IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 18, 2017, accepted September 8, 2017, date of publication September 18, 2017,
date of current version October 25, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2753246

The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems

**TYLER J. FORMICA[1], HASSAN ABBAS KHAN[2], (Member, IEEE),
AND MICHAEL G. PECHT[1], (Life Fellow, IEEE)**
[1]Center for Advanced Life Cycle Engineering, University of Maryland at College Park, College Park, MD 20742, USA
[2]Department of Electrical Engineering, School of Science and Engineering, Lahore University of Management Sciences, Lahore 54792, Pakistan
Corresponding author: Tyler J. Formica (tyler.formica@gmail.com)

ABSTRACT Return on investment (ROI) analyses of solar photovoltaic (PV) systems used for residential usage have typically shown that at least 10 to 12 years is needed to break even, with this amount varying based on tax credits and reliability. This paper discusses the challenges with the reliability of current solar photovoltaic systems and the key reliability bottlenecks, with a focus on the ROI. The problem stems primarily from reliability issues of currently available power electronics hardware. This paper's analysis of failure data shows that the short warranties and reliability concerns associated with solar PV inverters reduce the long-term ROI of residential solar PV systems by up to 10%. This paper, therefore, provides key insights for accurate ROI calculations for solar PV investments. Furthermore, methods to improve the reliability of PV inverters, such as selection of capacitors, inverter topology, and incorporating wide-bandgap semiconductor devices, are presented.

INDEX TERMS Solar energy, solar photovoltaic systems, reliability, inverters, warranty, microelectronics, return on investment.

I. INTRODUCTION

The solar photovoltaic (PV) industry has been one of the fastest growing renewable energy industries, contributing both to the security of the electricity supply and the reduction of greenhouse gas emissions [1]. By the end of 2016, the total installed global capacity of solar PV power has approximately been 295 GW (gigawatts) [2], a 31% increase from 2015. An even higher trend in solar PV deployments is seen in the United States with installations of approximately 15,000 MW (megawatts) in 2016, a 100% increase from 2015 [3].

Solar PV systems work by converting sunlight into direct current (DC) electricity through solar cells, which are integrated into PV panels/modules [4]. Since most homes today use alternating current (AC), the DC is converted into AC through an inverter. Solar PV systems are composed of solar panels; solar inverters; mounting equipment to attach the panels to surfaces or hold the panels in the air; a DC subsystem, which contains a DC combiner box (to connect multiple strings) with a DC disconnect switch for safety purposes; an AC subsystem, which in domestic deployments is just a switch; an electricity meter to measure the output of the system; and wiring to connect the components (see Fig. 1). A solar PV system is generally tied to the utility grid to deliver excess electricity to the grid during peak hours and receive electricity from the grid when the PV system is not producing enough solar power. PV systems can also act as stand-alone systems and use a solar battery to store electricity; this scenario is more common in off-grid communities and in developing regions where the grid power is intermittent [5], [6].

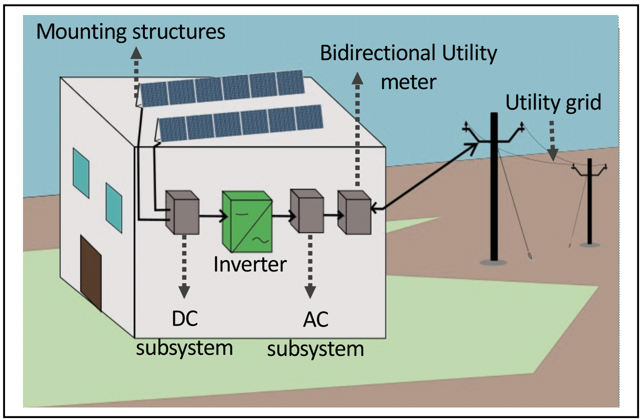

FIGURE 1. Configuration of a domestic grid-tied solar PV system.

The payback period, which is the time it takes to recoup funds from the initial start-up costs in an investment, is estimated to be within 10–12 years for contractor-installed residential PV systems [7]. However, current cost-analysis literature associated with PV systems does not account for reliability issues. If there are reliability problems with a solar PV system, it can take weeks to assess the cause of failure, obtain the needed replacement parts, and make the repairs. The costs can be substantial, and the inconvenience can be significant.

This article presents the different warranty structures offered by companies, the return on investment (ROI) challenges, the reliability concerns, and candidate solutions to these concerns associated with solar energy systems. We analyze warranty data from solar PV manufacturers and failure data from various studies available from literature.

II. SOLAR PHOTOVOLTAIC SYSTEM WARRANTIES

A warranty is a guarantee from the manufacturer that defines the responsibility for the product or service provided [8]. Warranties typically provide financial security for customers purchasing a product. Under a warranty, the costs associated with the repair or replacement of the product in the time period specified in the warranty is shifted from the customer to the manufacturer or the financer of the installation.

PV panel companies offer both performance warranties and product warranties. A performance warranty provides the customer with the assurance that the solar PV system will operate at a power output efficiency specified by the manufacturer for a set period of time. A product warranty provides the customer assurance that the solar panels will not fail due to a manufacturing error for a set period of time (e.g., physical damage due to hurricanes are typically not covered). There can also be a specific product warranty for the inverter.

Performance warranties focus on the efficiency of the solar PV system as a source of power (degradation based on an original efficiency guaranteed by the manufacturer). The amount of degradation in the performance of solar panels depends on environmental and operational conditions and is generally considered to occur at a rate of 1–2% per year [9]. Performance warranties typically guarantee about 90% power output compared to the efficiency when the PV system was purchased (the original efficiency) during the 10th year and 80% power output compared to the original efficiency during the 25th year of operation. For example, if the warranty guarantees 80% output during the 25th year of operation, then a 100 Wp (watt-peak) rated panel should produce at least 80 W under standard testing conditions (STCs). The STCs for solar panels include irradiance of 1000 $\mathrm{W/^{m2}}$ cell temperature of 25 °C, and wind speed of 1 m/s. For example, SunPower® guarantees at least 95% of power output compared to the original efficiency during the first 5 years, and a constant degradation in efficiency of 0.4% for years 5 through 25. Thus, the efficiency by year 25 is guaranteed to be at least 87% [10].

Product warranties for solar panels provide coverage against manufacturing defects and premature wear and tear. For the warranty to be honored, the customer must provide evidence that the malfunction in the product came from faulty parts when the product was bought [11]. For example, Canadian Solar’s 10-year product warranty states, “Any damages caused by abrasion, improper installation or animals are exempt from this warranty,” and then goes on to state that there must be proof that the malfunction can be traced back to a manufacturing error. SunPower provides a 25-year product warranty for their panels [12].

Warranties are also given for the solar PV inverters to cover defects in the workmanship and materials associated with the inverter. Residential systems generally use a central inverter but may alternatively use string inverters or micro-inverters. String inverters can be used for a group of panels and are smaller than central inverters but larger than micro-inverters. Micro-inverters are placed on individual panels, and each micro-inverter ties the available power to the grid. Therefore, micro-inverters have the inherent capability of measuring an individual panel’s performance.

Central inverter warranties vary from 5 to 15 years (e.g., SolarEdge offers a 12-year warranty [13]). The technology associated with central inverters is improving, but they are still the most likely components to experience failures in solar PV systems. Micro-inverters generally have longer warranties than central inverters, ranging from 15 to 25 years. This is due to higher reliability associated with micro-inverters because their switches and energy storage parts generally have lower power processing requirements (e.g., whereas central inverters are typically rated to handle 5 kW or higher, each micro-inverter is generally rated to handle 200–250 W [14]). ABB Group offers a 10-year product warranty for their micro-inverter systems and only a 2-year product warranty for their PVS800 central inverters [15], [16]. Enphase Energy offers a 25-year warranty for their micro-inverters [17].

III. FAILURE STUDIES

Failures of solar PV system components can significantly decrease the ROI for PV systems. In this section, field failure data was compiled and analyzed from three sources and categorized to determine the leading causes of failures in solar PV systems.

The first source was a SunEdison database that consisted of over 3,500 failure tickets from 350 commercial systems, approximately 150 kW, SunEdison® PV systems, operating between January 2010 and March 2012 [18], [19]. Failure tickets are issued when a system is underperforming, and these tickets are compiled to generate data regarding the cause of failure and the amount of kilowatt hours (kWh) lost due to system downtime during a failure. The kilowatt hours lost represents the energy production lost due to failures.

Table 1 is a compilation derived from the database that links the cause of failure (failure area) to the related ticket count as well as energy loss due to system downtime. In the

TABLE 1. Frequency of failure tickets and associated energy loss for each general failure area [18].

Failure Area	% of Tickets	% of kWh lost
Inverter	43%	36%
AC Subsystem	14%	20%
External	12%	20%
Other	9%	7%
Support Structure	6%	3%
DC Subsystem	6%	4%
Planned Outage	5%	8%
Module	2%	1%
Weather Station	2%	0%
Meter	1%	0%

table, "DC Subsystem" refers to parts that connect the solar panels to the inverter, including DC combiner boxes, wiring, and disconnects from the modules to the inverters. "AC Subsystem" includes everything between the inverter and the generation meter [19] (e.g., wiring, switch gears, and transformers). The external causes of failure stem from sources that are unrelated to the reliability of the PV system (e.g., grid outages and utility-mandated shutdowns) [19]. Support structures are the mounting equipment, which includes all the parts that hold the panels in place (e.g., clamps). Planned outage refers to outages that were already scheduled for preventive maintenance. Weather stations employ sensors to measure irradiance, temperature, and wind conditions to gauge the overall system performance.

The data in Table 2 indicates that PV inverter failures constitute the highest percentage of failures in SunEdison commercial PV systems. The inverter failures (see Table 2) were further categorized by the components that appeared to have induced the inverter failure, except in the first category, where no specific component could be assigned as the cause of the failure.

No-fault-found (NFF) failures are defined as instances in which a failure was observed but the failure cause could not be identified [20]. In this study, the NFF failures were considered intermittent, meaning the inverter failed but then recovered and functioned properly again after a manual restart. The failures were assumed to be due to control software because the maintenance personnel restarted the software and then observed no failure. However, the failures could also be attributed to hardware components since there was no investigation beyond restarting the inverter [18], and hardware failures are also capable of inducing software shutdowns.

Cards/boards are the printed circuit boards (PCBs) used in the inverter. All switching elements, power buffers, and heat sinks are mounted on PCBs, which are optimized for thermal management, parasitic minimization, and electrical noise perspectives. These PCBs fail due to internal routing issues, which result in failures in which the entire power module must be replaced. AC contactors are the primary disconnection source to switch AC power from the inverter to the grid on/off, and DC contactors operate similarly with DC power. Cooling fans are used to regulate the temperature. IGBTs are three-terminal solid-state semiconductor switches that allow efficient power flow from the panels (DC) to the grid side (AC). Capacitors are used to temporarily store energy and provide a stable DC rail voltage to the inverter input. Fuses consist of low-resistance metallic wire inside noncombustible material used to protect current from overloading. The impact of lightning strikes is minimized with surge protection components. Ground fault interrupter (GFI) components are used to compare the current in the neutral conductor with the ungrounded conductor.

TABLE 2. Frequency of failure tickets and associated energy loss for each general failure area [18].

Inverter Failure Area	% of Tickets	% of kWh lost
No-Fault-Found Failures	28%	15%
Card/Board	13%	22%
AC Contactor	12%	13%
Fan(s)	6%	5%
Matrix/IGBT	6%	6%
Power Supply	5%	5%
AC Fuses	4%	12%
DC Contactor	4%	1%
Surge Protection	3%	1%
GFI Components	3%	2%
Capacitors	3%	7%
Internal Fuses	3%	4%
Internal Relay/Switch	3%	2%
DC Input Fuses	2%	1%
Other	5%	2%

The second data source came from Collins *et al.* [21], who conducted a 5-year study of failures associated with a 4.6-MW solar PV plant consisting of 26 arrays, with each array comprised of 450 PV modules and 1 inverter. Of the 237 failures observed over 5 years, 125 of the failures were attributed to the inverters (see Table 3).

The third data source was derived from Huang *et al.* [22], who analyzed failure data gathered by the Industrial Technology Research Institute consisting of 202 PV systems in Taiwan over a 3-year span. Among the 202 PV systems, 62 experienced failures within the 3-year span. 60% of the failures in the 62 systems were attributed to the inverter (see Table 4).

A survey was conducted by Zaman *et al.* [23] that also indicates inverters contribute to the most failures. For the study, solar PV users and stakeholders in Australia reported

TABLE 3. Distribution of failures observed at a 4.6-MW PV plant over 5 years [21].

Failure Area	% of Tickets
Inverter	53%
AC Subsystem	14%
DC Subsystem	14%
Module	12%
Other (lightning)	7%

TABLE 4. Distribution of failures observed in 202 PV systems over 3 years [22].

Failure Area	% of Tickets
Inverter	60%
Balance of System Components	28%
PV Modules	12%

the failures they had observed in their solar PV systems. Of the 29 respondents, 26 of the problems reported were related to the inverter, including 10 instances of a complete functional failure of the inverter.

IV. COMPONENTS CONTRIBUTING TO SOLAR PHOTOVOLTAIC SYSTEM FAILURES

The data provided in the above-mentioned studies indicates that PV inverters comprise the most unreliable component in PV systems. In industry, solar PV system manufacturers openly admit the high likelihood of solar PV inverters failing. For example, SolarCity New Zealand [24] states on their website, "The inverter, which has a 10-year warranty, is likely to be the only piece of equipment you will need to replace."

Inverter topology significantly affects the reliability of solar PV systems. Table 5 summarizes the benefits and weaknesses of the three general inverter categories.

The failure of an inverter is usually precipitated by the capacitors, insulated-gate bipolar transistors (IGBTs), or metal-oxide-semiconductor-field-effect transistors (MOSFETs) that comprise the inverter [25]. With regards to specific switching requirements and operation, IGBTs perform well in high-voltage, high-temperature conditions where high-power processing is required [26]. MOSFETs, on the other hand, provide an efficient alternative to IGBTs in inverter topologies where higher switching speeds are required at relatively low power processing requirements [26].

A. CAPACITORS

The most common capacitors used in inverters are electrolytic and film; film capacitors are far more reliable but more expensive than electrolytic capacitors, with the price difference varying based on size [27]. Aluminum electrolytic capacitors have been estimated to be approximately one-third the price of film capacitors per amount of energy storage needed [28]. Although film capacitors offer improved reliability compared to electrolytic capacitors, replacing electrolytic capacitors with film capacitors in PV inverters is not cost-effective in all applications due to the higher price and smaller capacitance per volume ratio associated with film capacitors [29]. Schimpf and Norum estimate the capacitance per volume ratio of electrolytic capacitors to be 20 times greater than film capacitors [29].

TABLE 5. The Effect of inverter topology on reliability.

Inverter Topology	Effect on Reliability
Micro-inverter	Typically handles 200–300 W. Low power processing requirements lead to longer lifetimes and warranty periods of 25 years. Each micro-inverter is attached to an individual panel
Residential Size Central Inverter	Typically handles 1–10 kW. Medium power processing requirements lead to shorter lifetimes than micro-inverters and warranty periods of 5–15 years. These are generally used in residential applications
Utility-Scale Central Inverter	Typically handles greater than 100 kW. High power processing requirements lead to frequent maintenance and upkeep in utility applications.

Solar PV inverters with a single standard electrolytic capacitor (DC-link) are estimated to have a lifetime of about five years before a failure [30]. Electrolytic capacitors in solar PV inverters fail due to temperature cycling, power cycling, and high internal capacitor temperature [31]–[33]. Temperature cycling is particularly prominent in micro-inverter applications when the inverters are placed outdoors on individual panels. Electrolytic capacitors are significantly more prone to catastrophic failures than film capacitors [35]. In a catastrophic failure, a capacitor is completely non-functional and must be replaced. Sometimes the electrolytic capacitor will explode, which subsequently damages other components. Catastrophic failures usually occur in poorly sealed capacitors when ripple currents cause high internal temperatures leading to the vaporization of the electrolyte [32]. Film capacitors rarely fail catastrophically, rather they tend to fail due to degradation, which decreases performance [33].

B. IGBTs AND MOSFETS

Semiconductor devices used in solar PV inverters, such as IGBTs and MOSFETs, fail due to electrical degradation in the components or mechanical degradation associated with the electronic packaging [33]. Transistor failures frequently occur in PV inverters operating in high-voltage, high-current, or extreme temperature conditions exceeding the manufacturer's specifications [33]–[35] in the form of bond wire lift-off or deterioration of the die attach.

To test the reliability of IGBTs in solar PV inverter applications, Sandia National Laboratories [38] studied the effects of high-temperature and high-voltage conditions on IGBTs. The IGBTs were stressed at various conditions, such as their maximum rated current of 61 A at 25 °C for 45 min, and at temperatures above their rated current, such as 90 °C. The study did not specify how many IGBTs were used but stated that most IGBTs performed at a satisfactory level. However, in a few cases the IGBTs degraded significantly and in one case the IGBT degraded so drastically to the point it would have caused a complete failure in a solar PV inverter. MOSFETs tend to fail due to high junction temperatures [33].

In addition to electronic devices and capacitors, which perform core inverter operations, there are other inverter-related components which may result in system downtime. For instance, AC fuses may cause the inverter to stop functioning [36] if there are short circuits, which can occur when the insulation surrounding the wiring of the PV system is exposed. Pecan Street, a company that compiles data regarding energy needs and water supply, conducted a study of 255 residential solar PV systems over a period of 4 years [37]. Fifty-four of these solar PV systems reported minor maintenance issues within the time period. Of the 54 reports, 13 experienced PV inverter failures due to blown AC fuses in the inverters.

V. ANALYSIS OF THE EFFECT OF FAILURES AND DEGRADATION ON RETURN ON INVESTMENT

ROI analyses often assume components in solar PV systems will last 25 years without experiencing failures that constitute a replacement and only assume a constant maintenance cost to account for repairs [7], [38]. Central inverter warranties are most often between 5 to 15 years, and, as discussed in Section III, these inverters are likely to suffer multiple failures in 25 years. This section takes into account the effect of out-of-warranty PV inverter failures and module performance degradation on a 25-year ROI of a typical PV system setup in Florida taking Yang *et al.* [7] work as baseline. This residential 6.7-kW PV system in Gainesville, Florida, was installed by a contractor and qualified for the following benefits:

a) Feed-in tariffs (FITs): FITs offer lucrative rates for supplying electricity back to the grid to encourage users to invest in renewable energy. In this case, the FIT was \$0.21/kWh.

b) State tax-rebate: Florida offered a rebate for Gainesville that was calculated to be \$82.50/year.

c) U.S. Federal Solar Investment Tax Credit: An upfront cost subsidy was offered in the form of a 30% tax credit for start-up costs (purchasing the system and installation costs).

For simplicity, Yang *et al.* [7] did not account for inflation and future changes to tax credits offered by federal, state, and local governments, which are difficult to predict and quantify accurately. We took these assumption as the baseline for further analysis and incorporated the effect of panel degradation (not included in [7]) as well as the effect of multiple inverter failures in the ROI calculation.

Panel efficiency degradation must be accounted for in the calculations for more accurate predictions. Our analysis uses the minimum efficiency guaranteed each year by Suntech in their performance warranty [39] for their STP-280 panels as these panels were used in [7]. However, we do not account for any module replacements, which are not a significant failure area, as indicated in Section III. The energy produced over the lifetime is also averaged for yearly calculations. Further, an SMA inverter [40] with a 5-year warranty is taken for analysis (same as [7]) with decreasing inverter costs at 10% (case 1) and 15% per year (case 2). It is expected that the cost of inverters will decrease between 10% to 15% per year [41] in the future, and it is important to incorporate this effect for realistic projections. In order to calculate ROI, the equation shown at the top of the next page has been used and is adopted from [7].

Note that the normalized inverter replacement costs depend on the number of replacements included in the ROI analysis. For instance, in the case of two replacements in the 25-year lifetime of the system, we include inverter replacements at 8.33 and 16.66 years and incorporate the projected decrease in the cost along with the overall cost normalized over 25 years. The starting cost of the inverter was taken as \$2647.00 (at the time of installation) and the annual maintenance cost was taken as \$168.00 per year (same as [7]).

A plot showing the 25-year ROI for Yang *et al.* and our analysis is given in Fig. 2. Yang *et al.* predicts an ROI of 2.45 which, we believe, is unlikely to be the case in practice as it does not include the effect of panel degradation and potential inverter replacements. After incorporating panel degradation, the best-case scenario (albeit highly unlikely

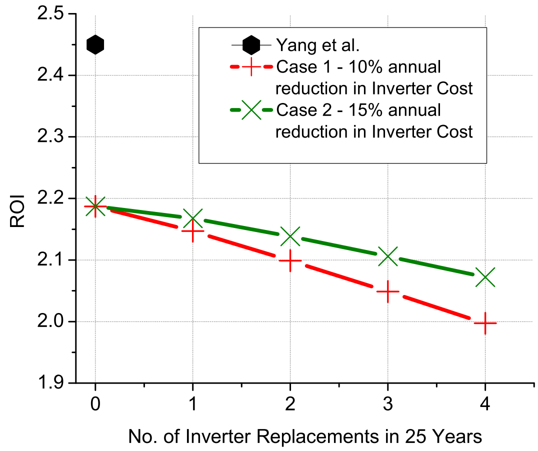

FIGURE 2. ROI of Gainesville, Florida, case study with the additions of inverter replacement costs and panel degradation [7].

$$\mathit{PV\ System\ ROI} = 25 \times \left\{ \frac{\begin{array}{l}[(\mathit{av.\ Annual\ Energy\ Yield}\ \times\ \mathit{FIT} + \mathit{Tax\ Rebate})\\ -(\mathit{Normalized\ Inverter\ replacement\ Cost} + \mathit{Annual\ Maintenance})]\end{array}}{\mathit{Startup\ Costs} - \mathit{Upfornt\ Cost\ Subsidy}} \right\}$$

with zero inverter replacements) shows the ROI closer to 2.2. We further modeled the ROI for scenarios in which the inverter fails multiple times without being covered by the 5-year inverter warranty during the 25-year guaranteed performance lifetime of the panels. It can be concluded that each inverter replacement will cause the overall ROI of the system to decrease. Further, two cases for inverter replacements are taken where the annual decrease in the inverter cost is 10% (case 1) and 15% (case 2). A worst-case scenario where the inverter fails every 5 years (just after the warranty expires) and requires 4 replacements shows a reduction in ROI to 1.95 for case 1 and 2.07 for case 2, which amounts to a decrease of up to 10% due to inverter failures.

It should be noted that this analysis does not account for potential shipping costs when the inverter needs to be replaced and the energy lost due to downtime when the PV system is not producing energy in the event of an inverter replacement. There is variation in the amount of these costs and whether these costs are covered by the manufacturer. Consumers should be cautious with these issues when negotiating contractor-based installations where contractors or system installers must be required to maintain an inventory for the likelihood of an inverter failure. This will prevent long system downtime associated with inverter failures due to assessment and shipping delays.

Many failure studies indicate that PV inverters have a lifetime of 1–20 years until failure [21], [22], [38]; this timeframe varies significantly based on power cycling conditions, inverter size, temperature cycling, inverter components (types of capacitors used, semiconductor materials used, etc.), and other conditions. Therefore, analysis on possible inverter failures will result in better estimation of ROI and suitability of the investment within a particular incentive scheme. A significant variation in ROI is observed (see Fig.2) due to inverter replacement costs, and therefore this variation must be accounted for in a detailed assessment at the planning stage.

VI. EMERGING TECHNOLOGIES TO IMPROVE THE RELIABILITY OF PV INVERTERS

Two major advances in electronics promise to improve the reliability of PV system inverters and, in turn, solar PV systems. The first advance pertains to wide-bandgap semiconductors (e.g., silicon carbide (SiC) and gallium nitride (GaN)), which are capable of providing high-temperature operation, long-term performance, and improved efficiency of the inverters compared to inverters employing silicon (Si)-based semiconductors. This advance improves the energy production and reliability of the PV inverter and, in turn, the overall ROI. The second advance involves improved inverter design topologies, including the development of micro-inverters.

SiC and GaN are wide-bandgap materials with superior conduction and switching properties compared to Si. When used in MOSFETs and IGBTs, they can withstand higher reverse voltages and temperatures and achieve higher frequencies than Si-based transistors [42]–[46]. Hinata *et al.* [42] tested a solar PV inverter using all SiC semiconductors with overall efficiency of 99% (mass-produced inverters have not yet reached 99% efficiency). Their SiC-based inverter design also achieved 50 times as many power cycles to failure as a Si-based design used for comparison. 500 thermal cycles with parameters of −40 °C and 175 °C showed failures in the Si-based inverter and no noticeable degradation in the SiC-based inverter. Sintamarean *et al.* [52] designed PV inverters to compare the performances of a Si IGBT-based solar inverter with a SiC MOSFET-based inverter in high-power applications (10 kW or higher). They achieved a switching frequency of 50 kHz for the SiC-based inverter compared to 16 kHz for the Si-based inverter. Sintamarean *et al.* [46] also concluded that, for particular settings, a SiC MOSFET-based inverter was more cost-effective and reliable due to higher switching frequency, which allowed 40% and 70% lower inductance and capacitance requirements, respectively. However, in general, the price of SiC- and GaN-based inverters is still considerably higher than Si-based inverters.

Micro-inverters promise improved reliability compared to central inverters due to lower power processing requirements for switches and energy storage elements. Each micro-inverter is typically connected to a 200–250 Wp panel, and the need for electrolytic capacitors is largely eliminated. Film capacitors, which are more reliable but have 1/20 the capacitance per volume ratio of aluminum electrolytic counterparts [32], can be used due to these lower power processing requirements [47]. In addition to better reliability, there are two more significant advantages of deploying micro-inverters. First, unlike a central inverter, if a single micro-inverter fails, only the module that the micro-inverter is attached to will fail, and the rest of the PV system will remain functional. Conversely, if a central inverter fails, all panels (attached to the inverter) stop delivering any power to the loads/utility until the inverter is replaced/fixed. Second, micro-inverters have a much better performance ratio (PR) compared to central inverters in deployments where there is a high shading effect [48] because micro-inverters deploy module-level MPPTs (maximum power point tracking) as opposed to string-level MPPT operation for central inverters [49]. MPPT is a process by which the input impedance of the inverter is changed to match the maximum power load-line from the panels [33].

Micro-inverters also have several disadvantages. First, the upfront system cost of PV deployments with micro-inverters may be considerably higher compared to central systems due to the larger number of micro-inverters used in the system along with higher installation costs. For instance, purchasing several 200–250 W rated micro-inverters in a residential PV system compared to one 3–10 kWp central inverter will result in a higher start-up cost. Moreover, micro-inverters may not necessarily be easy to replace because they may not be readily accessible in some systems without completely dismantling portions of the array. This may limit the ROI due to panel/system downtime associated with inverter replacement. Second, because they are placed outside on each individual panel, they are exposed to environmental conditions, such as high temperature and moisture, which decrease the reliability of PCBs and solder joints that are typically not built to last the 25-year warranty period of solar PV systems, especially when exposed to volatile outdoor climates [50]. However, no failure studies specific to micro-inverters are available in the literature to corroborate their suitability for a 25-year period. Despite these anticipated challenges, the 25-year warranties associated with micro-inverters is a significant advantage over central inverters, which typically offer lower warranty periods. Therefore, micro-inverter-based PV deployments are likely to have a higher and more predictable ROI owing to the likelihood that inverter replacements will be lower (if the initial costs for central and micro-inverter-based PV systems are the same).

Improvement in the reliability of solar PV inverters is a growing research area. In-depth analysis of the effects of the design, usage, and power conversion requirements of the inverter on reliability will undoubtedly lead to more reliable inverters in the years to come [51]–[56].

VII. CONCLUSIONS

While solar photovoltaic (PV) systems are generally reliable, failures associated with inverters will decrease the return on investment (ROI). The data presented in this study confirms that central inverters are the least reliable component in solar PV systems. Our study shows that the 25-year ROI of solar PV systems may vary from approximately 2 to 2.2 due to central inverter replacement costs, and even higher variance may occur when factors such as system downtime due to an inverter failure are incorporated. Central inverter warranties are most often less than 15 years, whereas the PV panels and mounting equipment are likely to last 25 years. Current ROI studies of solar PV systems often overlook repair and replacement costs associated with inverters. They also do not account for downtime during which the PV system is not performing while the user is in the process of filing a warranty claim and is waiting for the manufacturer to investigate and make a decision or for the inverter to be repaired or replaced. Even if an inverter is covered under warranty, inverter manufacturers are not always obligated to cover the costs of system downtime, shipping, and reinstallation of the replacement inverter. These factors all decrease the long-term ROI of solar PV systems, and consumers must guard against these issues when choosing contractor-deployed PV systems.

The 25-year warranties of some emerging micro-inverter manufacturers are likely to allow residential users to experience fewer system losses due to replacements as compared to system losses with central inverters. As the cost of micro-inverters decreases, their longer warranties for residential PV users can allow a higher and more predictable 25-year ROI as compared to current estimates.

REFERENCES

[1] P. Vithayasrichareon, G. Mills, and I. F. MacGill, “Impact of electric vehicles and solar PV on future generation portfolio investment,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 899–908, Jul. 2015.

[2] J. Pyper. “Global solar PV capacity will approach 295 GW in 2016.” Renewable Energy Focus, Global Data, (Dec. 2016). [Online]. Available: http://www.renewableenergyfocus.com/view/45114/global-solar-pv-capacity-will-approach-295-gw-in-2016-says-globaldata/

[3] “Solar industry data: Solar industry growing at a record pace.” Solar Energy Industries Association. Accessed: Aug. 18, 2017. http://www.seia.org/research-resources/solar-industry-data

[4] S. Islam, S. Mekhilef, and M. Hasan, “Single phase transformerless inverter topologies for grid-tied photovoltaic system: A review,” *Renew. Sustain. Energy Rev.*, vol. 45, pp. 69–86, May 2015.

[5] M. Das and V. Agarwal, “Novel high-performance stand-alone solar PV system with high-gain high-efficiency DC-DC converter power stages,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4718–4728, Nov. 2015.

[6] H. A. Khan and S. Pervaiz, “Technological review on solar PV in Pakistan: Scope, practices and recommendations for optimized system design,” *Renew. Sustain. Energy Rev.*, vol. 23, pp. 147–154, Jul. 2013.

[7] D. Yang, H. A. Latchman, D. Tingling, and A. A. Amarsingh, “Design and return on investment analysis of residential solar PV systems,” *IEEE Potentials*, vol. 34, no. 4, pp. 11–17, Jul. 2015.

[8] M. G. Pecht, “Establishing a relationship between warranty and reliability,” *IEEE Trans. Electron. Packag. Manuf.*, vol. 29, no. 3, pp. 184–190, Jul. 2006.

[9] R. Strecker. “Solar panels—Lifetime productivity and maintenance costs.” Boston Solar. (Sep. 2011). [Online]. Available: http://www.bostonsolar.us/blog/solar-panels-lifetime-productivity-and-maintenance-costs

[10] M. A. Maehlum. (Jun. 2013). *Solar Panel Warranty Comparison*. Energy Informative, accessed: Aug. 18, 2017. [Online]. Available: http://energyinformative.org/solar-panel-warranty-comparison/

[11] *Limited Warranty Statement Photovoltaic Diamond Module Products*. Canadian Solar, accessed: Aug. 18, 2017. [Online]. Available: http://www.canadiansolar.com/downloads/warranties/Warranty_Standard_PV_Module_en.pdf

[12] *Limited Product and Power Warranty for PV Modules*. SunPower, accessed: Aug. 18, 2017. [Online]. Available: http://us.sunpower.com/sites/sunpower/files/media-library/warranties/wr-sunpower-limited-product-and-power-warranty-pv-modules.pdf

[13] *Solar Edge Product Warranty Program*. SolarEdge, accessed: Aug. 18, 2017. [Online]. Available: http://www.solaredge.us/groups/us/service/warranty

[14] *Grid-Connected Solar Microinverter Reference Design Using a dsPIC Digital Signal Controller*, Microchip Technol. Inc., Chandler, AZ, USA, Aug. 2011.

[15] *Central Inverters PVS800 Warranty and Service Offering*. ABB Group, accessed: Aug. 18, 2017. [Online]. Available: https://library.e.abb.com/public/7488c31491241476c1257d89002aca52/17267_Warranty_and_service_offering_3AUA0000133536_RevC_lowres.pdf

[16] *ABB Micro Inverter System MICRO-0.25/0.3/0.3HV-I-OUTD 0.25kW to 0.3kW*. ABB Group, accessed: Aug. 18, 2017. [Online]. Available: https://library.e.abb.com/public/3b4b2359a4986e2685257dff005e1834/MICRO-0.25-0.3-0.3HV-Rev0.1.pdf

[17] (Jan. 2014). *Enphase Energy M215 Micro-Inverter 25-Year Limited Warranty—North America*. Enphase Energy, accessed: Aug. 18, 2017. [Online]. Available: http://www2.enphase.com/entrust/25-year-limited-warranty/

[18] A. Golnas, “PV system reliability: An operator’s perspective,” *IEEE J. Photovolt.*, vol. 3, no. 1, pp. 416–421, Sep. 2013.

[19] A. Golnas, *Telephone Interview*. Tech. Rep., Oct. 2015.

[20] R. Bakhshi, S. Kunche, and M. G. Pecht, "Intermittent failures in hardware and software," *J. Electron. Packag.*, vol. 136, no. 1, pp. 011014-1–011014-5, Mar. 2014.

[21] E. Collins, M. Dvorack, J. Mahn, and M. Quintana, "Reliability and availability analysis of a fielded photovoltaic system," in *Proc. 24th IEEE Photovolt. Specialist Conf. (PVSC)*, Jun. 2009, pp. 002316–002321.

[22] H. S. Huang, J. S. Jao, K. L. Yen, and C. T. Tsai, "Performance and availability analyses of PV generation systems in Taiwan," *World Acad. Sci. Eng. Technol.*, vol. 54, no. 6, pp. 731–735, 2011.

[23] A. Zaman *et al.*, "PV system reliability—Preliminary findings from the PV module and system fault reporting Website," in *Proc. Asia–Pacific Solar Res. Conf.*, 2014.

[24] *Warranties & Maintenance*. SolarCity, accessed: Aug. 18, 2017. [Online]. Available: http://www.solarcity.co.nz/residential/product/solar-life-expectancy/

[25] R. Olay, "Solar inverter components can raise efficiencies," *Solar Ind. Mag.*, vol. 5, no. 12, Jan. 2013.

[26] C. Black and C. Bull. (Oct. 1999). *IGBTs or MOSFETs: Which is Better for Your Design?*. Electronic Design. [Online]. Available: http://electronicdesign.com/power/igbts-or-mosfets-which-better-your-design

[27] G. Terzulli and B. W. Peace. *Film Technology to Replace Electrolytic Technology*. AVX Corporation, accessed: Aug. 18, 2017. [Online]. Available: https://www.avx.com/docs/techinfo/filmtech.pdf

[28] *Aluminum Electrolytic Capacitors vs Film Capacitors*. Heynen, Electronic Component Solutions, accessed: Aug. 18, 2017. [Online]. Available: http://www.heynen.com/aluminum-electrolytic-capacitors-vs-film-capacitors

[29] F. Schimpf and L. Norum, "Effective use of film capacitors in single-phase PV-inverters by active power decoupling," in *Proc. 36th Annu. Conf. IEEE Ind. Electron. (IECON)*, Nov. 2010, pp. 2784–2789.

[30] C. Rodriguez and G. Amaratunga, "Long-lifetime power inverter for photovoltaic AC modules," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2593–2601, Jul. 2008.

[31] M. C. Russell and G. RaySolar, "The promise of reliable inverters for PV systems: The micro-inverter solution," GTM Res., New York, NY, USA, Tech. Rep., Jun. 2010. [Online]. Available: https://www.greentechmedia.com/articles/read/the-promise-of-reliable-inverters-for-pv-systems-the-micro-inverter-solution

[32] J. Flicker, "Capacitor reliability in photovoltaic inverters," Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep., Jun. 2015. [Online]. Available: https://www.researchgate.net/publication/279448671_Capacitor_Reliability_in_Photovoltaic_Inverters

[33] J. Flicker and R. Kaplar, "Reliability of power conversion systems in photovoltaic applications," Ph.D. dissertation, Dept. IET Power Energy Series, Inst. Eng. Technol., Stevenage, U.K., 2016, pp. 398–403.

[34] A. Ristow, M. Begovìc, A. Pregelj, and A. Rohatgi, "Development of a methodology for improving photovoltaic inverter reliability," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2581–2592, Jul. 2008.

[35] R. Kaplar *et al.*, "PV inverter performance and reliability: What is the role of the IGBT?" in *Proc. 37th IEEE Photovolt. Specialists Conf. (PVSC)*, Jun. 2011, pp. 001842–001847.

[36] *Fuse and Types of Fuses*. Electrical Technology, accessed: Nov. 7, 2014. [Online]. Available: http://www.electricaltechnology.org/2014/11/fuse-types-of-fuses.html

[37] P. Street, "Minor maintenance issues proving difficult to detect for many solar PV system owners," *GTM Res., Pecan Street GTM PV Maintenance Rep.*, vol. 2, no. 5, pp. 1–10, Feb. 2015. [Online]. Available: http://www.pecanstreet.org/wordpress/wp-content/uploads/2015/02/Pecan-Street-GTM-PV-Maintenance-Report-Feb-2015.pdf

[38] E. Shouman, E. T. Shenaway, and N. M. Khattab, "Market financial analysis and cost performance for photovoltaic technology through international and national perspective with case study for Egypt," *Elsevier, Renew. Sustain. Energy Rev.*, Vol. 57, pp. 540–549, May 2016.

[39] Suntech. *280 Watt Polycrystalline Solar Module*. Accessed: Aug. 18, 2017. [Online]. Available: http://www.ecodirect.com/Suntech-STP280-24-VD-280W-35V-PV-Panel-p/suntech-stp280-24vd.htm

[40] SMA. (Mar. 21, 2016). *SMA America LLC Factory Warranty*. Accessed: Aug. 18, 2017. [Online]. Available: https://pdf.wholesalesolar.com/inverter%20pdf%20folder/Sunny-Boy-Warranty-8-13.pdf

[41] V. Shah and J. Booream-Phelps, "Solar grid parity in a low oil price era," Deutsche Bank, Frankfurt, Germany, Tech. Rep., Feb. 2015. [Online]. Available: https://www.db.com/cr/en/concrete-deutsche-bank-report-solar-grid-parity-in-a-low-oil-price-era.htm

[42] Y. Hinata, M. Horio, Y. Ikeda, R. Yamada, and Y. Takahashi, "Full SiC power module with advanced structure and its solar inverter application," in *Proc. 28th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2013, pp. 604–607.

[43] M. Oneill. *Silicon Carbide Diodes Make Solar Power Systems More Efficient*. EE Times, accessed: Aug. 18, 2017. [Online]. Available: http://www.eetimes.com/document.asp?doc_id=1273188&

[44] *Reaching for the High Fruit: Finding Room for SiC and GaN in the Solar Inverter Market*. Lux Research, accessed: Apr. 1, 2013. [Online]. Available: https://portal.luxresearchinc.com/research/report_excerpt/13342

[45] U. Schwarzer, S. Buschhorn, and K. Vogel, "System benefits for solar inverter using SiC semiconductor modules," in *Proc. PCIM Eur.*, May 2014, pp. 1–8.

[46] N. C. Sintamarean, E. P. Eni, B. Blaabjerg, R. Teodorescu, and H. Wang, "Wide-band gap devices in PV systems—Opportunities and challenges," in *Proc. Int. Power Electron. Conf.*, 2014, pp. 1912–1919.

[47] H. Haibing, S. Harb, N. H. Kutkut, Z. J. Shen, and I. Batarseh, "A single-stage microinverter without using eletrolytic capacitors," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2677–2687, Jun. 2013.

[48] K. Sinapis *et al.*, "A comprehensive study on partial shading response of c-Si modules and yield modeling of string inverter and module level power electronics," *Solar Energy*, vol. 135, pp. 731–741, Oct. 2016.

[49] Y. Sin and R. Winston, "Power conversion in concentrating photovoltaic systems: Central, string, and micro-inverters," *Prog. Photovolt., Res. Appl.*, vol. 22, no. 9, pp. 984–992, 2014.

[50] C. Tulkoff. *Reliability Challenges for Solar Electronics*. DfR Solutions, Solar Energy Industry Association, Solar Electric Power Association, accessed: Aug. 18, 2017.

[51] G. Adinolfi, "Multiobjective optimal design of photovoltaic synchronous boost converters assessing efficiency, reliability, and cost savings," *IEEE Trans. Ind. Informat.*, vol. 11, no. 5, pp. 1038–1048, Oct. 2015.

[52] P. Zhang, "Reliability evaluation of grid-connected photovoltaic power systems," *IEEE Trans. Sustain. Energy*, vol. 3, no. 3, pp. 379–389, Jul. 2012.

[53] G. Graditi, "Photovoltaic optimizer boost converters: Temperature influence and electro-thermal design," *Appl. Energy*, vol. 115, pp. 140–150, Feb. 2014.

[54] S. Harb and R. S. Balog, "Reliability of candidate photovoltaic module-integrated-inverter (PV-MII) topologies—A usage model approach," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 3019–3027, Jun. 2013.

[55] P. S. Shenoy, K. A. Kim, B. B. Johnson, and P. T. Krein, "Differential power processing for increased energy production and reliability of photovoltaic systems," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2968–2979, Jun. 2013.

[56] F. Spertino, "Power conditioning units in grid-connected photovoltaic systems: A comparison with different technologies and wide range of power ratings," *Solar Energy*, vol. 108, pp. 219–229, Oct. 2014.

TYLER J. FORMICA received the M.Sc. degree in mechanical engineering from the University of Maryland at College Park. He researched solar photovoltaic system reliability with the Center for Advanced Life Cycle Engineering while at the University of Maryland at College Park. He is currently a Systems Reliability Engineer with Raytheon Company.

HASSAN ABBAS KHAN received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from The University of Manchester, U.K., in 2006 and 2010, respectively. His current work is on low cost solar PV deployments.

MICHAEL G. PECHT (S'78–M'83–SM'90–F'92–LF'18) received the M.S. degree in electrical engineering and the Ph.D. degree in engineering mechanics from the University of Wisconsin. He is an ASME Fellow. He received the IEEE Reliability Society's Lifetime Achievement Award in 2008.

• • •