LIFE EXPECTANCY OF PV INVERTERS AND OPTIMIZERS IN RESIDENTIAL PV SYSTEMS

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The average Time To Failure (TTF) of PV inverters and PV optimizers is investigated in this paper. The focus is on residential and small commercial systems. The data used in this paper includes 1195 PV systems consisting of 2121 inverters and 8542 optimizers. The data is obtained by means of an online survey sent to the system operators (343 systems) and by analysing system service databases of professional PV system installers and operators (852 systems). Since most of the systems examined are still in operation and have never failed so far, the results are presented using Kaplan-Meier survival curves. After 15 years, 34.3 percent of inverters show a first failure. The most important factors influencing the TTF are the installation location of the inverter (indoor installations have a lower TTF than outdoor installations), the manufacturer and the inverter topology (installations with optimizers have a lower TTF than installations without optimizers).
Keywords: Life expectancy of PV inverters, Time to Failure (TTF), survival curve, Kaplan-Meier estimator

1 INTRODUCTION

PV inverters are typically said to have a life expectancy of 15 years and must therefore be replaced once in the service lifetime of a typical PV system [1]. Accordingly, the warranties for inverters usually only cover about half the time that the performance warranties for PV modules are valid for. However, optimizer manufacturers usually provide longer warranties than inverter manufacturers.

The cost of maintaining and replacing inverters accounts for the largest share of the operating and maintenance costs (O&M) of a PV system. Therefore, it is advantageous for investors and operators of PV systems to have an accurate estimate of the expected lifetime of an inverter and to know the factors that influence its lifetime.

1.1 Study to assess life expectancy of PV inverters

In a study by the Bern University of Applied Sciences, the life expectancy of PV inverters is investigated. Due to various practical limitations such as a lack of information on inverter repairs, the study uses the time to energy-related failures (called TTF in this paper) as the relevant parameter.

1.2 Literature research

P. Hacke et al. [2] makes a detailed inventory of the PV industry in terms of reliability and safety. The publication assesses inverter reliability in relation to existing regulations and standards. The study shows that there are big differences in the information on the quality of inverters and that these can have an impact on O&M costs. The recommendation is made to collect financial data for O&M. To improve quality standards, it is recommended that design validation tests should be conducted under realistic environmental and operation conditions including end-use field conditions.

In Gatla [3], the lifetime of a single-phase 3kW inverter (600V/30A IGBT) is simulated with PLECS. The differences in the top ten PV sales countries are compared. This reveals that not only the maximum temperature at the site but also the temperature and irradiation cycles have an influence on the service life. At the system level, in Australia an average of 10% of the devices failed after 11 years, while this rate for England is theoretically only reached after 99 years (Germany 47 years).

An IEEE publication from Aalborg University [4] deals with the influence of PV module degradation on the lifetime of inverters. The publication assumes inverters to have a higher life expectancy if a lower PV power capacity is connected to the inverter. A system in Denmark is compared with a more degrading one in Arizona (Denmark: 0.15%/a, Arizona: 1%/a). The lifetime of the inverter in Arizona is underestimated by 54% (7 years).

In [5] from Aalborg University it is shown that DC oversizing can have an effect on the lifetime, depending on the location, while the effect is more serious at other locations. In Arizona, for example, the lifetime hardly changes due to the persistently high irradiation values, while in Denmark it deteriorates significantly with increasing oversizing. The main cause is the increasing thermal load.

According to Jordan [6], inverters are still the most frequently failing components of PV systems, accounting for 4–6 % of all cases evaluated. The failure frequency of residential PV systems is slightly lower than that of commercial or industrial systems, possibly due to more reliable inverters. On the other hand, the average production loss of large-scale industrial systems is much lower than that of commercial and residential PV systems. According to this study, the failure frequency of module inverters and power optimizers, which together constitute a device class, is underestimated.

Herz et al. [7] focus mainly on the detailed type of failure, but do not investigate correlations of specific situations or the overall probability of a failure occurring.

Häberlin et al. [8] analysed the inverter reliability of PV systems in Switzerland between 1992 and 2009. He noted that the average age of the inverters has stagnated at around 110 months. However, many of the inverters had been repaired in the first years after commissioning. The TTF definition used in this paper is therefore assumed to be lower than the life expectancy calculated by Häberlin. The discontinued data collection does not allow any direct conclusions to be drawn about current inverter technologies.

2 METHODOLOGY

2.1 General approach

The aim of this study is to quantify inverter failures in the field. The focus is on systems in residential buildings. The aim is not to specify the details of failures, but rather their year of occurrence and their relative frequency compared to inverters without failures.

In addition, local conditions such as sizing ratio (SR), installation location, type of PV system and others are evaluated to investigate their influence on the inverter lifetime.

2.2 Data collection

Data is gathered from three sources between March and May 2022:

1. By means of an online survey, mainly filled in by private owners / operators of PV systems (343 systems).
2. Data of the PV system portfolio of a professional PV system operator (83 systems).
3. Data of the PV system portfolio from professional PV system installers and operators (769 systems).

2.3 Data gross error detection and correction

In the context of this survey, a large part of the data was collected with the help of people who know the history of the PV systems well. These are, in particular, the system operators. However, they are often not familiar with the technical details. For this reason, the survey gave respondents the opportunity to add their own comments to the technical data. With the help of these comments, the data was then manually corrected where possible. The corrections made are described below.

2.3.1 Deletion of incomplete or unrealistic data-sets:

- Incomplete and unanalysable data records were deleted. If data-sets are incomplete but can still be evaluated (e.g. inverter manufacturer is missing) they were not deleted completely, but they were only included in the evaluations for which the missing information is not relevant. Therefore, not all investigations are based on the same number of data-sets.
- Unrealistic entries deleted (e.g. if the first malfunction occurred before the year of commissioning).

2.3.2 Creation of a consistent nomenclature

- Comma replaced with full stop.
- Obviously wrong units replaced / corrected.
- Spelling of products and companies standardised.

2.3.3 Correction of obvious errors

- Inconsistent data corrected or deleted (e.g. obvious factor 1000 for power values).
- Incorrect category assignments of inverters corrected. For example, the category “hybrid inverter” is not listed, but recorded as “string or multistring inverter”.
- Uniform power information used for known products (e.g. AC power of inverters).
- Faults considered or not based on description. Two fictitious examples:
  - Fuse has blown, after switching back on the inverter was running again. This is not classified as a malfunction.
  - Inverter was making strange noises, so it was replaced. This was classified as a malfunction.

2.4 Survival curves

In order to assess the reliability of the inverters, the duration until the first energy-relevant fault occurs is considered. This duration is defined as Time to Failure (TTF).

The TTF is calculated and plotted using the concept of the nonparametric Kaplan-Meier estimator together with the corresponding Kaplan-Meier survival curve. The survival curve shows what percentage of the population is still alive after how many years. Applied to this study, this means what percentage of the inverters has still not had any yield-relevant faults after the specified number of years, while it adjusts for so-called censored data points. This means that the Kaplan-Meier estimator accounts for the fact that a lot of inverters did not show a failure up to the time point of investigation. However, those inverters are still included in the analyses with the given observation time used as lower bounds for the actual failure time sometime in the future. With the help of the survival curve method, various other information can be derived:

- The Kaplan-Meier estimator can be adjusted for different influencing factors, e.g. to the year of commissioning, the inverter manufacturer or the nominal power ratio.
- Statistical measures can be read from the survival curves. For example, it can be calculated what share of inverters has a first fault after five years. Or it can be seen what percentage of inverters reach their tenth year without any energy-relevant error.

The survival curve also takes into account how many inverters are still under observation in the corresponding year of operation (“samples at risk”). This means that, although the majority of the inverters have never had a malfunction, it can be estimated in which year of operation a certain percentage of the inverters will have their first expected malfunction. However, because only little data is available for old inverters, the uncertainty in the survival curve increases with increasing inverter life. The confidence interval is shown by the coloured area in the diagrams.

2.5 Avoidance of cross-correlations between dependent variables

In the survey, a set of system parameters (variables) is gathered for each inverter. Several of these variables cannot be assumed to be independent. For example, preliminary results have shown that both large inverters and inverters installed outside a building have a shorter TTF than small indoor inverters. In addition, small inverters are more likely to be installed indoors, while large inverters are predominantly installed outdoors. Comparing the TTF of inverters installed indoors and outdoors therefore shows results that do not reflect causality.

The qualitative dependency of variables is determined by means of mosaics. As shown in Figure 1, protected outdoor inverters are by far the biggest category for large inverters (> 20 kVA), whereas the share of protected outdoor inverters is a relatively small category for small inverters (< 20 kVA). Figure 2 shows, that manufacturer m1 is mainly represented with recent inverter installations, whereas old installations are dominated by manufacturer m5 and to some extent m4.

In order to exclude the influence of dependent variables, the method proposed in [9] is applied. According to Terry M Therneau et al., data is adjusted for several confounding factors by a (inverse probability) reweighting of the observed inverters before survival curves are computed. For example, it is known that the place of installation (indoor vs. outdoor) depends on the confounders power and manufacturer of the inverter. To adjust for these two confounders, the observations from the comparison indoor vs. outdoor are reweighted such that the two comparing groups are balanced with respect to the confounding variables power and manufacturer of the inverter.

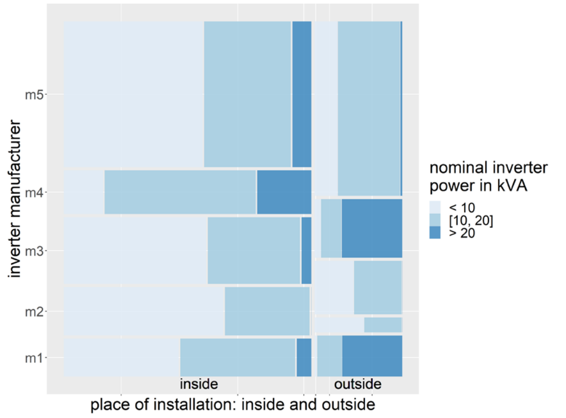

Figure 1: Mosaic showing inverter manufacturer, place of installation and inverter power.

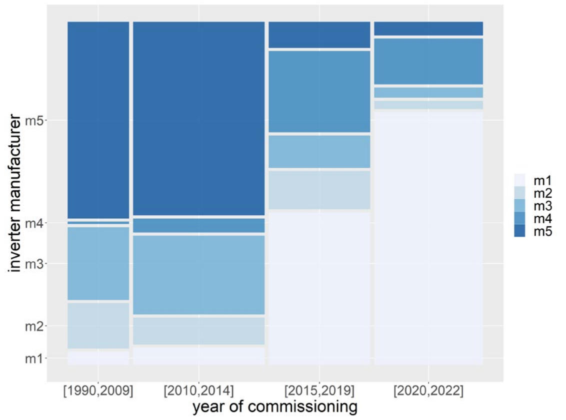

Figure 2: Mosaic showing inverter manufacturer, place of installation and inverter power.

3 RESULTS

The quantitative results of the survey and data gathering are presented using pie charts, histograms and other descriptive graphics. The TTF of the inverters are shown using Kaplan-Meier survival curves.

3.1 Description of the data

In the following figures (Figure 3 to Figure 10), the numbers of inverters are listed in different categories. Table I gives an overview of all data available in this paper. It shows the clear tendency, that data systems from professional owners have more inverters per system and higher power ratings than data from private owners and data from professional installers.

Table I: Data sources (abbreviations: sys. = system; inv. = inverter, priv. = private, prof. = professional, instal. = installer)

Source of data	No. of sys.	Total power (kVA)	No. of inv.	No. of inv. per sys	Power per sys (kVA)	Power per inv. (kVA)
Priv. owner	343	6172	546	1.6	18	11.3
Prof. owner	83	7050	314	3.8	84.9	22.5
Prof. instal.	769	13443	1261	1.6	17.5	10.7

The inverter manufacturers in this survey (Figure 3) are not representative of today's PV market. The manufacturers with most inverters analysed in this paper are Fronius, Huawei, Kostal, SMA, SolarEdge and Sputnik (alphabetic order, not corresponding to m1 to m5).

The inverter types are predominantly string and multi string inverters (Figure 4). Central inverters are underrepresented in a global context. In addition, several of the central inverters examined in this study are old, low-power models that are now usually replaced by transformerless multistring inverters.

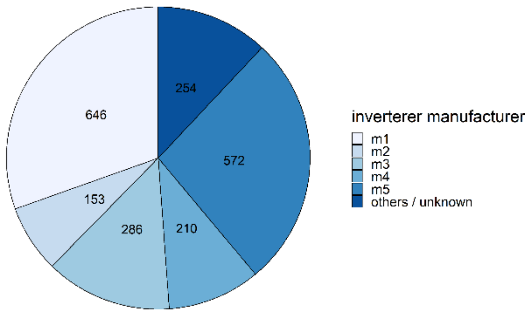

Figure 3: Number of inverters by manufacturer.

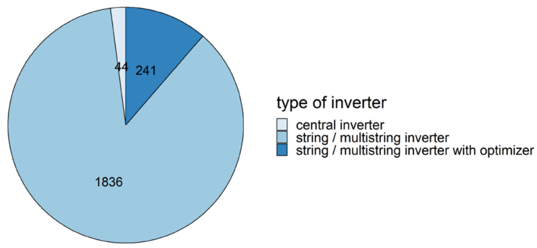

Figure 4: Number of inverters by type of inverter.

The oldest inverters investigated in this study are from the early 1990ies (**Figure 5**). However, most of the inverters were commissioned between 2008 and 2013 (first big installation boom in Switzerland due to the feed-in tariff introduced in 2009) and after 2017 (mainly driven by self-consumption).

As this paper is concerned with residential systems, most inverters have power ratings below 50 kVA (**Figure 6**). The biggest share of inverters has a power rating of 10 kVA to 15 kVA.

The distribution of Sizing Ratios SR (defined in this paper as AC power divided by DC power) is shown in **Figure 7**, peaking at roughly SR=0.9. Although it was assumed SR for new systems would change over time, the distribution stayed fairly uniform throughout the observed period.

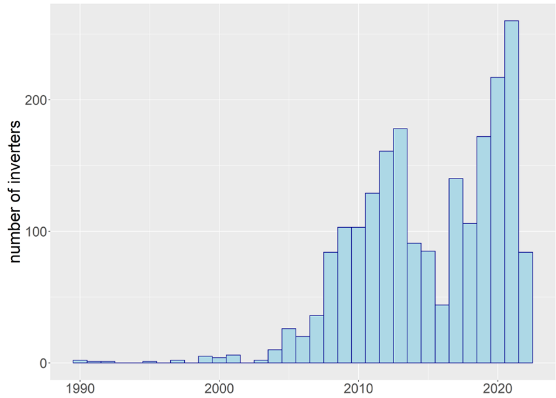

Figure 5: Number of inverters by commissioning year.

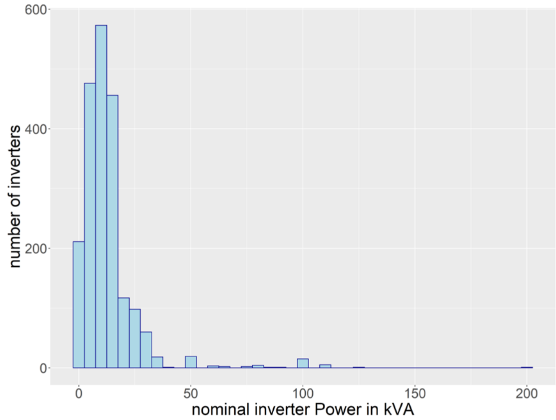

Figure 6: Number of inverters by nominal inverter power (AC power in kVA).

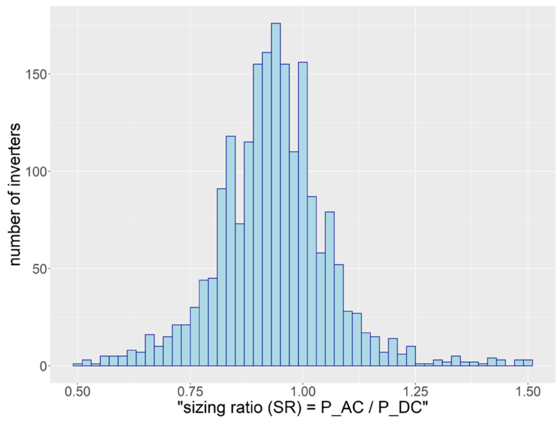

Figure 7: Number of inverters by sizing ratio.

The number of inverters by place of inverter installation is given in Figure 8. About half of the inverters are installed inside buildings. Only a minor share is installed outdoors, mostly protected from rain and direct sunshine. For a third of systems, the place of installation is unknown.

The tilt angles of the PV modules connected to the inverters are given in Figure 9. The type of the system (installation) is given in Figure 10. However, it was found that neither of these categories have a measurable impact on the TTF of the inverters.

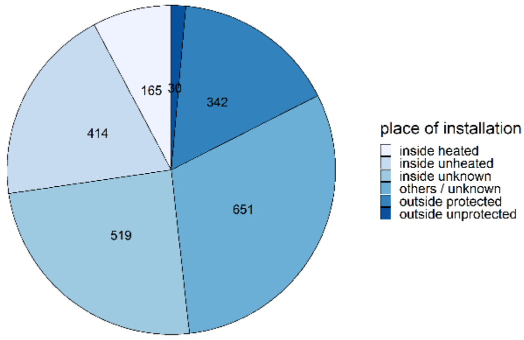

Figure 8: Number of inverters by place of installation.

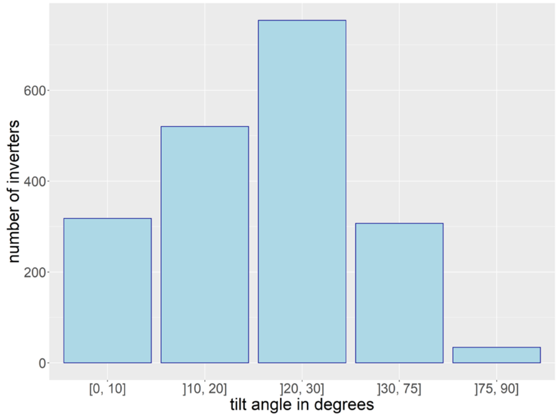

Figure 9: Number of inverters by tilt angle of the PV modules (typically corresponding to rooftop tilt angle).

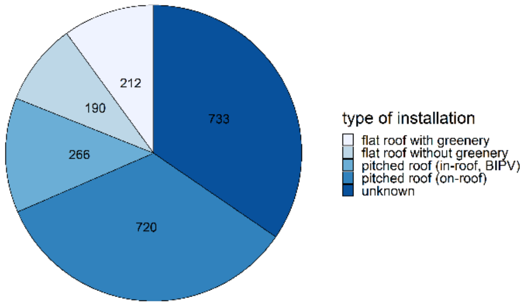

Figure 10: Number of inverters by type of installation.

3.2 Survival curves

The survival probability of all inverters is given in Figure 11. Because only a few inverters are older than 18 years, the survival curve is only plotted until year 18. In year 18, only 15 inverters were still in operation, resulting in a large confidence interval in the survival curve. After 18 years, the survival probability of all inverters is still 59.1% with a confidence interval of [52.1%, 67.0%].

Optimizers could only be observed during 8 years. Figure 12 shows the survival curve of inverters with and without optimizers. Throughout the observation time inverters with optimizers show roughly twice as many energy-relevant failures than inverters without optimizers.

For individual optimizers, the survival curve is relatively flat (Figure 13). However, as optimizers are normally used in larger quantities even for small systems, their TTF should rather be calculated for a whole fleet of optimizers than for a single device. Figure 14 shows the TTF after 5 and 10 years respectively for a given number of optimizers. Comparing the survival probability of a fleet of optimizers in Figure 14 with inverters without optimizers in Figure 12, a set of roughly 20 optimizers shows the same TTF after 5 and 10 years respectively as an inverter without optimizers. However, this comparison is only indicative, as optimizers cannot be operated without inverter.

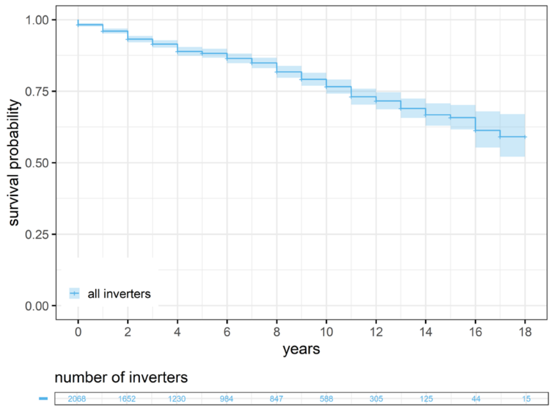

Figure 11: Survival probability of all inverters.

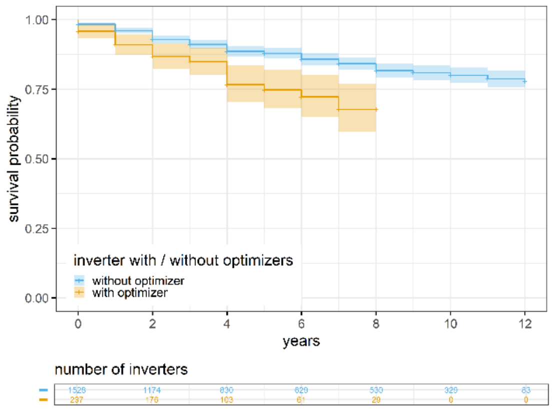

Figure 12: Survival probability for systems with and without optimizers.

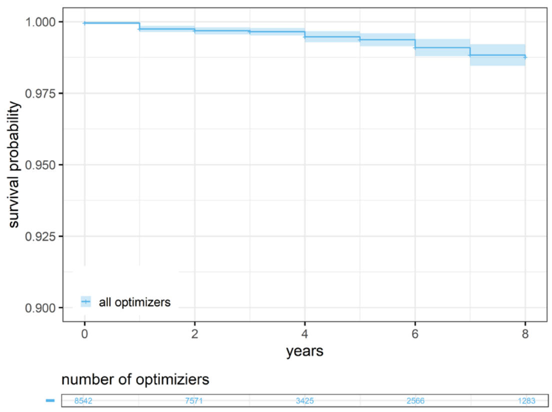

Figure 13: Survival probability of all optimizers (without inverter).

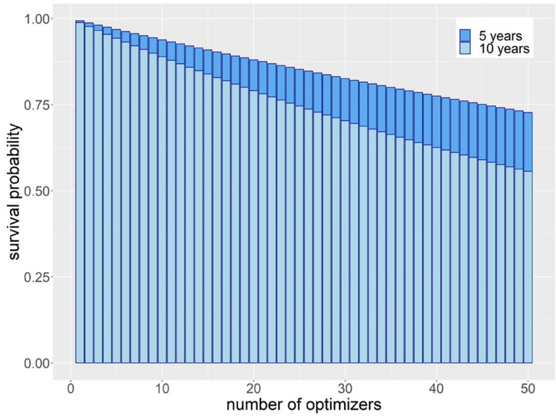

Figure 14: Survival probability after 5 and 10 years for a given number of optimizers (without inverter).

The survival curves of inverters split into three power categories are shown in Figure 15. A trend of more failures in large inverters can be observed. However, if these curves are adjusted for inverter manufacturer and place of installation (indoors/outdoors), this trend is not confirmed (Figure 16). This is most likely based on the fact that inverters installed outside a building have a lower TTF than inverters installed inside a building (Figure 17).

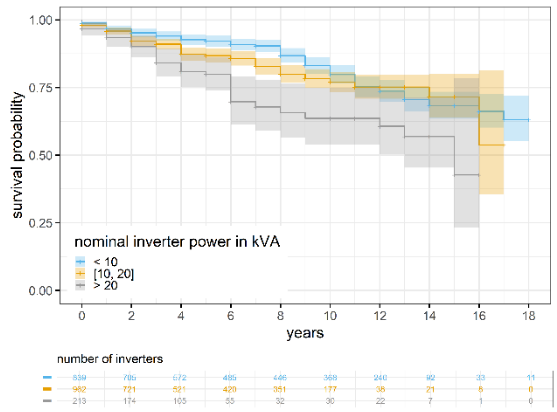

Figure 15: Survival probability for inverters of different power categories.

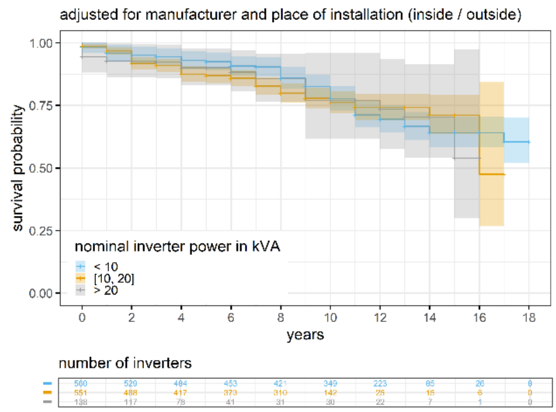

Figure 16: Survival probability for inverters of different power categories adjusted for manufacturer and place of installation.

Figure 17 shows the difference between the survival curves of inverters installed inside and outside a building. Because these variables are correlated to the inverter manufacturer and the nominal inverter power, an adjusted graph is shown in Figure 18. However, both figures show higher survival probabilities for systems installed inside a building. In the adjusted survival curve, this effect only becomes apparent after eight years.

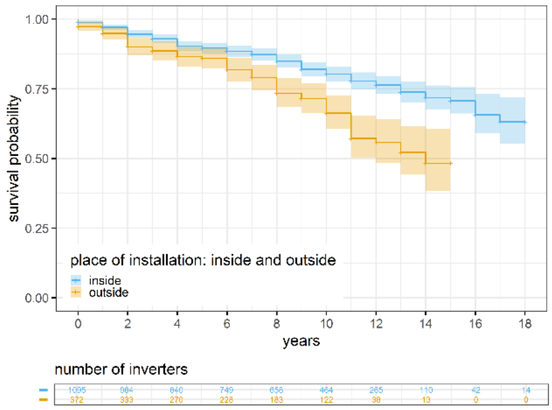

Figure 17: Survival probability of inverters installed inside and outside of a building.

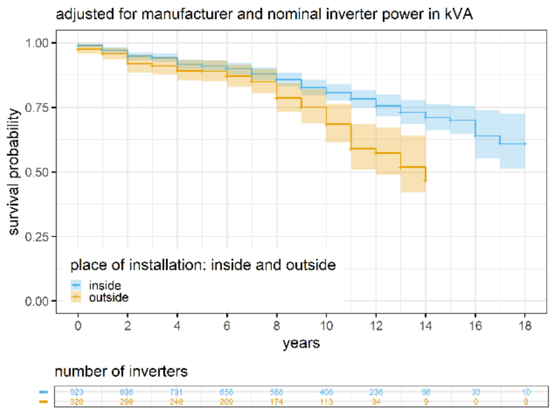

Figure 18: Survival probability of inverters installed inside and outside of a building, adjusted for manufacturer and inverter power.

Both inside and outside a building, inverters can face different situations. The survey asked whether installation rooms were heated or not (Figure 19). Outside the building, it was asked if the installation was protected against rain and direct sunlight (Figure 20). Both indoors and outdoors, stable conditions (heated room, protected installation site) seem to have a positive effect on the TTF of inverters. However, only little data is available to quantify these effects. The confidence intervals are overlapping in the outside case. Especially in this case, a clear conclusion therefore cannot be drawn from the available data.

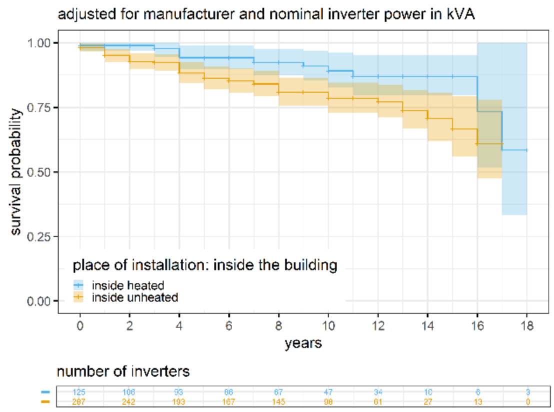

Figure 19: Survival probability of inverters installed inside the building.

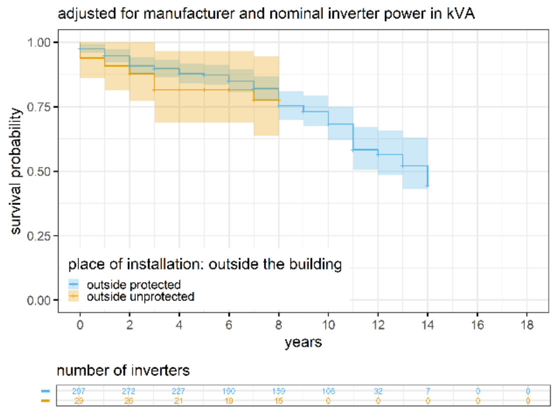

Figure 20: Survival probability of inverters installed outside the building.

No clear conclusion is possible from the survival curves of inverters installed with different sizing ratios (Figure 21). In the data-set, it is not the heavily loaded inverters with sizing ratios < 0.9 that have the lowest survival curve, but rather inverters with sizing ratios between 0.9 and 1.0. However, the confidence intervals overlap. This can indicate that too little data might be available to make a definite statement about the influence of the sizing ratio on the TTF. However, a clear conclusion is not possible.

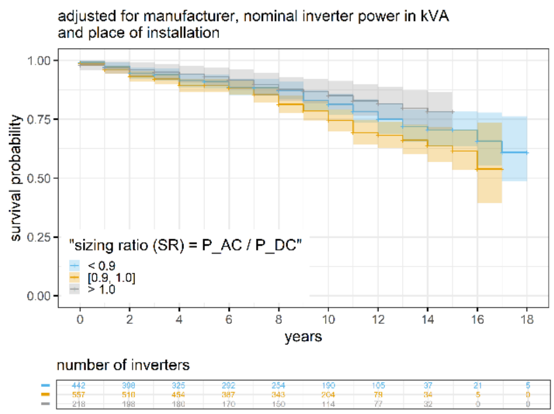

Figure 21: Survival probability of inverters with different sizing ratios.

The commissioning year has an influence on the survival probability of the inverters under investigation (Figure 22). Old inverters seem to have less energy-relevant failures in the beginning of their life span. The authors of this study cannot say whether this observation is biased by an effect not taken into account in this study, e.g. repair measures forgotten by the data providers.

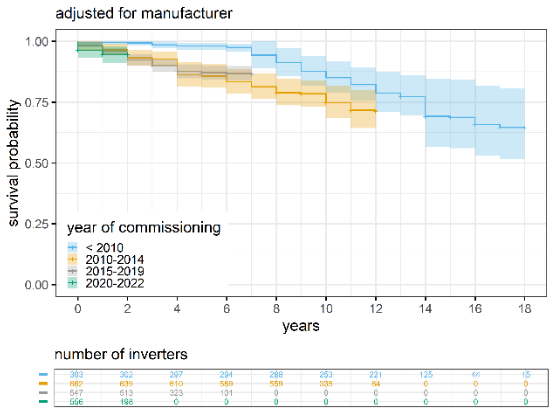

Figure 22: Survival probability of inverters with different commissioning years.

Finally, the survival probability of inverters from different manufacturers is shown in Figure 23. Although the confidence intervals of the curves are partly overlapping, the percentage of inverter failures observed varies by about a factor of three. The differences between the TTF varies thus remarkably between different manufacturers.

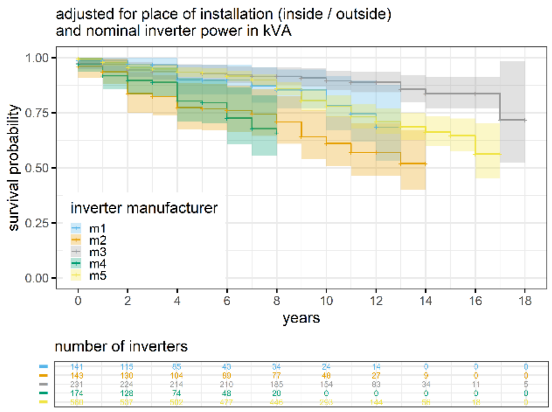

Figure 23: Survival probability of inverters from different manufacturers.

Several other questions have been asked in the survey to classify the PV systems, such as tilt angle of the roof or type of roof. However, the resulting data does not show relevant differences for such properties. Therefore, the corresponding survival curves are not shown in this paper.

4 DISCUSSION

4.1 Shortcomings of this study

Although the method chosen in this study allows the TTF of inverters to be quantified, there are several influences on the data that may negatively affect the results. Possible sources of error are discussed in the following sections.

4.2 Inverter as the system boundary

The relevant unit of this study is one inverter. For PV systems with optimizers, all optimizers are counted as part of one single inverter. Few systems in the scope of this study have many inverters with optimizers (>5); one case even had very many (>20) inverters with optimizers. In the case of the reported optimizer failures, it is not clear which inverter they were connected to. However, since the failures are assigned to one specific inverter in this study, it is unclear whether the reported defective optimizers are to be considered multiple failures on one inverter or many individual failures on several inverters. It was assumed that the optimizers with failures were randomly distributed within the PV systems. However, since the majority of the reported systems only involve one inverter, this error can be assumed to be insignificant.

4.3 Cause of failure unknown

The causes of the failures and defects are unknown. For example, it is not always possible to distinguish between a minor fault (such as the failure of a display) and a total loss (such as a full inverter breakdown including the failure of the display).

4.4 Rating of optimizer and inverter failures

The failure of an optimizer usually results in less yield loss than the failure of an inverter. However, in the survival curve (TTF), both failures are represented in the same way. If the failure of an optimizer triggers a maintenance service, the financial impact for the system owner is close to the financial impact of an inverter failure. However, if only the power of one module is lost and no maintenance is done, the impact of an optimizer failure is lower than that of an inverter failure. In the course of this study, the tendency was noted that individual defective optimizers were replaced in each case. Optimizers that are defective and have not been replaced were probably not detected within the scope of this study.

Under this consideration, however, some communication failures would also have to be evaluated as TTF as they can trigger maintenance. In this study, this is neglected, because the reason for communication errors is normally outside the PV system (e.g. poor mobile phone reception or security updates on the internet connection).

While inverters are usually repaired after the first fault occurs, even relatively young power optimizers with defects are not repaired but disposed of.

The number of optimizers resulting in the same TTF as one inverter is biased because the possible inverter failure is neglected in the case of optimizers. In reality, the TTF of inverters with optimizers would therefore be slightly lower than indicated in this study.

In general, the system comparison between plants with and without optimizers is critical because the monitoring and maintenance concept is different. Monitoring concepts with optimizers have the potential to detect more failures, which can trigger more maintenance activities, but also provide input for optimised maintenance concepts.

Inverter and optimizer technology has evolved greatly in the past. While the inverter industry is diverse and has decades of experience, optimizers are relatively new to the mass market and dominated by only a few manufacturers. Therefore, the learning curve of inverters can be assumed to be more advanced than the learning curve of optimizers. The results observed in this study might change with future inverter and optimizer generations.

4.5 Inverter replacement without failure

Especially in older systems, inverters are sometimes replaced pre-emptively without any immediate technical reason. In this study, this is counted as an inverter failure. This consideration is correct with regard to the economic calculation. However, it underestimates the life expectancy of the inverters.

4.6 Repair vs. end of life

It cannot be said without doubt whether an inverter failure indicates the end of the life of an inverter. Because installers and manufacturers often install second-hand replacement devices, even an inverter replacement does not necessarily mean the end of the inverter's service life. Due to this uncertainty, the TTF is defined as "time to first energy-relevant fault" in this study.

4.7 Non-representative data set

It can be assumed that the inverter brands and manufacturers that feature in the online survey are represented roughly proportionally to their market shares in German-speaking Switzerland. In the data from the institutional plant operators, however, individual products are naturally overrepresented. Because the inverters of different manufacturers have different TTFs, this leads to a distortion of the TTF of the entire inverter fleet.

It is not known whether one group of system operators felt particularly addressed by this survey. It is conceivable that system operators with defective systems would tend to fill out this survey more often than operators of systems without inverter defects. However, the comparison of the data from the online surveys with the data from institutional operators does not reveal a strong bias in this respect. On the other hand, it can be assumed that professional plant operators tend to pay more attention to quality and optimum operating conditions and therefore tend to have lower inverter failure rates.

Institutional system operators sometimes own systems that were predominantly built in certain time periods (for example, in the years 2008–2014 when Swiss feed-in tariffs, or FIT, were introduced). As a result, installations from these periods are overrepresented among these data providers. This leads to correlations in the statistics that have no causal link with the data providers.

4.8 Unknown initial failures

It is assumed that initial inverter failures are often not known to the building owner because they are either fixed by the installation companies or the inverters are replaced during installation. In the case of optimizers in particular, it must be assumed that initially defective devices were not reported in this study, as their replacement during plant commissioning causes only minor additional work and costs.

4.9 False information

It must be assumed that not all the information provided for this study was correct. The resulting errors cannot be quantified. However, from the personal comments made in the survey it can be assumed that most people correctly understood the questions. Obvious misunderstandings were corrected manually.

Certain errors are interpreted by the system operators as inverter errors, though fact they are not inverter errors. One example is earth faults in the module field, which lead to an error message on the inverter. As far as possible, these faults were masked as such and not evaluated within the scope of this study.

When optimizers are replaced in larger systems, it is not always clear how many optimizers were replaced. If no information is available, it is assumed that only one optimizer was replaced.

The data has shown some large (45 inverters, SR>1.5) and small (27 inverters, SR<0.5) sizing ratios. It is not known for sure if this data is realistic or not. However, it seems unrealistic and has therefore been deleted for the sizing ratio survival curve evaluation.

It was reported that many inverters were repaired in the years between 1992 and 2010 [8]. It is not clear if repairs of old inverters are always reported in this survey.

4.10 Misinterpretation due to correlated variables

As described in section 2.5, some survival curves are adjusted for possible confounders. However, not all possible influencing factors could be identified and eliminated. Therefore, it cannot be said for the graphs that the correlations found in the results correspond to the causes for the observed TTF.

5 FUTURE RESEARCH

The results of this study clearly show that the TTF of inverters depend on many different factors. It was possible to identify and quantify several of these factors. However, many questions remain open and many shortcomings could not be excluded (see chapter 4). Therefore, researchers are motivated to repeat this study and expand the data set to improve the quality and quantity of the results. The questionnaires should also be improved in order to reduce possible misinterpretations.

6 CONCLUSIONS

Data on inverter and power optimizer failures in PV systems were collected from PV system operators.

The inverters and optimizers in this study represent a broad, albeit not representative, cross-section of the inverters and optimizers used in PV systems on buildings in Switzerland and Europe. Inverters from the manufacturers Fronius, Sputnik and SMA are most widespread, while most optimizers are produced by SolarEdge. Compared to the European inverter market, the products from Sputnik (SolarMax) are probably overrepresented. In an international comparison, the European manufacturers are overrepresented.

The results across all inverters and power optimizers examined show that over 65% of inverters do not have a yield-relevant fault by their 15th year of operation.

Furthermore, the investigation shows that the TTF is dependent on various factors, in particular:

- Manufacturer: Different manufacturers have different TTF.
- Power: More powerful inverters have shorter TTFs; individually considered power optimizers have the longest TTFs. However, the overall reliability of a PV system increases significantly with the reduction in the number of power electronic components.
- Installation location: Outdoor power electronics have a shorter TTF than indoor power electronics.
- Topology: In PV systems with inverters with power optimizers, the first fault occurs earlier than in PV systems that do not have power optimizers.

Care should be taken not to overinterpret the results. Various factors play a role in the reliability of a PV system that are not taken into account in this study. It is also possible that certain influencing factors and correlations were not found within the scope of this study and were therefore wrongly neglected.

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