. It is given by equation 9:

$$P_{Grid_Loads} = max(0, BESS(t)) \quad (9)$$

e) P_{BESS_Load} : Power from the BESS going to the Loads. This is the negative part of the BESS(t). It is given by equation 10:

$$P_{BESS_Loads}(t) = |min(0, BESS(t))| \quad (10)$$

f) *Self Consumption (SC)*: Is given by equation 11:

$$SC = \frac{\sum_{t=1}^T (P_{PV_Loads}(t) + P_{PV_Bat}(t))}{\sum_{t=1}^T P_{PV}(t)} \times 100 \quad (11)$$

g) *Self Sufficiency (SS)*: Is given by equation 12:

$$SS = \frac{\sum_{t=1}^T (P_{PV_Loads}(t) + P_{Bat_Loads}(t))}{\sum_{t=1}^T P_{Loads}(t)} \times 100 \quad (12)$$

IV. RESULTS AND DISCUSSION

A. Baseline

The baseline results are presented in Table II. Three main observations emerge from the results: i) in terms of energy costs, the saving obtained from solar PV only are very similar in both UPACs. Yet, due to the lower self-sufficiency of UPAC A, the percentage of savings is naturally lower; ii) UPAC A has higher self-consumption, which happens due to the lower size of the installation, but also by the fact that house A tries harder to match consumption with solar PV production (as can be seen in Figure 2); iii) House B is at this point much more Self-Sufficient than house A, because of the higher solar PV installation, and the lower overall consumption.

TABLE II
 BASELINE RESULTS FOR THE ONE YEAR OF DATA AVAILABLE.

ID	Production (% of total)		Consumption (% of total)		SC (%)	SS (%)	Cost			Optimal SS (for SC = 100%)
	PV Loads	PV Grid	PV Loads	Grid Loads			No PV	PV	Diff. to No PV	
A	67.7%	32.3%	26.8%	73.2%	67.7%	26.8%	787.74€	561.88€	225.86€ (28.67%)	44.4%
B	51.9%	48.1%	40.0%	60.0%	51.9%	40%	593.97€	351.64€	242.33€ (40.8%)	81.65%

B. Simulations

The simulation results are presented in Table III. Some observations emerge from this.

First, if only considering total savings and SC, the 10 kWh battery is a clear winner. Yet, when considering the differences to the smaller batteries, it becomes clear that a 10 kWh battery is overkill in both cases. For example, in house A there is only a difference of less than three percentage points (pp) in savings between the 5 kWh and the 10 kWh batteries, which represents less than 9 Euros after one year. As for house B, the difference between 5 kWh and 10 kWh batteries is higher (9pp for the one kWp inverter and 13pp for the 1.5 and three kWp), which results in increases of about 40€ and 55€ in savings after one year, respectively.

Concerning SS, the differences between the different battery capacities are even smaller. For example, in house A, the difference in savings between 2 kWh and a 10 kWh is only of about 5pp (less than 2pp between 5 kWh and 10 kWh). Concerning house B, the difference is of about 20pp between 2 kWh and 10 kWh, but only of 10pp between 5 kWh and 10 kWh. Furthermore, when considering the best possible SS for each house (see Table I), a 5 kWh battery would leave house A at only 5pp of that value, and house B at 20pp. On the other hand, a 10 kWh battery leaves house A at less than 5pp from the best possible SS, whereas house B would still be 10pp behind optimal self-sufficiency.

Ultimately, these results show that under the current conditions, the solar PV installation of house B is oversized, whereas house A has an installation that is adequate to maximize self-consumption.

Another important aspect is the effect of the battery inverter in the obtained results. It is evident from the simulations that bigger inverters end up affecting the SS negatively, despite an increase in SC. This suggests that inefficiencies affect discharge more than charge, where the amount of power to transfer is lower. For example, in house A this affects all the batteries with 1.5 kW inverters. In house B this effect can be observed in 6 out of the 12 battery/inverter combinations, including all the combinations with the 3 kWp inverter and two with the 1.5 kWp.

V. CONCLUSION

This paper presented a Techno-Economic evaluation to assess the value proposition of introducing battery energy storage in scenarios where only self-consumption

is allowed, more precisely, Madeira Island. The assessment was conducted against two local micro-producers using one year of measurements of energy consumption and solar PV production.

The results show that in the current scenario of no grid-injection, battery energy storage can help to improve the value of solar PV installations by increasing SC and SS. The results also show that batteries themselves are not enough to reach 100% SC. In fact, the simulations show that not even with a 10 kWh battery this can be achieved in any of the cases considered. Consequently, in self-consumption only scenarios, it is of crucial importance to try to match consumption with production as much as possible, even when energy storage systems are available as suggested in the literature [3].

Furthermore, and even though battery energy storage represent increased SC, SS, and reduced energy bills, it is evident that with the current prices of energy storage devices the payback times are far from acceptable. For example, even in the most optimistic forecasts that set the price of lithium-ion batteries at around 175 €/kWh by 2020 [9] it would still take between 11 years (UPAC A) and 6 (UPAC B) years to pay the initial investment of a 5 kWh battery.

Against this background it safe to say that without additional value propositions, it is implausible that the market will see wide adoption of BESS by the domestic sector in the near future. Consequently, more ambitious battery control strategies must be devised. For example, co-optimizing for increased SC/SS and reduction of peak consumption would increase the original value proposition, since there is a fixed daily fee based on the installed PPC that could be lowered. For instance, a 6.9 kVA that represents a fixed fee of 110€ per year could be reduced to a 5.75 kVA PPC, with a fixed fee of 93€. [6].

Likewise, it is of vital importance to investigate the potential of using storage devices to enable controlled grid injection. In such a scenario, batteries would act as buffers between the solar PV panels and the grid, and specialized algorithms would orchestrate the transfer of green energy from the battery to the grid. This would, of course, require the development of new business models, where UPAC owners would get paid for the clean energy safely injected in the grid.

One limitation of this work is that it considers only the single-rate tariff, even though it is possible to choose from two additional Time-of-Use (ToU) tariffs. Thus, future work should also explore battery control strategies that

TABLE III
SIMULATION RESULTS FOR THE ONE YEAR OF DATA AVAILABLE.

ID	Bat kWh/kW	Production (% of total)			Consumption (% of total)			SC (%)	SS (%)	Cost	
		PV_Loads	PV_Bat	PV_Grid	PV_Loads	Bat_Loads	Grid_Loads			PV + Bat	Diff. to PV
A	1/0.75	66.11%	11.44%	22.44%	28.67%	4.21%	67.12%	77.55	32.88	528.73€	33.15€ (5.9%)
	1/1	66.11%	11.5%	22.38%	28.67%	4.22%	67.12%	77.61	32.89	528.71€	33.17€ (5.9%)
	1/1.5	66.11%	11.58%	22.31%	28.67%	4.18%	67.15%	77.69	32.85	528.96€	32.92€ (5.86%)
	2/0.75	66.1%	17.65%	16.25%	28.66%	6.5%	64.83%	83.75	35.16	510.72€	51.16€ (9.11%)
	2/1	66.1%	17.75%	16.14%	28.66%	6.52%	64.81%	83.85	35.18	510.56€	51.31€ (9.13%)
	2/1.5	66.1%	17.85%	16.04%	28.66%	6.49%	64.85%	83.95	35.15	510.81€	51.07€ (9.09%)
	5/0.75	66.08%	26.45%	7.47%	28.65%	9.75%	61.6%	92.53	38.4	485.23€	76.65€ (13.64%)
	5/1	66.08%	26.8%	7.12%	28.65%	9.86%	61.49%	92.88	38.51	484.37€	77.51€ (13.79%)
	5/1.5	66.08%	26.88%	7.04%	28.65%	9.81%	61.54%	96.96	38.46	484.8€	77.08€ (13.72%)
	10/0.75	66.03%	29.23%	4.74%	28.63%	10.76%	60.61%	95.26	39.39	477.42€	84.46€ (15.03%)
10/1	66.03%	30.09%	3.88%	28.63%	11.06%	60.31%	96.12	39.69	475.08€	86.8€ (15.45%)	
10/1.5	66.03%	30.22%	3.74%	28.63%	11.02%	60.35%	96.25	39.65	475.38€	86.5€ (15.39%)	
B	1/1	49.96%	8.29%	41.75%	40.79%	5.72%	53.48%	58.25	46.51	317.67€	33.97€ (9.66%)
	1/1.5	49.96%	8.35%	41.69%	40.79%	5.69%	53.51%	58.31	46.48	317.85€	33.79€ (9.61%)
	1/3	49.96%	8.51%	41.53%	40.79%	5.49%	53.72%	58.47	46.28	319.07€	32.57€ (9.26%)
	2/1	49.95%	14.94%	35.11%	40.79%	10.37%	48.84%	64.89	51.16	290.1€	61.54€ (17.50%)
	2/1.5	49.95%	15.03%	35.02%	40.79%	10.35%	48.86%	64.98	51.14	290.23€	61.41€ (17.46%)
	2/3	49.95%	15.20%	34.84%	40.79%	10.06%	49.15%	65.15	50.85	291.92€	59.72€ (16.98%)
	5/1	49.94%	31.47%	18.58%	40.78%	21.92%	37.30%	82.41	62.7	221.55€	130.09€ (37.00%)
	5/1.5	49.94%	32.0%	18.05%	40.78%	22.18%	37.04%	81.94	62.96	220.01€	131.63€ (37.43%)
	5/3	49.94%	32.20%	17.86%	40.78%	21.72%	37.50%	82.14	62.5	222.76€	128.88€ (36.65%)
	10/1	49.93%	41.56%	8.51%	40.77%	28.91%	30.32%	91.49	69.68	180.09€	171.55€ (48.79%)
10/1.5	49.93%	45.39%	4.68%	40.77%	31.39%	27.84%	95.32	72.16	165.37€	186.27€ (52.97%)	
10/3	49.93%	46.35%	3.72%	40.77%	31.13%	28.10%	96.28	71.9	166.9€	184.74€ (52.54%)	

take into consideration other billing models like ToU or even dynamic pricing.

Furthermore, since grid-injection seems inevitable, it is vital to assess the value proposition of energy storage in the possibility of providing controlled grid-injection (i.e., the feed-in tariff is no longer zero). In such scenarios, external signals and look ahead mechanisms like forecasting need to be considered, since a decision at time t , may affect the profitability of future decisions. Consequently, another important research direction is to explore how much look ahead is necessary to obtain optimal or near-optimal solutions.

Finally, future works should also consider the degradation of the equipment (PV and storage), since in the long-term this will undoubtedly affect the value proposition of the entire system.

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