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Parameterization of a Photovoltaic and a Battery System Add-On for a Consumer Based on a Sequential Linear Program

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Abstract

This paper describes a procedure for optimal sizing of the investment in a renewable electricity source and electricity storage for a particular consumer with a known electricity consumption profile, under the given conditions of allowed return on investment period and with the optimal operation of the battery storage system included. The optimal size of the PV system in terms of its power production under standard test conditions is provided, as well as the optimal size of the battery storage system in terms of its power converter power rating and the storage capacity. The procedure is based on a sequential linear programming method which enables the computations tractability on regularly sized computers.

Keywords: *optimal sizing, sequential linear programming, photovoltaic system, battery energy storage system*

1. Introduction

Energy storage is nowadays recognized as a key element in a modern energy supply chain. This is mainly because it can enhance grid stability, increase penetration of renewable energy resources, improve the efficiency of energy systems, conserve fossil energy resources and reduce environmental impact of energy generation

[1]. Furthermore, energy storages in combination with renewable energy sources can significantly reduce a consumer's electricity bill [2].

Because of the mature technologies, ease of use and installation, and relatively low prices, photovoltaic (PV) and battery energy storage systems (BESSs) are a good choice for a renewable energy source and energy storage solution. A procedure is proposed to support the design process of those systems for a new consumer. Unlike in [3] and [4] where authors used evolutionary algorithms to find (near) optimal parameters, this procedure uses a sequential/successive linear programming (SLP) method to determine parameters of the PV system and the BESS close to true optimal values. Those parameters are the peak power of the PV system, energy capacity of the BESS and maximum power of the BESS power converter. Peak power of the PV system is provided in terms of its power production under standard test conditions (STC): 1000 W/m^2 input irradiance and 25°C PV modules temperature.

The prices for feed-in energy are considerably low compared to the prices for energy coming from the utility grid. This difference in prices does not bring any cost benefit to the consumer when selling the excess of energy to the utility company. Therefore, the procedure focuses on net-zero rather than on net-positive approach. The goal is to keep the consumer as independent as possible of the utility, i.e. to have as little as possible energy exchange with the utility. That way the electricity bill for the consumer is minimized. The greater the difference in price between buying and selling the energy, the lower is the payback period when buying a BESS along with a PV system.

The similar procedure is described in [5], where the optimization consists of a single linear programming (LP) problem. However, such an LP problem is too large to be solved on a regular computer which is a targeted hardware for this procedure, as it is a part of an energy management tool freely available at [6]. This procedure, in contrast to the one described in [5], uses a SLP method where a series of smaller LP problems are solved which results in a somewhat slower execution but in significantly lower hardware requirements.

The rest of this paper is organized as follows. The procedure considered herein is formulated in Section 2. In Section 3 the results for a real-life consumer are presented. Concluding remarks are given in Section 4.

2. Procedure formulation

The mentioned optimal parameters are computed based on the measured electrical energy consumption at the consumer's grid connection point, and a PV energy production. As the PV system is yet to be installed, global solar irradiance measurements and sun angles (elevation and azimuth) during the year are used. Together with orientation and inclination angles of the planned PV solar arrays, a possible PV production profile, P_{PV}, is generated by scaling a reference profile $P_{PV,ref}$.

Instead of solving one large LP problem,

$$\begin{aligned} &\min_x f^T x \\ &s.t.\ A_{\text{ineq}} x \leq b_{\text{ineq}}, \\ &A_{\text{eq}} x = b_{\text{eq}}, \\ &x_{\min} \leq x \leq x_{\max}, \end{aligned} \tag{1}$$

the result is obtained by solving a series of smaller LP problems, i.e. by utilizing a SLP method, where solving one LP is called iteration. Iterations are separated into:

- Initial iteration (1 iteration),
- Efficiency and degradation iteration (1 iteration),
- Feed-in price iterations (≥1 iterations),
- Converging iterations (≥1 iterations).

The calculation process can be stopped in any iteration if the PV and BESS turn out to be economically non-viable.

Initial iteration

In the initial iteration, the state of energy of the battery, *SoE*, is influenced by BESS charging (or discharging) power, P_{bat}, without efficiency included, i.e. it is considered that there are no energy losses:

$$SoE(k+1) = SoE(k) + P_{\text{bat}}(k) T_s \tag{2}$$

where T_s is the sampling time and P_{bat} is positive while charging, and negative while discharging. The power exchange with the utility grid is calculated as

$$\begin{aligned} P_{\text{grid}}(k) = P_{\text{dem}}(k) + P_{\text{bat}}(k) \\ - \alpha_{\text{PV}} P_{\text{PV},ref}(k), \end{aligned} \tag{3}$$

where α_{PV} is a scaling coefficient used to calculate the optimal peak power of the new PV system with respect to the one obtained from the known solar irradiance profile.

The cost function, $f(x)$, which is minimized by solving each of the LP problems, equals the price of the energy exchange with the utility grid $J_{\text{yes,inv}}$:

$$\begin{aligned} J_{\text{yes,inv}} = c_{\text{grid}} \sum_{k=0}^{N-1} P_{\text{grid}}(k) T_s \\ + c_{\text{peak}} \sum_{l=1}^{12} P_{\text{peak}}(l) \end{aligned} \tag{4}$$

where c_{grid} is the price of electricity from the utility grid, N is the length of the horizon, c_{peak} is the price of the monthly peak power, and P_{peak} is the monthly peak power.

Before defining the optimization vector and the constraints, two more variables need to be defined: the cost of the investment denoted by J_{inv}, and the cost of yearly maintenance denoted by J_{ym}.

$$\begin{aligned} J_{\text{inv}} = c_{\text{bat}} SoE_{\max} + c_{\text{pc}} P_{\text{pc,max}} \\ + c_{\text{PV}} P_{\text{PV,peak},ref} \alpha_{\text{PV}}, \end{aligned} \tag{5}$$

$$J_{\mathrm{ym}} = \frac{c_{\mathrm{bat}}}{n_{\mathrm{bat}}} SoE_{\mathrm{max}} + \frac{c_{\mathrm{pc}}}{n_{\mathrm{pc}}} P_{\mathrm{pc,max}} + \frac{c_{\mathrm{PV}}}{n_{\mathrm{PV}}} P_{\mathrm{PV,peak,ref}} \alpha_{\mathrm{PV}}, \quad (6)$$

where c_{bat} is the price of the battery pack per unit of energy capacity, SoE_{max} is the energy capacity of the battery, n_{bat} is the lifetime of the battery pack in years, c_{pc} is the price of the power converter per unit of power, $P_{\mathrm{pc,max}}$ is the nominal power of the power converter, n_{pc} is the lifetime of the power converter in years, c_{PV} is the price of the PV system per unit of the installed power, and n_{PV} is the lifetime of the PV system in years.

The length of the prediction horizon is N, while the optimization vector x consists of:

- charging/discharging powers of the BESS, $P_{\mathrm{bat}}(k)$, $k \in [0 \dots N-1]$;
- monthly peak power of power exchange with the grid, $P_{\mathrm{peak}}(l)$, $l \in [1 \dots 12]$;
- starting state of energy of the battery, $SoE(0)$;
- energy capacity of the battery pack, SoE_{max};
- nominal power of the power converter, $P_{\mathrm{pc,max}}$;
- scaling coefficient of the PV system, α_{PV}.

To fully construct the LP problem (1) and to fully describe the overall system mathematically, equality and inequality constraints must be posed. The only equality constraint makes sure that the calculated sequence is repeatable, i.e. the last instance of the BESS state of energy must be equal to the starting one:

$$SoE(0) = SoE(N). \quad (7)$$

Inequality constraints, inter alia, make sure that:

- the battery is never under- nor over-charged,

$$(1 - DoD) SoE_{\mathrm{max}} \le SoE(k) \le SoE_{\mathrm{max}}, \quad \forall k \in [0 \dots N-1], \quad (8)$$

- the power converter operates within its limits,

$$-P_{\mathrm{pc,max}} \le P_{\mathrm{bat}}(k) \le P_{\mathrm{pc,max}}, \quad \forall k \in [0 \dots N-1], \quad (9)$$

- the peak power for each month is correctly evaluated ahead of minimization,

$$P_{\mathrm{peak}}(l) \ge P_{\mathrm{grid,max}}(k), \forall k \in \text{month } l \quad (10)$$

- the total investment does not exceed the limit determined by the user,

$$J_{\mathrm{inv}} \le J_{\mathrm{inv,max}} \quad (11)$$

- the investment is paid off within the set number of years,

$$J_{\mathrm{no,inv}} - J_{\mathrm{yes,inv}} \ge \frac{J_{\mathrm{inv}}}{n_{\mathrm{payoff}}} + J_{\mathrm{ym}}. \quad (12)$$

The variable $J_{\mathrm{no,inv}}$ is the cost of the energy exchange with the grid for the case of no investment performed, and DoD is the allowed depth of the battery system discharge.

Upon constructing and solving the LP with cost (4) and constraints (7) – (12), the results are saved and transferred to the next iteration.

Efficiency and degradation iteration

After solving the initial iteration, the efficiency of the BESS and the degradation of the battery pack can be introduced. Since the loss functions are linear at k only if $P_{\mathrm{bat}}(k)$ does not change its sign, a new auxiliary variable $CoD(k)$ is introduced, which determines if the battery charges or discharges at k: $CoD(k)=1$ while charging, and $CoD(k)=-1$ while discharging. After the initial iteration it is calculated as:

$$CoD^0(k) = \begin{cases} 1 \text{ when sign}\left(P_{\mathrm{bat}}^0(k)\right) = 0 \\ \text{sign}\left(P_{\mathrm{bat}}^0(k)\right) \text{ otherwise.} \end{cases} \quad (13)$$

where $CoD^0(k)=1$ if the battery was neither charged nor discharged. In further iterations enumerated with i the (dis)charging power $P_{\mathrm{bat}}(k)$ should be able to change the sign, and this is ensured by changing $CoD(k)$ from 1 to –1 when $P_{bat}(k)$ changes from positive value to zero, and from –1 to 1 when $P_{bat}(k)$ changes from negative value to zero:

$$CoD^i(k) = 2\,\text{sign}\left(P_{\mathrm{bat}}^{i-1}(k)\right) - CoD^{i-1}(k). \quad (14)$$

With the variable determining the direction of the power flow to/from the battery, the efficiency of the BESS at timestamp k, $\eta(k)$ can be expressed as:

$$\eta(k) = \max\left(0, \eta_{\mathrm{ch}} CoD(k)\right) - \min\left(0, \frac{1}{\eta_{\mathrm{dch}}} CoD(k)\right), \quad (15)$$

where η_{ch} and η_{dch} are charging and discharging efficiencies. The state of charge of the battery can now be expressed with:

$$SoE(k+1) = SoE(k) + \eta(k) P_{\mathrm{bat}}(k) T_s. \quad (16)$$

The cost of the battery degradation is expressed per unit of energy that goes through it, and it is calculated as:

$$c_{\mathrm{deg}} = \frac{c_{\mathrm{bat}}}{2 n_{\mathrm{cyc}} DoD}, \quad (17)$$

where n_{cyc} is the number of cycles that the battery pack can go through without significantly reducing its capacity. With the degradation costs defined, the costs of the annual maintenance are now calculated as:

$$J_{\text{ym}} = c_{\text{deg}}T_{\text{s}}\sum_{k=0}^{N-1} CoD(k)\eta(k)P_{\text{bat}}(k) + \frac{c_{\text{pc}}}{n_{\text{pc}}}P_{\text{pc,max}} + \frac{c_{PV}}{n_{PV}}P_{PV,\text{peak},ref}\alpha_{PV}. \quad (18)$$

Due to the new definitions of $SoE(k)$ and J_{ym}, the constraints (7), (8) and (12) are updated in the corresponding LP. Furthermore, a new set of constraints is introduced. It makes sure that the (dis)charging power of the battery does not change its sign:

$$\begin{cases} P_{\text{bat}}(k) \geq 0 \text{ when } CoD(k) = 1, \\ P_{\text{bat}}(k) \leq 0 \text{ when } CoD(k) = -1. \end{cases} \quad (19)$$

Feed-in price iterations

So far, the price for the energy exchanged with the utility grid was the same regardless of the sign. For example, if the energy is fed into the grid due to high PV production, the price for it was the same as for buying the energy. However, feed-in prices are normally significantly lower than buying prices. Therefore, a new auxiliary variable $BoS(k)$, which determines whether the energy is bought or sold at timestamp k, is introduced: $BoS(k)=1$ when buying the energy, and $BoS(k)=-1$ when selling the energy. After the initial iteration it is calculated as:

$$BoS^0(k) = \begin{cases} 1, \text{when sign}\left(P^0_{\text{grid}}(k)\right) = 0 \\ \text{sign}\left(P^0_{\text{grid}}(k)\right) \text{ otherwise} \end{cases}, \quad (20)$$

where $BoS^0(k)=1$ if the energy is neither bought nor sold. In further iterations the power exchanged with the grid $P_{\text{grid}}(k)$ should be able to change the sign, and this is ensured by changing $BoS(k)$ from 1 to –1 when $P_{\text{grid}}(k)$ changes from positive value to zero, and from –1 to 1 when $P_{\text{grid}}(k)$ changes from negative value to zero:

$$BoS^i(k) = 2\,\text{sign}\left(P^{i-1}_{\text{grid}}(k)\right) - BoS^{i-1}(k). \quad (21)$$

Therefore, the price of energy exchange with the grid, $c_{\text{el}}(k)$, can be defined depending on $BoS(k)$:

$$c_{\text{el}}(k) = \max\left(0, c_{\text{grid}}BoS(k)\right) - \min\left(0, c_{\text{feed}}BoS(k)\right), \quad (22)$$

where c_{feed} is the feed-in price of the electrical energy. With the newly defined energy price, the cost of energy exchange with the grid, equation (4), now becomes:

$$J_{\text{yes,inv}} = \sum_{k=0}^{N-1} c_{\text{el}}(k)P_{\text{grid}}(k)T_{\text{s}} + c_{\text{peak}}\sum_{l=1}^{12} P_{\text{peak}}(l). \quad (23)$$

Due to the new definitions of $J_{\text{yes,inv}}$ the cost function of the LP and constraint (12) are updated. Furthermore, a new set of constraints is introduced. It makes sure that the power exchange with the utility grid does not change its sign,

$$\begin{cases} P_{\text{grid}}(k) \geq 0 \text{ when } BoS(k) = 1, \\ P_{\text{grid}}(k) \leq 0 \text{ when } BoS(k) = -1. \end{cases} \quad (24)$$

There is no guarantee on feasibility for the newly formed LP. Because of the lowered feed-in price the revenue from selling the energy will be lowered which means a lower investment possible, and with fixed directions of power flows between the consumer and the grid there might be no feasible solution. Therefore, the feed-in price c_{feed} is gradually changed until the proper solution is found.

Firstly, the LP is formulated with the proper feed-in price c_{feed}. If the solution is feasible then the procedure proceeds to the converging iterations. On the other hand, if the solution of this LP is infeasible, the feed-in price is artificially brought halfway back to the buying price c_{grid} as $c_{\text{feed,artificial}}=(c_{\text{grid}}+c_{\text{feed}})/2$. If the solution is infeasible again, the halving of the interval between current feed-in price and the buying price is repeated until the feasible solution is found. After the feasible solution is found, the LP is formulated again with the proper feed-in price. This time, if the solution is infeasible, the new artificial feed-in price is brought halfway back to the feed-in price that resulted in feasible solution for the last iteration: $c_{\text{feed,artificial}}=c^{i-1}_{\text{feed}}+c_{\text{feed}})/2$. If the solution is infeasible again, the procedure of interval halving is repeated until a feasible solution is obtained.

Converging iterations

The last set of iterations is carried out until convergence. The LP problems have the same construction as the feed-in price iterations. The only difference is the feed-in price that is now fixed at the proper value. Every time the LP problem is solved auxiliary variables CoD and BoS are updated. Also, every time the LP is solved, the value of its cost function is compared with the minimal value so far. If it is less than the minimum so far, the procedure continues with further iterations. However, if the value of the cost function is greater than the minimum so far, the counter for convergence increases by 1. When the counter reaches the setpoint number the procedure ends, and the optimal result is the one with the minimum value of the cost function.

3. Results

The site used for showcasing the results of the procedure is Bračak manor in Croatia. It is a recently refurbished manor used as an office space. Its power consumption over a one-year horizon is shown in Figure 1. The length of the prediction horizon in this case is N = 35136, since 2018 was a leap year, and the sampling time was T_s = 15 min.

The canopy built at the site where the PV array was installed has south-west orientation, and it is inclined by 15°. With such an orientation and inclination angles the possible PV production with the peak power of 3 kWp has the profile shown in Figure 1.

The lifetime of the PV system is 25 years, which is a typical warranty time for solar panels. The results presented were obtained for two different prices of the PV system: 1050 €/kWp, and 420 €/kWp which is the original price with 60% subsidies. Other parameters are:

- Number of cycles (n_{cyc}): 2000
- Depth of discharge (DoD): 0.8 (80%)
- Discharging efficiency (η_{dch}): 0.9 (90%)
- Charging efficiency (η_{ch}): 0.9 (90%)
- Lifetime of power converter (n_{pc}): 25 years
- Price of the new battery pack (c_{bat}): 770 €/kWh
- Price of the new power converter (c_{pc}): 660 €/kW

The results are presented in Tables 1, 2, and 3.

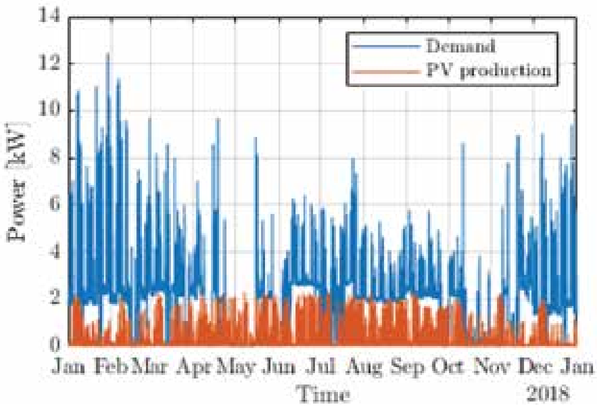

Figure 1. Electric power demand profile P_{dem} at Bračak site for year 2018, and the nominal (α_{PV}=1) PV production profile.

Table 1. Optimal PV + BESS sizes for the Bračak site for the investment payoff period, n_{payoff}, of 10 years.

PV system subsidies	0%	60%
Battery capacity (SoE_{max}) [kWh]	0.00	2.60
Power converter power ($P_{pc,max}$) [kW]	0.00	1.91
PV system peak power ($P_{PV,peak}$) [kWp]	0.00	9.97

Table 2. Optimal PV + BESS sizes for the Bračak site for the investment payoff period, n_{payoff}, of 15 years.

PV system subsidies	0%	60%
Battery capacity (SoE_{max}) [kWh]	0.00	3.23
Power converter power ($P_{pc,max}$) [kW]	0.00	1.65
PV system peak power ($P_{PV,peak}$) [kWp]	10.00	10.00

Table 3. Optimal PV + BESS sizes for the Bračak site for the investment payoff period, n_{payoff}, of 20 years.

PV system subsidies	0%	60%
Battery capacity (SoE_{max}) [kWh]	0.00	4.93
Power converter power ($P_{pc,max}$) [kW]	0.00	3.17
PV system peak power ($P_{PV,peak}$) [kWp]	10.00	10.00

4. Conclusion

In this paper a procedure to find optimal sizing parameters of a PV system in combination with a BESS for a particular consumer is outlined. Optimal parameters are the peak power of the PV system, and battery energy capacity and power converter rated power of the BESS. Furthermore, the procedure also gives optimal charging and discharging powers at each time step for the whole horizon. The procedure uses pre-recorded energy consumption of the consumer and possible PV power production. The backbone of the procedure is an SLP method that replaces the large and memory-intensive LP problem which guarantees to find the global optimum. The paper contains a detailed explanation of the procedure and the formulation of the subsequent LP problems with their constraints and cost functions and gives experimental results for a real consumer.

Acknowledgment

This work was supported by the Interreg CENTRAL EUROPE Programme, funded under the European Regional Development Fund, through the project Integration and smart management of energy storages at historical urban sites (Store4HUC, https://www.interreg-central.eu/Store4HUC).

References

[1.] Aneke, M. and Wang, M. (2016). Energy Storage Technologies and Real Life Applications – A state of the art review. Applied Energy, 179, 350-377.

[2] Sharma, V., Haque, M. H., and Aziz, S. M. (2019). Annual Electricity Cost Minimization for South Australian Dwellings through Optimal Battery Sizing. In Proc. IEEE Milan PowerTech, 1-6.

[3] Farahmand, M. Z., Nazari, M. E. and Shamlou, S. (2017). Optimal sizing of an autonomous hybrid PV-wind system considering battery and diesel generator. In Proc. Iranian Conference on Electrical Engineering (ICEE), 1048–1053.

[4] Mahesh, A. and Sandhu, K. S. (2016). Optimal sizing of a PV/Wind hybrid system using pigeon inspired optimization. In Proc. IEEE 7th Power India International Conference (PIICON), 1-6.

[5] Rukavina, F. and Vašak, M. (2020). Optimal parameterization of a PV and a battery system add-on for a consumer. In Proc. IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 619-622.

[6] Store4HUC project, Interreg Central Europe. (2019). Available at: www.interreg-central.eu/Store4HUC