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PV mission profile simplification method for power devices subjected to arid climates

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A R T I C L E I N F O

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A B S T R A C T

This paper will present a mission profile reduction technique to reduce the simulation time needed to simulate the yearly behaviour of a PV system.

Due to the strong climate dependency of the weather and thereby the PV mission profile, the simplification method is likewise strongly climate dependant.

The reduction technique will be applied to different PV mission profiles from different arid places around the world (Arizona, Colorado, Spain, Sacramento), where the speed-up of the method will be tested along with the error introduced by the reduction.

The method was found to decrease simulation time by up to 98% at a trade-off of a deviation in the damage estimation down to 1.7%.

1. Introduction

To determine the reliability and expected lifetime of a PV generator system, the yearly behaviour of the system should be modelled. Using this, the damage imposed upon the power electronic module or devices can be evaluated using the state of the art methodology presented in reference [1].

The power device junction temperature can be considered the main component stressor and therefore the key variable to model for life-time estimation. The behaviour of the junction temperature is based on the modelling presented in reference [1]. The rainflow counting is based on the work of reference [2], while the damage modelling is based on reference [3], with an improved model presented in [4]. The linear damage cumulation is originally based on the formulation in [5], but was tested for power electronics application in reference [6] and found to be a generally applicable assumption. This specific assumption warrants further investigation, however.

Fig. 1 shows an example PV mission profile, containing information about both the system input power and the ambient temperature. Fig. 2 shows the structure of a PV generator system and this structure will be used for all modelling and analysis of this work.

2. The proposed method

Any PV mission profile from a location on Earth contains the following exogenous timescale effects:

- Rotation of Earth around the Sun
- Rotation of Earth around its own axis
- Stochastic reductions of PV power due to clouds, birds, etc.

The rotation of Earth around the Sun creates the changing seasons and with it a change in solar intensity over the year, as well as a change in weather. From an analysis of real mission profiles, it was found that, while clouds should generally be classified as a stochastic phenomenon, for specific climates the intensity of clouds vary more with the seasons.

The impact of the change of seasons depends on the climate at the location of the PV system. Some climates experience a strong difference between summer and winter, for others, the difference is less severe. This rotation is strongly regular with each rotation lasting approximately 365 days.

Additionally, the rotation of the Earth around its axis causes a daily pulsation of both PV power and ambient temperature. PV generators will experience a period in each 24-hour cycle where the system will be inactive.

Finally, fluctuations in input power, and ambient temperature will to

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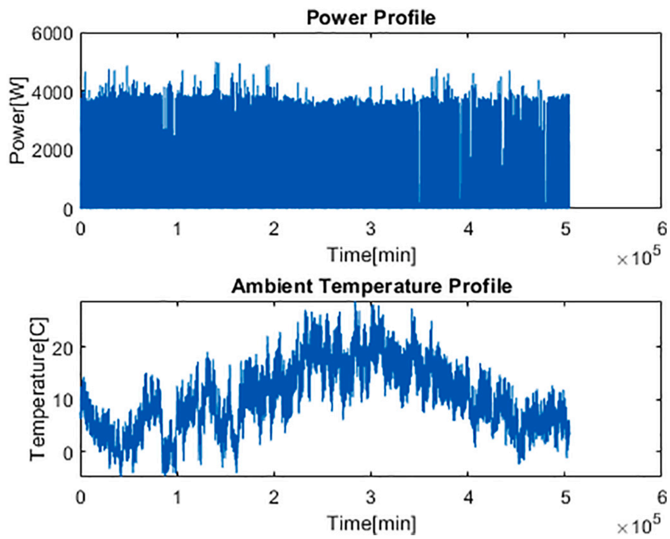

Fig. 1. Example of PV Mission Profile containing power and ambient temperature profiles during one year.

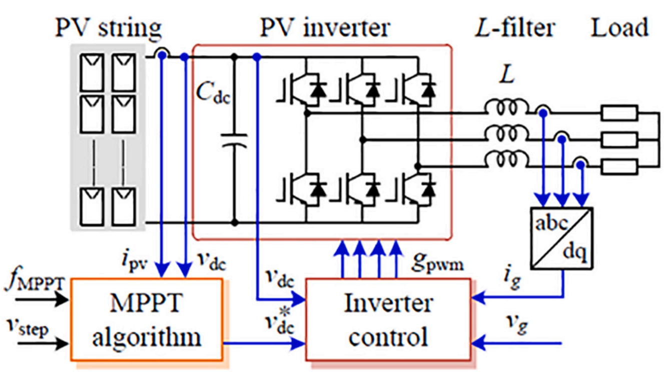

Fig. 2. The structure of the assumed PV generator system [1].

a lesser degree happen due to random events. Primarily, clouds will be the cause of these stochastic fluctuations, but other phenomena may also cause fluctuations. While stochastic, one thing is certain, these fluctuations will always give reductions in solar power compared to a sunny day.

The PV generator system will also contain several endogenous timescale effects such as: Device switching, fundamental frequency voltage and current fluctuations, fluctuations caused by control algorithms, etc.

2.1. Arid climates

Arid climates are defined by their low level of precipitation and generally low level of clouds compared to other climates [7]. Fig. 3 shows various arid parts of the world [8] rated from dry subhumid to hyperarid. These are the regions where the proposed methodology of this paper is primarily intended.

Upon inspection of the PV mission profile from arid climates, some conditions and similarities are seen:

- Fewer instances of clouds compared to other climates
- Lower power and ambient temperature variation caused by the seasons

These can be combined to make the mission profiles from arid climates relatively regular with smaller variations and comparatively less random content.

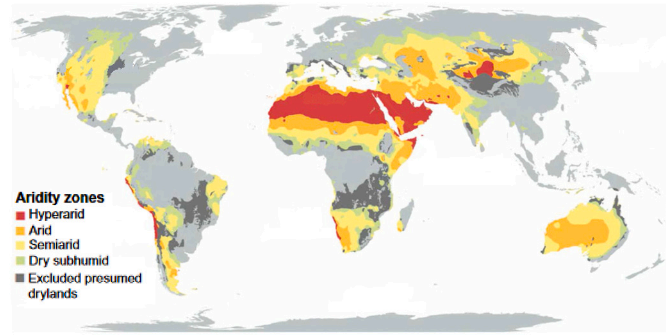

Fig. 3. Arid regions of the world [8].

2.2. The proposed method

The well-defined features of mission profiles from arid climates enable the use of reduction methods to accelerate the simulation.

Fig. 4 presents the PV mission profile simplification methodology. The method takes advantage of the high regularity of the arid mission profiles to reduce the required simulation time at a trade-off of slightly increased simulation error.

The method can be divided into four basic steps as indicated by the background colours in Fig. 4. The first step consists of the original mission profile containing both power and ambient temperature profiles.

The processing steps, highlighted in purple in Fig. 4, aims to create an averaged day for each month to represent the days and their power content and their clouds variability. First, the mission profile needs to be divided into a number of representing periods. We chose 12 periods to reflect the 12 months in a year. Then the maximum value of the power for each day is identified and averaged for each month.

The profiles of the days are averaged to find the shape of the average day of e.g. January. Then the averaged days representing the 12 months are modified so the maximum power is equal to the averaged maximum power of the days in the respective months.

From this a test profile of 12 days has been designed, these days can then be modelled using the selected model to find the junction-to-ambient Temperature. This is the red step in Fig. 4.

The method assumes that the damage can be calculated from the behaviour of the junction temperature and that the behavioural model describes the behaviour of the junction temperature using the mission profile as the input value. Fig. 5 shows the basic damage modelling approach which the proposed method is based on.

Finally, the Junction-to-Ambient Temperature is superimposed on the ambient temperature profile, with each averaged day being repeated for all the days in that month. This results in a junction temperature profile for the entire year, which can then be processed using rainflow counting [2] or other methods.

3. Results

The method has been applied to a real mission profile from Arizona. In this implementation, the mission profiles, both the original and reduced were applied to a simulation model of a physical PV system.

The system used for modelling is a three-phase inverter in a PV generator set-up where the architecture of which can be seen in Fig. 2. The simulation model used is based on experimental measurements of the system and more information about the PV set-up can be found in [1].

The results can be seen in Fig. 6. In subfigure A, the first 20 days of the original mission profile are shown, next, in subfigure B, the first 20 days in the modified mission profile are shown.

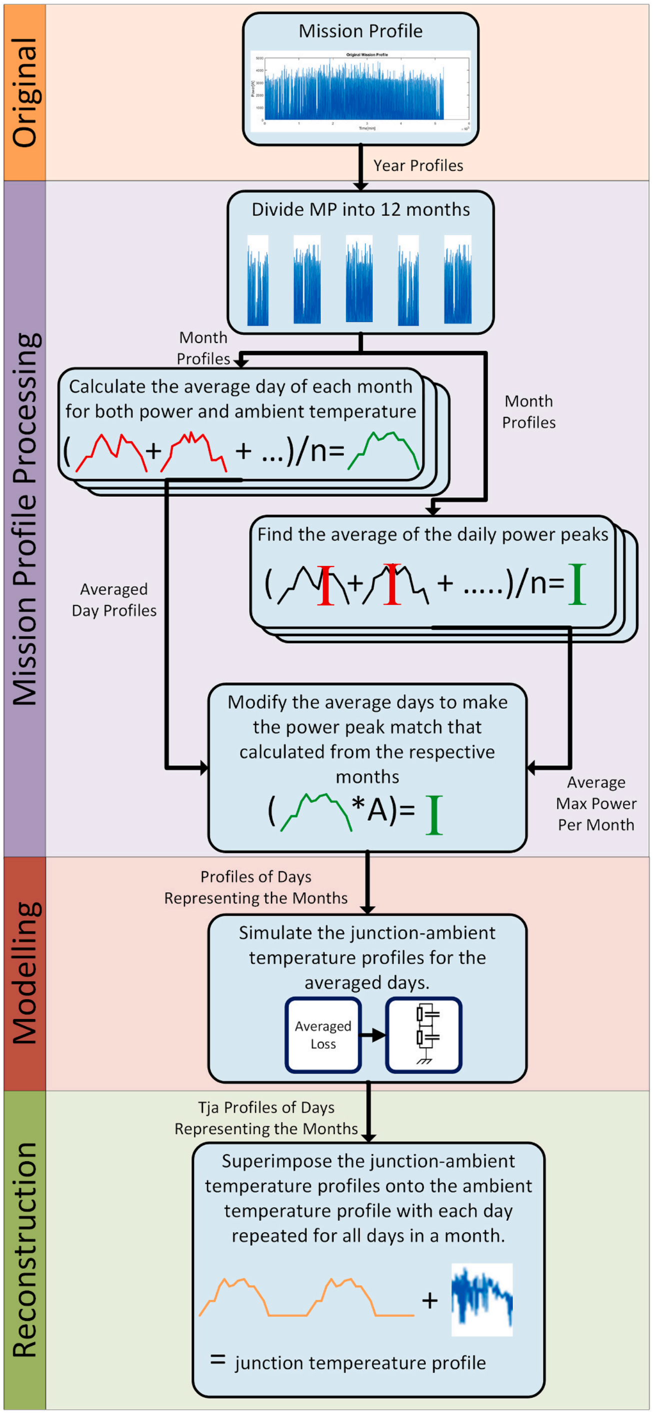

Fig. 4. The steps of the proposed method for reduction of arid mission profiles.

The next graph, subfigure C, shows the junction temperature profiles for both the original and the modified mission profiles overlaid in order to show the similarity of the profiles.

Table 1 shows the signed deviation of the damage calculated for the resulting junction temperature profile, according to the damage of the original profile. The damage calculated is the power semiconductor lifetime consumed during converter operation in those conditions for an entire year. Table 1 also shows the simulation time of the proposed method compared to the reference.

To further test the method it was applied to three additional PV mission profiles from different locations around the world. The error in damage estimation and computational time are reported in Table 1. The

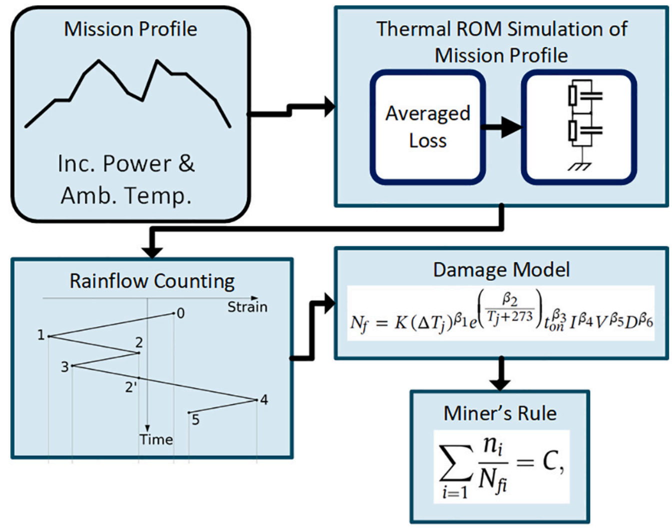

Fig. 5. Reduced order model for estimation of damage of PV inverter.

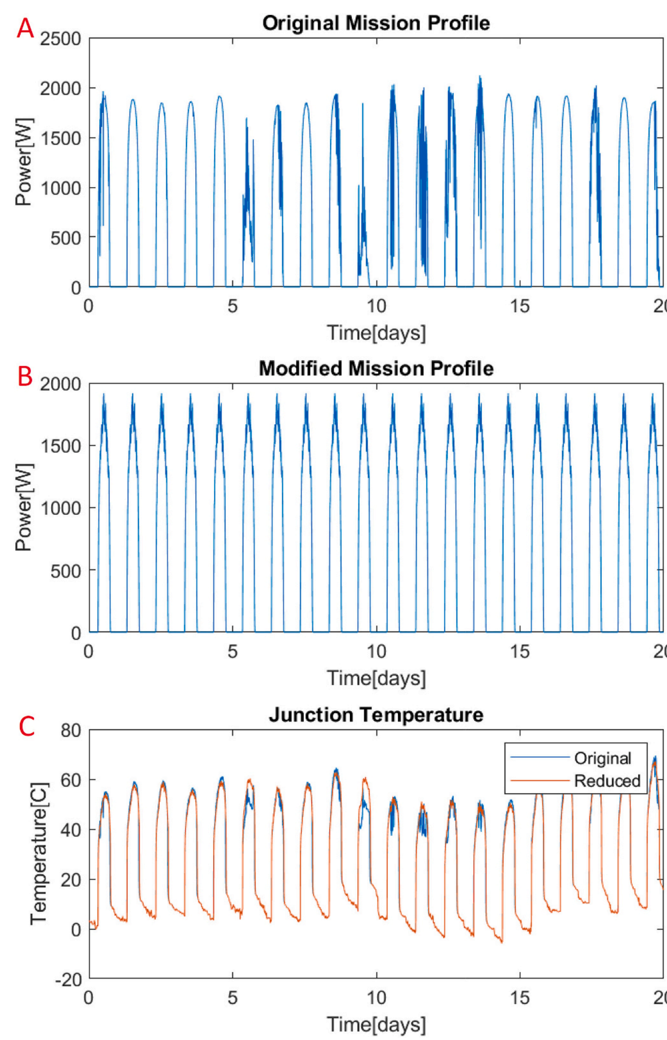

Fig. 6. Comparison of results from modelling of original Arizona mission profile and reduced mission profile.

Table 1
Damage error and computation time savings.

Location	Damage error	Time reduction
Arizona	+6.37%	−98.1%
Colorado	+20.02%	−97.9%
Sacramento	+3.43%	−97.7%
Spain	+1.68%	−95.6%
Denmark	+6e6%	−95.0%

damage error is reported as a percentage, i.e. the deviation in the consumed lifetime of a power device over a year calculated by the proposed methodology and the reference method.

From Table 1 it can be seen that the method has overestimated the damage of the Sacramento profile with 3.43%, but took 97.7% less computational time than the original. To offer perspective on the climate dependence of the method, the results for a non-arid climate is included in the table.

From Table 1 it can be seen that the method offers a strong reduction of simulation time with a trade-off error in the consumed lifetime estimation.

4. Discussion

In Table 1 the estimation error for different mission profiles can be seen. This varies from 1.7% for the best case to 20% for the worst case arid profile. How much error that is acceptable depends on the application and design specifications, but as life-time estimation methods have yet to achieve perfect predictions, some error may be permitted.

As the computational time of life prediction methods such as those employed in Ref. [1], Ref. [9] is well within the limits of practical usage, the presented methodology may be most effectively used to accelerate the usage of more complex and time-demanding behavioural models.

In Fig. 8 the relative time reductions achieved with various numbers of representative days can also be seen. The time reduction is reported as relative because it depends heavily on the behavioural model used in the red step in Fig. 4. The method used for the examples in this paper is based on that used in reference [1], and takes about 15–20 min to process the entire year. Different models will require different simulation times and the method may bring different benefits depending on the used model.

For some, the accelerated modelling can be used to perform design parameter sweeps to find the optimal converter design or control with regards to lifetime. For others, the 90% simulation time reduction may be a required as the simulation time without would make the model impractical.

Another application of accelerated lifetime estimation is to help train artificial intelligence for various applications.

Mission profiles and their temporal resolution is investigated and discussed in references [10,1]. Because of the impact of sampling resolution on reliability estimation, the mission profiles were under-sampled and re-analysed in order to see the effect of sampling resolution on the proposed methodology. Fig. 7 shows the performance of the methodology at different sampling resolutions. Here the error calculated is the deviation from under-sampled representative days to under-sampled mission profile reference. From Fig. 7, it is clear that the accuracy decreases with a decreasing resolution.

The presented method should primarily be used with mission profiles sampled at 15 min or faster. However, as most of the available mission profiles are sampled at 1 h resolution, it could be relevant to investigate ways to adapt the methodology for use with mission profiles sampled at 1 h resolution.

Also, the temporal division of the year has been investigated. In the example in Section 2.2, 12 divisions were chosen to represent each month of the year. The effect of the number of divisions on the damage deviation of the method was investigated.

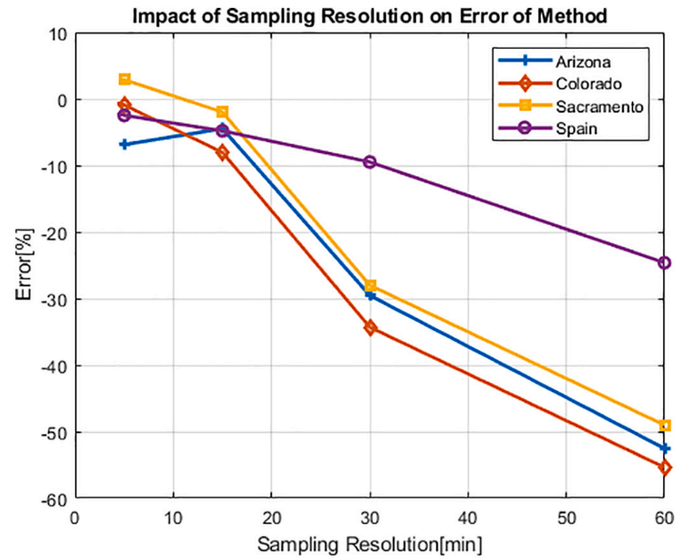

Fig. 7. Impact of sampling resolution on error introduced by the method.

One of the consequences of too few divisions is that days of different length will be combined in the algorithm of Fig. 4. If all days are combined then care should be taken with how to combine summer and winter days of quite a different length.

All available mission profiles were swept using the methodology at various division levels from 1 to 50. The results can be seen in Fig. 8, where it can be seen that the damage deviation is mostly independent of the groupings used in this sweep.

A consequence of the current method of averaging the days is that the peaks induced by passing clouds are mostly removed. In the top subfigure of Fig. 6, a few cloudy days can be seen where passing clouds almost instantly reduce the PV power from full power to very low power. This type of event is removed by the averaging used. Even if all of the days in a month contains events like these, they are only preserved in full if they happen at the same point during all of the averaged days. The representation of these events should be prioritized in future developments of this methodology.

Due to the averaging method used it becomes clear that the accuracy of the current implementation is inversely proportional to the amount

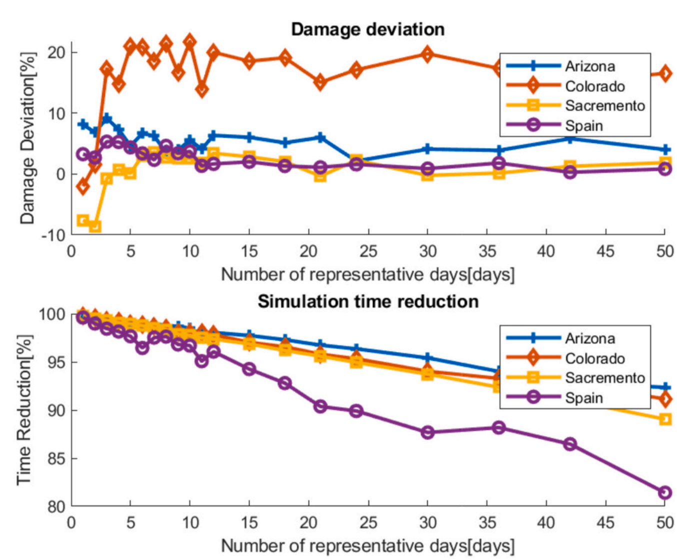

Fig. 8. Impact of number of representative periods on error introduced by the method.

and impact of clouds in a PV mission profile. To test this an index was formulated to express the normalized impact of clouds on a day. This index is an expression of how much the daily profile steps up and down during the day. An index value of 1 is a perfect day with no clouds, making it a sunny-ness or anti-cloud index. The average Anti-Cloud Index for each arid mission profile can be seen in Fig. 9.

As seen in Fig. 9 and Table 1, the profiles with a high score in Fig. 9 correspond with the profiles with low damage deviations in Fig. 8.

5. Conclusion

This paper has presented a methodology to reduce the simulation time needed to model the behaviour of a PV generator system in an arid climate. The methodology is based on the relative regularity of mission profiles from this type of climate.

When applied to four mission profiles, three from the U.S.A. and one from Mediterranean Spain, the methodology was found to reduce simulation time by around 96% at a trade-off of down to 1.7% error in the estimation of semiconductor damage.

The accuracy of the simplification method strongly depends on the climate of the mission profile. In Fig. 9 an index was shown for the different mission profiles indicating their cloud content. This index, or an improved version thereof, should be used prior to the use of the proposed simplification method to verify the suitability of the analysed mission profile.

Even though this work is primarily aimed towards damage estimation and lifetime prediction, the experimental representativeness of the modified mission profile warrants investigation. An experimental evaluation of this will also help bridge the gap between power cycling profiles and real mission profiles. It may also help when users are to design power cycling strategies based on real mission profiles.

The methodology was tested on four mission profiles from different parts of the world. This limitation comes from the unavailability of high-resolution mission profiles. Sample resolutions faster than the response time of the system are preferred.

The methodology of this paper is valid for PV mission profiles from arid climates. As seen in Fig. 3, these regions make up a significant part of the world, especially considering that some of these regions are also where people are most likely to install PV power.

Similar methodologies should be investigated for non-arid PV mission profiles.

CRediT authorship contribution statement

Martin Bendix Fogsgaard: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Amir Sajjad Bahman: Supervision, Writing - Review & Editing.

Francesco Iannuzzo: Supervision, Writing - Review & Editing, Project administration.

Frede Blaabjerg: Supervision, Writing - Review & Editing, Funding acquisition, Project administration.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

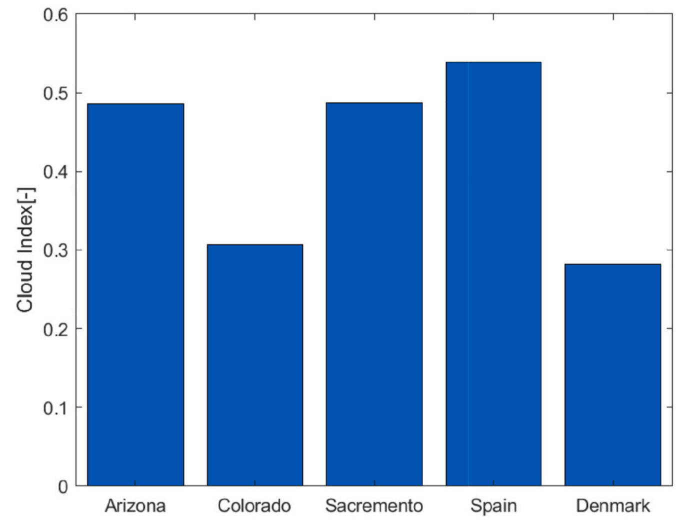

Fig. 9. Average Anti-Cloud Index value for different PV mission profiles.

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