Sizing and operation of a residential PV-battery system: Rule-Based and real time vs optimization and perfect foresight

Elena Sedano Ruiz
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
elena.sedano.ruiz@gmail.com

Jesús Huete Cubillo
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
j.huetecubillo@gmail.com

Jorge de la Vega Rodríguez
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
jorgedlvr@gmail.com

Sebastián Martín
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
smartin@uma.es

***Abstract*—Many residential customers are becoming prosumers, because of environmental concerns and falling prices of renewable generation technologies, as photovoltaic. In this context, typical residential installations consists of photovoltaic (PV) generation and batteries. Battery energy management poses a challenge because of the variability and uncertainty related to PV generation and customer consumption. Here, we propose easy to implement rules for the system (PV + battery) operation, to minimize the total cost for the customer. The main contribution is to use the rule-based operation for system sizing and operation, and to compare the results to those for an optimization based sizing and operation with perfect foresight. Based on this comparison, the value of information for the system operation is quantified and discussed. The optimization problem and the rule-based operation are applied to a case study for a residential customer in Southern Spain.**

***Index Terms*—battery, photovoltaic generation, ruled-based operation, optimization, perfect foresight**

NOTATION

Parameters and sets are indicated in uppercase. Variables and indices are indicated in lower case.

Indices and Sets

t, T	Index and set for time-steps, $t \in T$.
ω, Ω	Index and set for scenarios, $\omega \in \Omega$.

Parameters

CAB	Battery amortization cost, (€/(kWh $\cdot$ day)).
$CAPV$	PV amortization cost, (€/(kWp $\cdot$ day)).
CTP	Cost of grid connection capacity, (€/(kW $\cdot$ day)).
D_t^ω	User power consumption, time-step t scen. ω, (kW).
PEC_t^ω	Price of energy purchased from the grid, (€/kWh).
PEV_t^ω	Price of energy sold to the grid, (€/kWh).
PVA_t^ω	Available PV generation at t and ω, (kW/kWp).
Pr^ω	Probability of scenario ω.
α_C/α_D	Charging/Discharging battery capacity, (kW/kWh).
Δ_t	Lasting of time-step t, (Hours).
η_C/η_D	Charging / discharging battery efficiency, (p.u.).

Variables

b	Battery size, (kWh).
br_t^ω	Power from the battery to the grid at (t, ω), (kW).
bd_t^ω	Power from the battery to demand at (t, ω), (kW).
ccc	Grid connection capacity for consumption, (kW).
cci	Grid connection capacity for injection, (kW).
rb_t^ω	Power from the grid to the battery at (t, ω), (kW).
rd_t^ω	Power from the grid to demand at (t, ω), (kW).
pv	Rated peak power of PV generation, (kWp).
soc_t^ω	Energy in the battery at (t, ω), (kWh).
vr_t^ω	Power from PV to grid at (t, ω), (kW).
vd_t^ω	Power from PV to demand at (t, ω), (kW).
vb_t^ω	Power from PV to battery at (t, ω), (kW).
vs_t^ω	Power from PV not used at (t, ω), (kW).

I. INTRODUCTION

Traditional forms of energy production based on fossil fuels face serious difficulties, such as their non-renewable nature and the need of decarbonisation [1]. In this global context, an energy transition toward renewable generation is being promoted. Being one of the great challenges of today how to achieve more sustainable and responsible energy systems regarding the environment. There is certain agreement on the promotion of renewable energy, and the improvement of energy management and energy efficiency through innovative

The work of S. Martín was supported in part by the Spanish Ministry of Economy and Competitiveness through the project ENE2016-80638-R, and in part by the Universidad de Málaga (Campus de Excelencia Internacional Andalucía Tech).

technologies such as smart grids [2], to solve this challenge successfully.

Also, the energy sector is aware of the importance of the final consumer to reduce costs. In this sense, the use of smart grids and smart meters is bringing significant changes in the relationship between customers and energy providers, as explained in [3]. These technologies will enable customers to be active players in the energy system, on one hand becoming prosumers, and on the other hand to respond to grid prices to get a profit.

Nowadays, renewable energy is cost competitive regarding fossil fuel technologies, in particular photovoltaic and wind generation. For instance, according to [4], since 2014 the global-weighted average cost of electricity of photovoltaic (PV) generation has also fallen into the fossil-fuel cost range. The main difficulty of PV generation in domestic installations is that only a fraction of the available PV generation is in fact consumed, and this increases the relative cost of PV generation. If all the available PV generation could be consumed in the domestic installation (self-consumption), the energy cost from PV would be lower than the energy cost from the main grid. To this regard, energy storage plays a key role to manage the available PV generation to use the most of it.

To effectively integrate renewable generation into modern energy systems, it must be more flexible, as discussed in [5], because the need to balance supply and demand in real time. Electricity Storage Systems (ESS) seem to be a proper solution for the management of non-dispatchable renewable generation, as PV. A key aspect for the systems including ESS is the economic viability, to this regard it is very important an appropriate sizing and operation of the ESS.

It is difficult to optimally operate the installation of an user because that would require complete information on the user consumption and PV generation curves in advance, and the most we can have are forecasts of those curves. Thus, an important aspect to manage energy systems is the uncertainty and variability associated with the input parameters of the system. This uncertainty can be managed using a number of approaches, as referred in [6]. Here, we study the difference between the perfect foresight (optimization problem) and the rule-based operation using only the information available on real time. Only relatively few works consider this question, and those that consider it usually do not consider the sizing problem, as for instance [7].

Also, other problems in the management of PV systems are those related to the control of the maximum ramps for consumption/injection from/to the grid because of sudden changes in PV generation, as discussed in [8] for PV + battery, and in [9] for PV + battery + super-capacitor. Here, we do not deal with these problems.

Here, we assume each single user manages its own installation. Other approaches can be found in the literature, for instance: centralized, decentralized or distributed, as described in [10] and [11]. Also here, we take the consumption curves as input data, modelled as scenarios, and they are not modified by the system operation. Other approaches can be found in the literature, as those considering demand side management but not sizing, as it is done in [12].

In this work there are two main contributions:

- One hand, how to manage the system (PV + battery) to minimize total cost (investment + operation) for the customer. Two strategies are proposed, one based on rules and only the available information on real time, the other based on an optimization problem that considers scenarios and perfect foresight.
- And the other contribution is, to use both strategies to calculate the optimal system size. In the sizing problem, PV and battery capacities, are variables to be computed to minimize total cost, and this is the main difference of this work regarding some recent works as [7].

In the rest of the document we found the methodology in section II, the description of an illustrative case study in section III, the discussion of results for the case study in section IV, and finally conclusions are summarized in section V.

II. METHODOLOGY

This section presents the assumptions and simplifications, as well as the mathematical model and the equations implemented. In addition, the rules for system operation are described. To conclude this section, technical aspects of the software used and the computation cost are detailed.

A. Assumptions and simplifications

A simulation horizon of a whole year is considered in our models. The year is represented by a set of four scenarios, each one describing a profile for a whole day in time-steps of 15 minutes (96 values per scenario). Our goal is none other than to size and to simulate the operation of a system composed of PV + battery for a residential customer during a whole year, using two approaches, one based on an optimization problem and perfect foresight, the other rule-based and using only available information on real time.

Regarding the input data, we have deterministic data such as the purchase price of electricity from the grid, and also parameters with uncertainty as: user demand and photovoltaic generation. The value of parameters with uncertainty are modelled through scenarios, where each scenario represents a day. Each scenario has a probability and consists of 96 values for the parameter, one value for each time-step during a day.

Values for scenarios are based on historical records for each parameter, these values are grouped what follows for each scenario:

- Scenario 1: December, January, February.
- Scenario 2: March, April, May.
- Scenario 3: June, July, August.
- Scenario 4: September, October, November.

The values in each scenario ω and for each time-step t are calculated as the average of the values on its corresponding set of historical data.

The objective for both strategies (optimization or rules) is the same, to minimize the total cost for the user. The optimization problem is posed as a two-stage stochastic problem and described in Section II-B, the rule-based operation is described in Section II-C.

B. Optimization Problem

In this section, the mathematical model used for the optimal sizing and operation of the system (PV + battery) for a single-user residential installation, is presented. The problem is posed as a two-stage stochastic optimization problem. It is a linear programming problem with an objective function and a set of constraints that are described in what follows.

The objective function to minimize represents the total cost (investment and operation) for the user in (€/day):

$$\begin{aligned}\min\Big\{ & CAPV\cdot pv + CAB\cdot b + CTP\cdot ccc+ \\ & + \sum_{t\in T}\sum_{\omega\in\Omega} Pr^{\omega}\cdot\Delta_t\cdot[PEC_t^{\omega}\cdot(rd_t^{\omega}+rb_t^{\omega}) \\ & - PEV_t^{\omega}\cdot(br_t^{\omega}+vr_t^{\omega})]\Big\}\end{aligned} \tag{1}$$

The objective function to be minimized is defined as the sum of the, so called, first and second stage. The first stage stands for the investment cost and includes the amortization costs of: the PV installation, the battery, and the connection to grid. The second stage corresponds to the expected operation costs of the installation, including all the consumptions (costs) from the grid and injections (incomes) to the grid. A net billing scheme is assumed for the customer.
Subject to:

$$rd_t^{\omega}+bd_t^{\omega}+vd_t^{\omega}=D_t^{\omega};\quad \forall t\in T,\forall\omega\in\Omega \tag{2}$$

$$vd_t^{\omega}+vr_t^{\omega}+vb_t^{\omega}+vs_t^{\omega}=pv\cdot PVA_t^{\omega};\quad \forall t\in T,\forall\omega\in\Omega \tag{3}$$

$$\begin{aligned}soc_t^{\omega} = {} & soc_{u,t-1}^{\omega}+\eta_C\cdot\Delta_t\cdot(vb_t^{\omega}+rb_t^{\omega}) \\ & -\frac{\Delta_t}{\eta_D}\cdot(br_t^{\omega}+bd_t^{\omega});\quad t=2,\ldots,|T|,\forall\omega\in\Omega\end{aligned} \tag{4}$$

$$soc_{u,1}^{\omega}=soc_{u,|T|}^{\omega};\quad t=1,\quad \forall\omega\in\Omega \tag{5}$$

$$soc_t^{\omega}\le b;\quad \forall t\in T,\forall\omega\in\Omega \tag{6}$$

$$rb_t^{\omega}+vb_t^{\omega}\le\alpha_C\cdot b;\quad \forall t\in T,\forall\omega\in\Omega \tag{7}$$

$$bd_t^{\omega}+br_t^{\omega}\le\alpha_D\cdot b;\quad \forall t\in T,\forall\omega\in\Omega \tag{8}$$

$$rd_t^{\omega}+rb_t^{\omega}\le ccc;\quad \forall t\in T,\forall\omega\in\Omega \tag{9}$$

$$br_t^{\omega}+vr_t^{\omega}\le cci;\quad \forall t\in T,\forall\omega\in\Omega \tag{10}$$

Where: (1) is the objective function, that minimizes the expected final cost for the user; (2) sets the balance for the user demand with the joint contribution of the power taken from the grid, the battery, and the PV generation; (3) corresponds to the energy balance equation in the PV generation; (4) corresponds to the energy balance for the battery for $t > 2$; (5) corresponds to the energy balance for the battery for $t = 1$; (6) sets a lower bound for battery size; (7) corresponds to the upper bound for battery charging; (8) corresponds to the upper bound for battery discharging; (9) defines an upper bound for power consumption from the grid; (10) defines an upper bound for the power that can be injected into the grid.

C. Rule-Based Operation

In this section, the rule-based operation is described. Rules are defined by ordered sequences of steps. In each step the conditions for admissible power and energy are checked, these conditions are the same as those described by (2)-(10). In case of a surplus of energy and/or power in a step, this surplus is sent to the next step. For each scenario ω and each time-step t we have two possible paths (only one holds):

- In case the PV generation at time-step t and scenario ω is greater (or equal) than demand at that time-step, then the sequence of operations is (in this order):
  1) The user consumes directly from the PV generation as much as possible.
  2) If there is a surplus from PV generation it is stored in the battery.
  3) If the battery is full, or reaches its full capacity, the surplus of energy is sold to the grid.
  4) If the upper bound for the connection capacity for injection is reached, then the PV generation surplus is not used.
- In case the PV generation at time-step t and scenario ω is less than demand at that time-step, then the sequence of operations is (in this order):
  1) The energy available in the battery is used first.
  2) If there is not enough energy (or power) in the battery to satisfy the demand (apart from the PV contribution), then the grid is used.
  3) In case the connection capacity from the grid is not enough to satisfy the remaining demand, the problem is infeasible. We indicate this case in the results by fixing the operation cost to a high value (5 €/day as it is shown in Fig. 3c). Feasibility can be assured by different means, for instance by increasing the connection capacity.

The rule-based operation was implemented in MATLAB [13], with a size of 3456 variables and a solving time of around 0.071 seconds/simulation. The optimization problem was implemented in GAMS [14], with a size of 4608 variables and 3840 equations, and a solving time of 0.015 seconds/simulation. Both codes running in a machine with Intel Core i7-8750H @ 2.20 GHz and 16.0 GB RAM under Windows 10 64-bits.

III. CASE STUDY

The two proposed approaches are applied to a case study for a residential customer with moderately high consumption in Southern Spain. Demand scenarios for this customer are depicted in Fig. 1, the probability of each scenario is $Pr^{\omega}\approx 0.25$. The values for the parameters in the models are: η_C=0.92 p.u., η_D=0.92 p.u., α_C=0.5 kW/kWh , α_D=0.5 kW/kWh, $CAPV$=0.1315 €/(kWp·day), CAB=0.0913 €/(kWh·day).

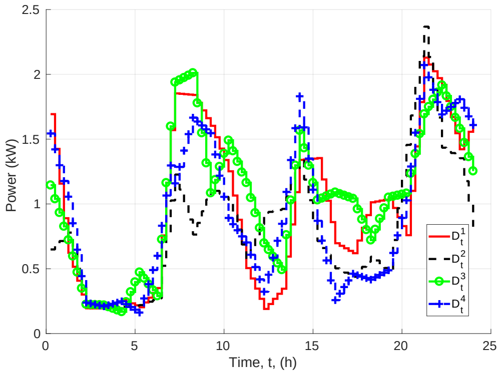


Figure 1. Demand scenarios for the case study.

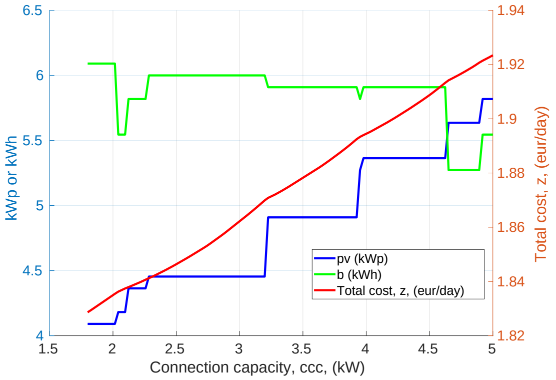


Figure 2. Optimal values for pv, b and total cost for a given value of ccc in the case of rule-based operation.

Grid prices correspond to a commercial tariff in Spain, and have these values [15]:

- Energy purchased from grid (PEC_t^ω): reduced price of 0.0918 €/kWh for t in 22:00 pm - 12:00 pm during winter season ($\omega = 1$ and $\omega = 4$), and for t in 23:00 pm - 13:00 pm during summer season ($\omega = 2$ and $\omega = 3$). The rest of the time the price is 0.1831 €/kWh. And the cost of connection capacity is CTP= 0.1233 €/(kW·day).
- PEV_t^ω is not in the tariff, here we assume a value of $PEV_t^\omega = 0.3 \cdot PEC_t^\omega$.

The values of PVA_t^ω have been obtained considering photovoltaic panels by [16] and the solar irradiation in the station of Churriana in Malaga (Spain) from [17].

IV. RESULTS

The results from the two approaches are described and discussed in this section. The results from the optimization problem are taken as a benchmark, because they are calculated with perfect foresight. The results from the rule-based operation are calculated using only the available information on real time, and therefore are always worst or equal to the results from the optimization problem.

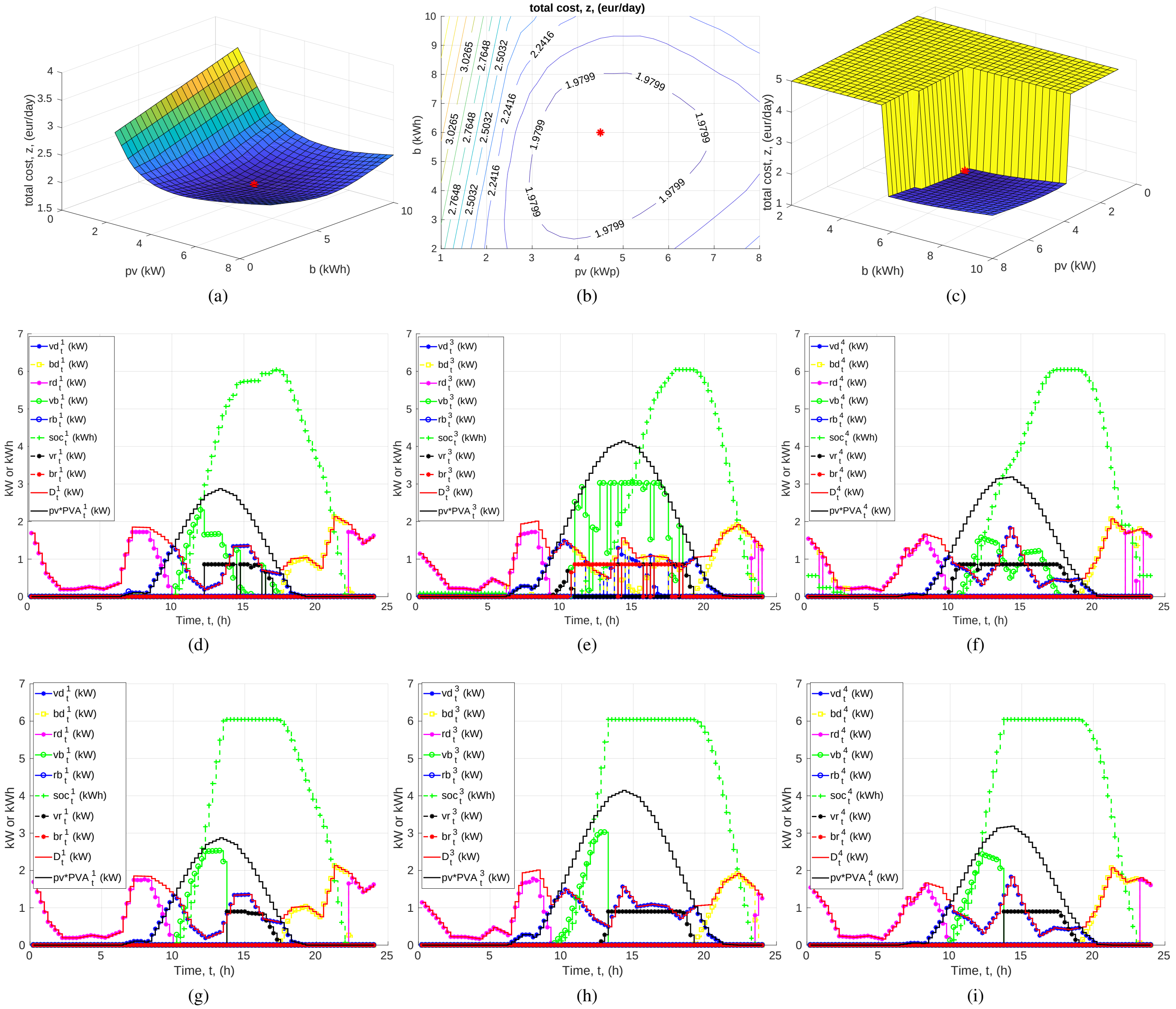
For the optimization problem and the data for the case study we get these results: pv = 4.44 kWp, b = 6 kWh, ccc = 1.72 kW, $cci = 0.5 \cdot ccc$, and a total cost of 1.75 €/day. The equation for the total cost is (1), and the operation for typical days is shown in Figs. 3d (winter), 3e (summer), and 3f (autumn). In case of being a passive consumer (without PV + battery) the total cost for the customer is 3.32 €/day, (energy + connection). The total cost for the rule-based operation, with the sizes provides by the optimization problem, is 1.83 €/day. The total cost for the rule-based operation is only 4.6% greater than the value from the optimization problem with perfect foresight. That is quite interesting because shows that an implementation based on simple rules and using only information available in real time can be quite effective, almost as effective as an optimization assuming perfect foresight.

Rules defined in Section II-C allows us to calculate the total cost for a given installation size, but those rules can be used also to size the system. We have to calculate the value of three components: ccc, pv and b. Here, we get those values by inspection, by calculating the total cost for a number of configurations with different values of ccc, pv and b, and selecting the configuration that provides the minimum cost. For a given value of ccc the optimal values (minimum total cost) for pv and b are calculated by evaluating the configuration for pv and b taking values in a certain range. That results in a three dimensional surface for the total cost, with pv in an axis, b in other axis, and total cost in the third axis, as it is shown in Fig. 3a (ccc = 2.5 kW) and Fig. 3c (ccc = 1.8 kW). In these surfaces the point of minimum cost is indicated with a red asterisk. In Fig. 3a all the configurations are feasible but in Fig. 3c some configurations are unfeasible, those with a cost of 5 €/day.

Optimal values for pv and b, and also the total cost, for different values of ccc are depicted in Fig. 2. It is interesting to note that the total cost is almost linear with ccc and that the optimal values for pv and b change slowly with ccc. The slope of total cost respect to ccc is smaller than the additional cost of the connection capacity (smaller than CTP). That indicates the additional capacity is used to reduce the total cost, in this case by injecting the surplus of energy to the grid, examples are shown in Figs. 3g, 3h, and 3i.

The sizing results using the rule-based operation are robust, in the sense that the total cost for configurations in a relative wide area around the optimal value are very close to the optimum. We can see and example of that in Fig. 3b, that corresponds to the contours of surface in Fig. 3a. We can observe in Fig. 3b a wide flat area around the optimal value (red asterisk).

Power flows among the system components are depicted in Figs. 3d, 3e, and 3f for the optimization problem, and in Figs. 3g, 3h, and 3i for the rule-based operation. As it can be seen in Figs. 3d, 3e, and 3f, the battery is not charged from the grid in the optimization problem, that is because that energy could be used only in some hours in the morning, just before the PV installation begins to produce energy. In that time-step, the tariff has the same price (reduced price) than in the night time-steps at which the battery could be charged. Thus, it is



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 3. (a) Surface for total cost in rule-based operation with *ccc* = 2.5 kW; (b) Contour for total cost in rule-based operation with *ccc* = 2.5 kW; (c) Surface for total cost in rule-based operation with *ccc* = 1.8 kW (unfeasible configurations are marked with a total cost of 5 €/day); (d) Power flows for optimization and perfect foresight, for scenario ω = 1; (e) Power flows for optimization and perfect foresight, for scenario ω = 3; (f) Power flows for optimization and perfect foresight, for scenario ω = 4; (g) Power flows for rule-based operation, for scenario ω = 1; (h) Power flows for rule-based operation, for scenario ω = 3; (i) Power flows for rule-based operation, for scenario ω = 4.

not profitable to charge the battery from the grid with this tariff. Also, for the same reasons, it is not profitable to charge the battery from the grid in the rule-based operation.

Figs. 3d, 3e, and 3f, show the power flows among the system components in rule-based operation using only information available in real time. On the one hand, it is observed how the demand is completely covered by direct consumption from the PV generation when there is enough PV generation. In the hours with low or no PV generation the demand that is not covered by the PV generation is compensated with the battery and the grid. While if the PV generation is high and exceeds demand, there will be a surplus of energy that is first intended to charge the battery. It is also observed that the battery is mainly charged during the dawn and in the time interval with greater solar irradiation, this stored energy is used to cover the demand when the PV generation is insufficient.

On the other hand, in the optimization problem, we appreciate the battery is used in more time-steps than in the rule-based operation, Figs. 3g, 3h, and 3i. That is because in the optimization problem the temporal distribution is better designed to optimally take advantage of the variability in the price of electricity, the demand and the PV generation, since the future values are known.

V. CONCLUSIONS

The optimization problem with perfect foresight is a good reference benchmark to compare the rule-based operation to. In this way, it is quantified how the optimal system size changes depending on the operation method, and also how the operation cost increases when only the real time information is available (no perfect foresight).

One of the great advantages of rule-based operation is the robustness of the solution. There is a relative wide flat area around the optimal value, what allows us to select the design parameters in this area with certain freedom. Since we can move in a relatively wide range. In addition, this flexibility in the design allows us to find different optimum depending on the constraints that we must assume for the design of our installation, for instance constraints in the available room for the installation.

Also, we have to highlight that charging the battery from the grid at valley hours will probably be not profitable because the scheduling of the tariff prices and the availabity of power from the PV installation. In any case, it is strongly depending on the tariff, and should be studied for each particular case.

Using rules and only the information available in real time, the cost is around 5% greater than in the case of optimal solution with perfect foresight. Thus, we can say that it is possible to get an almost optimal solution using rule-based operation with easy to implement rules.

REFERENCES

[1] Y. Li and Z. Lukszo, "The cost-effective pathways for power decarbonization: Low-carbon generation technologies," pp. 1–6, Dec 2014.

[2] M. Liserre, T. Sauter, and J. Y. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Industrial Electronics Magazine*, vol. 4, pp. 18–37, March 2010.

[3] International Energy Agency (IEA), "Smart Grid - Smart Customer Policy Needs," Tech. Rep. Grayson Heffner, April 2011.

[4] International Renewable Energy Agency (IRENA), "Renewable Power Generation Costs in 2018," Tech. Rep. ISBN: 978-92-9260-126-3, May 2019.

[5] T. Weitzel and C. H. Glock, "Energy management for stationary electric energy storage systems: A systematic literature review," *European Journal of Operational Research*, vol. 264, no. 2, pp. 582 – 606, 2018.

[6] A. Soroudi and T. Amraee, "Decision making under uncertainty in energy systems: State of the art," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 376 – 384, 2013.

[7] D. Azuatalam, K. Paridari, Y. Ma, M. Förstl, A. C. Chapman, and G. Verbič, "Energy management of small-scale pv-battery systems: A systematic review considering practical implementation, computational requirements, quality of input data and battery degradation," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 555 – 570, 2019.

[8] N. Jayasekara, P. Wolfs, and M. A. Masoum, "An optimal management strategy for distributed storages in distribution networks with high penetrations of PV," *Electric Power Systems Research*, vol. 116, pp. 147 – 157, 2014.

[9] W. Ma, W. Wang, X. Wu, R. Hu, F. Tang, and W. Zhang, "Control strategy of a hybrid energy storage system to smooth photovoltaic power fluctuations considering photovoltaic output power curtailment," *Sustainability*, vol. 11, no. 5, 2019.

[10] A. Chauhan and R. Saini, "A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 99 – 120, 2014.

[11] T. Morstyn, B. Hredzak, and V. G. Agelidis, "Control Strategies for Microgrids With Distributed Energy Storage Systems: An Overview," *IEEE Transactions on Smart Grid*, vol. 9, pp. 3652–3666, July 2018.

[12] Z. Wu, X. Zhang, J. Brandt, S. Zhou, and J. Li, "Three Control Approaches for Optimized Energy Flow With Home Energy Management System," *IEEE Power and Energy Technology Systems Journal*, vol. 2, pp. 21–31, March 2015.

[13] The MathWorks, Inc., "Matlab release 2018b." Natick, Massachusetts, United States, 2018.

[14] GAMS Development Corporation, "General Algebraic Modeling System (GAMS) Release 24.1.3." Washington, DC, USA, 2013.

[15] Iberdrola, "Tarifa plan noche (night plan tariff)." Consulted on January 2020, [Online] https://www.iberdrola.es/luz/mac/plan-noche.

[16] Amerisolar, Worldwide Energy and Manufacturing USA Co., Ltd, "ASK-M." Consulted on January 2020, [Online] http://www.weamerisolar.com.

[17] Agencia Andaluza de la Energía (AAE), "Aplicación Radiación Solar." Consulted on April 2019, [Online] https://www.agenciaandaluzadelaenergia.es/radiacion/radiacion1.php.