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Mission profile simplification method for reliability analysis of PV converters

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ABSTRACT

This paper presents a simplification method for photovoltaic (PV) mission profiles to be used in reliability modelling. The method is based on the formulation of a shorter, representative mission profile formed using select days from the mission profile. The method is thoroughly explained and is applied to a number of PV mission profiles as a demonstration. Unlike the previously published simplification method from the same authors, this method is applicable to PV profiles from any climate.

The methodology is demonstrated with three applications of the method. The time reduction yielded by the method is useful in enabling simulation sweeps of parameter variation for sensitivity analysis, in finding design values for system lifetime or profitability, and for other analyses.

1. Introduction

Reliability analysis of power electronics is a field with ever-increasing interest as power electronics become more widespread, but also more critical to the power network infrastructure.

Photovoltaic generator systems use power electronics both in the general operation of power point tracking and may contain power converters to boost the output voltage and/or convert to alternating current to connect to the power grid.

When a PV generator system is planned, the reliability of the system is of great interest both for commercial and residential systems [1].

Reliability analyses can be used for different purposes. It may be used as a yardstick for product qualification [2], as design metric when designing new products [3], it can also help to decide when to perform preventive maintenance [4].

When designing PV generator systems, it is necessary to know the solar irradiance and ambient temperature of the intended location of the system, both to determine the projected power and thus, profits generated by the system, but also to estimate the lifetime of the installed generator system. To accurately determine the yearly loading of the system, the thermal behaviour of the system must be modelled for the entire year.

A model derived from the system design is used to determine the thermal system behaviour, which, for power electronics, is the main driver behind power device degradation and failure [5]. The thermal behaviour is quantified using rainflow counting and processed using a damage model [6–8] and the Palmgren-Miner's Rule for linear damage accumulation [9]. Depending on the model complexity, this simulation can be more or less time-consuming [10,11].

The previous work of the authors [12] presents a simplification method for PV mission profiles from arid climates. This methodology is able to reduce simulation time with more than 90 % compared to the reference method (Fig. 1) at a trade-off of a minor accuracy decrease. This is useful for enabling more time-consuming system models, rapidly testing various system configurations or performing sweeps for training of artificial intelligence or optimization.

The main drawback of the method from [12] is the limitation to arid climates. Specifically, climates with clouds are troublesome for the methodology. This is also what led to the increased error in the Colorado profile compared to the others.

Additionally, while much PV power is installed in areas with an arid climate, a great amount is also installed in cooler and wetter climates.

The next section (Section 2) will introduce the proposed method for PV mission profile simplification. Then the life predictions of the method will be compared to the un-simplified reference method in Section 3. Section 4 presents two application examples using the proposed method. The paper is concluded in Section 5.

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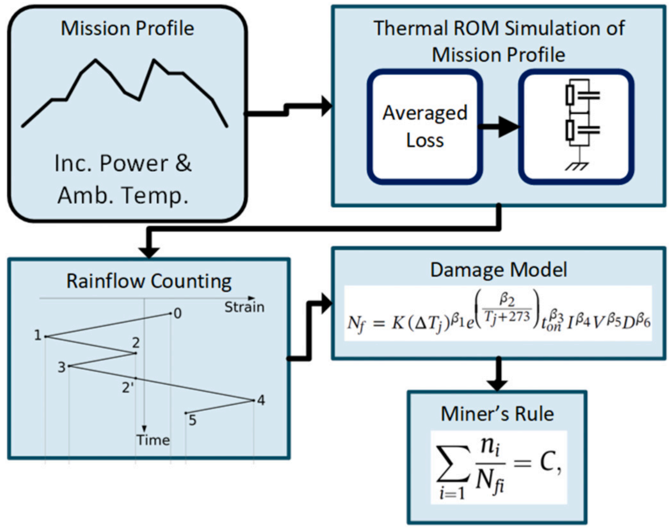

Fig. 1. Commonly used reliability analysis workflow for power electronics using [5,7,9,13].

2. The method

In this paper, the reliability of a photovoltaic system such as that in Fig. 2 is analysed.

The methodology of our previous paper [12] was based on the similarity and regularity of days in a cloudless climate. This fact was used to devise a way to synthesise representative daily profiles for a number of sections of a year.

An unintended side effect of the synthesis method was the inability of the synthesised profile to represent certain types of cloudy days accurately. The method has no issue with sunny days, nor days with constant cloud covering, but the days of intermittent sun and clouds are processed erroneously, resulting in representative days without any intermittency similar to those with a constant cloud covering.

To counter this phenomenon, the methodology presented in this paper chooses representative days from the original mission profile, rather than synthesising them.

The selection of days is based on the damage caused by the loading of each day. This is estimated efficiently with a "zero order" loading model. This is proposed in Section 2.1 and can be seen in Fig. 3. That and the following Sections 2.2 to 2.5, detail the steps in Fig. 4.

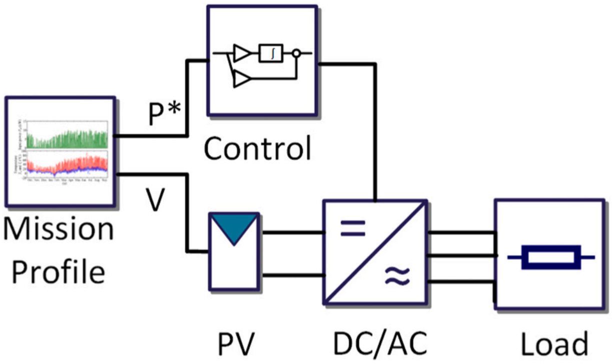

Fig. 2. The basic photovoltaic (PV) generator system model including inputs. P* is the reference power from the mission profile. V is the voltage from the mission profile. The DC/AC inverter block is electrically connected using direct current to the PV cells, to the load using alternating current, and to the control block with control signals.

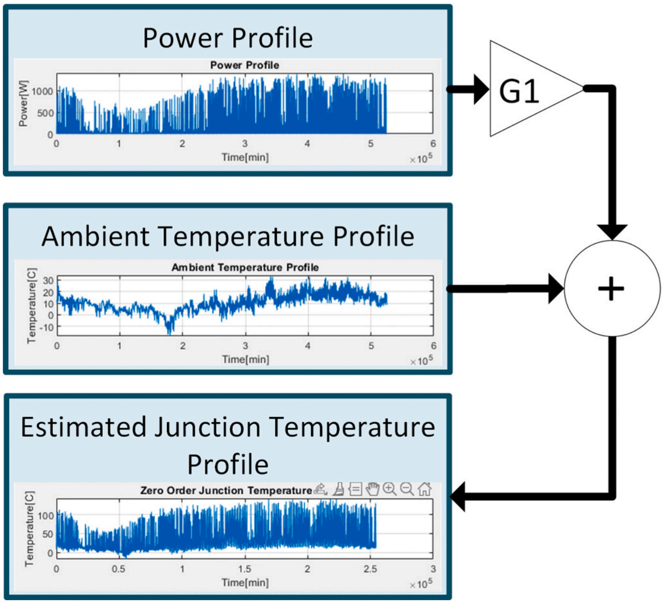

Fig. 3. The zero order junction temperature estimation method is a static simulation of the junction temperature based on the input power and ambient temperature and a gain representing the power loss and thermal resistance of the system. The estimated junction temperature profile is analysed using [7,9,13] to find the estimated damage.

2.1. *"Zero order" loading model*

The "zero order" loading or damage model is the minimum effort that can be performed while still ending up with an estimation of the consumed lifetime of a profile.

A power and ambient temperature profile is needed, a gain is calculated for the power profile based on the efficiency and thermal resistance of the analysed system. Then the modified power profile and unmodified temperature profile are combined into a junction temperature approximation profile which is subjected to conventional damage modelling via rainflow counting [13], linear damage accumulation [9] and a damage model [6,7]. Fig. 3 shows the proposed model.

The zero order model is not used for end-of-life predictions in this method. The zero order model is very fast, but is a poor representation of a physical system as the loss and thermal models are extremely simple. However, it is useful for providing preliminary estimations of the consumed lifetime of each day in the mission profile such that the days can be sorted according to their estimated damage. This is used in the next section.

2.2. *Mission profile processing*

The mission profile, both power and temperature profiles, are split into a user-defined number of sections. The number of sections determines the time saved by this method, but must also not be too low, as that will increase the error introduced by the method.

Using the results from the zero order model, the consumed lifetime of each day in a section are compared to find the day which consumed lifetime is closest to the average of that section. The most average days in each section are used to represent each section and a representative mission profile is formed using these days. The resulting representative mission profile is similar to the original mission profile as it contains both a power and ambient temperature profile, but much shorter.

2.3. *Modelling*

The representative mission profile is simulated in the same manner

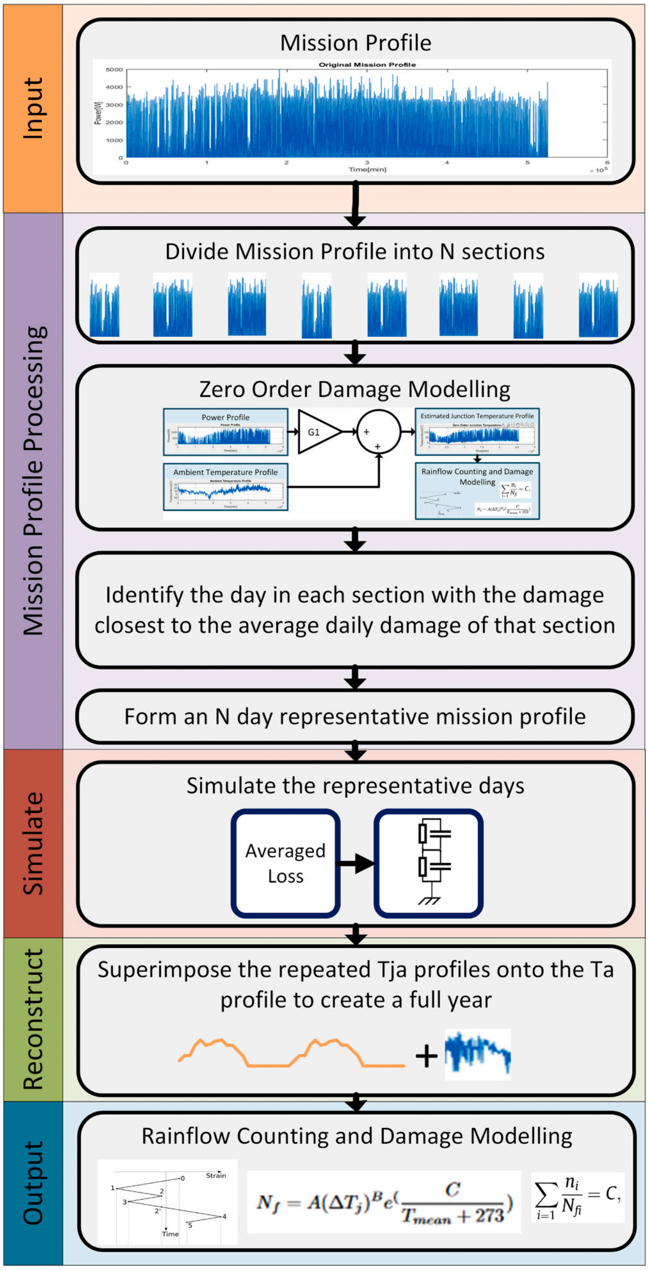

Fig. 4. The steps of the proposed method for reduction of mission profiles.

as one would normally simulate a full 365-day mission profile. In Fig. 4 the modelling methodology used is an averaged loss model together with a Reduced Order thermal model [5]. Any model can be used, as long as it takes a mission profile input and gives a junction-to-ambient temperature profile output.

2.4. Reconstruction

The junction-to-ambient temperature profile of each representative day is repeated for each day in that section and superimposed on the ambient temperature profile.

2.5. Damage modelling

The reconstructed junction temperature profile from the previous paragraph is a yearly profile, and the damage from said profile is estimated as in Fig. 1.

The junction temperature profile is processed using rainflow counting [13] to extract the thermal cycles. These cycles are evaluated using a damage model [6,7] to find the damage caused by each cycle in the profile and linear damage accumulation [9] is used to sum the damage of all the cycles to find the total consumed lifetime of the year [14]. More information on how to find the damage caused by varying temperatures can be found in either of the references of this section.

3. Results

The analysis workflow presented in Section 2 was applied to the same five mission profiles from ref. [12]. Four of these profiles are from arid climates and one is from a temperate climate, two of the profiles contain too much cloud interference for the methodology of ref. [12] to be useful.

Fig. 5 show the damage deviation of the presented method compared to the unmodified reference method. The deviation is calculated by comparing the damage calculated by the proposed method to the damage calculated by the reference method of Fig. 1. This is repeated for different numbers of section divisions and different climates.

Fig. 5 proves that the simplification methodology of this method is independent of mission profile climate.

As the process of dividing a mission profile of ≈365 days into sections of whole days is quite discrete, the damage deviation of Fig. 5 does not exhibit a smooth trend from high deviation at a lower number of sections to a low deviation at a higher number of sections. If the days are sorted based on the consumed lifetime after the zeroth order modelling, perhaps a smoother trend would be achieved.

At a 12 section split the damage deviation of all mission profiles is less than 5 %.

The simulations of Fig. 5 were timed, and the resulting time reductions can be seen in Fig. 6.

4. Applications

When lifetime estimation can be performed in only 5 % of the time it usually takes, some reliability analysis workflows become easier and more practical.

4.1. Parameter sensitivity

Normally, parameter sensitivity analysis is conducted as in [15], but

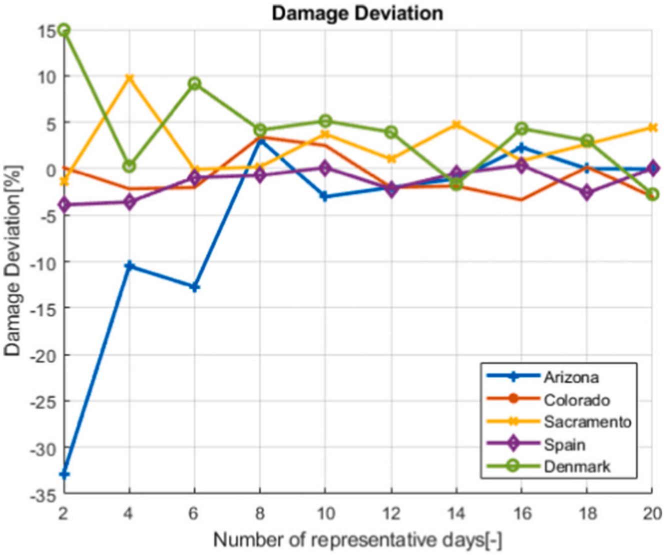

Fig. 5. The damage deviation of the proposed method for multiple mission profiles.

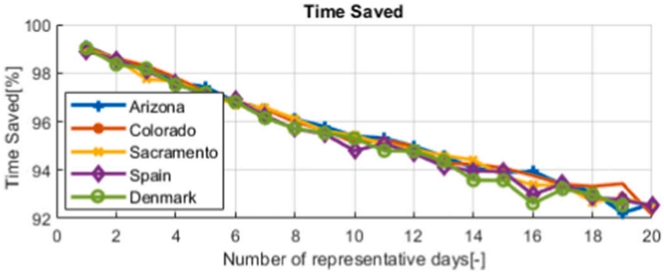

Fig. 6. The time reduction of the proposed method for multiple mission profiles.

with the presented methodology it becomes practical to perform direct parameter sweeps for any relevant parameters. Fig. 7 shows theoretical lifetime results for variations of the thermal resistance of the thermal interface material. If the distribution of the analysed parameter is known, the statistical lifetime can be calculated directly (see Fig. 8). The analysis was repeated for multiple mission profiles.

In Figs. 7 and 8, the thermal resistance was analysed for its impact on system lifetime. Thanks to the speed offered by the proposed method, it does not take long to repeat the sweep for another parameter. In Fig. 9, the impact of varying thermal capacitance was investigated. As with the thermal resistance (Figs. 7 and 8), if the variance is known the lifetime distribution can be calculated directly. This may be repeated for any relevant model parameter.

4.2. System planning

When PV generator systems are planned, several design steps are undertaken to ensure optimal cost/benefit of the design. If a certain converter system is given, as well as the location of the system, the optimal size of the PV panels can be found by fast parameter sweeps.

The impact of panel power on profit generated was investigated by varying the input power profile from 50 % to 150 % and simulating the resulting lifetime. The resulting theoretical lifetime can be seen in Fig. 10. With increased power comes increased inverter losses and thermal stress, leading to lower lifetime.

The gross profits generated by the system for each configuration found in Fig. 10 were calculated with a electricity price of 10 eurocents/kWh [16]. The net profits from the system configurations can be seen in Fig. 11, here the PV system cost of 6700 EUR [17] is subtracted from the gross profit.

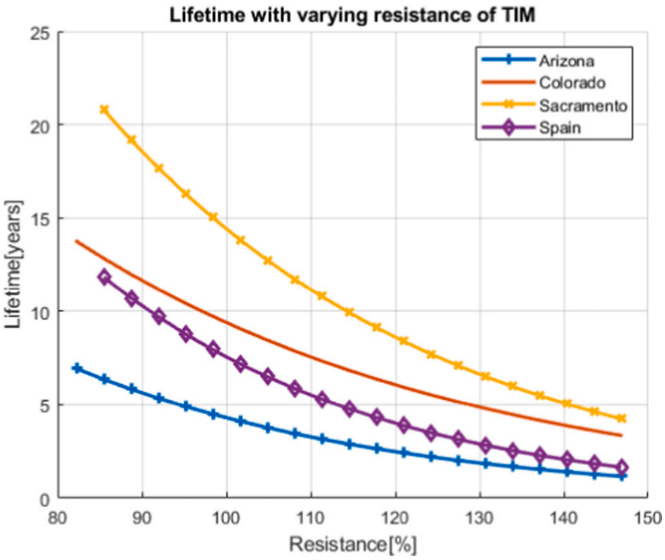

Fig. 7. Resulting lifetime of converter with varying thermal resistance of thermal interface material (TIM). Analysis repeated for 4 locations.

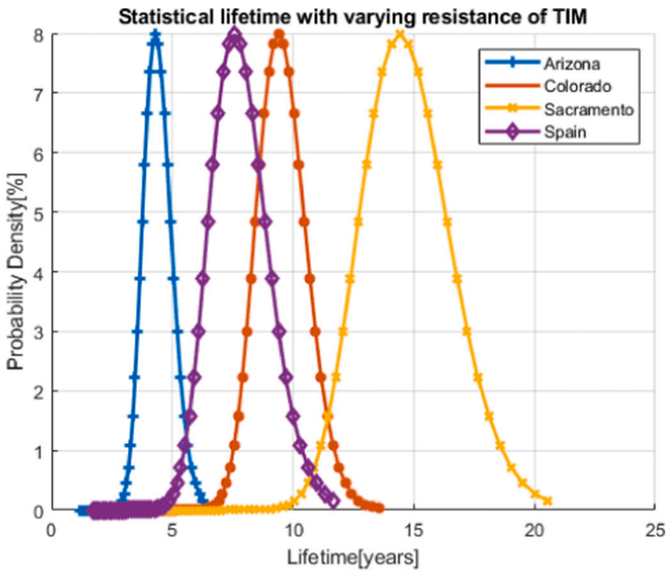

Fig. 8. With a known distribution of the thermal resistance, the distribution of lifetime can be directly calculated. In this case only one variable was varied, but it is possible to include variation of multiple parameters. Analysis repeated for 4 locations.

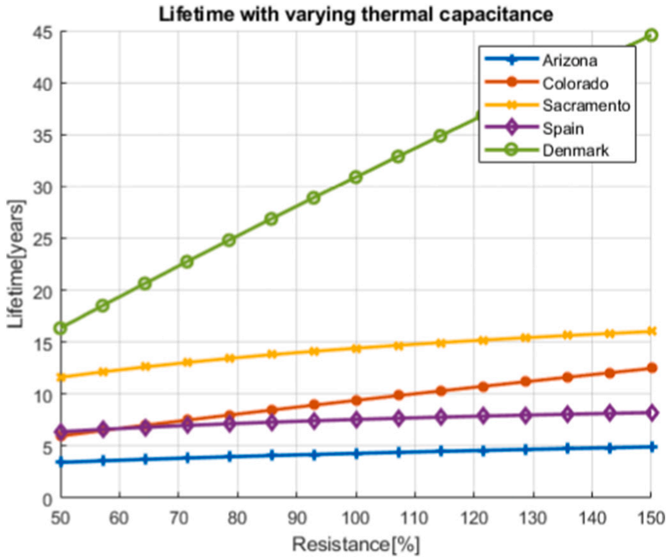

Fig. 9. Resulting lifetime of converter with varying thermal capacitance of thermal interface material (TIM). Analysis repeated for 5 locations.

Finally, the lifetime is compared to the threshold of when the PV system has paid for itself. In Fig. 12, the configurations where the lifetime is higher than the threshold (blue with pentagrams) are profitable.

The prices used in this example are entirely exemplary and the costs are simplified.

5. Conclusion

This paper presented an improvement on previous work by the authors, with the simplification method based on choosing the days for the representative profile rather than synthesising them. The method was applied to mission profiles from both arid and non-arid climates, and with a split of 12 sections, it reduced the simulation time to less than 10

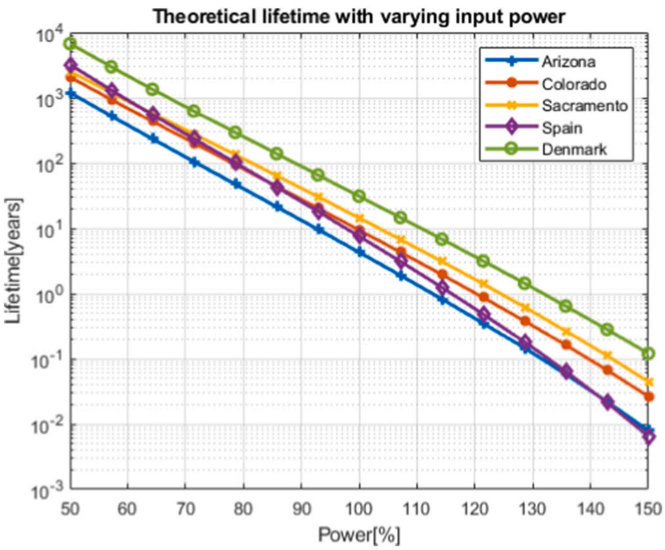

Fig. 10. Theoretical lifetime of converter with varying power. Analysis repeated for 5 locations.

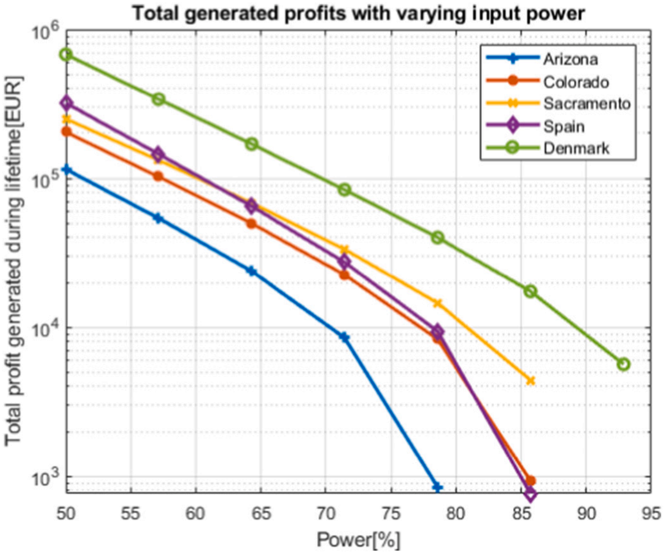

Fig. 11. The net profit from PV generator system. Gross profit calculated with fixed power price of 10 eurocents/kWh [16] and a fixed price of 6700 EUR [17] for the PV system. Analysis repeated for 5 locations.

% of the original at a slight trade-off of less than ±5 % damage deviation from the slower reference methodology.

The applications of the methodology were demonstrated with three different cases. First, as a method to perform direct simulation of the lifetime impact of parameter variation. Using this method, component variations can be directly mapped to lifetime distributions.

Finally, the method was used to help size the PV panels for the profitability of a generator system in various locations. Net profits were calculated and the profitable configurations were identified.

CRediT authorship contribution statement

Conceptualization	Martin Bendix Fogsgaard
Methodology	Martin Bendix Fogsgaard
Software	Martin Bendix Fogsgaard
Validation	Martin Bendix Fogsgaard
Formal analysis	Martin Bendix Fogsgaard
Investigation	Martin Bendix Fogsgaard
Resources	Martin Bendix Fogsgaard
Data curation	Martin Bendix Fogsgaard
Writing – Original draft	Martin Bendix Fogsgaard
Writing – Review and editing	Martin Bendix Fogsgaard, Amir Sajjad Bahman, Francesco Iannuzzo, Frede Blaabjerg
Visualization	Martin Bendix Fogsgaard
Supervision	Amir Sajjad Bahman, Francesco Iannuzzo, Frede Blaabjerg
Project administration	Frede Blaabjerg
Funding acquisition	Frede Blaabjerg

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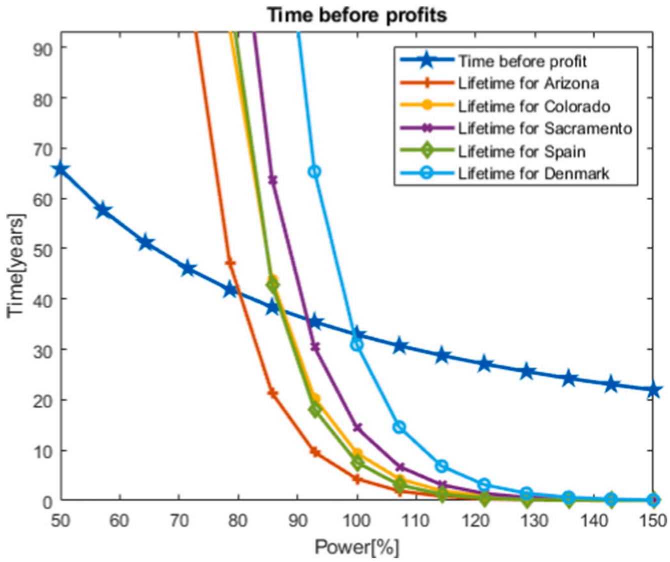

Fig. 12. Comparison of the theoretical lifetime of the system and the time it takes for the PV system to pay for itself based on the prices of Fig. 11. Analysis repeated for 5 locations.

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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