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***Abstract*—To ensure high performance, reliability, and economic profitability of a PV-battery system, the sizing of key components, such as PV panels and battery, are important during the design stage. Sizing procedures with low complexity and minimum input data requirement have become a more appealing solution than complex optimization methods. However, accuracy of such simplified sizing principles, e.g., compared to comprehensive models, should be investigated for different installation site conditions. Hence, in this paper, a robustness evaluation of currently available simplified sizing principle is performed where various mission profiles are considered. The analysis results have shown that using a simplified sizing principle results in less than 5% error in economic profitability compared to ones from the comprehensive model which includes advanced performance, lifetime and economic aspects.**

***Index Terms*—Photovoltaic system, battery, DC/DC converters, economic profitability, lifetime, net present value, reliability.**

I. Introduction

Since 2010, photovoltaic (PV) systems have continuously accounted for the largest share of the investments out of all renewable energy sources [1], [2]. Moreover, an increasing number of PV systems are nowadays coupled with battery energy storage due to the improved technology and decreasing price of battery units [3]–[5]. These systems need an adequate design to ensure the economic profitability with considered high system performance, efficiency, reliability, etc. One of the key parameters to ensure the aforementioned requirements is a proper sizing procedure of the key components during the system design.

Previous research on the topic of PV-battery sizing has mainly focused on developing complex optimization algorithms, as e.g., non-linear and linear optimization models [6]–[10]. Two of the main disadvantages of such sizing approach are high complexity and computational burden. Moreover, developed optimization methods are often tested for single case study [11]–[13] and their accuracy under other operating conditions, e.g., mission profiles, have not been investigated yet. Additionally, it is worth mentioning that PV power generation and load demand time series profile including longer time periods (e.g., years) are not always accessible. For that reason, short time periods examining specific set of operating conditions are often considered in the sizing procedure [14]. However, current industry requirements imply fast and accurate solutions in the sizing process covering a large spectrum of operating conditions. Hence, simplified principles which are used as a sizing guidance based on limited information are often seen as advantageous compared to comprehensive and complex optimization models.

One of the simplified sizing principles, which has been widely used is presented in [15], where only the information about the annual PV energy production and load demand are used for the sizing of the battery system. This approach is characterized as simple and practical from the availability of data point of view. However, the sizing principle proposed in [15] is to a certain degree an approximation and its robustness against different operating conditions has not be validated. Hence, it is unclear whether the simplified sizing principle can be applied to the PV-battery system over a wide range of installation sites.

With respect to that, the robustness of the simplified sizing principle is investigated in this paper. This is done by comparing the profitability of the PV-battery system sized based on the simplified sizing approach and a comprehensive one, which includes the performance model, lifetime model, and economic model of the system. In that way, the error introduced by the simplified sizing procedure in the design stage is evaluated. Furthermore, six different mission profiles covering a large spectrum of operating conditions (in terms of solar irradiance and temperature characteristics) are used as a part of the robustness analysis. The information on accuracy and robustness of simplified sizing principle resulting with this study is of a great value for practical applications. In fact, it gives a valuable information on extend to which the simplified sizing rule can be used and still achieve high efficiency and economic profitability of PV-battery systems. With respect to that, in Section II, two sizing approaches based on a simplified sizing rule and a comprehensive model are presented. A case study covering different operating conditions (six geographical locations) is outlined in Section III. In Section IV, the results of a robustness analysis are presented and general guidelines for PV-battery system sizing are discussed. Finally, Section V provides concluding remarks.

II. Sizing of Residential PV-Battery Systems

A. *Simplified Sizing Rule*

A simplified rule used for PV-battery sizing is presented in [15] in details. To determine the adequate battery size (e.g., capacity), the annual rate of the energy yield from the PV panels and load demand are required as input parameters. If the annual energy demand of the local (household) load is higher than the annual PV energy generation, the battery size (e.g.,

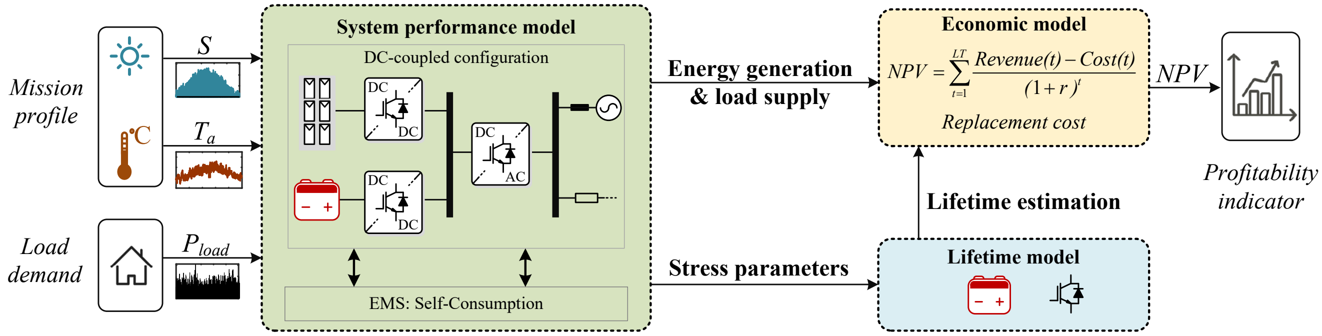

Fig. 1. Diagram of the comprehensive model used for the determination of adequate PV and battery size. Model consists of three parts – system performance, lifetime and economic. Inputs to the model are solar irradiance S, ambient temperature T_a and load demand P_{load}. Output of the comprehensive model is net present value NPV.

energy capacity) should be selected as a half of the average daily PV energy generation. On the contrary, if the annual energy demand is lower than the annual PV energy generation, the battery size is a half of the average daily energy demand. The simplified battery sizing principle can thus be summarized as follows:

$$E_{bat} = \begin{cases} 0.5 \times \frac{E_{PV}}{365} & , E_{PV} < E_{load} \\ \\ 0.5 \times \frac{E_{load}}{365} & , E_{PV} > E_{load} \end{cases} \quad (1)$$

where E_{bat} is sized battery energy capacity being determined by the simplified sizing rule, E_{PV} is annual rate of energy yield from the PV panels and E_{load} is annual energy demand of the local load.

This sizing methodology requires limited input information (the annual PV energy generation and load demand) which, in general, can be easily obtained/estimated. Furthermore, both input parameters are installation site dependent. However, the energy yield from the PV panels is subjected to greater variations due to the different environmental conditions at the installation site (e.g., solar irradiance and ambient temperature) than the local (household) load demand. In fact, the majority of the household load profiles at different geographical locations share similar statistical characteristic due to common habits of the household consumers [16]. Thus, the estimated battery size based on (1) is dominantly influenced by the installation site conditions (e.g., solar irradiance and ambient temperature).

B. Comprehensive Model for Sizing

In contrary to the simplified sizing procedure, a comprehensive sizing principle requires a certain set of models in order to determine the optimal battery size for a given operating condition, e.g., mission profile. The results of sizing procedure based on this model are not influenced directly by the installation site condition in a same manner as in the simplified rule. In the comprehensive model, the installation site conditions are reflected in the performance, lifetime, and economic parameters as well as their interaction. For that reason, three adequate models used to capture those contributions are required.

The first one is the system performance model to evaluate the energy generation and distribution. This model is, further on, connected to the lifetime model which estimates lifetime of the system components for given set of operating conditions. Finally, the resulting lifetime estimation and energy generation and distribution are connected to the economic model which determines the system profit. An overview of the comprehensive model and the connections among its parts is shown in Fig. 1. In the following, the descriptions of the three models are presented. A more detailed modelling process and the associated mathematical expressions are provided in [17].

1) System Performance Model: The system performance model is required to evaluate energy generation and distribution based on the operating conditions at the installation site. First two input parameters consist of the time series of solar irradiance, S, and ambient temperature, T_a. To determine the associated PV panel power generation, electrical characteristic model of the PV panel presented in [18] is used. The third input parameter is time series of load demand, P_{load}. To supply the load demand with the energy generated by the PV panels, the self-consumption energy management strategy is implemented. The main aim of self-consumption is to always prioritize the household load supply from the PV-battery system over electricity supplied from the grid [19]. Considering that, this energy management strategy determines the loading of the battery system, as well as power electronic interface. Notably, when neither PV nor battery can provide power, the load is supplied from the grid.

2) Lifetime Model: During operation, the components of the system are exposed to the stress causing gradual ageing and, eventually, failure [20]. In the PV-battery, power converters and battery are the system's life-limiting components [21]. Hence, it is necessary to evaluate their stress parameters (outlined in Table I) during operation and determine the associated damage. In the developed model, the stress profiles of power converters and battery are junction temperature of Insulated-Gate Bipolar Transistor (IGBT), T_j and battery state-

TABLE I
LIFETIME MODELLING APPROACH OF POWER CONVERTERS AND BATTERIES.

Component	Failure Mechanisms	Stress Factors	Lifetime Model
IGBT in power converter	Bond wire lift-off, solder fatigue	Junction temperature T_j	Number of cycles to failure
Battery	Loss of electrolyte, depletion of active chemicals	State-of-charge SOC	Capacity fade

of-charge, SOC, respectively. Both are obtained in the system performance model. A detail procedure of mapping electrical parameters to the stress parameters is provided in [17], [22]. The stress parameters are, further on, used in the relevant lifetime models to evaluate their lifetime consumption for a given operating conditions [23], [24]. Finally, the evaluated information about the time of failure is used in the economic model for the calculation of the replacement cost.

3) Economic Model: The economic model is used to evaluate the system profitability. Net Present Value (NPV) is the relevant evaluation metric [25], which represents the accumulated profit over system lifetime (LT) and it is defined as:

$$NPV = \sum_{t=1}^{LT} \frac{Revenue(t) - Cost(t)}{(1+r)^t} \quad (2)$$

where r represents discount rate and is used to account for the time value of money, LT is project lifetime, and t is a year of operation. $Revenue$ in the system is generated either by selling excess power to the grid (feed-in tarrif) C_{feed} or as savings in electricity bill due to internal load supply (prioritizing cheaper energy yield from PV-battery system over grid electricity). It is calculated based on the energy distribution evaluated with the performance model, as shown in Fig. 1. $Cost$ of the system accounts for capital cost C_{cpt}^{PV} and C_{cpt}^{bat} and the operation and maintenance cost $C_{o\&m}^{PV}$ and $C_{o\&m}^{bat}$ of the PV and battery unit, respectively. Additionally, it includes the replacement cost of battery C_{rep}^{bat} and power electronics units C_{rep}^{conv}. A summary of the relevant economic parameters is provided in Table II and is based on [26], [27], while a detailed modelling process is presented in [17].

Replacement cost and its occurrence during project lifetime is determined based on the components lifetime information acquired by the lifetime model (see Fig. 1). Hence, the final NPV is influenced by both, performance and lifetime components. For that reason, this parameter can be solely used to examine the influence of different environmental conditions at the installation site.

III. CASE STUDY

A. System Configuration

A PV-battery system under study is a DC-coupled, single-phase, grid-connected system, like shown in Fig. 2(a). Detailed configuration parameters of the system and its components are given in [28]. The power generation unit is PV panel and the energy storage is employed through the lithium-ion battery. The power electronic interface consist of DC/DC converters, i.e., PV converter and battery converter, as well as DC/AC inverter. A uni-directional boost converter topology is used for PV converter which is connected to the PV panels and is used to step up the voltage to DC bus level. The power rating of the DC/DC PV converter system is 6 kW. It consists of two 3 kW units connected in parallel. The loading of the PV converter system is defined by the PV power generation and is equally distributed to the two 3 kW units. Further more,

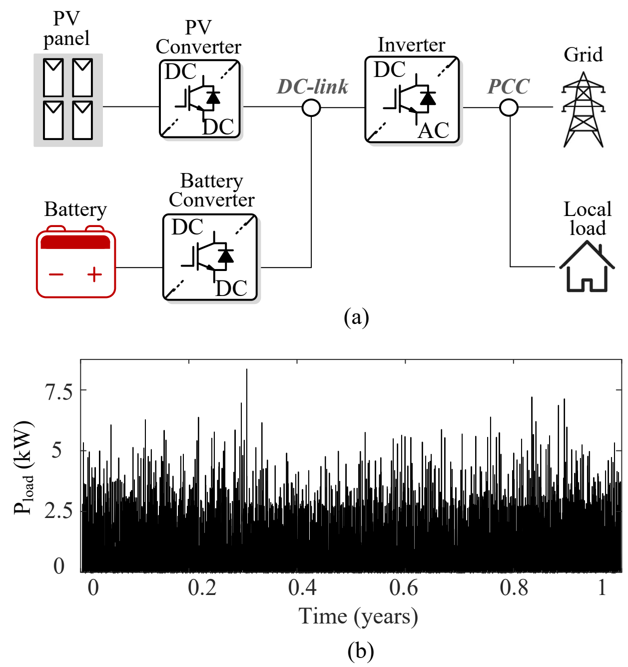

Fig. 2. PV-battery system: (a) DC-coupled configuration, (b) one-year household load profile P_{load}.

TABLE II
PARAMETERS OF THE ECONOMIC MODEL.

Parameter	Value	Description
C_{cpt}^{PV}	1550 USD/kW	PV investment cost
C_{cpt}^{bat}	400 USD/kWh	Battery investment cost
$C_{o\&m}^{PV}$	14.15 USD/kW	PV O&M cost
$C_{o\&m}^{bat}$	7 USD/kWh	Battery O&M cost
C_{rep}^{conv}	18% of C_{cpt}^{PV}	Converter replacement cost
C_{rep}^{bat}	20% of C_{cpt}^{bat}	Battery replacement cost
C_{feed}	0.14 USD/kWh	Feed-in tariff
r	3%	Discount rate
LT	25 years	PV-battery project lifetime

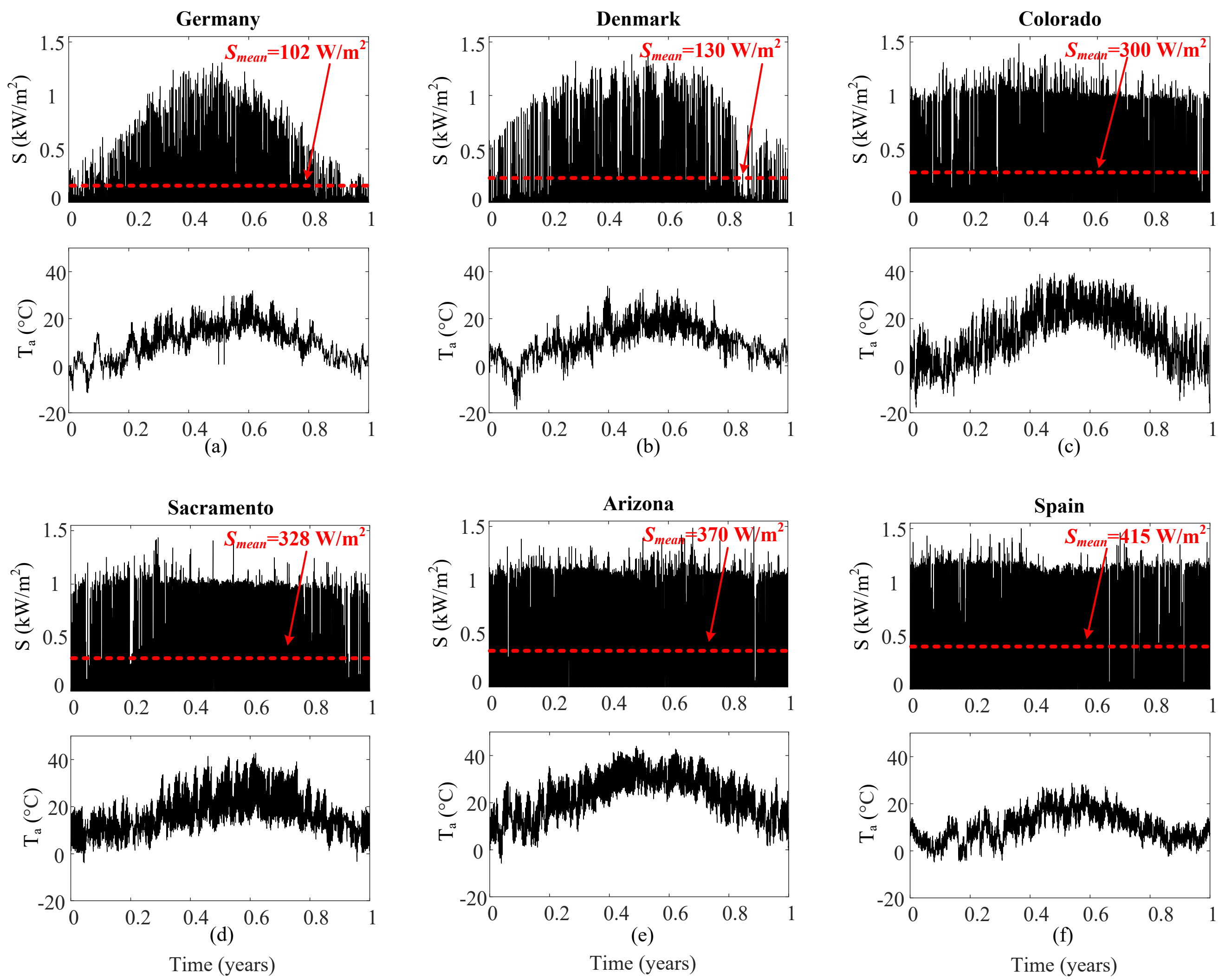

Fig. 3. Mission profile of solar irradiance S and ambient temperature T_a with 5 minutes per sample resolution at the installation site in: (a) Germany, (b) Denmark, (c) Colorado, (d) Sacramento, (e) Arizona, and (f) Spain.

TABLE III
CONFIGURATION PARAMETERS OF THE PV-BATTERY SYSTEM.

Fixed size parameters	
PV converter rated power	6 kW (3 kW x 2 units)
Battery converter rated power	3 kW
PV inverter rated power	6 kW
DC-link voltage	v_{dc}^{*} = 450 V
Grid nominal voltage (RMS)	V_g = 230 V
Varied size parameters	
PV panel rated power	1.5 kW - 6.5 kW
Battery energy capacity	3.5 kWh - 8.5 kWh

a bi-directional buck-boost converter topology is employed for the battery converter. The operation mode depends on the battery charging/discharging processes. The power rating of the DC/DC battery converter is 3 kW. Finally, a 6 kW full-bridge single-phase inverter with four IGBTs is used as a DC/AC inverter to transfer the extracted power to AC side. While performing robustness analysis, in all considered cases, the power rating of the power electronic interface remains unchanged. Contrary, the power rating of the PV panels and the battery energy capacity are varied. This is done in order to find the optimal battery size that results in the highest NPV for each operating condition (e.g., mission profile). The power rating of the PV panels is varied between 1.5 kW and 6.5 kW, with 1 kW increment in each step. The battery energy capacity is varied between 3.5 kWh and 8.5 kWh (with 1 kWh increments), while its power rating remains unchanged and equal to 3 kW, as summarized in Table III.

B. Mission Profile Characterization

To evaluate the robustness of the sizing principle, six mission profiles from different installation sites are considered. The mission profiles are shown in Fig. 3, where the average

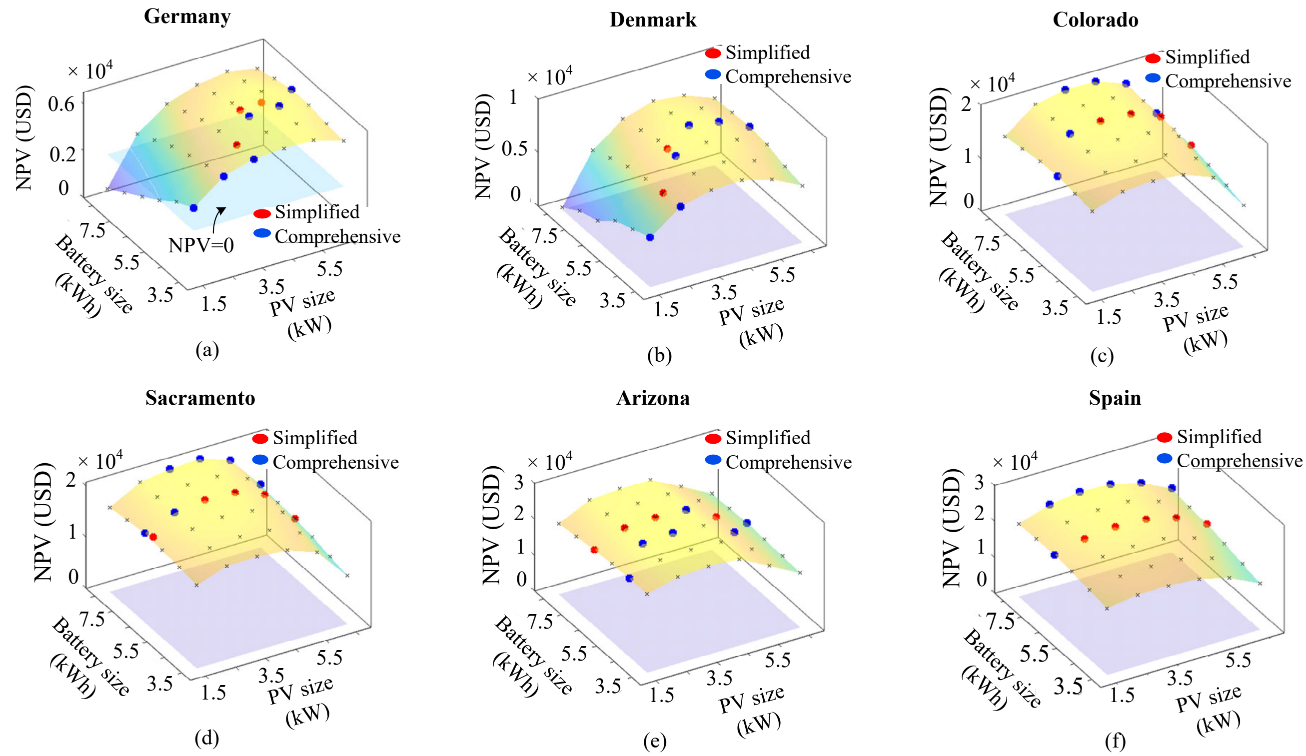

Fig. 4. Net Present Value (NPV) for different PV and battery size of the installation site in: (a) Germany, (b) Denmark, (c) Colorado, (d) Sacramento, (e) Arizona, and (f) Spain. The optimal battery size for chosen PV size marked in red are obtained by following a simplified rule while the blue ones by using a comprehensive model.

solar irradiance S_{mean} is also indicated. The installation sites with generally low solar irradiance and ambient temperature all year round are the mission profiles from Germany and Denmark. The installation sites with larger changes in solar irradiance and ambient temperature during the year with more distinguished seasonal changes are represented by the mission profiles from Colorado and Sacramento. Finally, the installation sites with high solar irradiance and smaller temperature swings are represented by the mission profiles from Arizona and Spain. All the aforementioned profiles are based on the real measurement data sampled with a rate of 5 minutes per sample.

A load profile of a 4-member household like presented in [29] is used in this analysis. The average yearly consumption is 4653 kWh and the one-year load profile is shown in Fig. 2(b). In the case study, the load profile remains the same regardless the installation site analysed. This is done in order to simplify the analysis and demonstrate the impact of mission profile characteristic on the sizing results.

IV. Robustness Analysis

A. Mission Profile Influence

Simulation results obtained from the comprehensive model are shown in Fig. 4 for all six mission profiles. As a part of each NPV diagram, a surface fulfilling the $NPV = 0$ requirement of all sizing combinations is placed. It is indicating the marginal requirement for the project profitability. In fact, for NPVs of all sizing combinations above the $NPV = 0$ surface, the project is considered profitable. This indicates that the generated $Revenue$ during project lifetime LT was higher than the $Cost$.

According to the results, only NPVs for the certain PV-battery sizing combinations in Germany (see Fig. 4(a)) do not fulfill this requirement. This is due to the mission profile characteristics of Germany with low solar irradiance, especially in the winter months, which results in low PV power generation. This can be further analysed on the example of 1.5 kW PV size and 8.5 kWh battery size which yields the lowest NPV. Low solar irradiance results with low PV power production, which is additionally restricted with the small PV panel size. In such case, 8.5 khWh battery energy capacity is greatly over-dimensioned. This results with high initial investment cost, which cannot be covered with the revenue generated due to low PV power production during the project lifetime. Similar is observed in case of Denmark. As shown in Fig. 4(b), in the region of low PV sizes (1.5 kW and 2.5 kW), NPV is low and significantly decreases with the increase in the battery size.

Furthermore, it is observed that the higher the high solar irradiance, the higher the final NPV. For that reason, the NPVs of installation sites in Arizona and Spain are the highest of six installation sites. However, a decrease in NPV for those installation sites is seen for large PV sizes. The main reasoning is the additional replacement cost resulting

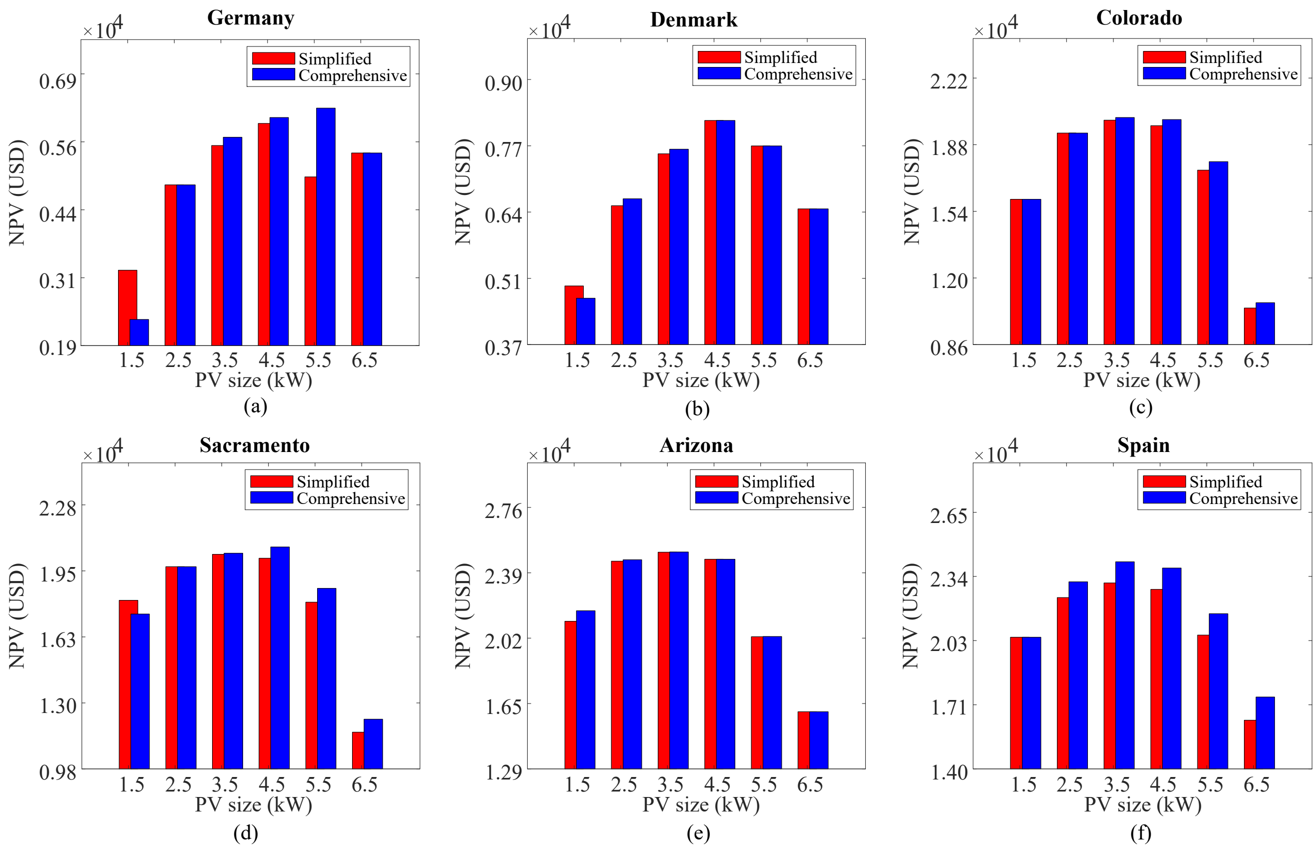

Fig. 5. Comparison of Net Present Value (NPV) for optimal battery size of each investigated PV size at the installation site in: (a) Germany, (b) Denmark, (c) Colorado, (d) Sacramento, (e) Arizona, and (f) Spain.

TABLE IV

RELATIVE DIFFERENCE BETWEEN NPV OF THE OPTIMAL PV AND BATTERY SIZES ACQUIRED BY THE SIMPLIFIED AND COMPREHENSIVE METHOD.

	Optimal PV size and battery size		
Mission profile	Simplified model	Comprehensive model	Relative difference in NPV
Germany	4.5 kW & 6.0 kWh	5.5 kW & 5.5 kWh	4.49 %
Denmark	4.5 kW & 6.5 kWh	4.5 kW & 6.5 kWh	0.00 %
Colorado	3.5 kW & 6.5 kWh	3.5 kW & 8.5 kWh	0.67 %
Sacramento	3.5 kW & 6.5 kWh	4.5 kW & 8.5 kWh	1.75 %
Arizona	3.5 kW & 6.5 kWh	3.5 kW & 5.5 kWh	0.05 %
Spain	3.5 kW & 6.5 kWh	3.5 kW & 8.5 kWh	4.28 %

from the limited lifetime of the system components. This can be further analysed in the case of 6.5 kW PV size and 3.5 kWh battery size yielding the lowest NPV for the installation site in Spain (see Fig. 4(f)). High solar irradiance results with a high PV power production and a great amount of the excess PV power all year round. The excess energy needs to be absorbed by the battery unit with limited capacity. Such situation then leads to accelerated battery ageing and more frequent replacement. Additionally, high PV power production does not only influence the battery lifetime, but also imposes additional loading to the power converters (resulting in lower lifetime). Hence, additional replacement cost in this case has the highest impact on the NPV reduction.

For each investigated PV size, the battery size that results in the highest NPV by using the comprehensive model is marked in blue. Based on the simplified principle, the optimal battery size is determined for each PV size and marked in red. Those optimal sizes are, further on, extracted and shown in 2D diagrams in Fig. 5. As observed, the optimal PV-battery sizes obtained with the two methods are closely aligned for mission profiles with lower solar irradiance (such as Denmark and Germany). On the contrary, the largest mismatch in the optimal PV and battery sizes is seen in the case of Spain (see Fig. 4(f)). Hence, it can be concluded that the mission profile is influencing the alignment in the size of PV and battery according to the two methods. However, it is necessary to investigate the mismatch impact on economic profitability, which is discussed in the following.

B. General Guidelines for Sizing

The analysis of the NPV results in Fig. 5 has shown that NPV of the system size designed with the comprehensive model yields higher NPV in more than 90% cases. To further investigate the mismatch in NPV, the optimal sizes for each installation site are analysed. Only in case of Denmark, the optimal PV and battery sizes obtained by the comprehensive model are equal to ones obtained by the simplified rule. Regarding the optimal PV size, the sizes obtained by the two models match to a great extend. On the other hand, the optimal battery size matches only in case of Denmark. Generally, optimal battery size should be smaller for installation sites with the low solar irradiance than the size obtained from the simplified rule. Accordingly, for installation sites with higher solar irradiance, larger battery storage yields highest NPV with the comprehensive model. Hence, it can be concluded that the simplified rule does not show a high level of robustness in the determination of the adequate battery size.

In order to demonstrate the impact of optimal sizing, NPV of each optimal size obtained by the two models is analysed. The results in Table IV indicate that the relative difference in NPVs is less than 5%. Additionally, the larger the difference in battery size between the two methods, the larger the difference in NPV.

Finally, based on the aforementioned results, a conclusion regarding the usage of the simplified rule in the sizing procedure of the PV-battery system is drawn. Regardless the fact that different battery sizes are considered optimal, the resulting NPV does not differ greatly. The maximum expected error is sufficiently low (e.g., estimated to less than 5% based on the study analysis) while complexity and required data are limited to a great extent. For that reason, the simplified rule is suitable for usage in the PV-battery design in a fast and simple manner.

V. Conclusion

In this paper, a robustness evaluation of currently available simplified sizing principle for residential PV-battery system is performed. The economic profitability of the PV-battery system sized by using this principle is investigated. The results are compared to the ones obtained by the comprehensive model consisting of the system performance, lifetime, and economic aspects. The case study is performed for various installation site conditions. The results indicate that using a simplified sizing principle results in less than 5% error in economic profitability compared to ones from the comprehensive model. Hence, it is concluded that the simplified sizing procedure (requiring minimum input data and complexity) can serve as a sizing procedure in practice under a wide range of mission profile characteristics.

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