ABSTRACT

Title: **THE EFFECTIVENESS OF WARRANTIES IN THE SOLAR PHOTOVOLTAIC AND AUTOMOBILE INDUSTRIES**

Tyler J. Formica, Master of Science, 2017

Thesis Directed By: George E. Dieter Professor, Michael G. Pecht,
Department of Mechanical Engineering

A warranty is an agreement outlined by a manufacturer to a customer that defines performance requirements for a product or service. Although long warranty periods are a useful marketing tool, in 2011 the warranty claims expense was 2.6% of total sales for computer original equipment manufacturers (OEMs) and is over 2% of total sales in many other industries today.

Solar PV systems offer inverters with 5-15 year warranties and PV modules with 25-year performance warranties. This is problematic for the return on investment (ROI) of solar PV systems when the modules are still productive and covered under warranty but inverter failures occur due to degradation of electronic components after their warranty has expired. Out-of-warranty inverter failures during the lifetime of solar panels decrease the ROI of solar PV systems significantly and can cause the annual ROI to actually be negative 15-25 years into the lifetime of the system. This thesis analyzes the factors that contribute to designing an optimal warranty period and the relationship between reliability and warranty periods using General Motors (GM) and the solar PV industry as case studies. A return on investment of a solar photovoltaic system is also conducted and the effect of reliability, changing tax credit structures, and failure areas of solar PV systems are analyzed.

THE EFFECTIVENESS OF WARRANTIES IN THE SOLAR PHOTOVOLTAIC AND AUTOMOBILE INDUSTRIES

Tyler J. Formica

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2017

Advisory Committee:
Professor Michael G. Pecht, Chair
Professor Patrick McCluskey
Professor Peter Sandborn

Acknowledgements

i. I would like to thank Prof. Michael Pecht for advising my academic progress at University of Maryland and for significant contributions and guidance with this thesis.

ii. I would also like to thank Dr. Diganta Das for feedback regarding this work and guidance with my academic progress at University of Maryland.

iii. I would like to thank Dr. Michael Azarian, Dr. Carlos Morillo, Dr. Robert Utter, and the rest of the Prof. Pecht's research group in providing me feedback regarding my thesis progress.

iv. I would like to thank CALCE professors Prof. Peter Sandborn, Prof. Abhijit Dasgupta, Prof. Bongtae Han, and Prof. Patrick McCluskey whom have all advanced my knowledge on power electronic applications, fatigue modeling, life-cycle cost analysis, and general mechanical and electrical engineering principles.

v. I would like to thank Prof. Michael Pecht, Prof. Hassan Abbas Khan, Dr. Dimosthensis Katsis, and Mr. Peter Rundle for co-authoring and contributing to articles pertaining to this thesis.

vi. I would like to thank Mr. Anastasios Golnas, Mr. Jeff Rundle, and others who have provided interviews for this work.

vii. I would like to thank the editors at Elsevier and IEEE were also very helpful by providing suggestions and pointing out how to improve this work as well.

Table of Contents

Chapter 1: Introduction to Warranties

Throughout history, consumers have desired assurance of reliability when purchasing a product or service. Contracts and agreements have been used to specify the usage and conditions of products and consequences in the case of a malfunction. Today, manufacturers offer assurance that their products will function properly under specific usage guidelines in the form of warranties. A warranty is a guarantee from a manufacturer to a customer that states a responsibility regarding a product or service provided [1]. Warranties give customers a form of insurance if the product or service they purchased does not adhere to quality standards. If a product does not function up to the standards outlined by the manufacturer, the purchaser receives compensation as outlined in the warranty agreement. This section discusses the usage of warranties in different eras of history and the various warranty laws in the United States and other countries such as China.

1.1 Warranties in the Babylonian Dynasty and Medieval England

Warranties were used in product transactions as early as the Babylonian period (2128B.C. – 2004B.C.) [2]. Hammurabi, the 6th king of the First Babylonian Dynasty, addressed the concept of warranties in “Code of Hammurabi.” Hammurabi wrote “Code of Hammurabi,” the oldest known writings of significant length in the world, on clay tablets during his rule from 1792B.C. – 1750B.C. Hammurabi’s Code is infamous for the “eye-for-an-eye” concept. The eye-for-an-eye concept provides justice in transactions. If the seller or provider of a service were to fail to provide a reliable product or service, they would face a consequence similar to the suffering of the customer. For example, Hammurabi states that if a house builder builds a house that collapses on the house owner, the house builder must be put to death. Hammurabi also addresses what is known as today as money-back guarantees. If a slave were to fall ill with the “bennu disease” and not fulfill their duties, the slave was to be returned to the seller and the buyer would be refunded [2].

As early as the 1100s in Midieval England, warranties were used in land transactions [3]. Landowners could create warranties specifying what should happen and who should obtain their land after death. If a father wanted to grant land to another person as opposed to giving land to their son after death, the father could create a warranty outlying the specifications of who should inherit the land and what should happen to the land. By law the warranty must be honored as outlined by the father. Warranties exist today with manufactured products and services in most industries such as the automobile industry, cell-phone industry, and computer industry.

1.2 Uniform Commercial Code

The Uniform Commercial Code, which was officially published in the United States in 1952, outlined laws regarding expressed and implied warranties [4]. It described what should be constituted as an express warranty and what should be expected of implied warranties. The Uniform Commercial Code (UCC) was criticized as being very ambiguous and inefficient at specifically outlining rights to consumers with seller warranties [5]. Many believed the UCC was too broad and nonspecific when describing express warranties. The UCC states that a seller has to make a guarantee to a buyer for an express warranty to be relevant. The problem with this approach is the seller could simply claim that the guarantees and aggrandizement regarding their product was merely an opinion and should not have been interpreted as a fact [5]. The UCC also failed to clearly describe the difference between what should be constituted as an expressed warranty or an implied warranty. The legal actions against the seller differs based on whether the warranty falls under an implied warranty or an expressed warranty, and the UCC did not effectively outline boundaries to distinguish between the two types of warranties. The UCC has been criticized as being the work of private legislature made up of people with biases and interest groups [6]. It has been argued that the UCC is vague because of these individuals from competing interest groups.

1.3 Magnuson-Moss Warranty Act

Before the1970s, large manufacturing companies were focused on mass production with minimum costs [7] in the United States. As outlined in the previous paragraph, the vagueness of the UCC left a need for a much more detailed and effective act to outline consumer warranty law. Without many rights to customers regarding mass-produced products, there were significant issues with product quality. In 1975, the Magnuson-Moss Warranty Act was passed by the U.S. Congress. The Magnuson-Moss Warranty Act effectively gave rights to customers and outlined laws regarding warranty practices. The Magnuson-Moss Warranty Act helped customers by forcing manufacturers to be more specific about warranty agreements and the actions that should be taken next if the product or service fails to meet warranty requirements. The act outlined three specific requirements for merchants [7], "As a warrantor, you must designate, or title, your written warranty as either "full" or "limited." As a warrantor, you must state certain specified information about the coverage of your warranty in a single, clear, and easy-to-read document. As a warrantor or a seller, you must ensure that warranties are available where your warranted consumer products are sold so that consumers can read them before buying." Congress wanted customers to be able to compare brands and create competition amongst brands with warranty periods. By creating competition between brands in the same industry regarding warranty periods, brands began creating stronger warranties and more reliable products. The Magnuson-

Moss Warranty Act also effectively ended fraudulent advertising from merchants regarding full warranties by explicitly stating that the manufacturer must offer a 100% full warranty to advertise their warranty as a full warranty.

The Magnuson-Moss Warranty Act also gave customers rights regarding settling their warranty claims. The act gave customers incentives to sue merchants in the event that the merchant breaches a warranty contract by forcing merchants to pay for court costs and attorney fees in the event a customer files a lawsuit. Previously manufacturers had an advantage in regards to warranty claims as most customers would not want to dedicate the time or spend money to go to court to resolve warranty claims. Merchants were also encouraged to use cheap and quick methods to resolve disputes rather than forcing the customer into court proceedings to have their claims honored [8]. The FTC outlined the rules merchants must abide by when creating dispute resolutions for consumers in the FTC's Rule on Informal Dispute Settlement Procedures. Three important rules for merchants is that they must [8], "Be adequately funded and staffed to resolve all disputes quickly, be available free of charge to consumers, and be able to settle disputes independently, without influence from the parties involved." The Act forced merchants to be fair regarding dispute settlements. The act also gave the Federal Trade Commission (FTC) broad authority to govern cases regarding warranty law. Although the act allowed buyers and sellers in most cases to present their cases, the FCC would police cases involving warranty law [9]. The FCC could also establish rules upon interpretations of section in the act.

Although the Magnuson-Moss Warranty Act has been widely regarded as an act that improved warranty law and gave more rights to consumers, it has drawn criticism as being too vague in some regards. For example, the act was derided for giving the Federal Trade

Commission (FTC) too much broad authority to govern cases regarding warranty law. The FCC did not fully replace the UCC; rather it supplemented the UCC in regards to warranty law [9]. The connections between the Magnuson-Moss Warranty Act and the UCC and the conflictions between federal and state law regarding warranties has made developing warranty contracts and warranty periods difficult and expensive for merchants [9].

1.4 Warranty Law Development in Europe

To give consumers more rights when purchasing goods and services, Directive 99/44/EC was passed by the European Parliament and of the council May 25, 1999 [10]. The act forced traders and sellers in the European perform the necessary maintenance or replacement on defects in products within 2 years after the sale. Consumer can request malfunctioned good be repaired or replaced free of charge in a reasonable time frame with little inconvenience to the consumer. If the repair or replacement is very inconvenient or slow, the consumer can request a price reduction. By forcing companies in Europe to have a fair 2-year minimum warranty period, this act effectively gave consumers in the European Union more rights and protection from unreliable products.

1.5 China's "3-R" Warranty Policy

China has been a leading manufacturer of automobiles with a reputation of very lenient manufacturing standards [11]. China's automotive industry had only produced more than 100,000 units by 1971 and only had about 50 small manufacturing companies producing automobiles. Annual car production increased from less than 50,000 total cars produced in 1990 to greater than 600,000 cars produced per year by 2000 [11]. With the rapid increase in automobile manufacturing in China, there was a need for more stringent manufacturing standards by year 2000. In 2001,

China proposed the “Three R’s Regulation” was proposed to force Chinese manufacturers to honor return claims, replacement, and repair of domestic automobiles [12]. The “Three R’s Regulation” effectively gives more rights to consumers and forces manufactures to have a reasonable warranty period. The regulation forces a warranty period of at least 2-years 50,000-km for the entire vehicle and 3-years 60,000-km for important components in the automobile to be offered by automobile manufacturers. These components include components in the engine, transmission, chassis, suspension and steering. Users must have these warranty claims inspected by a third party to seek compensation from a manufacturer. This regulation applies to all vehicles sold for use in China from domestic manufacturers after September 31, 2013 [13]. The act will continue to improve manufacturing standards for Chinese automobiles and give more rights to Chinese automobile consumers [14].

1.6 Types of Warranties

The function of warranties depends on the industry the warranty is being used in. In some industries such as the automotive industry the components in the automobile are covered under different warranties. While in other industries such as the solar photovoltaic (PV) inverter industry a standard warranty is given to cover any malfunction in the inverter and the warranty is not divided to the different components in the inverter. This section discusses the coverage consumers receive with different warranty structures today and provides analysis of warranties from manufacturers that are currently offered.

Warranties can either be expressed or implied. A manufacturer directly states the terms of the warranty in expressed warranties. In implied warranties it is implied that the product will not immediately malfunction. If one is to purchase a phone and it malfunctions after one day but is not under warranty, this would constitute as an implied warranty. Explicit warranties are offered to customers in the course of a sales transaction [15]. A claim in an advertisement and warranty contracts in person or on a company's website would constitute as an expressed warranty.

Manufacturers promise the purchaser that a product will function properly for a set period of time if the product is used under acceptable conditions. If a product malfunctions due to a manufacturing defect during the set period of time, the manufacturer must honor the warranty by performing the necessary maintenance on the product, providing new parts, or providing a new product to the purchaser. Regarding coverage of Apple iPhones, iPads, and iPods, Apple states [16], "Apple Inc. of One Infinite Loop, Cupertino, California, U.S.A. 95014 ("Apple") warrants the Apple-branded iPhone, iPad or iPod hardware product and accessories contained in the original packaging ("Apple Product") against defects in materials and workmanship when used normally in accordance with Apple's published guidelines for a period of ONE (1) YEAR from the date of original retail purchase by the end-user purchaser ("Warranty Period")." Manufacturer warranties are most often outlined to only cover customers if the customer is using their product within specified guidelines. For example, if a customer were to experience a malfunction in their Apple iPhone due to leaving the iPhone in a freezing environment, Apple would not be obligated to honor the warranty as this would violate Apple's guidelines for proper usage.

Most warranties also carefully outline what is not covered. Regarding what is not covered in the warranty agreement, Apple states in their iPhone, iPad, and iPod warranty [16], "This

Warranty does not apply to any non-Apple branded hardware products or any software, even if packaged or sold with Apple hardware. Manufacturers, suppliers, or publishers, other than Apple, may provide their own warranties to you – please contact them for further information. Software distributed by Apple with or without the Apple brand (including, but not limited to system software) is not covered by this Warranty. Please refer to the licensing agreement accompanying the software for details of your rights with respect to its use. Apple does not warrant that the operation of the Apple Product will be uninterrupted or error-free. Apple is not responsible for damage arising from failure to follow instructions relating to the Apple Product's use." Apple states that the warranty is invalid if the defect is due to software not associated with the Apple brand. Manufacturers almost always outline in their warranty agreement that they will not honor a warranty if it is due to a defect from software from a different brand. Regarding what is not covered in their warranty, Dell states [17], "Monitors, keyboards, and mice that are Dell branded or that are included on Dell's standard price list are covered under this limited warranty; all other monitors, keyboards, and mice (including those products purchased through the Software & Peripherals department) are not covered." Therefore if a Dell computer system is not usable and the part that needs to be fixed is a monitor purchased from another brand, Dell would not be obligated to honor the warranty.

Multiple types of warranties can be used to cover different functions of a product. For example, the solar energy industry offers a warranty to cover solar panels against degradation in efficiency in the solar cells and another warranty to cover panels against manufacturing defects In the solar energy industry, solar photovoltaic (PV) manufacturers offer product warranties, which function as a standard warranty to cover manufacturing malfunctions which cause the product to not work properly similar to the Apple warranty, and performance warranties.

Performance warranties differ from normal warranties as they protect customers from products or services that are not working as efficiently as stated in the warranty agreement. Performance warranties exist to honor customers in the instance a product or service has not malfunctioned to the point that it cannot be used but is underperforming. In the solar energy industry, solar photovoltaic (PV) systems are covered under performance warranties which guarantee minimum power outputs from the solar PV systems at different time periods [18]. Canadian Solar guarantees their solar PV systems to produce 90% of the power output guaranteed when the system was purchased by year 10 and 80% of the power output guaranteed when the system was purchased by year 25 [19]. Therefore, if a Canadian Solar has not malfunctioned and is working effectively at a power output of 78% by year 10, the performance warranty would cover the customer and Canadian Solar would be forced to fix or replace their panel system to meet the proper power output.

1.7 Warranty Statistics

Although offering a strong warranty as compared to competitors can give a manufacturer an advantage when marketing their products in their respected industry, manufacturers must estimate and analyze the expense associated with offering their warranties. For example, for automotive original equipment manufacturers (OEMs) the warranty expense is often over 2% of their sales [20]. Offering a weak warranty to ensure a relatively low warranty expense compared to competitors in a manufacturer's respected industry can turn customers away from purchasing from a manufacturer as it can be interpreted as a sign of poor reliability. This section presents the warranty costs in industries today, reliability models to predict the lifetime of manufacturer's products, comparison between warranty costs associated with a standard free replacement warranty structures and a pro-rata warranty structures and literature that discusses warranty costs for manufacturers and finding the optimal warranty period to ensure the manufacturer is profiting as much as possible from their warranty.

Over the past 13 years, Warranty Week, a newsletter that specializes in compiling data related to warranty costs, compiled data regarding the total warranty claims from 1,235 public companies in the United States [21]. Warranty claim payments from these public companies totaled approximately $26,400,000,000 in 2015 which was $500,000,000 less than total claim payments in 2014. The industries that contributed to the majority of the total 2015 warranty claim payments were automotive original equipment manufacturers (OEMs), computer technology OEMs and appliance manufacturers. Of the $26,400,000,000 total claim payments, 38% were from automotive original equipment manufacturers, 25% were from computer technology OEMs and appliance manufacturers made up 6.6% of the $26,400,000,000. Warranty Week chose 17 industry categories to divide the warranty claim payments; automotive OEMs, automotive parts, aerospace, computer technology OEMs, telecommunications equipment , semiconductor and printed circuit boards, consumer electronics, medical, data storage, computer peripherals, appliance, new homebuilders, building materials, power equipment, material handling, security and sports equipment. In 12 of the 17 categories warranty claim payments decreased from 2014 to 2015. Telecommunications equipment, computer peripherals, computer original equipment manufacturers, and homebuilders were the only 5 industries in which the total warranty claim payments increased from 2014 to 2015.

From 2014 to 2015 the amount of warranty claims paid from vehicle manufacturers decreased by about $846,000,000. Figure 1 shows the total warranty claims expense from automotive OEMs, automotive part manufacturers and aerospace manufacturers per year from

2003 to 2015. Although the automotive OEM warranty claims paid decreased from 2014 to 2015, it was still greater than the claims paid in 2009, 2010, 2011, 2012 and 2013.

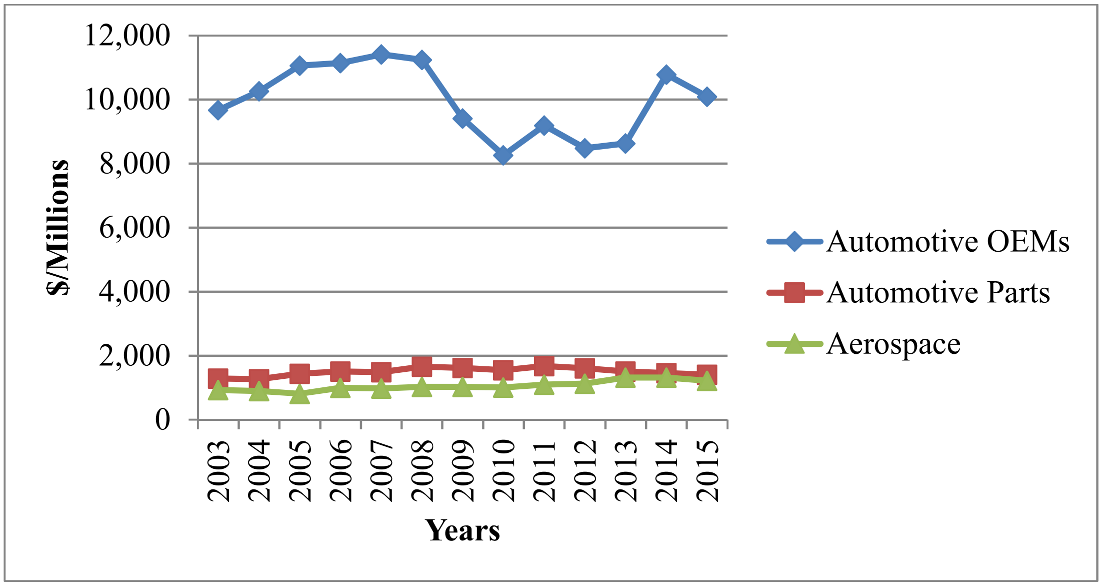


Figure 1: Warranty Claims Paid by Vehicle Manufacturers per Year from 2003-2015 [21]

The high-technology company with the most warranty claim payments in 2015 was Apple [21]. Apple's warranty claim payments totaled approximately $900,000,000 in 2015. Warranty Week grouped high-technology companies into 7 categories; computer OEMs, telecommunications equipment, semiconductor and printed circuit boards, peripheral computers, medical equipment, data storage and consumer electronics. They concluded that the total claim payments from these 7 categories increased by approximately $382,000,000 from 2014 to 2015. Figure 2 shows the total warranty claim payments per year from computer OEMs, telecommunications equipment manufacturers, semiconductor and printed circuit board manufacturers, medical equipment manufacturers and data storage companies from 2003 to

2015. As seen in Figure 2, computer OEMs represented more than $6,000,000,000 of the total warranty claims paid by high-technology manufacturers while each of the other 4 categories had warranty claims totaling less than $1,500,000,000.

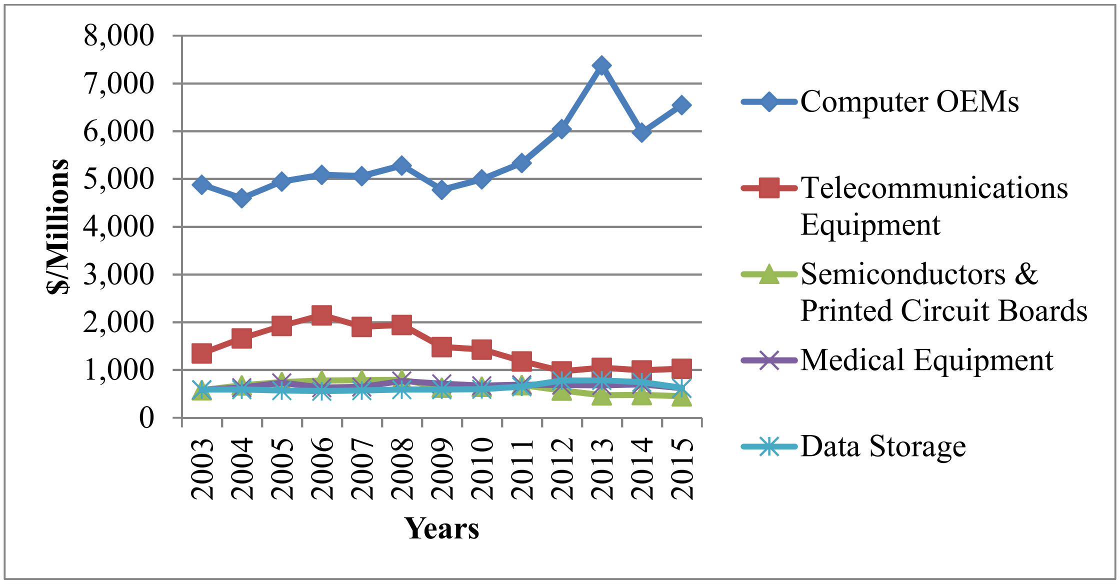


Figure 2: Warranty Claims Paid by High-Technology Manufacturers per Year from 2003-2015 [21]

Original equipment OEMs of computers incurred a total warranty claims expense of approximately $4,777,000,000 in 2009, $4,995,000,000 in 2010, and $5,339,000,000 in 2011 [20]. This warranty claims expense was 2.6% of total sales for computer OEMs in the 4th quarter of 2011. Automotive OEMs in the U.S. automotive industry accumulated a total warranty claims expense of approximately $9,461,000,000 in 2009, $8,289,000,000 in 2010, and $9,179,000,000 in 2011. This warranty claims expense was 2.1% of total sales from automotive OEMS in the 4th quarter on 2011. Heating, venting, and air conditioning companies incurred a total warranties claims expense of about $1,062,000,000 in 2009, $1,003,000,000 in 2010, and $1,073,000,000 in 2011. Companies in these industries are constantly trying to improve reliability, decrease the costs associated with honoring warranties, and design optimal warranty periods to match the expected lifetime of their products.

1.8 Reliability Models Used in Warranty Cost-Analysis

Before implementing a warranty model, companies must be aware of the reliability and expected lifetime of their products. Companies need to be aware of the amount of failures and expected timing of failures to compose failure distribution data [22]. A warranty period set too short will cause consumers to think a company produces unreliable product, whereas a warranty period set too long can cause the warranty claims expense for the manufacturer to be too high. Therefore it is imperative companies know the expected lifetime of their products and amount of failures expected.

An exponential distribution can be used as a lifetime statistical distribution for products [23], [24]. To calculate the probability a product will still be function at a certain point in time "t," the reliability function illustrated in Equation 1.1 can be used. Companies must understand the reliability of the product at different times in the warranty period, especially when the warranty nears expiration.

$$R(t) = e^{-\lambda t} \tag{1.1}$$

R(t): Reliability at time “t”

λ: Failure Rate

t: Total time

The assumption of the constant failure rate is the major drawback from using exponential models to predict reliability [25]. If a product does not have a consistent failure rate, the value to input for the failure rate can be difficult to determine. Inserting the same failure rate into this model at different parameters and instantaneous moments for these models will not yield exact results. Automobiles, computers, and phones are examples of products with hardware that degrades over time and therefore tend to have higher failure rates later in the lifetime of the product than earlier in the lifetime.

The Weibull Distribution is also used in estimating the reliability of products over a time period. The Weibull distribution differs as it takes into account the change in the rate of failures throughout the period, which is very useful for products that degrade. By using the scale and the shape parameters of the Weibull distribution a more accurate representation of the estimated lifetime of a product can be deciphered [26]. However, quantifying the “β” value can be difficult as the change in the failure rate over time must be known. In the exponential distribution, a constant change in the failure rate over a time period needs to be known. Equation 1.11 illustrates a Weibull distribution used for the reliability of a product over a time period.

$$R(T) = e^{-(\frac{t}{\alpha})^{\beta}} \tag{1.11}$$

R (t): Reliability at time “t”

β: Slope of the probability of failure

α: Scale (Characteristic Life) Parameter

t: Total time

Another commonly used distribution function for calculating the estimated reliability of products is the lognormal probability density function. With lognormal distributions, the failure rate initially increases but decreases as the time in the distribution approaches infinity [27]. The distribution is used often in the fields of economics and medicine. Equation 1.12 illustrates a lognormal distribution which can be used to find the reliability of products over an estimate time period. The mean time to failure and the standard deviation of the natural logarithms of time to failure must be known to accurately use this model.

$$R(T) = \int_{ln(x)}^{\infty} (1/(\sigma' \sqrt{2\pi}))e^{-\left(\frac{1}{2}\right)*((x-u')/(\sigma'))}dx \tag{1.12}$$

t= Time Period

u= Mean of the Lognormal Distribution

σ'= Standard Deviations of Natural Logarithms to Failure

1.9 Free Replacement Warranties

Warranty coverage in terms of the relationship between the time within the warranty period in which a product fails and the amount of compensation the purchaser receives can be categorized into two main types. Free replacement warranty coverage offers the same warranty coverage regardless of the time within the warranty period in which the product malfunctioned to the point where the warranty must be honored. Free replacement warranties are used in the automotive industry and by computer OEMs among many other industries. Free replacement warranties offer a replacement or repair of the product free of charge to the consumer if the product fails within a specified time period or usage amount. For example, replacement warranties are often offered by boat manufacturers. Boston Whaler, a prominent boat manufacturer in the United States, offers a 10-year structural hull warranty in which the company will replace or repair damage to the hull of their boats within 10 years after purchase free of charge to the customer [28].

1.10 Pro Rata Warranties

In some cases, manufacturers do not want to offer the benefit of free replacement warranties as it may not be realistic for all products in electronic systems such as batteries to avoid degradation [29]. Most components in automobiles, such as components that make up the engine, are covered under extensive powertrain warranties that will repair or replace the components regardless of their age as long as they are still within the warranty period. However products such as batteries and tires are inevitable to suffer from degradation, regardless of quality of the manufacturing. Therefore these components are not included using free replacement warranty structures rather batteries and tires are most often covered using pro-rata warranty structures. Pro-rata warranties save manufacturers the expense of paying to replace products at their full price. With pro-rata warranties, the amount of payment the purchaser receives if the product fails within the warranty period varies depending on the time during the warranty period in which the product failed [30]. The amount of money refunded in a warranty claim decreases throughout the lifetime of the product. These warranty structures in the battery industry offer 100% free replacement for a set period of time and then begin offering a fraction of the suggested retail price of the product in the event of the warranty needing to be honored for the remaining period. If the product fails near the end of the warranty period, the pro-rata warranty offers a small fraction of money refunded to the customer compared the original suggested retail price. Interstate Batteries is a large United States battery manufacturer specializing in offering batteries for cellphones, labtops, cameras, and automobiles. The Mega-Tron II from Interstate Batteries is offered in many different sizes from Interstate Batteries for automobiles. The current suggested retail price for their "Mega-Tron 59 Automotive Battery Five-Year Performance 590 CCA" is from $124.95 to $142.95 [31]. Due to the high price and inevitable degradation of batteries when used frequently, Interstate Batteries uses a pro-rata warranty for their Mega-Tron II batteries. For the first 2 years, full replacement is offered for the battery [32]. If the battery fails in the 3rd year, Interstate Batteries will refund 45% of the suggested retail price. Interstate Batteries will refund 25% of the suggested retail price if the battery fails during the 4th year. If the battery fails during the 5th year, only 10% of the suggested retail price will be refunded. Therefore, if one were to purchase a "Mega-Tron 59 Automotive Battery Five-Year Performance 590 CCA" and experience a failure during the fifth year, only about $12.50 to $14.30 would be refunded to the customer. In a free replacement warranty model, the customer would receive a new battery free of charge.

1.11 Warranty Cost-Analysis Models

If the reliability can be quantified accurately, the total cost of providing warranty coverage for the manufacturer can be calculated. Equation 1.13 illustrates the total cost of providing warranty coverage for a manufacturer using free replacement warranty coverage. Free replacement warranty coverage entails the manufacturers to replace or repair the product completely regardless of the time in the warranty period in which the product failed. Fixed costs of providing warranty coverage consists of costs associated with creating a warranty system including training employees, creating a web site, and creating a telephone number for customers to call [33]. Manufacturers often have a team of customer service employees with salaries that spend time assisting customers with having their warranty honored. The renewal function represents an estimate of the amount of warranties honored per product sold. It depicts the reliability of a product. Factors that contribute to the average cost to servicing one warranty claim include the repair cost, replacement cost, shipping cost, administrative costs, and penalty costs [34]. These penalty costs include costs associated with poorly handling warranty claims from customers. A manufacturer may lose loyal customers or be forced to compensate them in the case that they cannot use their product because the replacement or repair time is too long. The amount of products sold and amount of warranties honored per product sold are very reasonable for a manufacturer to quantify, whereas costs associated with losing loyal customers, having administration spend time dealing with warranties, and the costs associated with the amount of time customer service must spend dealing with warranties can be difficult to quantify. The exact amount of time a salary employee must spend dealing with warranties is most likely not meticulously monitored by a company.

$$\boldsymbol{C_{rw} = C_{fw} + \alpha M(Tw) C_{cw}}$$

(1.13)

C_{rw}= Total Cost of Providing Warranty Coverage

C_{fw} =Fixed Cost of Providing Warranty Coverage

α =Quantity of Products Sold

$M(Tw)$ = The Renewal Function: Expected Number of Renewal Events per Product During the Interval (0, Tw)

Tw = The Warranty Period

C_{cw} = The Aveage Cost of Servicing One Warranty Claim

For pro-rata warranty coverage, the fixed cost of providing warranty coverage is similar to the fixed cost of providing warranty coverage for free replacement warranty coverage. Manufacturers will still need to create a website, a call center and other fixed costs. However, the calculation of the warranty claims rate differs from free replacement warranty calculations because the costs of honoring the warranties decrease over time. As modeled in Equation 1.14, the rebate, refund to customer when the product fails, decreases as the warranty period approaches the end of lifetime. The product price with warranty coverage will therefore differ based on the rate implemented by manufacturers to address how much the warranty coverage decreases over time.

$$Rb(t) = \theta\,(1 - (\frac{t}{Tw})) \tag{1.14}$$

θ =Product Pricing (Including Warranty Coverage)

Tw = The Warranty Period Duration

t =Time in Which the Product Under Warranty Fails

Some warranties, such as warranties in the automotive industry, can expire by either time or usage. These two-attribute warranty policies can save the manufacturer's costs associated with honoring the warranties of customers that use their products excessively. The lifetime of automobiles, for example, is strongly correlated with the amount of usage and wear and tear the automobile receives. As seen in Equation 1.15, the maximum lifetime of these warranty models is the time period "x^*." However, in the automotive industry, the mileage for many powertrain warranties tends to expire before the warranty age ends. The average miles driven by an American driver according to the Federal Highway Administration is 13,476 miles [36]. This statistic does not take into account cars being used by multiple drivers, so the amount of mileage per car is most often greater than 13,476 miles. As of January 2016, Ford, GM, and Fiat Chrysler and Honda all offer 5-year 60,000-mile powertrain warranty coverage. Therefore if we are to assume the driver accumulates the average mileage driven by a person per year and does not share their automobile, their powertrain warranty with these companies would expire in 4.452 years. According to the Federal Highway Administration, the average miles driven per year by males between age 35 and 54 is 18,858 miles. For this group, if we assume someone is driving the average miles driven per year and is not sharing their car, the warranty would expire in 3.1817 years for these powertrain warranties.

$$x's = \min\left[x^*, \frac{y^*}{S}\right] = \begin{cases} x^*, if\ S \le \frac{y^*}{x^*} \\ \frac{y^*}{S}, if\ S \ge \frac{y^*}{x^*} \end{cases} \tag{1.15}$$

$x's$ = Total Length of Warranty Period

x^* =Time Length of Warranty Period

y^* =Mileage Length of Warranty Period

S =Miles Driven by Customer

Regardless of the warranty structure used, the manufacturers strive to produce reliable products that can outlast their warranty periods [37]. Figure 3 illustrates the potential consequences of offering poor product reliability that cannot last as last as long as the warranty periods implemented by manufacturers and the effects of offering improper warranty service. The combination of poor reliability and long warranty periods can lead to excessive warranty claims. For example, in 2013, Apple's warranty accruals were a total of $5 billion which was 2.9% of their total revenue [38]. This was the 2nd year in the history of the company that their warranty accruals were greater than 2.5% of their total revenue. If Apple were to increase the reliability of their products to decrease warranty accruals to below 2.5%, the company could save over $1 billion. Not only is this warranty expense immediately costly to Apple, it also can lead to dissatisfied customers who may start to purchase products from other competitive brands. Quantifying the amount of customers lost can be difficult, however losing loyal customers that have been purchasing multiple products from companies throughout their lifetime can be very costly.

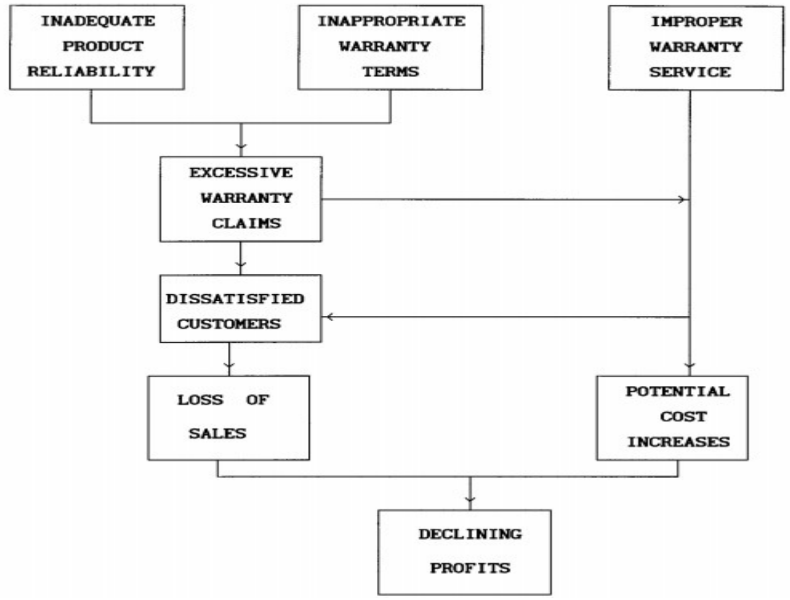


Figure 3: Consequences of Mismatch Between Technical and Commercial Aspects of Warranty [37]

If customers want more security against poor reliability when purchasing a product, they can purchase extended warranties. Extended warranties are not added to the cost of the product when purchased, they act as service contracts because they cost extra [39]. They are sold as separate purchases from the original purchase in the automobile industry. Residential homes, tech supplies, and even credit cards offer extended warranties [40]. Credit card warranties with extended coverage can coverage consumers from fraudulent purchases. Residential Warranty Coverage (RWC) specializes in offering extended home warranties in which they will cover mechanical systems in the home such as electrical, heating, and plumbing systems and appliance in the home such as the central vacuum, garage, and door opener [41]. For their appliance and mechanical system coverage, a homeowner can cover their appliances and systems with a payment of $310 for 1 year or $560 for 2 years. The average extended warranty payment for

Mercedes-Benz owners according to a 2014 Consumer Reports publication was $2,200, BMW owners paid an average of $2,007 for extended warranties, and Chrysler owners paid $1,525 [42]. Extended warranties can be purchased by either automobile dealerships or third-parties. Third-party warranties have been associated with scams [42].

Manufacturers strive to find an optimal warranty period to retain as much profit as possible. Manufacturers must understand the amount they gain to profit under different warranty periods and without offering a warranty altogether [43]. Market surveys and analysis of sales under different warranty periods are used by companies to attempt to quantify how much consumers value a quality warranty and their dissatisfaction with short warranty periods. Warranty periods should also be implemented to acknowledge the customers the manufacturers are targeting. For example, consumers who are risk-averse prefer to have longer warranty periods and more reliable products than consumers who are risk neutral or risk seeking [44]. In the automobile industry, warranties are particularly valued by customers and automobile companies often market their warranties in commercials and billboards.

Singpurwalla, N. researched measuring the probability and risk associated with warranty structures using Bayesian approach [45]. A diagram depicting the probability elements of Baye's theorem is seen in Figure 4. A Bayesian approach in warranty cost-analysis involves using random variables to predict failures that will result in warranty claims. Singpurwalla states regarding the need for analysis to identify risks associated with warranties, "During the 1980s, pressures of consumerism, competitiveness and litigation have forced manufacturers and service organizations to use quantified measures of reliability for specifying assurances and designing warranties" Singpurwalla argues that since products such as automobiles have many different failure modes, a Bayesian method for estimating the lifetime of a product by taking into account the many methods in which the product can fail can be useful. He argues that when estimating the lifetime of products and developing a warranty period it is beneficial to account for exchangeability as the order of failure modes for products such as automobiles is inter-changeable. The failure modes are not independent of each other. Of the many failure modes that could cause a manufacturer to honor a warranty only one failure mode is needed to occur to cause an end to the product's lifetime however each failure could lead to another failure so they are not necessarily independent.

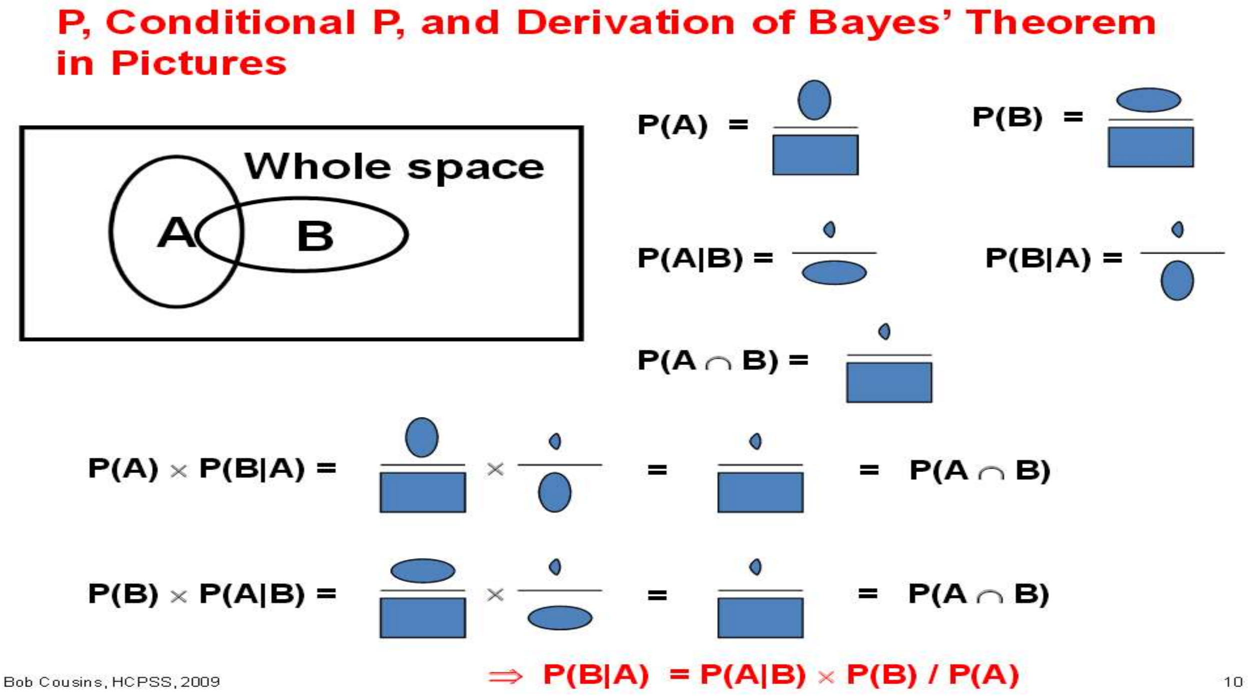


Figure 4: Probability Laws in Baye's Theorem [46]

Figure 4 illustrates a Bayesian approach to probability. These conditional probabilities can be applied to reliability analysis using Bayesian properties as the failure modes are not independent of each other in many industries such as the automobile industry. For example, if we are estimating the correlation between two failure modes in a product, the probability of failure mode "A" given the probability of failure mode "B" is equal to the probability of failure mode "B" given the probability of failure mode multiplied by the probability of failure mode "B" divided by the probability of failure mode "A" if the probabilities are dependent on one another. When failure modes can be seen as related, the probability of both failures occurring is not just a multiplication of both failures, rather the influence of one failure mode on the other must be known.

Xie, W. et al. argue that many factors in estimating the amount of repairs a manufacturer will need to provide to customers during a warranty period are overlooked such as the likelihood that a customer will actually seek out a repair [47]. The customer may feel the repair process is too cumbersome or in the case of technologies that are frequently seeing advancements such as cell phones the customer may just want to upgrade cell phones rather than seek out a replacement under warranty. Xie, W. et al. developed models for estimating the warranty and post-warranty repair demand from customers. If a manufacturer can accurately model sales and the warranty repair demand, then the aggregate warranty repair demand model can be calculated.

Murthy, D.N.P. et al. [48] proposed quality control methods for detecting and cost-efficiently eliminating defective items for manufacturers to ensure these products will never make it into the market and need warranties honored. The paper proposed three methods of quality control; no testing at all, testing all the products, or testing products near the end of a batch. The most effective method for testing products varied based on the failure rate, the warranty period, and the effectiveness of the testing. In the case of a free replacement warranty period, the equation Murthy, D.N.P. et al. proposed for the warranty cost per items released based on the amount of batches "k" is seen in Equation 1.16.

$$C_{w,k}(T) = [C_R \sum_{i=1}^{K} (N_{if}^{n} + N_{if}^{d})]/(KN - \sum_{i=1}^{K} N_i) \tag{1.16}$$

$C_{w,k}(T)$ = Total Warranty Cost per Items Released

K =Number of Manufacturing Batches

C_R =Total Cost to Manufacturer per Warranty Claim

N =Number of Products per Batch

N_i = Number of Products Released for Use per Batch

N_{if}^{n} =Number of Failures of Non-Defective Items

N_{if}^{d} = Number of Failures of Defective Items

Murthy, D.N.P. et al. argue that the warranty cost to the manufacturer per item released must be compared to the total cost of testing per item released to determine if testing should be done to all items, no items, or items near the end of a manufacturing batch.

Wu, S. [49] published a paper in 2012 in which he reviewed warranty cost-analysis literature and concluded by outlining the future research needs in the warranty field. Wu, S. argues that with the emergence of big data and wireless technologies to monitor product performance, there is a need for more advanced techniques of analyzing big data related to warranty claims and cited the covariate analysis as one that should be research further. He argues that covariates can be used for analysis with many factors influencing potential failures to build regression models. He also argues that further research needs to be conducted in early detection of potential failures to ensure safety and less product failures especially with products with long warranties. He argues that it is extremely difficult to design an optimal warranty period for emerging technologies with long warranties such as newly launched automobiles and solar PV systems since there is not much previous data as a basis for designing an optimal warranty period.

Alam, M. and Suzuki, K. [50], using the assumption that failures depend only on cumulative mileage, calculated maximum likelihood (ML) estimations considering only a lifetime variable consisting of a Weibull with lognormal as the censoring variable. They then used the Gauss-Hermite quadrature method for approximating the unobserved part in the likelihood function. They then estimated the lifetimes using the exponential and Weibull variables with the lognormal as the censoring variable. Alam, M. and Suzuki, K. argued that by using these parameters they were able to extract reliable estimates of the failures of automobiles based on cumulative mileage.

Chun, Y. and Tang, K. [51] argued that warranty cost-analysis literature is often flawed as many publications do not take into account the influence of warranty structures on the demand of products. They concluded that two-attribute warranty structures in the automotive industry can be improved by not just offering a fixed two-attribute warranty but rather offering choices for consumers. The article showed the similarities in the total warranty cost utilizing different warranty models. Chun, Y. and Tang, K. stated that a pro-rata warranty structure could be beneficial in the automotive industry as manufacturers could then offer longer warranties while keeping the total warranty cost relatively constant as under the pro-rata warranty structure they would not have to pay for a repair or replacement of an automobile entirely if the automobile malfunctions near the end of the warranty period. Therefore under the pro-rata warranty structure manufacturers could state that they are using longer warranty periods which could then increase sales.

Vinta, S. [52] used time and cumulative mileage to estimate the warranty costs. Reliasoft was utilized to analyze the market failure data. Vinta, S. concluded that based on market data customers are a driving an average of 40 miles per day and approximately 80% of the vehicles in the study are having their warranties expire due to cumulative miles rather than time. He stated that the failure rate data correlates more with usage than time.

Lu, Louis Y. and Chiang, Chih-Chyi [53] conducted a case study by using field returns data consisting of 89,958 repair records over 54 months from on original equipment manufacturer (OEM) solution provider to develop a prediction model to estimate the total warranty cost to the manufacturer. They claim their prediction model can allow companies to make a quotation for products under a target quality level. They developed polynomial regression curves based on return data to predict the warranty costs over the 54 month time span and compared the regression curve to the actual cost. Their R-Square data was over 0.999 and they conclude that the cumulative return percentages can be used efficiently to predict the amount of repairs. They argue that this approach can be extended to quotations of warranties, predictions for future amounts of repairs, preparations of buffer sets and amount of spare parts needed and out-of warranty repairs.

Park, M. and Pham, H. [54] used a quasi-renewal process model and exponential distribution to model warranty costs to manufacturers. The quasi renewal process used takes into account the imperfect repair of multi-components systems and single-component systems. The imperfect repair takes into account repairs that do not improve the quality of the product significantly and result in another failure which applies to industry applications as not all repairs are effective. Equation 1.17 illustrates their proposed equation to estimate the expected warranty cost for a single component system.

$$E(C) = c \sum_{n=1}^{\infty} n \sum_{i=1}^{n} ((C_{in} * \propto^{n}) / (\propto^{i-1} - \propto^{n})) * (e^{-\frac{w}{\lambda * \alpha^{t-1}}} * e^{-(\frac{w}{\lambda * \propto^{n}})}) \quad (1.17)$$

$c =$ Warranty Cost per One Failure in Warranty Period

$w =$Perfixed Warranty Period

$C =$System Cost per Prefixed Warranty Period

$n =$ Number of Component Failures

$\lambda =$ Parameter of Exponential Distribution

$\propto =$ Time Until Failure After Each Renewal

Park, M. and Pham, H. also extended this model to parallel and series multi-component systems. A parallel multi-component system is defined as a system where every component must fail to constitute a complete failure of the product whereas a single component system only needs one component to fail to cause the product to completely fail.

Bai, J. and Pham, H. [55] investigated determining warranty costs for minimally repaired series systems. The two main problems with designing a warranty period their work focused on was determining the warranty reserve fund and finding an optimal warranty period. Equation 1.18 is the equation Bai, J. and Pham, H. proposed for calculating the optimal warranty period. They state that manufacturers must find a balance to offer the best possible warranty period while ensuring that they stay under or equal to the given budget.

$$w^* = \sup\{w : P[C(w) > c_0] \leq \propto\} \tag{1.18}$$

w^* = Optimal Warranty Period

$C(w)$ =Discounted Warranty Costs per Product

c_0 =Budget for Warranty Policy

$\propto$= Probability True Warranty Cost is Over Budget

Kleyner, A. and Sandborn, P. developed a model for forecasting two-dimensional warranties using Monte Carlo simulation and demonstrated how the model could be applied to automobile warranties [56]. The model was intended to help users forecast warranty return trends at the product planning stage and forecast ongoing warranty returns for products currently manufactured and sold.

Chapter 2: Introduction to Warranties in the Automobile Industry

Warranty claims from automotive OEMs were higher in 2015 than any other category in the “Thirteenth Annual Product Warranty Report” compiled by Warranty Week [21]. As discussed in section 1, Warranty Week stated in their report that of the warranty claim data they compiled from 1,235 public companies in 2015 there were approximately $26,400,000,000 in warranty claims paid in 2015. Automotive OEMs accounted for about 38% of the total warranty claims paid in 2015 which was more than any other category in the study. This section discusses the structure of automobile warranties, automobile warranty claims data, comparisons of automobile warranties offered from different automobile manufacturers. The section will also review literature that analyzes the costs that contribute to providing an automobile warranty, finding an optimal automobile warranty period and reliability problems that cause automobiles to fail and lead to high warranty costs for manufacturers.

2.1 Automobile Warranties

Automobile manufacturers most often offer a bumper-to-bumper warranty, powertrain warranty and corrosion warranty with the purchase of an automobile. Additional benefits may be added such as free maintenance visits. For example, General Motors (GM) offers the following warranty coverage with the purchase of a 2016 GM automobile [57]; “a 3-year 36,000-mile bumper-to-bumper warranty, a 5-year 60,000-mile powertrain warranty, 5-year 60,000-mile roadside assistance, 5-year 60,000-mile courtesy transportation, 5-year 60,000- mile corrosion protection, 2 free maintenance visits within the first 24 months of purchase, 6-month trial of OnStar Guidance Plan and 5-year OnStage Basic Plan.”

Automobile manufacturers demand consumers to follow guidelines if they want their vehicles to be covered under warranty. This ensures the malfunction that leads to warranty coverage is an error by the automobile company rather than the consumer placing the automobile through conditions in which efficient automobiles and poorly constructed automobiles will fail. GM lists circumstances in which they will not cover an automobile as [57], “damage due to accident, misuse, alteration, insufficient or improper maintenance, contaminated or poor quality fuel, damage or corrosion due to chemical treatments or Aftermarket Products, impact, use or environment.”

The courtesy transportation offers consumers another mode of transportation in the event that GM needs to honor a warranty and repair their vehicle. The roadside assistance coverage assists consumers in the event the automobile malfunctions while driving and the consumer needs assistance. GM offers 2 free maintenance visits for the first 2 years after the automobile has been purchase. The maintenance coverage expires when the 2 years have passed or the 2 free visits have been used.

The two most comprehensive warranties offered by automobile manufacturerws are the powertrain warranty and the bumper-to-bumper warranty. The bumper-to-bumper warranty is the most comprehensive warranty offered from a manufacturer. The term “bumper-to-bumper” is derived from the warranty covering the automobile against malfunctions for most components from the front bumper to the back bumper [58]. The bumper-to-bumper warranty covers far more components in the automobile than the powertrain warranty. The powertrain warranty generally covers engine, transmission and driveshaft components. For example, Chevrolet lists components covered under the powertrain warranty for 2016 Chevrolet vehicles as the engine, diesel engine/components, transmission/transaxle, transfer case and drive systems [59]. Bumper-to-bumper warranties generally offer coverage for all components covered under the powertrain warranty. However, the bumper-to-bumper warranties are almost always shorter than powertrain warranties. For example, Chevrolet offers a 3-year 36,000-mile bumper-to-bumper warranty and a 5-year 60,000-mile powertrain warranty. Once the age or mileage has expired on the bumper-to-bumper warranty the powertrain components would continue to be covered until the expiration of the powertrain warranty in this case. Not all manufacturers follow this warranty structure. BMW covers all their 2016 automobiles under a 4-year 50,000-mile bumper-to-bumper warranty and offers no separate powertrain warranty [60]. Therefore all components in the powertrain of a 2016 BMW automobile will be covered for the 4-year 50,000-mile period and after this period expires there will be no additional coverage for powertrain components.

2.2 Automobile Warranty Costs to Manufacturers

Warranty Week calculated the total warranty claims to automotive manufactures in 2014 to be $15,650,000,000 [61]. This was 20% more than the total in 2013. Ford's warranty claims paid increased by 24% from 2013 to 2014, Chrysler's by 24% and GM's by 41%.

When analyzing the impact of warranty claims on manufacturers, it is beneficial to compare the total warranty claims expense from manufacturers to their total revenues. Warranty Week compiled warranty expense data from automotive OEMs and suppliers from 2003 to 2014. They divided their warranty expense data for warranty claims as a percentage of product sales for automobile manufacturers into 2 categories [61]; small vehicles (passenger cars and light trucks) and large automobiles (large trucks/heavy equipment). Figure 5 shows the warranty claims as percentage of product sales for U.S. based manufacturers of small vehicles in 1st quarter of each year from 2003 to 2014. As seen in figure 5, warranty claims expense is generally between 1% and 2% of the total product sales for small vehicles [61]. The report also noted that in the 4th quarter of 2015 the warranty claims rate rose to 1.7% of total product sales.

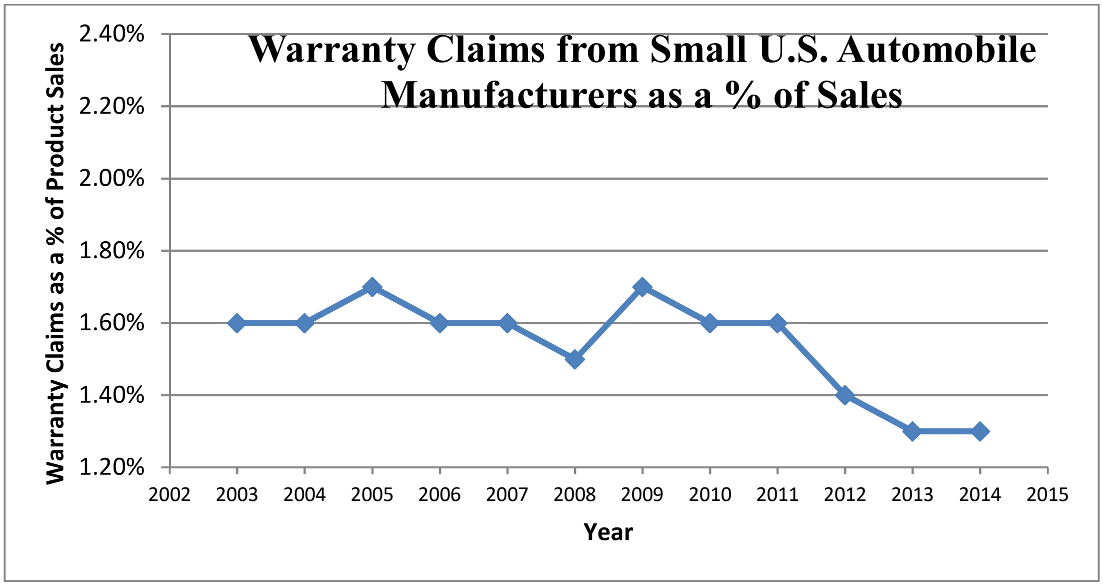


Figure 5: Warranty Claims as a Percentage of Sales for Small U.S. Vehicle Manufacturers [61]

Figure 6 illustrates the warranty claims rate as a percentage of product sales for U.S. manufacturers of large automobiles in the first quarter of each year from 2003 and 2014. As seen in figure 6, the warranty claims as a percentage of sales is often greater for large automobiles manufacturer than for small automobiles manufacturers.

Figure 6: Warranty Claims as a Percentage of Sales for Large U.S. Vehicle Manufacturers [61]

It can be concluded from Figure 5 and Figure 6 that the warranty rate most often constitutes between 1% and 2% of the total product revenue from automotive companies. The report notes that automotive OEMs in the small vehicle category that deal with customers have higher warranty expense rates than their suppliers in most years.

Chapter 3: An Analysis of GM's Powertrain Warranty Reduction

After introducing a competitive 5-year 100,000-mile powertrain warranty in 2007, General Motors (GM) reduced this warranty to 5 years and 60,000 miles for all 2016 Chevrolet and GMC vehicles. GM claimed that the powertrain warranty was not an effective marketing tool for the company. However, this paper has identified more likely reasons for this reduction in coverage, including the poor reliability of GM's automobiles, a history of massive recalls, problems in GM's supply chain management and GM's loss of profitability.

3.1 Introduction

A warranty is a guarantee from a manufacturer to a customer that states the manufacturer's responsibility with respect to the product or service provided [62]. The manufacturer ensures the purchaser that a product will function properly for a set period of time. If the product malfunctions due to a manufacturing defect during that time, the manufacturer must repair, provide new parts, or replace the product.

The Magnuson-Moss Warranty Act, passed by the U.S. Congress in 1975, ensures that consumers receive complete and accurate information about warranty coverage from manufacturers and requires manufacturers to resolve warranty claims quickly and with as little inconvenience to customers as possible [63]. The act also makes it illegal for automobile manufacturers to void a warranty if a customer buys parts from an aftermarket provider or if an unauthorized mechanic works on the car [64].

The price, reliability, and warranty of a product are inter-related [65]. The warranty terms are chosen by the manufacturer to maximize profits, and warranty costs are usually added to the product costs. Manufacturers may choose to offer longer warranty periods than their competitors to provide customers with increased assurance as to the quality and reliability of the product. However, warranty claims due to inadequate product reliability can incur costs to the manufacturer. Manufacturers strive to implement an optimal warranty period by collecting data related to the number of warranty claims honored, the effectiveness of warranty periods on the marketing of their products, and costs associated with improving the reliability of their products [66].

In the automotive industry, a free replacement warranty is offered by manufacturers such as GM in which they will pay the full price of maintenance or replacement of an automobile if the automobile malfunctions under conditions stated in the warranty agreement within the warranty period. The average free replacement warranty cost can be calculated if the fixed cost of providing the warranty, the amount of products sold, the total amount of warranties serviced, the amount of replacements, and the average cost of service for a warranty claim are known. Equation 1.19 is used to calculate the ordinary free replacement warranty cost [67]:

$$C_{\mathrm{rw}} = C_{\mathrm{fw}} + \alpha M(Tw) C_{\mathrm{cw}} \tag{1.19}$$

where C_{rw} is the total cost of providing warranty coverage; C_{fw} is the fixed cost of providing warranty coverage; a is the quantity of products sold; $M(T_{\mathrm{w}})$ is the renewal function or the expected number of renewal events per product during the interval $(0, T_{\mathrm{w}})$; and T_{w} is the warranty period.

If T_{w} is close to zero, the total cost of the warranty coverage is primarily the fixed cost of providing warranty coverage. An unreliable product with a high number of renewal events will drive up the average warranty cost and force the manufacturer to compensate by reducing the warranty period. When honoring a warranty claim, manufacturers must pay not only repair, replacement, and shipping costs, but also administrative costs [68]. Administrative costs include meetings to discuss warranty issues and decide whether a warranty should be honored, business reviews regarding warranties, compiling data to make decisions about warranties, and tracking the progress of product warranties. These costs exist even when claims are not honored.

3.2 Automobile Warranty Structures

A two-attribute warranty period is commonly used in the automotive industry to measure the length of the warranty [69]. These attributes are the mileage the automobile has been driven and the age of the automobile after purchase. If one of these parameters is surpassed, the warranty period is over. According to the U.S. Department of Transportation, Americans drive an average of 13,476 a year [70], so a 5-year 60,000-mile warranty will expire in approximately 4.5 years. If the vehicle is being shared within a family, the powertrain warranty will expire in an even shorter period.

The main types of automobile warranties are the basic warranty, also known as the bumper-to-bumper warranty, the powertrain warranty, roadside assistance coverage, and the rust and corrosion warranty [71]. Bumper-to-bumper warranties cover all parts related to suspension, exhaust, electronics, and steering [71]. GM states that almost every part in the vehicle is covered under their bumper-to-bumper warranty except damage caused by accidents, alterations, use of poor-quality fuel and corrosion [72].

Most automobile manufacturers structure their powertrain warranties d so they supplement the bumper-to-bumper warranty when it expires. For example, the bumper-to-bumper warranty for GM’s 2016 vehicles expires after 3 years or 36,000 miles, and the powertrain warranty extends coverage to 5 years or 60,000 miles [73]. A powertrain warranty covers the engine, the transmission, and the drivetrain [74]. Engine parts covered include internal components in the engine and transmission such as the cylinder head assemblies, the timing case, and the timing belt; transmission parts include the speed sensors and the torque converter; and drivetrain parts include the drive shafts, propeller shafts, and bearings.

3.3 GM's Reduced Powertrain Warranty Structure

Previous to 2006, GM offered only a 3-year, 36,000-mile bumper-to-bumper warranty to cover the powertrain components in their automobiles [75]. In September of 2006, GM announced a new 5-year 100,000-mile powertrain warranty for all 2007 GMC, Buick, Chevrolet, and Cadillac vehicles to supplement their bumper-to-bumper warranty [76]. GM's announcement was shortly after Ford implemented a powertrain warranty with the same coverage. GM claimed that their new powertrain warranty would back up their vehicles' reliability. [76]. Rick Wagoner, GM's former CEO, stated, "We've been telling everyone how strong GM's cars and trucks are in terms of value, design, quality and durability. Now we're going to back it up." GM was likely under pressure from Hyundai as Hyundai had maintained a 10 year 100,000 mile powertrain warranty since 1998 [77]. He went on to say, "This new warranty, combined with GM's outstanding quality, competitive pricing, relevant technologies and a strong new lineup of cars and trucks, provides motorists with an unprecedented level of value and peace of mind." GM used this increased warranty structure as way to self-aggrandize the reliability and pricing of their automobiles.

Buick and Cadillac maintained the 5-year, 100,000-mile powertrain warranty until 2013 and then changed it to a 6-year 70,000-mile warranty [77]. This decrease in mileage indicates GM was attempting to decrease the amount of warranty expense from Buick and Cadillac automobiles by eliminations claims within the 70,000- to 100,000-mile period. GM also decreased the number of free maintenance visits from four visits for the first two years to two visits for the first two years after purchase.

Chevrolet and GMC maintained the 5-year, 100,000-mile powertrain warranty until 2015 when GM announced plans to scale their powertrain warranty to 5 years and 60,000 miles [78]. GM and Chevrolet vice presidents justified this reduced warranty structure by stating, “Through research, we have determined that when purchasing a new vehicle, included maintenance and warranty rank low on the list of reasons why consumers consider a particular brand over another.” The memo went on to say, “As a result, we have benchmarked our competitors, reviewed our current offerings and have concluded the following modifications to align closely with our customers’ needs and expectations [79].” A GM spokesman also stated, “The financial impact of this change is immaterial and any savings will be reinvested in features customers value like advanced vehicle technology.” In another statement, GM said “We will reinvest the savings in features consumers’ value more, such as advanced connected vehicle technology [80].” With these statements, GM is attempting to convince the public that reducing the warranty structure was an attempt to appease customers. “We talked to our customers and learned that free scheduled maintenance and warranty coverage do not rank high as a reason to purchase a vehicle among buyers of non-luxury brands [81].” However, GM says nothing about reliability of their vehicles.

Korenok et al. [82] investigated the effect of warranty improvements and curtailments on a company’s market share. The study looked at data from GM, Ford, Chrysler, Toyota, Nissan, Honda, other Japanese manufacturers, and other European manufacturers’ from 1996 to 2004 and concluded that a manufacturer’s decision to reduce their warranty caused a “24.88% decline in one's market share growth, with the coefficient being significant." The authors stated they were surprised that the effect on market share growth was this high when a manufacturer decreased their warranty structure. This study contradicts GM's claim that consumers do not value warranties highly.

3.4 Analysis of GM's Reduced Warranty Structure

When GM decided to implement their 5 year, 100,000-mile powertrain warranty structure in 2006, they were adamant that this lengthened warranty period reflected the exceptional quality of their vehicles compared to their competitors [76]. When GM reduced the warranty period, they did not mention how the new warranty reflects on their current profitability or the reliability of their products. However, reliability and the impact of a warranty period on sales are criteria a manufacturer considers when determining an optimal warranty period.

A reduction in a warranty structure may be implemented to save expenses in the event that a company is struggling financially. GM's financial burdens in China and Europe were likely incentives contributing to the decision to reduce the powertrain warranty structure.

Since 2000, GM has lost more than $15 billion in Europe [83], $844 million of that total in 2013 alone. In December of 2013, GM decided to pull all Chevrolet brands except the Corvette from Europe [84]. A representative from GM cited "a challenging business model and the difficult economic situation in Europe" as the reason for this pullout [84]. GM more than doubled earnings in China from 2009 to 2013, but with increased competition in China from Chinese manufacturers GM is unlikely to have a significant gain in China in 2015 according to a Morgan Stanley analyst [83]

To gain a better perspective of the reliability of GM vehicles compared to other car brands, Jeff Brown, an Automotive Service Excellence (ASE) certified consultant for Rising Sun Motors, was interviewed. Rising Sun Motors is an automotive repair shop located in College Park, MD [85]. When asked about changes in the components GM has been using in the past 10 years, Brown stated, “The quality of GM vehicles has gone down. There seems to be a higher failure rate associated with the engine and transmission parts which can lead to catastrophic failures. A lot of the manufacturers are outsourcing the parts manufacturers to China and the same qualities just aren’t there. Suspension, brakes, everything is worse. The interior does not hold up as well [85].” When asked about the reliability of GM automobiles compared to other brands, Brown stated, “GM is significantly worse. GM is the least reliable. It used to be Ford, but somewhere in the late 90s early 2000s GM went downhill surpassing Ford as the worst [85].”

When asked about the reasoning behind GM reducing their powertrain warranty, Brown speculated, “I think they did this probably to save themselves money and they know that their product won’t last that long due to poor quality and workmanship. GM and many other manufacturers are extending their maintenance intervals. It used to be 3,000 mile intervals for an oil change, then 5,000 miles, but anything more than that for you to change your oil your car is going to turn to crap real fast. But the GM stuff seems to degrade the worst. It might be poor design. At 65,000/75,000 miles when something breaks because the oil wasn’t changed the warranty is over and the customer will have no coverage [85].” He also stated that an incentive to increase the maintenance mile intervals for automobile manufacturers is that it can improve a manufacturer’s ranking with JD Power, a leading market research company in the automobile industry. To summarize the GM powertrain warranty reduction, Brown stated, “GM saying warranties are a bad marketing tool is just a way of covering themselves for a product that will not last that long. Hyundai and Kia are more reliable products. Their warranty may change also but that would not be a deterrent to recommend their product. Regardless of the warranty, I would not recommend a GM product. You want something that will be reliable and dependable [85].”

GM announced in October of 2015 a recall of 1.4 million vehicles due to possible oil leaks [86]. This recall includes the 1997-2004 Pontiac Grand Prix and Buick Regal; the 2000-2004 Chevrolet Impala; the 1998 and 1999 Chevrolet Lumina and Oldsmobile Intrigue; and the 1998-2004 Chevrolet Monte Carlo [86]. Oil can seep through the gaskets during hard slams on the brake pedal, and fires can start when the oil drips into the exhaust manifold. This issue has already caused over 1,300 fires [87].

In June of 2014, GM recalled 467,000 vehicles (Chevy Silverados, GMC Sierra, Chevy Tahoes, and GMC Suburbans) due to transmission failures [88]. According to GM, a software glitch was causing the transmission transfer cases to change to neutral on their own on the 2014 and 2015 models of these automobiles. The automobiles could then roll away when parked or could lose power [89].

GM issued a recall in 2014 on Cadillac ATS vehicles due to transmission issues [90]. The transmission shift cables were detaching in the Cadillac ATS 2013 and 2014 models. If this were to happen while someone was operating the vehicle, the direction of the automobile could be altered and the risk of a crash would be increased significantly. The driver could not reliably put the car in the “park” position [90], making it dangerous to park on a hill.

In December of 2015, GM India announced a recall of 101,597 units of the Chevrolet Beat due to potentially faulty clutch pedal levers [91]. GM claimed that the lever may crack after continuous use of the vehicle. This was the second recall in 2015 for GM India. GM India’s largest recall in terms of units was in July of 2015—the GM Spark, GM Beat, and GM Enjoy were recalled due to issues with the remote key-less entry accessory, which is supposed to open these vehicles without a mechanical key [92].

Table 1 shows total number of automobile recalls from January 2014 to November 2014 by the five automobile manufacturing companies with the most automobile recalls in the time period. For the first 10 months of 2014, the number of automobiles recalled by GM was more than the next four automobile manufacturers with the highest amount of recalls combined. GM had recalled over 20,000,000 more automobiles than any other manufacturer in the first 10 months of 2014.

Table 1: Five Leading Manufacturers in Total Automobiles Recalled for the First 10 Months of 2014 [93]

Manufacturer	Total Automobiles Recalled
GM	28,967,917
Honda	5,566,013
Toyota	5,543,303
Fiat Chrysler	5,512,697
Ford	3,815,051

The financial liability of warranty claims issued and assumed to be related to recalls and courtesy transportation has increased significantly from 2013 to 2014 for GM according to GM's

2014 annual report [94]. GM's 2014 Annual Report states the cost of these warranties was $775,000,000 in 2012, $640,000,000 in 2013, and $2,910,000,000 in 2014. This $2,270,000,000 increase from 2013 to 2014 is due to these massive recalls. GM also stated that this increase included, "approximately $680 million for 2.6 million vehicles to repair ignition switches that could result in a loss of electrical power under certain circumstances that may prevent front airbags from deploying in the event of a crash [94]."As of May 2014, there have been 13 deaths due to these faulty ignition switches [95].

Large automobile manufacturers like GM have an extensive supply chain and partners all over the world [96]. If just one of these suppliers makes a mistake in the manufacturing process or does not adhere to quality standards, it can lead to a problematic recall. Mike Rozembajgier of Stericycle, a large business-to-business consulting firm claimed that the growing technical complexity of automobiles is contributing to these recalls. According to the "Stericycle Recall Index Q1 2014," 70% of the recalls of vehicles in the first quarter of 2014 were produced in the last five years [97]. The report states that equipment, a category defined by mechanical and electrical issues, and problems with navigation systems, has caused 23.6% of the total recalls from 2010 to the first quarter of 2014, more recalls than any other category from 2010 to the first quarter for 2014. Rozembajgier also stated, "With small manufacturers and suppliers contributing to the majority of [2014 first quarter] events, it's clear that no organization is safe and that auto brands are only as strong as their weakest link" [97].

The "North American Automotive Tier 1 Supplier Working Relations Index" is a study conducted by tracking supplier opinions of relationships with automaker customers related to Nissan, Honda, Toyota, Ford, GM, and Fiat Chrysler [98]. The 2015 study contained input from 541 sales persons and 435 Tier 1 suppliers, and had approximately 59% of the six original equipment manufacturers' annual buy respond to the survey. In 2014 the 14th annual study had GM ranked last in supplier relations relative to the other six giant automakers [99]. The main reasons contributing to this poor rating included a lack of supplier trust, poor supplier communication, and the insufficient amount of help GM provides to suppliers to lower costs and improve the quality of the products [99]. In the 2015 report, GM was still ranked in last place among these six giant automakers [98]. Of the six automakers, GM was ranked lowest in supplier trust. The percent of buying situations with poor relations was 58% for GM [98].

In August of 2014, an explosion in China at a subcontractor of a supplier to GM's plant killed over 75 workers due to poor oversight of the plant [100]. GM's president responded by stating, "Our tier-one suppliers on a global basis are required to make sure that they are sourcing from suppliers that are implementing the right safety standards [100]." Although GM replaced their VP of Procurement and Supply Chain in 2009 and implemented new supply chain practices after the infamous government bailout, their supply chain management is still poor compared to competitors [101].

3.5 Conclusions

Although GM claims their powertrain warranty was reduced because it was not a strong marketing tool, reliability issues associated with GM automobiles were likely the major contributing factor to GM reducing their powertrain warranty. Massive recalls, poor craftsmanship, poor supply chain management practices, and financial losses in China and Europe have likely forced GM to reduce their powertrain warranty to increase their profitability.

GM claims powertrain warranties are not strong marketing tools; however Hyundai continues to maintain their 10-year 100,000-mile powertrain warranty [77]. It should be noted that while GM ranked first in total automobiles recalled from January 2014 to November 2014, Hyundai did not rank in the top 10 [93]. Jeff Brown of Rising Sun Motors also commented that Hyundai vehicles are in his opinion far less prone to failures and maintenance than GM vehicles [85]. In May of 2015, Fiat Chrysler announced a decision to reduce their 5-year 100,000-mile powertrain warranty to a 5-year 60,000-mile powertrain warranty [102]. Fiat Chrysler was ranked fourth in total automobiles recalled among automobile manufacturers in the same time period with 5,512,697 automobile recalled. These recalls and reliability problems likely contributed to the decision to decrease their warranty period as well.

When GM first implemented the 10-year 100,000-mile powertrain warranty in 2006, they talked extensively about how the long warranty period reflected superior reliability compared to their competitors [75]. After reducing their warranty period, GM has not mentioned the relationship between this decrease and reliability. If GM's statement in 2006 about a strong warranty correlating to a reliable product are to be believed, than a weak warranty must correlate to a less reliable product.

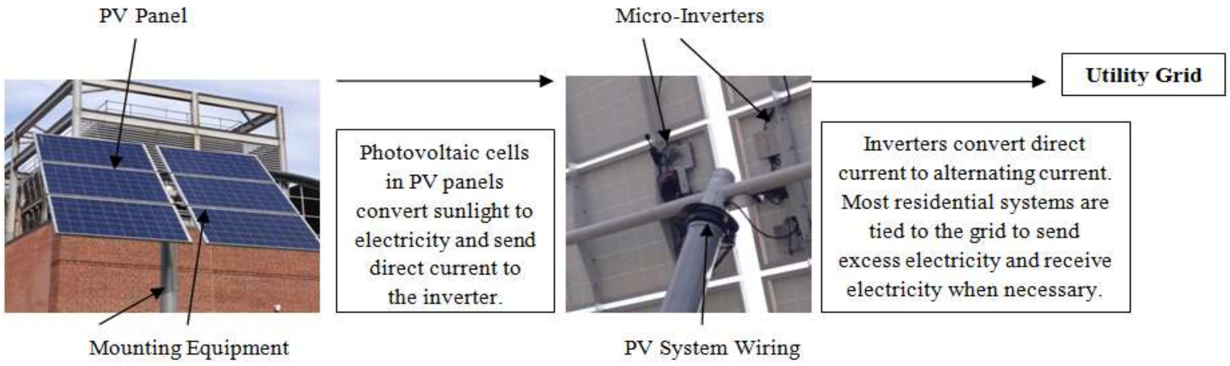
GM has also been claiming that they are reducing their powertrain warranty to appease to other features desired from automobile customers [81]. The results of this study have concluded that this statement is not accurate. The significant reduction of GM's powertrain warranty coverage from a 5-year 100,000 mile warranty to a 5-year 60,000 mile warranty indicates that GM is not confident with the reliability of their automobiles.

Chapter 4: Solar Photovoltaic (PV) Technology

This chapter presents an overview of solar PV systems. The materials and technologies used in solar panels and inverters, industry trends, the reliability of solar PV systems, and the warranty structures of solar PV systems will be presented.

4.1 Solar PV Conversion Process

Solar PV systems convert light from the sun to energy with the use of photovoltaic cells in solar panels [103]. The direct current in the panels is then converted to alternating current using solar inverters. Most solar PV systems are tied to the utility grid to have access to electricity when panels are unable to receive sunlight. However, as storage capacity in batteries improves solar PV systems can run as stand-alone systems more frequently. Solar PV systems do not release harmful gases like carbon dioxide and therefore can help reduce the amount of greenhouse gas emissions. Figure 7 illustrates the solar PV conversion process. PV panels are held together with mounting equipment, also referred to as racking equipment. The panels are wired to inverters and the inverters are connected to the utility grid.



Photovoltaic cells in PV panels convert sunlight to electricity and send direct current to the inverter.

Inverters convert direct current to alternating current. Most residential systems are tied to the grid to send excess electricity and receive electricity when necessary.

Figure 7: Configuration of a Grid-Tied Solar PV System

To produce electrical current, panels contain photovoltaic cells to convert photons from the sun to energy. Semiconductor panels (silicon comprises most panels manufactured today) are doped with many impurities and fused together [104]. Doping allows electrons to break free of their atomic bonds when photons strike the panel, which produces electrical current [104]. Dopants used are often either boron and phosphorous. Negatively charged phosphorous matched with positively charged boron creates a p-n junction allowing electrons to be knocked loose by photons from the sun which then creates direct current. This direct current then needs to be converted to alternating current using solar inverters unless the system is only using direct current and is a stand-alone system, which is rarely the case in residential applications.

4.2 Solar Cell Materials

Solar panel manufacturers strive to make panels which utilize solar cells that are both cost-effective and efficient. Efficiency in solar PV panels is the ratio of the amount of photons from the sun striking a solar cell to the amount of electricity the solar cell is able to create. Efficiency is measured as a percentage. Silicon panels have the advantage of being cost-effective while still reaching efficiencies of 15-22%, making them the most manufactured panels as of 2016. Silicon panels, which make up about 90% of all residential panels today [105] are divided into two categories; monocrystalline silicon and polycrystalline silicon. Monocrystalline silicon panels are the highest purity silicon of the two and look more uniform and tend to be darker colors in most cases. Polycrystalline panels tend to have more of a blue color. Monocrystalline panels tend to be in higher efficiency than monocrystalline, with SunPower's X-series panels holding the highest efficiency of any mass-produced solar PV panel at 21.5% available on the market as of June 2016.

Thin-film solar panels such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon comprise about 10% of panels on the market as of 2016 and are growing in popularity due to lower costs than silicon cells [105], [106]. However, thin-film solar cells still in most cases have lower efficiencies than silicon, usually in the range of 12-15 %. Multi-junction cells such as triple junction cells are currently the most efficient solar cells as of 2016 reaching efficiencies of greater than 40% [107]. However, these cells are still not cost-effective to be manufactured on a wide-scale. Organic solar cell technologies are also being developed but still have very low efficiencies of around 10%.

4.3 Solar PV Industry Trends

Although still not used as much as other forms of renewable energy such as hydroelectric or even close to as much as coal, solar energy has grown from 1,546 megawatt hours (mWh) used in the U.S. in January 2016 to 2,721 mWh used in March 2016 [108].

Table 2: U.S. Net Generation by Energy Source in the First 3 Months of 2016 (1,000 Megawatt Hours) [108]

	Coal	Nuclear	Hydroelectric Conventional	Solar
January	113,751	72,536	25,535	1,546
February	92,900	65,638	24,257	2,423
March	72,313	66,149	27,158	2,721

Federal governments, state governments, and local governments offer tax credits to decrease costs associated with developing and maintaining solar PV systems to allow solar PV system prices to compete with nonrenewable forms of energy. Net metering, which gives credits to solar PV owners if they feed more energy back to the grid than the grid feeds back to their PV system, is a benefit also offered in most developed countries. For example, the extension of the U.S. Solar Investment Tax Credit in December of 2015 contributed to the increase in installations from January to March and will lead to a continued rise in installations and usage in the U.S. Residential and large-scale commercial systems are both eligible to receive this tax credit. Both the residential and commercial tax credit will be a 30% credit on installations from 2016 to 2019, then 26% in 2020, 22% in 2021, and finally in 2023 there is no credit for residential systems and there will be a 10% credit for commercial systems [109]. The startup costs of a residential solar PV system, which includes purchasing the system (panels. inverter, mounting equipment) vary based on the size of the system, location, and many other factors. If the costs added to $25,000.00, the user would receive an $7,500.00 credit on the system, reducing the costs for the user to $17,500. Before this extension, the tax credit was set to expire at the end of 2016 therefore this tax credit will lead to far more residential solar PV system installation than if the credit had not been extended.

The demand for solar PV systems is also growing rapidly worldwide. In their 2015 report on solar industry trends, IHS estimated the demand for solar PV to grow 25% worldwide in 2015 [110]. Table 3 depicts leading countries in projected new solar PV installations in 2015. As seen in Table 3, China was the leading country in projected newly installed solar PV systems in 2015 with 14.4 gigawatts. The US was projected to increase new solar PV installations from 2014 to 2015 by 1.5 gigawatts, more than any other country. Although Germany was only 5th in projected new installations in 2015, they still are the leader in cumulative PV installations and plan on having a total solar PV capacity of about 200 gigawatts by 2050 [111].

Table 3: Solar PV Growth by Country in Gigawatts (GW) [110]

	PV Installations 2014	Forecasted Installations 2015
China	13.1	14.4
Japan	9.4	9.0
USA	6.9	8.4
UK	2.8	3.2
Germany	2.0	2.5
India	1.1	1.9

This increase worldwide is due largely to government subsidies and tariffs offered by these countries. Germany and the United Kingdom offer benefits similar to net metering policies that the U.S. offers, which they refer to as tariffs [112], [113]. These are constantly changing but consistently greater than net metering benefits offered by the U.S.

Deutsche Bank released a market research report which displayed the predicted falling prices of installing residential solar PV systems that accounts for all costs including installation, inverters, and panels. Figure 2 displays these projections. As seen in Figure 2, the price per watt of installing a solar PV system is projected to fall from almost $3.00 in 2014 to approximately $1.75 in 2017.

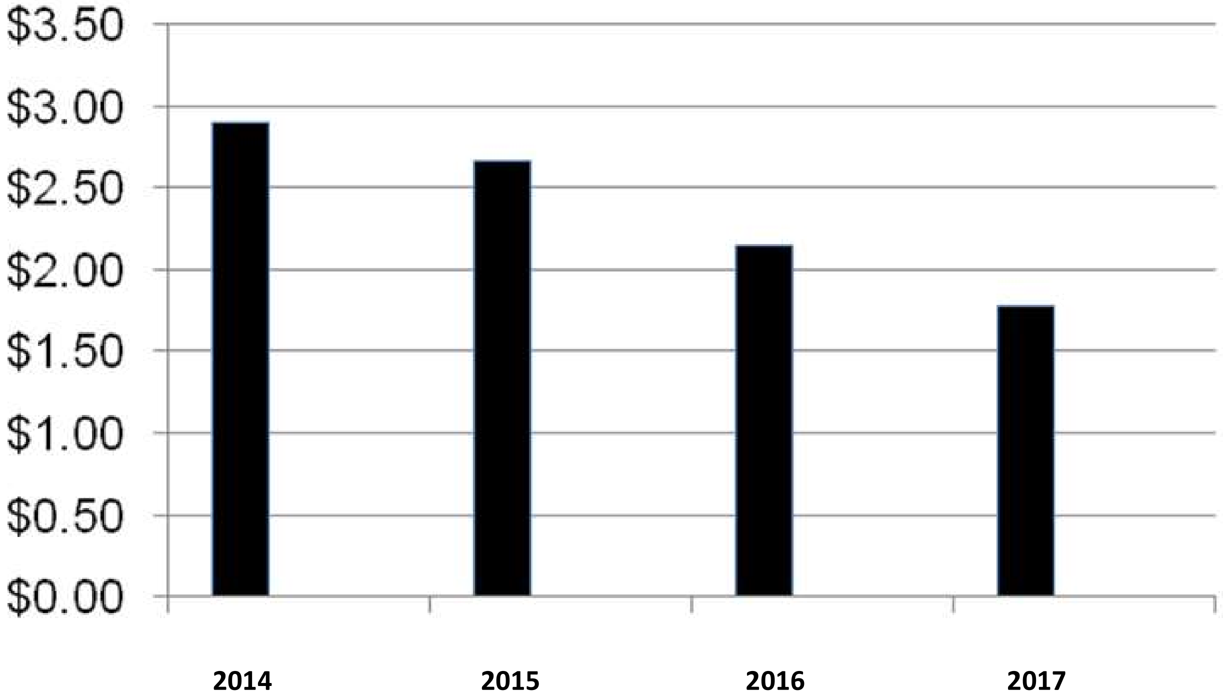


Figure 8: Cost Trajectory for Solar PV Installations: US Trajectory ($ per Watt) [114]

Chapter 5: The Effect of Reliability and Warranties on Return on Investment of Solar Photovoltaic Systems

A return on investment analysis of solar photovoltaic systems used for residential usage has typically shown that at least 10 to 12 years is needed to break-even. While some companies offer even higher warranties, our analysis of failure data shows that even 10 year warranties cannot be realized at this time. The problem stems from reliability issues of currently available electronics hardware. This paper discusses the challenges with the reliability of current solar photovoltaic systems, and the key reliability bottlenecks with a focus on the return on investment.

5.1 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 [116]. By the end of 2014, the total installed global capacity of solar PV power was approximately 177 gigawatts [117]. Furthermore, the solar industry provided about 40% of all new U.S. electricity-generating capacity in the first half of 2015 [118]. 7,260 megawatts (MW) of solar PV was installed in the US in 2015 and the US is projected to install more than double this amount of solar PV power in 2016 [119].

Solar energy can be converted to electricity in the form of direct current (DC) through the use of PV cells, which are integrated into PV panels. Since most homes today use alternating current (AC), the direct current is converted to AC using 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 Figure 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].

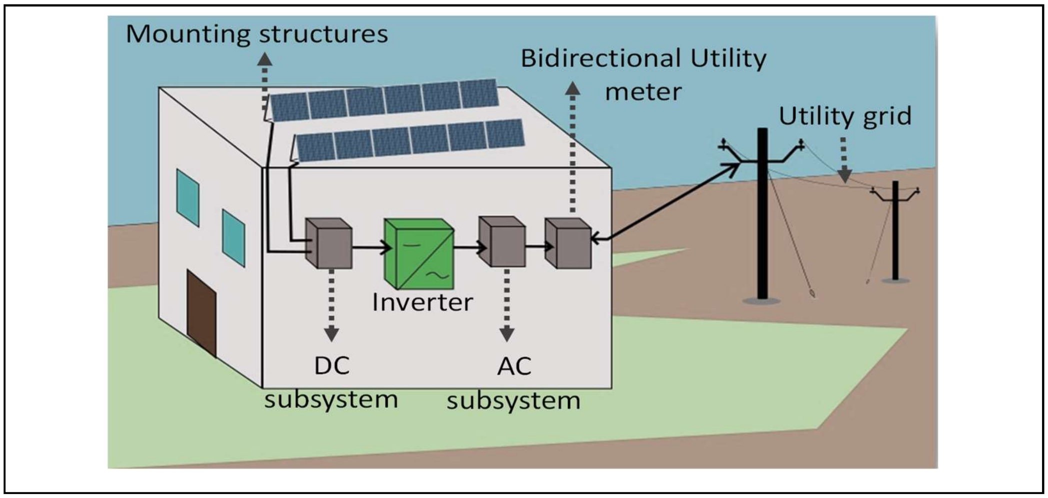


Figure 9: Configuration of a domestic grid-tied solar PV system

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 inconvenience can be significant.

For a solar PV system to be viable, its return on investment (ROI), calculated by dividing the net profit by the total of the investment minus any tax credits or discounts offered, must be recoverable within 10 – 12 years for contractor-installed systems using power purchase agreements or leases, and approximately the same time period for systems directly purchased by the homeowner without government rebates and tax credits [122].

This article presents the different warranty structures offered by companies, the return on investment challenges, the reliability concerns, and candidate solutions to these concerns associated with solar energy systems. Warranty data from solar PV manufacturers and failure data from studies were compiled for this analysis.

5.2 Solar PV System Warranties

A warranty is a guarantee from the manufacturer that defines the responsibility for the product or service provided [123]. 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.

Solar 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. The 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 degrade at a rate of 1–2% per year [124]. Performance warranties typically guarantee about 90% power output compared to the efficiency when the PV system was purchased during the 10th year and 80% power output compared to the efficiency when the PV system was purchased during the 25th year of operation. For example, if the warranty guarantees 80% output during the 25th year of operation then a 100Wp (watt-peak) rated panel should produce at least 80W under standard testing condictions (STCs). The STCs for solar panels include irradiance of 1000W/m^2, cell temperature of 25°C and wind speed of 1m/s. 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% [125].

Product warranties for solar panels typically 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 [126]. For example, CanadianSolar'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 [127].

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 individual panel's performance.

Central inverter warranties vary from 5 to 15 years (e.g. SolarEdge offers a 12-year warranty [128]). 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 as they generally have lower power processing requirements for their switches and energy storage parts (e.g. central inverters are typically rated to handle 5kW or higher, each micro-inverter is generally rated to handle 200-250W [129]). 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 with their micro-inverters [132].

5.3 Failure Data

This section presents and analyzes field failure data from solar PV systems. The causes for the failures of the components are investigated in section 4.

Early failures of solar PV system components can significantly decrease the ROI for PV systems. Field failure data was compiled and analyzed from 3 sources and categorized.

The first source consisted of over 3,500 failure tickets from 350 commercial (about 150 kW) SunEdison® PV systems, operating between January 2010 and March 2012 [133], [134]. Failure tickets are maintenance reports based on a conclusion that a PV system is not performing efficiently after observing a decrease in performance. The data (see Table 1) was derived from a SunEdison® database that tracks these failure tickets by the cause of failures and the amount of kilowatt hours (kWh) lost due to system downtime during a failure. The kWh lost represents the energy production lost due to failures.

In Table 3, the 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. The AC Subsystem includes everything between the inverter and the generation meter (e.g. wiring, switch gears and transformers). The external causes of failure consist of failures from external sources (e.g. grid outages and utility mandated shutdowns) that are unrelated to the reliability of the PV system [134]. Support structures are the mounting equipment which includes all the parts (e.g. clamps) that hold the panels in place. Planned outage refers to outages that were already scheduled for preventive maintenance. Weather stations employ sensors to improve efficiency of the modules by adjusting them to current conditions and fail due to harsh environment conditions (e.g. hurricanes).

Table 4: Frequency of failure tickets and associated energy loss for each general failure area [133].

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%

The data indicates PV inverter failures constitute most failures in SunEdison® commercial PV systems. The inverter failures (see Table 4) were further categorized by component that induced the inverter failure.

Table 5: Frequency of failure tickets and associated energy loss for inverter-related components [133]

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 Contractor	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%

No-fault found (NFF) failures are defined as instances in which a failure was observed but the failure mechanism could not be found and the failure could not be repeated [135]. In this study the NFF failures are intermittent failures, 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 as 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 software.

Card/boards are the printed circuit boards used in the inverter. All switching elements, and power buffers and heat sinks are mounted on printed circuit boards (PCBs) which are optimized from thermal management, parasitic minimization and electrical noise perspectives. These PCBs fail due to improper routing which can result in catastrophic 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. The cooling fans are used to regulate the temperature. IGBTs are three-terminal solid-state semiconductor switches which 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 are minimized with surge protection components. Ground fault interrupter (GFI) components are used to compare the current in the neutral conductor with the ungrounded conductor.

Collins et al. [136] conducted a 5-year study of failures associated with a 4.6-megawatt (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).

Table 6: Distribution of failures observed at a 4.6-MW PV plant over 5 years [136]

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

Huang et al. [137] 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 years span. 60% of the failures in the 62 systems were attributed to the inverter (see Table 7). This study does not use a subsystem category rather Huang states that balance of system components consist of transformers and switches. Golnas and Collins classified these components as AC subsystem or DC subsystem failures.

Table 7: Distribution of failures observed in 202 PV Systems over 3 years [137]

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

Zaman et al. [138] conducted a survey which also indicates inverters contribute to the most failures. For the study, solar PV users and stakeholders in Australia reported 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.

Ahadi et al. [139] used a Markov model for smart monitoring of solar inverter failures which found most solar inverter failures to be related to capacitors. The categories used were capacitor failures, inverter bridge failures, or mechanical failures. Mechanical failures were caused by stress to components, extreme temperatures, or contamination. The study concluded that the percentage of failures related to capacitors, inverter bridges, and mechanical was 60%, 35%, and 5%, respectively.

AC fuses consist of low-resistance metallic wire inside noncombustible material used for AC flow [140]. AC fuses are incorporated in the inverter but unlike the other electronic components discussed in this section are not part of the function of the inverter. Manufacturing defects in the inverter or short circuits can lead to blown AC fuses, which will cause the inverter to fail [141]. Short circuits often 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 [141]. 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.

Although not as prominent as inverter failures, mounting equipment failures also contribute to solar PV system failures. [142], [143]. As indicated in Section 3, mounting equipment contributed to 28% of the failures in the study by Huang et al. and 6% of the failure tickets in the Golnas study. Improper PV installation practices such as incorrectly installing the mounting clamps position or tightness leads to stress on the panels which then lead to panel failures.

Solar PV shingles, which are nailed to the rooftop like asphalt shingles, eliminate the need for mounting equipment in residential applications. Thus, poor installation practices are not an issue with solar shingles. However, because solar shingles are placed directly on the roof's surface, they are exposed to a higher operating temperature compared to solar PV installations with mounting equipment holding up the panels. This can decrease the efficiency of the solar PV cells. Increased operating temperatures and decreased solar PV cell efficiency are strongly correlated [143], [144].

TÜV Rheinland analyzed 2000 IEC certification projects for failures in solar PV modules from 2002 to 2012. The projects were tested for failures according to the IEC 61215, which is a qualification test for crystalline silicon modules, and the IEC 61646, which is a qualification test for thin-film modules [145], [146]. The percentages of projects tested according to IEC qualifications with at least one module not meeting qualifications (see Figure 2) thus constituting as a failed module was compiled and categorized by thin-film panels and silicon crystalline module types.

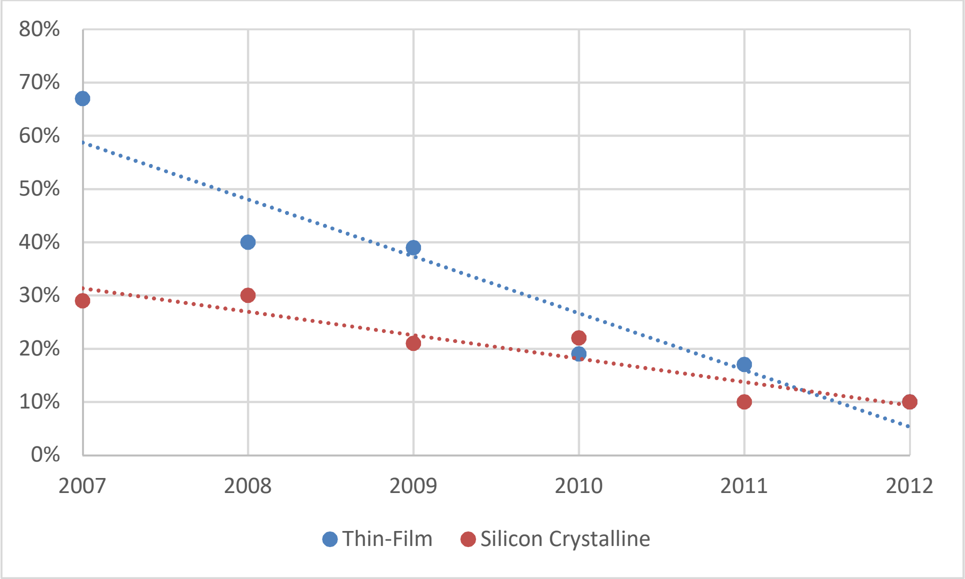


Figure 10: Percentage of Solar Panel Module Failures Observed Among 2,000 Solar PV Systems [145], [146]

In 2012 the failure rates for both panel types was 10%, down from about 70% for thin-film and 30% for silicon crystalline in 2007. Panels not meeting IEC qualifications are attributed to insufficient lab testing by manufacturers. The high amount of thin-film failures observed in 2007 can be attributed to a large amount of thin-film solar PV startup companies with poor lab testing [145].

5.4 Components Contributing to Solar PV Inverter Failures

The data provided in the above-mentioned studies indicates that PV inverters are 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 [147] 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."

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 [148]. With regards to specific switching requirements and operation, IGBTs perform well in high-voltage, high-temperature conditions where high power processing is required [149]. 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 [149].

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 [150]. Aluminum electrolytic capacitors have been estimated to be approximately one-third the price of film capacitors per amount of energy storage needed [151]. 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 [152]. Schimpf and Norum estimate the capacitance per volume ratio of electrolytic capacitors to be 20 times greater than film capacitors [152].

Solar PV inverters with a single standard electrolytic capacitor (DC-link) are estimated to have a lifetime of about five years before a failure [153]. Electrolytic capacitors in solar PV inverters fail due to temperature cycling, power cycling, and high internal capacitor temperature [39-41]. 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 [155]. In a catastrophic failure, a capacitor is completely non-functional and must be replaced. Sometimes the electrolytic capacitor will explode which subsequently causes damage to other components. Catastrophic failures usually occur in poorly sealed capacitors when ripple currents cause high internal temperatures leading to the vaporization of the electrolyte [155]. Film capacitors rarely fail catastrophically rather they tend to fail due to degradation which decreases performance [156].

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 [156]. Transistor failures frequently occur in PV inverters operating in high voltage, high current, or extreme temperature conditions exceeding the conditions specified by the manufacturer [156-158] 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 studied the effects of high-temperature and high-voltage conditions on IGBTs [158]. 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 [156].

5.5 Analysis of the Effect of Failures and Degradation on ROI

Return on investment analyses often assume components in solar PV systems will last 25 years without experiencing failures which constitute a replacement and only assume a constant maintenance cost to account for repairs [159], [122]. Central inverter warranties are most often between 5-15 years and as discussed in section 3 central inverters are likely to suffer multiple failures in 25 years. This section simulates the effect of out-of-warranty PV inverter failures and module performance degradation on a 25-year ROI of a PV system.

Yang et al. [122] estimated the ROI of a residential 6.7 kW PV system installed by a contactor that would qualify for feed-in tariffs (FITs) and federal credits in Gainesville, Florida. FITs offer credits to renewable energy users to encourage investing in renewable energy and the U.S. Federal Solar Investment Tax Credit which offers a 30% credit on start-up costs (purchasing the system and installation costs). In this case the FIT rate was 0.21. The study did not account for inflation and the likelihood that government reduces FITs in the near future to encourage technological advances which is difficult to quantify.

The SMA brand inverter by Yang has a warranty of 5 years [160], therefore from years 5 to 25 the owner would incur inverter replacement costs if the inverter fails in this timeframe. Although Yang accounts for operation and maintenance (O&M) costs at $25.00 per kW per year, which in the case of the 6.72kW system used leads to $168.00 per year, inverter replacement costs are not accounted for. Yang also does not account for panel efficiency degradation. Solar PV cell efficiency is defined as the ratio of the amount of photons striking solar cells to the amount of photons able to be converted to electrical current. We have used the minimum efficiency guaranteed each year by Suntech in their performance warranty for their STP-280 panels as these panels were used by Yang [161].

Yang [122] stated the average ROI per year is 0.098. Yang then used this constant annual ROI to calculate a payback period of 10.2. It should be stated that Yang's analysis of the payback period and ROI did not include a discount rate. The savings to investment ratio, a financial tool that measured by dividing amount saved in an investment by the total start-up costs and variable costs (e.g. operation and maintenance), has been calculated to incorporate inverter costs. The ROI is modeled under scenarios in which the inverter were to fail multiple times without being covered by the 5-year inverter warranty during the 25-year guaranteed performance lifetime of the panels using an inverter replacement cost of $2,647 (the cost of the inverter used by Yang). Huang et al. [137] monitored 202 PV systems in Taiwan and observed a mean time to failure of 3.96 years for the PV systems with inverters constituting 60% of the failures. Collins et al. [136] monitored failures associated with a 4.6 MW solar PV plant in Arizona over a 5-year time span and concluded the inverter repair rate per year was 0.96, meaning that on average each inverter had to be repaired or replaced about once per year. Current PV inverters based on available data have a lifetime of 1-20 years until failure [136], [137], [153] with this timeframe varying based on power cycling conditions, size of the inverter, temperature cycling, components in the inverter (types of capacitors used, semiconductor materials used, etc.), and other conditions. Since there is variation as to inverter replacements based on these conditions and the overall reliability of the inverter manufacturer, we have modeled the effect of inverter replacements on the annual savings to investment ratio by amount of inverter replacements. Yang estimated an average savings to investment ratio of 0.098. We calculated the savings to investment ratio by assuming the panel efficiency to be the average efficiency guaranteed by the manufacturer throughout the lifetime of the system according to their performance warranty, constant inverter costs (the price of inverter replacements are the same as the current start-up costs), and no discount rate. The discount rate and future inverter costs have been cited as very uncertain in determining the ROI of PV systems. The savings to investment ratio is a financial measurement used to determine whether the savings of a project justifies the start-up costs and variable costs of a project. The first year savings to investment ratio, the amount of savings generated by the system divided by total start-up and variable costs, would decrease to 0.045 if the system would require 7 inverter replacements throughout the lifetime of the system and the user purchased 7 inverters at the start of the project and divided that cost over 25 years, 0.051 if the system required 6 inverter replacements, 0.057 if the system required 5 inverter replacements, 0.063 if the system required 4 inverter replacements, 0.069 for 3 replacements, 0.075 for 2 replacements, and 0.081 for 1 replacement.

When these inverter replacements and panel efficiency degradation are accounted for a payback period of 10.2 years is unrealistic. Note that this analysis does not account for potential shipping costs when the inverter needs to be replaced, energy lost due to downtime when the PV system is not producing energy after the inverter has failed and before the inverter has been repaired or replaced, or reinstallation costs which would further decrease the ROI. There is variation in the amount of these costs and whether these costs will be covered depending on the manufacturer. We have not accounted for module replacements as indicated in section 3 PV modules are not a significant failure area. Also, PV modules have product warranties of at least 10 years to protect them against manufacturing defects and 25 years for protection against underperforming solar cells so in a 25-year span out-of-warranty failures are seldom. Furthermore, the effect on the overall ROI would be small as the cost of each module in this study is only about 12% the inverter cost.

5.6 Emerging Technologies to Improve the Reliability of Solar PV Systems

Two major advances in electronics promise to improve the reliability of inverters and in turn solar PV systems. The first 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 improves the energy production and reliability of the PV inverter and in turn the overall ROI. The second 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, and when used in MOSFETs and IGBTs have ability to withstand higher reverse voltages, higher temperatures, achieve higher frequencies than Si-based transistors [162-166]. Hinata et al. [162] 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 -40ºC and 175ºC showed failures in the Si-based inverter and no noticeable degradation in the SiC-based inverter. Sintamarean et al. [166] designed PV inverters to compare the performances of a Si IGBT-based solar inverter compared a SiC MOSFET-based inverter in high power applications (10kW of higher). They achieved a switching frequency of 50 kilohertz (kHz) for the SiC-based inverter compared to 16 kHz for the Si-based inverter. Sintamarean also stated the SiC-based inverter was able to achieve a 40% lower inductance and 70% lower capacitance than the Si-based inverter thereby reducing capacitor and filter costs. The SiC MOSFET-based inverter designed was more cost-effective and reliable as it could employ less switches and superior thermal loading distribution than the Si IGBT-based inverter. However, the price of SiC and GaN-based inverters in an industry setting is still considerably higher than Si-based devices.

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 [152], can be utilized due to these lower power processing requirements [167]. If a central inverter fails, the entire PV system will fail. If a single micro-inverter fails, only the module which the micro-inverter is monitoring will fail and the rest of the PV system will remain functional.

However, micro-inverters have several disadvantages. First, because they are placed outside on each individual panel, they are exposed to environmental conditions such as high temperature and moisture that a central inverter placed indoors would not be exposed to [168]. Second, printed circuit boards and solder joints in the micro-inverters are still not built to last the 25-year warranty period of the solar PV systems especially when exposed to volatile outdoor climates [168].

Even with these disadvantages, the 25-year warranties associated with micro-inverters compared to the less than 15-year warranties of central inverters can improve the ROI for users by reducing replacement costs in residential systems. However, purchasing several 200-250 Wp rated micro-inverters in a residential PV system compared to one 3-10 kWp central inverter will result in a higher start-up cost.

5.7 Conclusions

The amount of failures associated with out-of-warranty inverters will affect the ROI of residential solar PV systems. If a central inverter costing at least $2,000.00 fails 3 or more times within the lifetime of solar PV system the ROI will be decreased due to replacement costs and the downtime when the failed inverter is causing the PV system to not produce energy. Central inverter warranties are most often less than 15 years and the PV panels and mounting equipment in residential PV systems can last at least 25 years, with most solar PV cells being protected under warranty to perform at a specified efficiency for 25 years. Current ROI studies of solar PV systems do not account for repair and replacement costs associated with inverters. They also do not account for downtime in which the PV system is not performing while the user is in the process of filing a warranty claim, waiting for the manufacturer to investigate and make a decision, and waiting for the inverter to be repair or replaced. Even if an inverter is covered under warranty, inverter manufacturers are not obligated to cover these costs associated with the power the PV system was not producing while the inverter failed, shipping costs of the replacement inverter, and reinstallation of the replacement inverter.

The 25-year warranties of micro-inverters allow residential users to deal with less replacements than systems with a single central inverter and in the event of a replacement after 25 years a micro-inverter is less expensive to replace than a central inverter. As the costs of micro-inverter decrease their longer warranties can ensure residential PV users do not have suffer from a significant decrease in ROI when a central inverter warranty expires.

The mean time to failure of electronic components in PV inverters such as capacitors, IGBTs, and MOSFETs must improve to increase the lifetime of PV inverters. Utilizing more film capacitors as opposed to electrolytic capacitors, SiC and GaN-semiconductors as opposed to Si-semiconductors will improve the mean time to failure of PV inverters.

Chapter 6: Return on Investment Analysis and Simulation of a 9.12 Kilowatt (kW) Solar Photovoltaic System

Residential solar photovoltaic (PV) systems have been emerging as an economically feasible energy source. In the United States, an extension of the federal solar investment tax credit was granted in December 2015 to encourage solar investments by giving residential users a 30% discount on start-up costs (equipment and installation costs) with the 30% discount decreasing slightly each year until it expires in 2023. This article presents a simulation of the return on investment of a residential solar PV system in College Park, Maryland, using weather conditions and tax credits specific to the Maryland area. A bundle package was selected with components that are cost-effective in residential applications, and the total amount of expected energy production was calculated by inputting information regarding the location, components, and design into the "PV Watts Calculator" tool available from the National Renewable Energy Laboratory (NREL) along with eligible tax credits. An analysis of the conditions that affect the long-term return on investment including reliability and changing tax credit structures is then presented.

6.1 Introduction

Solar photovoltaic (PV) systems are used in residential and large-scale settings to convert sunlight to electricity. These systems consist of modules that contain semiconductor material capable of absorbing photons from the sun to produce an electric current [169]. The solar PV modules are electrically connected to an inverter, which converts the direct current (DC) generated from the panels to alternating current (AC). In residential applications, these inverters are then connected to either a storage battery or the utility grid. Figure 1 shows a solar PV system on the University of Maryland campus. The PV panel array absorbs electricity in the form of direct current, the micro-inverters (small inverters placed on each individual panel, unlike a central inverter which handles energy conversion for several panels) convert DC to AC, and then the AC is sent to the electric grid. Mounting equipment holds the components of the PV system in place.

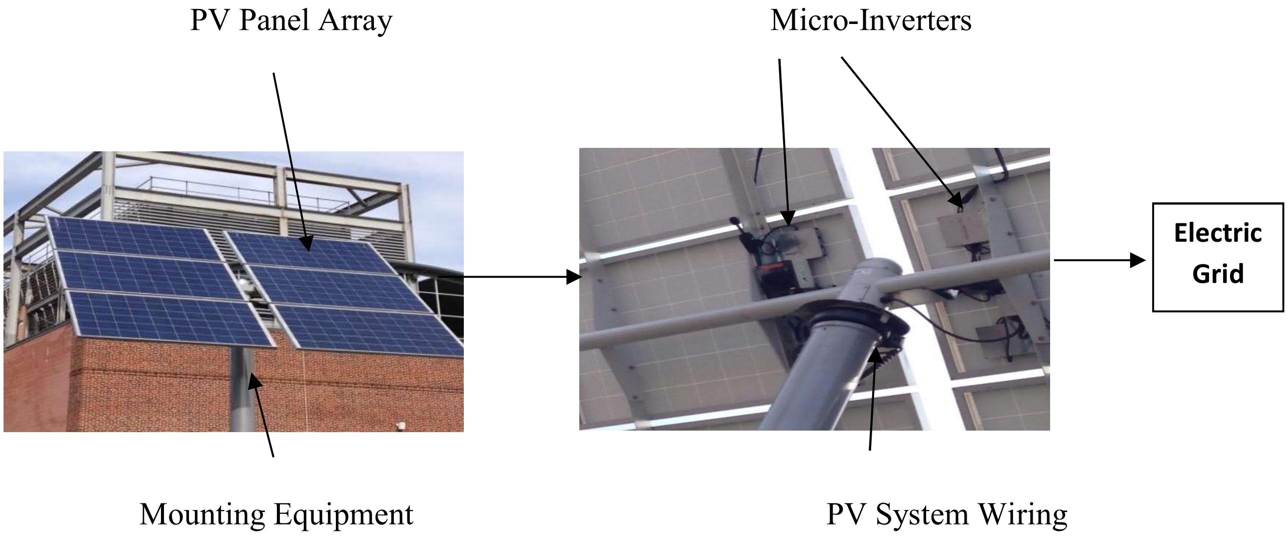


Figure 11: Configuration of a grid-tied solar PV system.

Solar PV systems are becoming more prevalent worldwide as a source of renewable energy. In the third quarter of 2015, the United States installed 1,361 megawatts (MW) of solar PV capacity [170]. Large-scale installation contributed to 42% of this total, and residential installation made up 41% [171]. From the third quarter of 2014 to the third quarter of 2015, residential installation grew by about 69%. In the first half of 2016, over four gigawatts (GW) were installed in the United States [172]. This represented a 45% growth compared to the first half of 2015. Decreasing solar PV life cycle costs are expected to help increase the global capacity of solar PV and compete with the global capacity of major nonrenewable fossil fuel energy sources including coal, natural gas, and petroleum. In 2014, fossil fuels accounted for 78.3% of global energy capacity, whereas renewable energy only contributed 19.2% [173].

Solar PV systems have high start-up costs due to the price of the components (inverters, panels) and installation. Residential solar PV systems in the U.S. are usually tied to utility grids so users can receive tax credits on the start-up costs and supply energy to the grid to receive additional production-based tax credits. Grid-tied systems do not require a costly storage battery because the grid supplies electricity when the PV system is not producing energy due to a lack of sunlight. While off-grid battery storage systems are often considered the most effective for the customer, they are more costly and used in less than 10% of solar PV power installations in the U.S.; thus this study focuses on grid-tied systems [174].

Before installing a solar PV system, owners should have an accurate estimate of the return of investment (ROI) to determine if it is indeed a promising investment compared to using standard electricity. The ROI is the gain made from an investment, in this case, the amount saved by using a solar PV system compared to standard electricity divided by the initial start-up costs. Before discussing a detailed ROI simulation of a PV system, the factors that affect the ROI of a solar PV system and a literature review will be presented.

According to the most recent data from the U.S. Energy Information Administration, in August 2016 retail electricity was estimated to cost an average $0.13 per kilowatt hour (kWh) [175]. Solar PV electricity is currently about $3.00 per watt in residential applications [176], and

GTM Research estimates that by 2020 the U.S. Department of Energy will reach their goal of decreasing the price of solar PV electricity to below $1.00 per watt for large utility-scale solar plants. As of August 2016, the price for panels was at an all-time low of $0.45 per watt [177]. Furthermore, the average cost of solar PV electricity is projected to decrease by 59% from 2016 to 2025 [178]. In addition to hardware costs, residential solar PV users in the U.S. qualify for the Solar Investment Tax Credit, which offers residential users a 30% tax credit from 2016 until the end of 2019, a 26% credit from the end of 2019 until the end of 2020, and then a 22% credit from the end of 2020 to the end of 2021. At the end of 2021 the residential credit will expire and a credit on commercial and utility systems will still be offered until the expiration in 2023 [179]. There are also state and local tax credits to encourage residential users to invest in solar PV systems.

Huld et al. [180] calculated the levelized cost energy for a solar PV system to measure the competitiveness of solar PV prices compared to other forms of electricity in Europe. The levelized cost of electricity is a measurement of an energy system investment that takes into account costs over the lifetime of an energy system, including the initial investment, operation and maintenance, capital costs, and fuel costs. It measures the net present value of the electricity cost per unit over the lifetime of the energy system. Their analysis took into account start-up costs (e.g., panel, inverter, and installation costs), sales tax, capital for the ROI, and operation and maintenance. They compared the levelized cost of electricity from solar PV to standard residential rates from utility companies and concluded that solar PV electricity is less than or equal to residential utility prices for 79.5% of the European population.

Yang et al. [181] simulated the payback period and ROI for a 6.7-kW residential solar PV system in Gainesville, Florida. The payback period is the time it takes to fully recoup the costs of the initial investment. Their study used Suntech 280-W solar panels with 14.4% efficiency and assumed that the inverter would be 95.5% efficient. Calculations of the total start-up cost of the PV system included 24 Suntech 280-W panels, 2 solar panel cables, 2 fuse holders, 1 inverter, 2 lightning arrestors, 1 combiner box, 1 direct current disconnect, and the mounting system. They noted that when using federal credits and the solar electric rebates offered by Florida, which provide credits for users based on the amount of power produced from their system, the payback period would be 2.77 years for a self-installed system and 12 years for a contractor-installed system. Users who apply for the Solar Electric System Rebate Program in Florida are not permitted to also apply for the feed-in tariff (FIT) program, which offers credits based on utility companies buying electricity from solar PV customers at a rate of $0.21 per kWh for systems equal to or less than 10 kW. When using the FIT program, the payback period was projected to be 5.26 years for self-installed systems and 10.2 years for contractor-installed systems. Their calculations assumed the annual ROI would be the same every year and did not account for degradation of PV cells and the reliability of components.

Matthews and Matthews [182] simulated the ROI of a stand-alone residential PV system in South Africa. They used the market price for the panels, the inverter, and a Tesla Powerwall lithium-ion battery; a constant rate of inflation of about 6% per year; and lifetimes for the components of the solar PV system until the end of the warranty period. They then calculated the initial start-up costs and assumed a constant energy production based on data local to South Africa and efficiency rates of standard panels and inverters. For a medium income household with a PV system producing 855.45 kWh of power, they calculated the payback period to be about 7.52 years. They concluded that even though solar PV systems can achieve a payback period of less than 10 years the high start-up costs can deter people from investing.

Ahsan et al. [183] simulated the energy production and initial investment of a 1-kW residential solar PV system in India using "PVsyst" software. Their start-up costs were about $1,200, and they concluded their 1-kW system could generate 8,109 watts of energy per day using conditions in India and efficiency data from manufacturers. Their simulation did not specify a payback period or provide life-cycle cost analysis.

Shouman et al. [159] conducted a life-cycle cost analysis case study of a grid-tied 10-MW large-scale PV system and an off-grid PV system to supply 5.075 kWh of electricity to a residential home in Egypt. The estimated payback period for an on-grid PV system was 6.08 years. With the off-grid system, the total life-cycle costs over 25 years and cost of electricity per kWh were calculated using local weather data and the assumption that the battery would need replacement every 7–8 years. Their calculations took into account the costs of the initial purchase and installation as well as maintenance and replacement. The reduction in electricity production due to degradation of the system was also part of the calculations. They concluded that the life-cycle cost of the PV system will be about $3,600 over a 25-year span and the cost of energy will be about $0.17 per kWh, which is competitive with utility rates in Egypt.

Muhammad-Sukki et al. [185] analyzed the payback period under various feed-in tariff (FIT) schemes for solar PV systems in Malaysia. With Malaysia's Renewable Energy Act of 2011, the FIT varies based on the size of the PV system and therefore the payback period of systems between 4-kW and 30-MW would be 21 years and the average annual ROI would be about 5% of the original investment. Their assumption was based on start-up costs and consistent annual output of electricity from the system.

Many other studies have calculated the ROI and life-cycle costs of solar PV systems compared to other forms of renewable energy in various regions that offer different credit schemes than the U.S., have different environmental conditions, and use different PV system sizes [186-189]. The ROI of solar PV systems is constantly changing as costs of solar PV components decrease and the cost of standard utility electricity from nonrenewable resources increases [190].

6.2 ROI Simulation of a Residential Solar PV System in College Park, MD

This study simulates the ROI of a solar PV system in College Park, Maryland, with prices, reliability, technology, and tax credits as of June 2016.Environmental conditions and tax credits are also specific to the College Park area. Rather than using market prices, this study uses the prices and efficiency rates of a currently available solar PV system design. Furthermore, the reliability of solar PV systems and its effect on ROI are presented in the next section.

The average electricity consumption per residential household in Maryland is about 1,005 kWh per month [191], and the average residential electricity rate in College Park, MD, is $0.1128 per kWh. These figures are the basis for calculating the amount saved using the solar PV system.

This simulation is based on a 9.12-kW system with 32 solar panels, each with an efficiency rating of 17.34%. The total purchase price of this system from Wholesale Solar, including all components but not including installation, was listed at $15,120.00 as of June 2016 [192]. One inverter is used to convert the DC current produced from the panels to AC current. Nine hardware components in the PV system (see Table 1) add up to a total hardware cost of

$15,120.00.

Table 8: Components of the Solar PV System [192]

Quantity	Component
32	Suniva OPT285-60-4 100 Silver Mono Solar Panel
1	SolarEdge SE10000A-US-U Inverter
32	IronRidge XR100 Option D Racks per 65" X 39" Module Inc. Grounding
16	IronRidge Mounting Hardware Kit - T-Bolt 1/4" X 3/4"
1	Electrical Design Diagram
1	Square D DU222RB Safety Disconnect
1	Four Star Solar MC4 Unlocking Tool
2	Four Star Solar Dual MC4 10 AWG - 100' Cable Extension
32	SolarEdge P300 - 5NC4ARS Power Optimizer

The total start-up costs for the PV system were calculated using the listed price of $15,120.00, the installation cost, the state and local tax credits, and the savings from the 30% U.S. Solar Investment Tax Credit (see Table 8). The installation cost is the total cost of paying an installer to set up the PV system and tie it to the grid. This simulation used an installation cost of $12,500, an amount that has been used in recent literature for residential systems [181]. It should be noted that the installation cost varies based on the installation company contracted to perform the installation and the size of the system. The price per kilowatt peak (kWp) measures the total value of a system, assuming electricity is produced at peak sunlight. Since it is a 9.12-kW system, the kWp would be about $1,660 before installation costs and tax credits. The final start-up cost of this residential system ($13,634) is less than half the start-up cost of the system without the state, local, and federal tax credits ($27,620). Therefore, the final price per kWp of this system after tax credits and installation costs is approximately $1,500. This analysis assumes the system will meet all requirements and be eligible for the Prince George's County Solar Residential Property Tax Credit and the Maryland Residential Clean Energy Act.

Table 9: Start-Up Cost Total Price Calculation of the Solar PV System

Start-Up Costs of Solar PV System	**Price**
Component costs	$15,120
Installation cost	$12,500
Total PV system start-up costs before application of state, federal, and local credits	$27,620
Maryland Residential Clean Energy Act	($1,000)
Prince George's County Solar Residential Property Tax Credit	($5,000)
Total PV system start-up costs after application of state and local credits	$21,720
Solar investment tax credit savings (30% of total start-up cost)	($7,986)
Final total PV system start-up costs	$13,634

The National Renewable Energy Laboratory (NREL) has a calculation tool, "PV Watts Calculator" [193] that tracks the average solar radiation throughout a year in different areas of the U.S. The tool allows users to calculate the total energy output of a solar PV system per year after inputting conditions (i.e., size of system, efficiency of panels, tilt angle, azimuth angle, array type). For the simulation of energy output per year, the simulation assumed system losses (e.g., wiring, shading, degradation of photovoltaic cells) of 14%, an angular tilt of 20° (degree that panels are tilted on the roof), irradiation conditions based on yearly data of area weather conditions (from the NREL), and an azimuth (vector from the panels to the sun projected perpendicularly on a plane) of 180°. These inputs projected 11,889 kWh of electricity production per year from the PV system. This system would therefore generate kWh/kWp per year, the amount of kWh produced per year divided by the total power of the system, of about 1,300 kWh/kWp. This system would also be eligible for Maryland's Clean Energy Incentive Tax Credit [194], which discounts \$0.0085 per kWh of energy produced for the first 5 years. The total savings per year, assuming a constant energy production for this system, would be \$101.06 applicable for the first 5 years of the system. Utility companies pay PV users \$160 (\$0.16/kWh) for solar renewable energy certificates (SRECS) [195], which are savings per megawatt of solar electricity a system produces, from residential users. With a projected 11,889 kWh of electricity production per year, this system would be eligible for about \$1,900 in savings from SRECs per year, assuming a constant production rate. The NREL lists an average cost of operation and maintenance [196] of \$21 per kW per year. For this 9.12-kW system, an estimation of operation and maintenance costs based on a \$21 per kW per year rate yields about \$190 per year.

Equation 1 shows the calculation for the annual savings to investment ratio with this PV system.

$$\text{Annual savings} = ((E_{\text{ut}} + Cr_{\text{pv}}) * Pr_{\text{pv}}) - \text{O\&M} \tag{1}$$

where E_{ut} is the average price per kWh of the utility electricity (\$0.1128), Cr_{pv} is the credits the PV system receives per year (in this case, the Clean Energy Incentive Tax Credit and SRECs, which total \$0.1685/kWh), Pr_{pv} is the annual production of the PV system (11,889 kWh/year), and $\mathrm{O\&M}$ is the annual operation and maintenance costs (\$190). The projected total savings earned from this PV system amounts to about \$3,150 per year This \$3,150 total savings can be used to determine the first-year savings to investment ratio. The savings to investment ratio is a financial measurement used to determine whether the savings earned from a project justifies the start-up costs and variable costs the project can expect. With projected yearly savings of \$3,150 and projected start-up costs of \$13,364, the PV system would expect a first-year savings to investment ratio of 23.57% assuming constant energy production and no reliability issues. Therefore, with constant energy production and tax credits, this system would yield a payback period of less than 5 years. With constant energy production and tax credits, this system would yield a payback period of less than 5 years. The ROI over 25 years would depend heavily on future costs of utility electricity, reliability of the system, and future tax credit structures. If utility electricity costs increase significantly due to scarcity of nonrenewable energy sources, residential PV users could see a 25-year ROI of over 5 assuming no reliability issues and constant tax credits.

6.3 Effect of Reliability and Tax Credit Cuts on ROI

This section discusses reliability factors and the likelihood that tax credits will change in upcoming years, resulting in a significant decrease of this ROI over a 25-year span. The number of failures of a solar PV system over a 25-year span depends on the maintenance of the system by the user, the reliability of the manufacturer supplying the inverter and panels, the operating conditions the system must endure (power cycling, temperature cycling), and the quality of the installation. Since these factors are difficult to simulate and vary from system to system, this section will not provide a specific number to quantify the amount that reliability will decrease the 25-year ROI. Rather, this section analyzes the key reliability issues and problems with tax credits.

The reliability of solar PV inverters and potential reductions in government tax credits decrease the ROI of residential solar PV systems. Although these factors are difficult to quantify because the reliability of PV systems varies based on electronic components used and operating conditions (e.g., power and temperature), they must be taken into account when determining the expected ROI of a PV system.

Solar PV inverters are known to be the least reliable component in PV systems [198, 199], with an estimated time to failure of 5 years [199]. As of August 2016, the cost of replacing the SolarEdge inverter [200] used in this simulation is approximately $1,900. Many inverters have warranties of 5 years or less, however, this inverter comes with a 12-year warranty. Replacement costs are unlikely to occur in this simulation until after the 12th year unless the inverter fails (e.g., due to terms not covered in the warranty agreement) or the manufacturer is not able to cover the warranty (e.g., due to bankruptcy) [201]. Even if a warranty is honored, the downtime during which the system is not producing electricity may not be compensated by companies.

SunEdison's failure study [197] of large-scale solar PV systems indicates that inverters are a major cause of failure problems (tickets), as shown in Table 3. A failure ticket is compiled when a PV system is underperforming. This data consists of over 3,500 failure tickets compiled in a 27-month time frame from January 2010 to March 2012 from 350 solar PV systems operated and designed by SunEdison. As seen in Table 3, inverters account for more than three times the number of failure tickets as any other component in SunEdison systems. The reliability of inverters must improve to decrease the potential impact that failed inverters can have on ROI.

Table 10: Frequency of failure tickets and associated energy loss for each general failure area [197]

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

Zaman et al. [202] gathered feedback from residential PV users in Australia to determine whether their PV systems had been experiencing reliability issues. The survey found that 26 of the 29 respondents had experienced problems with the inverter and of these 26 respondents, 10 reported their inverter had completely failed and needed replacement. Collins et al. [198] conducted a 5-year study at a 4.6-mW solar PV plant comprised of 26 arrays, with each array consisting of 450 panels. They concluded that the average inverter repair rate was 0.96 per inverter per year. Of the 237 failures observed in their study, 125 were inverter failures.

Another concern with the ROI of residential PV systems is that the state and federal governments may cut tax credits in the coming years [203, 204]. It was uncertain whether the federal solar investment tax credit would be extended in December 2015, and when it expires again the government may decide not to extend the credit [204, 205]. The federal tax credit is currently set to drop from 30% to 26% at the end of 2019 and to 22% at the end of 2020. At the end of 2021 the tax credit expires for residential users but will remain at 10% until 2023 for commercial and utility applications. The federal tax credit decreased the start-up cost of the PV system in this simulation by about $8,000. The average annual ROI, assuming constant production without this tax credit, would be about 14.5% of the original investment compared to 23.6% of the original investment with the federal tax credit. The state and local tax credits in this study also decreased the start-up costs by about $6,000. States have already begun cutting tax credits [205]. Without these state, local, and federal tax credits, the first-year savings to investment ratio, assuming constant energy production and no reliability issues, would only be approximately 11.4%. With a constant annual savings to investment ratio of 11.4% it would take about 9 years to break-even. The ROI during those first 10 years would be just over 1, assuming constant electricity costs and no discount rate .The discount rate and future electricity costs have been cited as very uncertain in literature [186]. This ROI would only be attractive to investors if they can afford the high start-up costs of a PV system and endure a payback period of about 9 years without PV system failures or even longer if their system experiences PV system failures.

6.4 Conclusions

Owing to the current local, state, and federal tax credits for residential solar PV systems in the U.S., consumers can expect to see an annual ROI as high as 23.6% of the original investment, as determined by this paper's simulation, assuming no reliability issues. This would yield a payback period of about 4.25 years. However, component failures in solar PV systems, particularly the electronic components in the inverter, can add costs especially if the components are not properly covered under warranty. Even if an inverter is covered under warranty, the downtime when a PV system is not operating adds more costs. Therefore, the reliability of electronic components in PV systems must improve to ensure a more predictable ROI in the later years of a PV system.

Furthermore, it is likely that U.S. federal and state governments will cut tax credits in the coming years. On the other hand, the start-up costs of PV systems will also continue to decrease as inverters and solar panels become less expensive.

If an investor can afford the start-up costs and the risks associated with reliability of components and tax credit decreases, an annual ROI of 23.6% of the original investment is an adequate investment. In this simulation the investor could expect a payback period, the amount of time to recoup the start-up costs of an investment and reach a break-even point, of about 4.25 years assuming constant energy production, no reliability problems, and no tax credit changes. Determining whether to invest in a residential solar PV system depends on the investor's risk tolerance and net worth.

Reliability issues and a decrease in tax credits are factors an investor must analyze before deciding whether to invest. If the inverter used in this simulation fails during the payback period and is not covered by warranty, the replacement cost of $1,900 would increase the payback period to 4.85 years without accounting for downtime when the system is not producing while the inverter is awaiting replacement. As stated in the previous section, with all tax credits removed from the simulation the average annual ROI is only 11.6%, less than half the annual ROI of 23.6% when tax credits are factored in the simulation. Assuming constant energy production and no reliability problems, this 11.6% annual ROI would yield a payback period of about 8.6 years and cause the investment to no longer be adequate unless the investor is very risk tolerant.

A market research report from Deutsche Bank estimated the average cost per kWh of installing solar power in residential homes worldwide will decrease from about $2.66 in 2015, to $2.15 in 2016, and finally to $1.77 in 2017. These calculations take into account panel, inverter, mounting equipment, and installation costs. As these prices continue to decrease and the reliability of solar PV systems continues to improve, residential solar PV systems can begin to see a more consistent and predictable payback period of less than 5 years.

Finally, new technologies are being used in PV inverters to increase their efficiency and reliability. Emerging wide-bandgap semiconductors materials, primarily gallium nitride (GaN) and silicon carbide (SiC), are replacing silicon in insulated-gate bipolar transistors (IGBTs) and metal-oxide semiconductor field-effect transistors (MOSFETs). The reliability of these wide-bandgap semiconductors is superior in high-voltage, high-temperature, high-frequency, and high-power applications. Companies have also started to replace electrolytic capacitors with more reliable film capacitors in PV inverters. Increased reliability and decreased component costs have the potential to offset the effect of reduced tax credits on the annual ROI.

Chapter 7: Conclusions

In the automobile industry, warranties are directly related to reliability. If the reliability and lifetimes of automobiles had improve significantly in the past 20 years, these warranty periods would be increased. However, the recent reduction in warranty periods by automobile companies such as GM and Chrysler suggests reliability is actually not improving and these companies are seeing a warranty claim expense which exceeds the financial benefit of having a long warranty period as a marketing strategy. A decrease in a powertrain warranty period is correlated to financial struggles and poor reliability

The variation of reliability and warranty periods among components (the 5-15 year warranty of inverters compared to the 25-year performance warranties of solar PV modules) in solar PV systems decreases the ROI of solar PV systems after the expiration of the inverter warranty and before the end lifetime of the solar PV modules. The reliability of solar PV inverters must improve to ensure inverters can achieve a lifetime similar to modules. The 25-year warranties of micro-inverters can help residential PV system owners achieve a more predictable ROI as this will eliminate replacement costs during the 25-year lifetime of the solar PV modules. Wide bandgap materials such as SiC and GaN must continue to replace Si in the solar PV inverters and film capacitors must continue to replace aluminum electrolytic capacitors to ensure a longer lifetime of solar PV inverters. The ROI of a solar PV system over 25 years is only about 40-85% of what it could be if solar cell degradation and out-of-warranty inverter failures were nonexistent.

The costs of solar PV components such as inverters, panels, and mounting equipment are projected to decrease significantly in the next 5 years. As these start-up costs decrease and the reliability of electronic components in the inverter improve, residential users can expect a significantly shorter payback period. The return on investment analysis using a 9.12 kilowatt solar PV system in Maryland presented in this thesis is evidence that if tax credits are maintained and electronic components can remain reliable for the 25-year lifetime of a solar PV system, residential users can see a payback period of under 5 years.

8. Works Cited

[1] Pecht, M., “Establishing a Relationship Between Warranty and Reliability,” IEEE Transactions on Electronic Packaging and Manufacturing, Vol.29, No.3, July 2006.

[2] Wallace, B., “Product Warranty Handbook,” CRC Press, 1st Edition, Nov 3, 1995.

[3] Biancalana, J., “The Fee Tail and the Common Recovery in Midieval England 1176-1502,” Cambridge Studies in English Legal History , February 2007, pp. 213.

[4] Bandsuch, M., “Warranty,” Encyclopedia Britannica, Date Accessed: January 26, 2016.

[5] Indiana Law Journal, “Implied and Express Warranties and Disclaimers Under the Uniform Commercial Code,” Indiana Law Journal: Vol. 38: Iss. 4, Article 5, 1963.

[6] Rasmussen, R., “The Uneasy Case Against the Uniform Commercial Code,” Louisiana Law Review, 2002, pp. 1101.

[7] Thomas, M., “Reliability and Warranties: Methods for Product Improvement and Quality Improvement,” Boca Raton, FLA, Taylor & Francis, 2006 pp. 148.

[8] MLMLaw.com, “Understanding the Magnuson-Moss Warranty Act,” Law Library, MLMLaw.com Date Accessed: January 14, 2016.

[9] R. Kutner, “Consumer Product Warranties Under the Magnuson-Moss Warranty Act and the Uniform Commercial Code,” 62 Cornell Law Review. 738, pp. 760-761, 1977.

[10] EUR-Lex, Access to European Law, “Product Guarantees for Customers,” EUR-Lex, Access to European Law, Date Accessed: January 15, 2016

[11] Committee on the Future of Personal Transport Vehicles in China; Policy and Global Affairs; National Research Council; National Academy of Engineering, Chinese Academy of Engineering “Personal Cars and China,” National Academic Press, pp. 37-60, 2003.

[12] Burdick, C., “Two Chinese Auto Manufacturers Get Ahead of ‘Three R’s Regulation,” Carroll Burdick & McDonough, Date Accessed: February 15, 2016. Available Online: http://www.cbmlaw.com/news-resources/resources/emeabriefings/Two-Chinese-Auto-Manufacturers-Get-Ahead-of-Three-R-s-Regulation-

[13] Appleman, T. and Wang, Y., “China’s New 3Rs- Warranty Policy for Domestic-Use Automobiles: An Overview,” Miller Canfield, January 2014.

[14] Beconcini, P., “Getting Ahead of China’s 3R’s,” Law360, August 2012. Available Online: http://www.law360.com/articles/365470/getting-ahead-of-china-s-3-r-s

[15] Federal Trade Commission, “Businessperson’s Guide to Federal Warranty Law,” Federal Trade Commission, Date Accessed: January 13, 2016. Available Online: https://www.ftc.gov/tips-advice/business-center/guidance/businesspersons-guide-federal-warranty-law

[16] Apple, “Your Hardware Warranty,” Apple, Date Accessed: January 14, 2016.

[17] Dell, “Warranties,” Dell, Date Accessed: January 14, 2016.

[18] SolarEnergy.net, “Guide to Understanding Solar Warranties,” SolarEnergy.net, Date Accessed: January 13, 2016. Available Online: http://solarenergy.net/solar-power-resources/guide-to-understanding-solar-warranties/

[19] Canadian Solar, “Limited Warranty Statement Photovoltaic Diamond Module Products,” Canadian Solar, Date Accessed: January 14, 2016.

[20] Warranty Week, “Average Warranty Costs per Industry,” Warranty Week, May 31, 2012. Available Online: http://www.warrantyweek.com/archive/ww20120531.html

[21] Warranty Week, “Thirteenth Annual Product Warranty Report,” Warranty Week, March 24, 2016.

[22] Murthy, D.N.P., “Product Warranty and Reliability,” March 2006, Volume 143, Issue 1, pp 133-146

[23] Schenkelberg, F., “Using the Exponential Distribution Reality Function,” Word Press, Date Accessed: January 15, 2016. Available Online: https://creprep.wordpress.com/2015/04/12/using-the-exponential-distribution-reliability-function/

[24] Weibull.com, “Reliability Glossary,” Reliability Engineering Resources, Weibull.com, Date Accessed: January 15, 2016. Available Online: http://www.weibull.com/knowledge/rel_glossary_ld.htm

[25] Weibull.com, “The Reliability Function,” Reliability Engineering Resources, Weibull.com, Date Accessed: January 19, 2016. Available Online: http://weibull.com/hotwire/issue7/relbasics7.htm

[26] Hartzell, Allyson L., da Silva, Mark G., Shea, Herbert, “MEMS Reliability,” Springer Science + Business Media, Springer US, 2011 pp.13-15.

[27] R. C. Gupta and S. Lvin, “Reliability Functions of Generalized Log-Normal Model,” Science Direct, Elsevier, 2005.

[28] Boston Whaler, “Boston Whaler Limited Warranty,” Boston Whaler, Date Accessed: January 20, 2016

[29] Matis, T., Jayaraman, R., Rangan, “Optimal Price and Pro Rata Decisions for Combined Warranty Policies with Different Repair Options,” Taylor & Francis Group, IIE Transactions, 40:10, 984-991, 2008.

[30] Chien, Y., “The Effect of a Pro-Rata Rebate Warranty on the Age Replacement Policy With Salvage Value Consideration,” IEEE Transactions on Reliability, Vol. 59, No. 2, June 2010.

[31] Interstate Batteries, “Interstate Batteries’ Limited Warranty- United States,” Interstate Batteries, Date Accessed: January 20, 2016. Available Online: http://www.interstatebatteries.com/static/pdf/warranty/IB_warranty_2015_USenglish.pdf

[32] Interstate Batteries, “Mega-Tron 59 Automotive Battery Five-Year Performance 590 CCA,” Interstate Batteries, Date Accessed: January 20, 2016. Available Online:

http://www.interstatebatteries.com/p/automotive-truck/mt-59-ford-taurus-2010-ex-sho-oem-cca-540-v6-3-5l?dsNav=N~21-2147384906

[33] Sandborn, P., 2013, "Cost Analysis of Electronic Systems," Singapore, WSPC Series in Advanced Integration and Packaging, pp. 260-263.

[34] Isaacson, D., Reid, S., Brennan, J., "Warranty Cost-Risk Analysis," Reliability and Maintainability Symposium, 1991. Proceedings., Annual, IEEE. Available Online:http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=154458

[35] Young H. Chun and Kwei Tang, "Cost Analysis of Two-Attribute Warranty Policies Based on the Product Usage Rate," IEEE Transactions on Engineering Management, Vol. 46, No. 2, MAY 1999 201

[36] U.S. Department of Transportation, Federal Highway Administration, "Average Annual Miles per Driver by Age Group," Federal Highway Administration, Date Accessed: January 22, 2016. Available Online: https://www.fhwa.dot.gov/ohim/onh00/bar8.htm

[37] Murthy, D.N.P. and Blischke, W., "Strategic Warranty Management: A Life-Cycle Approach," IEEE Transactions on Engineering Management, Vol. 47, NO. 1, February 2000.

[38] Jones, C., "Higher Warranty Expense Hit Apple's September Quarter's Earnings By About $0.30," Forbes, November 4, 2013.

[39] Clarke, W., "Understanding Extended Warranties," Edmunds.com, May 2009. http://www.edmunds.com/auto-warranty/understanding-extended-warranties.html

[40] Kraft-Linder, A., “Extended Warranties: Some Are Worth It, Most Are Worthless,” Daily Finance, October 2014. Available Online: http://www.dailyfinance.com/2014/10/18/extended-warranties-worth-it-worthless/

[41] Residential Warranty Company, “Extended Warranties – Existing/Resale Homes,” 2015 Residential Warranty Company, LLC. Available Online: http://www.rwcwarranty.com/homeowners/other-coverage-options/extended-warranties

[42] Consumer Reports, “Extended Car Warranties: An Expensive Gamble,” Consumer Reports, February 2014. Available Online: http://www.consumerreports.org/cro/magazine/2014/04/extended-warranties-for-cars-are-an-expensive-game/index.htm

[43] Pham, H., “Springer Handbook of Engineering Statistics,” Springer, 2006 Springer-Verlag London Limited pp.133-134.

[44] DeCroix, G., “Optimal warranties, reliabilities and prices for durable goods in an oligopoly,” European Journal of Operational Research 112 (1999) 554±569, Elsevier, September 1997.

[45] Singpurwalla, N., “Reliability and Risk: A Bayesian Perspective,” Wiley Series in Probability and Statistics, John Wiley & Son, Ltd, 2006.

[46] Cousins, B., “Advanced Statistics for High Energy Physics,” Hadron Collider Physics Summer School, pp. 10, June 2009.

[47] Xie, W., Haitao, L. “Some Aspects in Estimating Warranty and Post-Warranty Repair Demands,” Naval Research Logistics, July 23, 2013.

[48] D.N.P. Murthy, R.J. Wilson, I. Djamaludin, “Product Warranty and Quality Control,” Quality and Reliability Engineering International, Vol. 9, 431-444, John Wiley & Sons, Ltd., 1993.

[49] Wu, S., “Warranty Data Analysis: A Review,” Quality and Reliability Engineering International Vol. 28, Iss. 8, pp. 795-805, John Wiley & Sons, Ltd. December 2012.

[50] Alam, M., Suzuki, K., “Lifetime Estimation Using Only Failure Information from Warranty Database,” IEEE Transaction on Reliability, Vol. 58, No. 4, IEEE, December 2009.

[51] Chun, Y. and Tang, K., “Cost-Analysis of Two Attribute Warranty Policies Based on the Product Usage Rate,” IEEE Transactions on Engineering Management, Vol. 46, No. 2, May 1999.

[52] Vinta, S., “Analysis of Data to Predict Warranty Cost for Various Regions,” Annual Reliability and Maintainability Symposium, 2009, IEEE, January 2009. \

[53] Lu, Louis Y. and Chiang, Chih-Chyi, “Prediction Model for Warranty Costs: A Case Study of a LCD Monitor Company,” 2008 IEEE Asia-Pacific Services Computing Conference, IEEE, December 2008.

[54] Park, M. and Pham, H., “Warranty Cost Analyses Using Quasi-Renewal Processes for Multicomponent Systems,” IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, Vol. 40, No. 6, November 2010.

[55] Bai, J. and Pham, H., “Discounted Warranty Cost of Minimally Repaired Series Systems,” IEEE Transactions on Reliability, Vol. 53, No. 1, March 2004.

[56] Kleyner, A. and Sandborn, P., “A Warranty Forecasting Model Based on Piecewise Statistical Distributions,” Elsevier, Reliability Engineering and System Safety 88 (2005) 207–214, September 2004.

[57] GMC, “2016 Warranty and Protection,” GMC, Date Accessed: March 28, 2016. Available Online: http://www.gmc.com/owners/warranty-details.html

[58] DeMuro, D., Autotrader, “Powertrain Warranty vs. Bumper to Bumper: What’s the Difference?” Autotrader, May 2015. Available Online: http://www.autotrader.com/car-shopping/powertrain-warranty-vs-bumper-to-bumper-whats-the-difference-239994

[59] Chevrolet, 2016 Warranty Coverage, Chevrolet, Date Accessed: March 29, 2016. Available Online: http://www.chevrolet.com/owners/warranty.html

[60] BMW, “BMW Service and Warranty Books,” BMW, Date Accessed: March 29, 2016. Available Online: http://www.bmwusa.com/Standard/Content/Explore/BMWValue/BMWUltimateService/ServiceandWarrantyBooks.aspx

[61] Warranty Week, “Automotive Warranty Report,” Warranty Week, March 26, 2015.

[62] Michael G. Pecht, “Establishing a Relationship Between Warranty and Reliability,” IEEE Transactions on Electronic Packaging and Manufacturing, Vol.29, No.3, July 2006.

[63] Federal Trade Commission, “Businessperson’s Guide to Federal Warranty Law,” Federal Trade Commission, Last Updated: March 2015, Date Accessed: January 8, 2016.

[64] Federal Trade Commission, “Auto Warranties & Routine Maintenance,” Federal Trade Commission, Date Accessed: February 16, 2016.

[65] Karen Mohan, Duane Huffman, and Jennifer Akers, “Optimization of Warranty, Period, Price, and Allocated Reliability,” Reliability and Maintainability Symposium, 2009, RAMS 2009. Annual, IEEE, 2009.

[66] D.N.P. Murthy, “Product Warranty and Reliability,” Springer, Annals of Operation Research, Vol.143, No.1, pp. 133-146, March 2006.

[67] Sandborn, P. , 2013, “Cost Analysis of Electronic Systems,” Singapore, WSPC Series in Advanced Integration and Packaging, pp. 260.

[68] Donald N. Isaacson, Selina Reid, James R. Brennan, “Warranty Cost-Risk Analysis,” Reliability and Maintainability Symposium, 1991. Proceedings., Annual, IEEE. Available Online: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=154458 .

[69] Young H. Chun and Kwei Tang, “Cost Analysis of Two-Attribute Warranty Policies Based on the Product Usage Rate,” IEEE Transactions on Engineering Management, Vol.46, No.2, May 1999.

[70] US Department of Transportation, “Average Annual Miles per Driver by Age Group,” Office of Highway Policy Information, Last Updated: February 20, 2015. Available Online: https://www.fhwa.dot.gov/ohim/onh00/bar8.htm.

[71] Automotive.com, “Different Types of Car Warranties,” Automotive.com, Date Accessed: December 21, 2015. Available Online: http://tools.automotive.com/new-cars/14/warranty/53140/different-types-of-car-warranties.html

[72] GM, “Bumper-to-Bumper Limited Warranty,” GM, Date Accessed: December 21, 2015. Available Online: http://www.gmcertified.com/certified-benefits/used-car-warranty.

[73] Chevrolet, “Warranty Coverage,” Chevrolet, Date Accessed November 6, 2015. Available Online: http://www.chevrolet.com/owners/warranty.html.

[74] Doug DeMuro, “Powertrain Warranty vs. Bumper-to-bumper: What’s the Difference?” Autotrader, May 2015. Available Online: http://www.autotrader.com/car-shopping/powertrain-warranty-vs-bumper-to-bumper-whats-the-difference-239994.

[75] Gina Chon, “GM Ups the Ante in the Warranty War,” Wall Street Journal, Sept 2006. Available Online: http://www.wsj.com/articles/SB115755049294755067.

[76] John Neff, “GM Increases Warranty to Five Year/ 100,000-mile,” Autoblog, Sept 2006. Available Online: http://www.autoblog.com/2006/09/06/gm-increases-warranty-to-five-year-100-000-miles/.

[77] Hyundai, “America’s Best Warranty,” Hyundai, Date Accessed: December 22, 2015. Available Online: https://www.hyundaiusa.com/assurance/america-best-warranty.aspx.

[78] James R. Healey, “GM Slices Warranties, Free Service on Chevy, GMC,” USA Today, March 2015. Available Online: http://www.usatoday.com/story/money/cars/2015/03/12/gm-chevrolet-gmc-warranty-service-cut-reduced/70210660/.

[79] Mike Colias, “GM to Cut Chevy, GMC Powertrain Warranty to 60,000 Miles from 100,000,” Automotive News, March 2015. Available Online:

http://www.autonews.com/article/20150312/RETAIL/150319950/gm-to-cut-chevy-gmc-powertrain-warranty-to-60000-miles-from-100000.

[80] Anita Lienert, “GM Cuts Powertrain Warranty, Maintenance Program on Some 2016 Vehicles,” Edmunds.com, Mar 2015. Available Online: http://www.edmunds.com/car-news/gm-cuts-powertrain-warranty-maintenance-program-on-some-2016-vehicles.html.

[81] Michael Wayland, “GM Cutting Warranty, Maintenance Programs,” The Detroit News, Mar 2015. Available Online: http://www.detroitnews.com/story/business/autos/general-motors/2015/03/12/gm-cutting-warranty-maintenance-programs/70212524/.

[82] Korenok, Oleg & Hoffer, George E. & Millner, Edward L., “Non-price determinants of automotive demand: Restyling matters most,” Journal of Business Research, Elsevier, vol. 63(12), pp. 1282-1289, December 2010.

[83] Chris Isidore, “Recall Isn’t GM’s Biggest Problem,” CNN Money, March 2014. Available Online: http://money.cnn.com/2014/03/25/news/companies/gm-recall-problem/.

[84] Aaron Smith, “GM to Discontinue Chevrolet Brand in Europe,” CNN Money, December 2013. Available Online: http://money.cnn.com/2013/12/05/news/companies/gm-chevrolet-europe/?iid=EL.

[85] Brown, Jeff. Telephone Interview. November 18, 2015.

[86] Tom Krisher “GM Recalling 1.4M Cars; Oil Leaks Can Cause Engine Fires,” ABC News, Oct 2015. Available Online: http://abcnews.go.com/US/wireStory/gm-recalling-14m-cars-oil-leaks-engine-fires-34757457.

[87] The Associated Press, “GM Recall to Replace Key Engine Parts to Fix Car Problem,” WREX, December 2015, Available Online: http://www.wrex.com/story/30707338/2015/12/09/gm-recall-to-replace-key-engine-parts-to-fix-car-fire-problem.

[88] WFSB Staff, “GM recalls more vehicles for transmission problems,” Eyewitness News, June 2014. Available Online: http://www.wfsb.com/story/25897407/gm-recalls-more-vehicles-for-transmission-problems.

[89] Tom Krisher, “GM Issues 3 More Vehicles, Covering 474,000 Vehicles,” Huffington Post Business, June 2014. Available Online: http://www.huffingtonpost.com/2014/06/27/gm-recalls-sierra-silverado_n_5538542.html.

[90] AutoBlog, “General Motors Recall List,” AutoBlog, Oct 2014. Available Online: http://www.autoblog.com/2014/10/22/general-motors-recall-list/.

[91] Aditi Shah, “General Motors India to Recall 101,597 Beat Diesel Cars,” Business News, Dec 2015. Available Online: http://in.reuters.com/article/gm-india-recall-idINKBN0TY1AE20151215.

[92] Ketan Thakkar, “General Motors to Recall 1.01 LAKH Units of Beat Diesel,” The Economic Times, Dec 2015. Available Online: http://economictimes.indiatimes.com/industry/auto/news/industry/general-motors-to-recall-1-01-lakh-units-of-beat-diesel/articleshow/50187492.cms.

[93] Eric Schaal, “Recall Rankings: 10 Automakers Leading the Industry This Year,” Autos Cheat Sheet, November 2014, Available Online: http://www.cheatsheet.com/automobiles/10-automakers-with-the-most-vehicle-recalls-in-a-record-2014.html/?a=viewall.

[94] GM, “General Motors Company 2014 Annual Report,” GM, Apr 2015. Available Online: http://www.gm.com/content/dam/gmcom/COMPANY/Investors/Stockholder_Information/PDFs/2014_GM_Annual_Report.pdf.

[95] Rebecca R. Ruiz, “13 Deaths, Untold Heartache, From G.M. Defect,” The New York Times, May 2014. Available Online: http://www.nytimes.com/2014/05/27/business/13-deaths-untold-heartache-from-gm-defect.html?_r=1.

[96] Robert Bowman, “This Year’s Recall ‘Pileup’ is a Supply-Chain Nightmare for Manufacturers,” Forbes, July 2014. Date Accessed: http://www.forbes.com/sites/robertbowman/2014/06/10/this-years-recall-pileup-is-a-supply-chain-nightmare-for-automakers/.

[97] Stericycle, “Stericycle Recall Index Q1 2014,” Stericycle, Date Accessed: November 12, 2015. Available Online: http://www.stericycleexpertsolutions.com/wp-content/uploads/2015/03/Recall-Index_US_Q1_2014_v1.pdf.

[98] John W. Henke, Jr., “OEM-Supplier Relations Study Shows Strong Gains for Toyota and Honda, with Ford, Nissan, FCA and GM falling well behind,” PR Newswire, May 2015. Available Online: http://www.prnewswire.com/news-releases/oem-supplier-relations-study-shows-strong-gains-for-toyota-and-honda-with-ford-nissan-fca-and-gm-falling-well-behind-300084605.html.

[99] Supply and Demand Chain Executive, “Rating the Automotive Suppliers,” Supply and Demand Chain Executive, May 2014. Available Online: http://www.sdcexec.com/news/11457831/rating-the-automotive-suppliers?utm_source=WMS%2FLogistics+eNL&utm_medium=email&utm_campaign=SDCE140507002.

[100] Colum Murphy, Joseph B. White, Jake Maxwell Watts, “GM Doesn't Plan to Change Supply-Chain Safety Process,” The Wall Street Journal, Aug. 2014. Available Online: http://www.wsj.com/articles/gm-doesnt-plan-to-change-supply-chain-safety-process-1407236398.

[101] SCDigest Editorial Staff,“Supply Chain News: Will Change in GM’s Supply Chain Leadership Finally Open Door to Improved Supplier Relationships,” Supply Chain Digest, July 2009. Available Online: http://www.scdigest.com/assets/On_Target/09-07-07-2.php?cid=2562.

[102] David Phillips, “Fiat Chrysler Reducing Powertrain Warranties to 60,000 miles for 2016 models,” Automotive News, May 2015. Available Online: http://www.autonews.com/article/20150527/RETAIL05/150529876/fiat-chrysler-reducing-powertrain-warranties-to-60000-miles-for-2016.

[103] SolarCity, “How Does Solar Energy Work?”SolarCity, Date Accessed: November 15, 2015. Available Online: http://www.solarcity.com/commercial/how-does-solar-energy-work

[104] Solar Energy Industries Association, “Photovoltaics: Solar Electric,” Solar Energy Industries Association, Date Accessed: December 11, 2015.

[105] Maehlum, M. “Which Solar Panel Type is Best? Monocrystalline vs. Polycrystalline vs. Thin-Film?,” Energy Informative, May 18, 2015, Available Online: http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/

[106] T.M. Razykov, C.S. Ferekides, D. Morel, E. Stefanakos, H.S. Ullal, and H.M. Upadhyaya, "Solar Photovoltaic Technology: Current Status and Future Prospects," Elsevier, Science Direct, Solar Energy Vol. 85, 2011, pp.1580–1608.

[107] National Renewable Energy Laboratory, "Best Research-Cell Efficiencies," Natioanl Renewable Energy Laboratory, Date Accessed: June 15, 2016.

[108] U.S. Energy Information Administration, "Table 1.1. Net Generation by Energy Source: Total (All Sectors), 2006-March 2016," U.S. Energy Information Administration, Date Accessed: June 15, 2016. Available Online: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01

[109] Solar Energy Industries Association, "Solar Investment Tax Credit (ITC)," Solar Energy Industries Assocation, Date Accessed: June 15, 2016. Available Online: http://www.seia.org/policy/finance-tax/solar-investment-tax-credit

[110] IHS, "Top Solar Power Industry Trends for 2015," IHS, 2015. Available Online: https://www.ihs.com/pdf/Top-Solar-Power-Industry-Trends-for-2015_213963110915583632.pdf

[111] Harry Wirth, "Recent Facts about Photovoltaics in Germany," Fraunhofer Institute for Solar Energy Systems ISE, Oct 2015, Available Online:https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/recent-facts-about-photovoltaics-in-germany.pdf

[112] Gov. UK, "Feed-in Tariffs: get money for generating your own electricity," Gov.UK, April 16, 2016. Available Online: https://www.gov.uk/feed-in-tariffs/overview

[113] Nelsen, R., "German Solar Ambitions at Risk From Cuts to Subsidies," The Guardian, Nov. 14, 2014. Available Online:

https://www.theguardian.com/environment/2014/nov/05/subsidy-cuts-and-weak-eu-targets-cloud-german-solar-energy-revolution

[114] Vishal Shah, Jerimiah Booream-Phelps, “Deutsche Bank report: Solar grid parity in a low oil price era,” Deustche Bank, Feb 2015. Available Online: https://www.db.com/cr/en/concrete-deutsche-bank-report-solar-grid-parity-in-a-low-oil-price-era.html

[115] Munsell, M., “Solar PV Prices Will Fall Below $1.00 per Watt by 2020,” GTM Research, June 01, 2016. Available Online: http://www.greentechmedia.com/articles/read/solar-pv-prices-to-fall-below-1.00-per-watt-by-2020

[116] Vithayasrichareon, P., Mills, G., and F. MacGill, I. F., “Impact of Electric Vehicles and Solar PV on Future Generation Portfolio Investment,” IEEE Transactions on Sustainable Energy, Vol. 6, No. 3, July, 2015.

[117] Pyper, J., “The Global Solar PV Market Hit 177GW in 2014, A Tenfold Increase from 2008,” Greentech Media, GTM Research, March, 2015. Available online: http://www.greentechmedia.com/articles/read/The-Global-Solar-PV-Market-Hit-177GW-in-2014-A-Tenfold-Increase-From-2008

[118] Solar Energy Industries Association, “Solar Industry Data: Solar Industry Breaks 20GW Barrier- Grows 34% over 2013,” Solar Energy Industries Association, Accessed Nov. 13, 2015. Available online: http://www.seia.org/research-resources/solar-industry-data

[119] Solar Energy Industry Association, “Solar Market Insight 2015 Q4,” Solar Energy Industry Association, Date Accessed: April 21, 2016. Available Online: http://www.seia.org/research-resources/solar-market-insight-2015-q4

[120] Das, M. and Agarwal, V., “Novel High-Performance Stand-Alone Solar PV System With High-Gain High-Efficiency DC–DC Converter Power Stages,” IEEE Transactions on Industry Applications, IEEE, Nov. 2015, Vol. 51, Iss. 6, Nov., 2015.

[121] Qaiser, M.N. et al. “Low cost, robust and efficient implementation of MPPT based buck-boost converter for off-grid PV applications,” IEEE 40th Photovoltaic Specialist Conference (PVSC), IEEE, pp. 3701-3706, 2014.

[122] Yang, D., Latchman, H. A., Tingling, D. and Amarsingh, A. A., “Design and Return on Investment Analysis of Residential Solar PV Systems,” IEEE Potentials, Vol. 34, Iss. 4, July, 2015.

[123] Pecht, M. G., “Establishing a Relationship Between Warranty and Reliability,” IEEE Transactions on Electronic Packaging and Manufacturing, Vol. 29, No. 3, July, 2006.

[124] Strecker, R., “Solar panels – Lifetime Productivity and Maintenance Costs,” Boston Solar, Sept., 2011. Available online: http://www.bostonsolar.us/blog/solar-panels-lifetime-productivity-and-maintenance-costs

[125] Maehlum, M. A., “Solar Panel Warranty Comparison,” Energy Informative, June, 2013, Accessed Oct. 30, 2015. Available online: http://energyinformative.org/solar-panel-warranty-comparison/

[126] Canadian Solar, “Limited Warranty Statement Photovoltaic Diamond Module Products,” Canadian Solar, Accessed Nov. 3, 2015. Available online:

http://www.canadiansolar.com/downloads/warranties/Warranty_Standard_PV_Module_en.pdf

[127] SunPower, “SunPower Limited Product and Power Warranty for PV Modules,” SunPower, Accessed Nov. 13, 2015. Available Online:http://us.sunpower.com/sites/sunpower/files/media-library/warranties/wr-sunpower-limited-product-and-power-warranty-pv-modules.pdf

[128] SolarEdge, “Solar Edge Product Warranty Program,” SolarEdge, Accessed: Nov. 3, 2015. Available online: http://www.solaredge.us/groups/us/service/warranty

[129] Microchip, “Grid-Connected Solar Micro-inverter Reference Design Using a dsPIC ® Digital Signal Controller” 2010-2011 Microchip Technology Inc, Aug.,, 2011.

[130] ABB Group, “Central Inverters PVS800 Warranty and Service Offering,” ABB Group, Date Accessed: Apr. 10, 2016. Available Online: https://library.e.abb.com/public/7488c31491241476c1257d89002aca52/17267_Warranty_and_service_offering_3AUA0000133536_RevC_lowres.pdf

[131] ABB Group, “ABB Micro Inverter System MICRO-0.25/0.3/0.3HV-I-OUTD 0.25kW to 0.3kW,” ABB Group, Date Accessed: Apr. 10, 2016. Available Online: https://library.e.abb.com/public/3b4b2359a4986e2685257dff005e1834/MICRO-0.25-0.3-0.3HV-Rev0.1.pdf

[132] Enphase Energy, “Enphase Energy M215 Micro-inverter 25-Year Limited Warranty – North America,” Enphase Energy, Jan., 2014, Accessed Nov. 3, 2015.

[133] Golnas, A., “PV System Reliability: An Operator’s Perspective,” IEEE Journal of Photovoltaics, Vol. 3, pp. 417-418, Jan., 2013.

[134] Golnas, A., Telephone Interview. Oct.7, 2015.

[135] Bakhshi, R., Kunche, S. and Pecht, M. G., “Intermittent Failures in Hardware and Software,” Journal of Electronic Packaging, Vol. 136 Iss. 1, pp 011014-1, Mar. 2014.

[136] Collins, E., Dvorack, M., Mahn, J., Mundt, M. and Quintana, M., “Reliability and Availability Analysis of a Fielded Photovoltaic System,” 2009 24th IEEE Photovoltaics Specialist Conference (PVSC), IEEE, June, 2009.

[137] Huang, H.S., Jao, J.S., Yen, K.L. and Tsai, C.T., “Performance and Availability Analyses of PV Generation Systems in Taiwan,” World Academy of Science, Engineering and Technology, Vol. 54, 2011.

[138] Zaman, A., Parlevliet, D., Calais, M., Djordjevic, S., Pulsford, S., Bruce, A. and Passey, R., “PV System Reliability- Preliminary Findings from the PV Module and System Fault Reporting Website,” 2014 Asia-Pacific Solar Research Conference, 2014. Available Online: http://apvi.org.au/wp-content/uploads/2015/02/3-Parlevliet_APVI_PVPerformance-2_PeerReviewed.pdf

[139] Ahadi, A., Hayati, H. and Miryousefi Aval, S.M., “Reliability Evaluation of Future Photovoltaic Systems with Smart Operation Strategy,” Frontiers in Energy, Springer, pp. 1-11, Jan. 5, 2016.

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

[141] Pecan Street, “Minor Maintenance Issues Proving Difficult to Detect for Many Solar PV System Owners,” GTM Research, Pecan Street GTM PV Maintenance Report, Vol. 2 No. 5, Feb., 2015.

[142] Köntges, M., Kurtz, S., Packard, C., Berger, U. J. K. A., Kato, K., Friesen, T., Liu, H. and Van Iseghem, M., "Review of Failures of Photovoltaic Modules," International Energy Agency, pp. 55-63, Mar., 2014.

[143] O'Brien, C., "Roof-Mounted Solar Photovoltaic Arrays," RCI Incorporated, Date Accessed: February 6, 2016.

[144] Skoplaki, E., Boudouvis, A.G. and Palyvos, J.A., "A Simple Correlation for the Operating Temperature of Photovoltaic Modules of Arbitrary Mounting," Elsevier, Solar Energy Materials & Solar Cells, July, 2007.

[145] International Energy Agency, "Review of Failures of Photovoltaic Modules," International Energy Agency, Photovoltaic Power Systems Program, 2014.

[146] A. Richter, Schadensbilder nach Wareneingang und im Reklamationsfall, 8. Workshop "Photovoltaik-Modultechnik," November 2011, TÜV Rheinland, Köln.

[147] SolarCity, "Warranties & Maintenance," SolarCity, Accessed Jan. 12, 2016. Available online: http://www.solarcity.co.nz/residential/product/solar-life-expectancy/

[148] Olay, R., "Solar Inverter Components Can Raise Efficiencies," Solar Industry Magazine, Vol. 5 No. 12, Jan., 2013.

[149] Black, C. and Bull, C., "IGBTs Or MOSFETs: Which Is Better For Your Design?" Electronic Design, Oct. 1999. Available Online: http://electronicdesign.com/power/igbts-or-mosfets-which-better-your-design

[150] Terzulli, G., and Peace, B. W., "Film Technology to Replace Electrolytic Technology," AVX Corporation, Accessed Sept. 30, 2015. Available online: https://www.avx.com/docs/techinfo/filmtech.pdf

[151] Heynen, “Aluminum Electrolytic Capacitors vs Film Capacitors,” Electronic Component Solutions, Date Accessed: June 02, 2016. Available Online: http://www.heynen.com/aluminum-electrolytic-capacitors-vs-film-capacitors

[152] Schimpf, F. and Norum, L., “Effective Use of Film Capacitors in Single-Phase PV-Inverter by Active Decoupling,” IECON 2010- 36th Annual Conference on IEEE Industrial Electronics, IEEE, Nov., 2010.

[153] Rodriguez, C. and Amaratunga, G. A. J., “Long-Lifetime Power Inverter for Photovoltaic AC Modules,” IEEE Transactions on Industrial Electronics, Vol. 55, No. 7, pp. 2594, July, 2008.

[154] Russell, M. C. and Green RaySolar, “The Promise of Reliable Inverters for PV Systems: The Micro-inverter Solution,” GTM Research, June, 2010.

[155] Flicker, J., “Capacitor Reliability in Photovoltaic Inverters,” Sandia National Laboratories, June, 2015.

[156] Flicker, J. and Kaplar, R., “Reliability of Power Conversion Systems in Photovoltaic Applications,” Reliability of Power Electronic Converter Systems, IET Power and Energy Series, Shuhung Chung, H., Wang, H., Blaabjerg, F. and Pecht M. G., Stevenage Herts, United Kingdom, The Institution of Engineering and Technology, 2016, pp. 398-403.

[157] Ristow, A., Begovic, M., Pregelj, A. and Rohatgi, A., “Development of a Methodology for Improving Photovoltaic Inverter Reliability”, IEEE Trans. Industrial Electronics, IEEE, Vol. 55, pp. 2581-2592, 2008.

[158] Kaplar, R., Brock, R., DasGupta, S., Marinella, M., Starbuck, A., Fresquez, A., Gonzalez, S., Granata, J., Quintana, M., Smith, M. and Atcitty, S., “PV inverter performance and reliability: What is the role of the IGBT?" 2011 37th IEEE Photovoltaic Specialists Conference (PVSC), IEEE, June 2011.

[159] Shouman, E., Shenaway, E.T., and Khattab, N.M., "Market Financial Analysis and Cost Performance for Photovoltaic Technology Through International and National Perspective with Case Study for Egypt," Elsevier, Renewable and Sustainable Energy Reviews, Vol. 57, pp. 548, May 2016.

[160] SMA, "SMA America LLC Factory Warranty," SMA, Mar. 21, 2016, Date Accessed: June 16, 2016.

[161] Suntech, "280 Watt Polycrystalline Solar Module," Suntech, Date Accessed: June 16, 2016

[162] Hinata, Y., Horio, M., Ikeda, Y., Yamada, R., Takahashi, Y., "Full SiC Power Module with Advanced Structure and its Solar Inverter Application," 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE, Mar., 2013.

[163] Oneill, M., "Silicon Carbide Diodes Make Solar Power Systems More Efficient," EE Times, Oct., 2008, Date Accessed Oct. 30, 2015. Available Online: http://www.eetimes.com/document.asp?doc_id=1273188&

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

[165] Schwarzer, U., Buschhorn, S., and Vogel, K., "System Benefits for Solar Inverter using SiC Semiconductor Modules," PCIM Europe 2014; Proceedings of International

Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, VDE, pp. 1-8, May, 2014.

[166] Sintamarean, N. C., Eni, E. P., Blaabjerg, B., Teodorescu, R., Wang, H., "Wide-Band Gap Devices in PV Systems- Opportunities and Challenges," Proc. International Power Electronics Conference, pp. 1912-1919, 2014.

[167] Haibing, H., Harb, S., Kutkut, N.H., Shen, Z.J. and Batarseh, I., "A Single-Stage Micro-inverter Without Using Electrolytic Capacitors," Power Electronics, IEEE Transactions on, Vol. 28, pp. 2677-2687, 2013.

[168] Tulkoff, C., "Reliability Challenges for Solar Electronics," DfR Solutions, Solar Energy Industry Association, Solar Electric Power Association, Date Accessed: Nov. 3, 2015.

[169] Knier, G., "How Do Photovoltaics Work?" National Aeronautics and Space Administration, 2002. Available online: http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/

[170] Solar Energy Industries Association, "US Solar Market Set to Grow 119% in 2016, Installations to Reach 16 GW," Solar Energy Industries Association, March 9, 2016. Available online: https://www.seia.org/news/us-solar-market-set-grow-119-2016-installations-reach-16-gw

[171] Munsell, M., "US Solar Market Prepares for Biggest Quarter in History," GTM Research, December 09, 2015. Available online: http://www.greentechmedia.com/articles/read/us-solar-market-prepares-for-biggest-quarter-in-history

[172] Solar Energy Industries Association, "Solar Industry Data," Solar Energy Industries Association, Accessed on Jan. 10, 2017. Available online: http://www.seia.org/research-resources/solar-industry-data

[173] Sawin, J. L. et al., "Renewables 2016 Global Status Report," Ren21, Accessed on Sept. 8, 2016.

[174] Masson, G., Orlandi, S., and Rekinger, M., "Global Market Outlook for Photovoltaics 2014-2018," European Photovoltaic Industry Association.

[175] U.S. Energy Information Administration, "Electricity Data," U.S. Energy Information Administration, Accessed on Nov. 10, 2016. Available online: http://www.eia.gov/electricity/data/browser/#/topic/7?agg=2,0,1&geo=g&freq=M

[176] Munsell, M., "Solar PV Prices Will Fall Below $1.00 per Watt by 2020," Greentech Media, June 1, 2016. Available online: https://www.greentechmedia.com/articles/read/solar-pv-prices-to-fall-below-1.00-per-watt-by-2020

[177] Ryan, J., "Solar Industry Braces with Looming Glut Eroding Panel Prices," Bloomberg, August 23, 2016. Available online: http://www.bloomberg.com/news/articles/2016-08-23/solar-industry-braces-as-looming-glut-threatens-to-erode-prices

[178] Habboush, M. and Carpenter, C., "Solar Power to Grow Sixfold as Sun Becoming Cheapest Resource," Bloomberg Technology, June 22, 2016. Available online: https://www.bloomberg.com/news/articles/2016-06-22/solar-power-to-grow-sixfold-as-sun-becoming-cheapest-resource

[179] Solar Energy Industries Association, "Impacts of Solar Investment Tax Credit Extension," Solar Energy Industries Association, December 2015. Available online: http://www.seia.org/research-resources/impacts-solar-investment-tax-credit-extension

[180] T. Huld, A. Jäger Waldau, H. Ossenbrink, S. Szabo, E. Dunlop, and N. Taylor, "Cost Maps for Unsubsidised Photovoltaic Electricity," JRC Scientific and Policy Reports, European Commission, 2014.

[181] Yang, D., Latchman, H. A., Tingling, D., and Amarsingh, A. A., "Design and Return on Investment Analysis of Residential Solar PV Systems," IEEE Potentials, vol. 34, no. 4, pp. 11-17, July, 2015.

[182] Matthews, G. and Matthews, E., "Household Photovoltaics – A Worthwhile Investment," 2016 International Conference on Domestic Use of Energy (DUE), IEEE, March 30-31, 2016.

[183] Ahsan, S., Javed, K., Rana, A., and Zeeshan, M., "Design and Cost Analysis of 1 kW Photovoltaic System Based on Actual Performance in India Scenario," Recent Trends in Engineering and Material Sciences, Elsevier, vol. 8, pp. 642-644, Jul. 2016.

[184] Shouman, E., Shenaway, E. T., and Khattab, N. M., "Market Financial Analysis and Cost Performance for Photovoltaic Technology Through International and National Perspective with Case Study for Egypt," Elsevier, Renewable and Sustainable Energy Reviews, vol. 57, pp. 540-549, May 2016.

[185] Muhammad-Sukki, F., Ramirez-Iniguez, R., Abu-Bakar, S., McMeekin, S., and Stewart, B., "An Evaluation of the Installation of Solar Photovoltaic in Residential Houses in Malaysia: Past, Present, and Future," Energy Policy, Elsevier, vol. 39, no. 12, pp. 7975-7987, Dec. 2011."

[186] Muneer, W., Bhattacharya, K., and Canizares, C., “Large-Scale Solar PV Investment Models, Tools, and Analysis: The Ontario Case,” IEEE Transactions on Power Systems, vol. 26, no. 4, pp. 2547-2555, Nov. 2011.

[187] Gutowski, T., Gershwin, S., and Bounassisi, T., “Energy Payback for Energy Systems Ensembles During Growth,” IEEE International Symposium on Sustainable Systems and Technologies, Washington, DC, May 16-19, 2010.

[188] Black, A., “PV Energy Payback vs PV Input Energy Due to Market Growth,” Proceedings of Solar World Congress, Orlando, Florida, August 2005.

[189] Del Fabbro, B., Valtentincic, A., and Gubina, A., “An Adequate Required Rate of Return for Grid-Connected PV Systems,” Elsevier, Solar Energy, vol. 132, pp. 73–83, 2016.

[190] Shah, V. and Booream-Phelps, J., “Solar Grid Parity in a Low Oil Price Era,” Deutsche Bank, March 2015. Available online: https://www.db.com/cr/en/concrete-deutsche-bank-report-solar-grid-parity-in-a-low-oil-price-era.html

[191] Electricity Local, “College Park, MD Electricity Statistics,” Electricity Local, Accessed April 8, 2016. Available online: http://www.electricitylocal.com/states/maryland/college-park/

[192] Wholesale Solar, “9.12 kW Grid-Tied Solar PV System with SolarEdge and 32x Sunviva 280 Solar Panels,” Wholesale Solar, Accessed on June 26, 2016. Available online: http://www.wholesalesolar.com/1892432/wholesale-solar/complete-systems/9.12-kw-grid-tied-solar-system-with-solaredge-and-32x-suniva-285-panels

[193] National Renewable Energy Laboratory, "PV Watts Calculator," National Renewable Energy Laboratory, Accessed on June 14, 2016. Available online: http://pvwatts.nrel.gov/pvwatts.php

[194] Comptroller of Maryland, "Clean Energy Incentive Tax Credit," Spotlight on Maryland Taxes, 2016. Available online: http://taxes.marylandtaxes.com/Business_Taxes/General_Information/Business_Tax_Credits/Clean_Energy_Incentive_Tax_Credit.shtml

[195] Solar Power Rocks, "Maryland 2016 Solar Report Card," Maryland, Accessed on Aug. 2, 2016. Available online: https://solarpowerrocks.com/maryland/

[196] National Renewable Energy Laboratory, "Distributed Generated Renewable Energy Estimate of Costs," Energy Analysis, Updated Feb. 2016. Available online: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

[197] Golnas, A., "PV System Reliability: An Operator's Perspective," IEEE Journal of Photovoltaics, vol. 3, pp. 417-418, Jan. 2013.

[198] Collins, E., Dvorack, M., Mahn, J., Mundt, M., and Quintana, M., "Reliability and Availability Analysis of a Fielded Photovoltaic System," 2009 24th IEEE Photovoltaics Specialist Conference (PVSC), IEEE, June 2009.

[199] Schimpf, F. and Norum, L., "Effective Use of Film Capacitors in Single-Phase PV-Inverter by Active Decoupling," IECON 2010- 36th Annual Conference on IEEE Industrial Electronics, IEEE, pp. 2784-2789, Nov. 2010.

[200] Wholesale Solar, "SolarEdge SE10000A-US-U Inverter," Wholesale Solar, Accessedon Aug. 5, 2016. Available online:

http://www.wholesalesolar.com/9900117/solaredge/inverters/solaredge-se10000a-us-u-inverter

[201] SolarEdge, “Single Phase Solar Inverters” SolarEdge, Accessedon Aug. 5, 2016. Available online: http://www.solaredge.com/us/products/pv-inverter/single-phase#/

[202] Zaman, A., Parlevliet, D., Calais, M., Djordjevic, S., Pulsford, S., Bruce, A. and Passey, R., “PV System Reliability- Preliminary Findings from the PV Module and System Fault Reporting Website,” 2014 Asia-Pacific Solar Research Conference, 2014. Available online: http://apvi.org.au/wp-content/uploads/2015/02/3-Parlevliet_APVI_PVPerformance-2_PeerReviewed.pdf

[203] Hollingsworth, B., “Report: Danger of Government-Created Solar Bubble Bursting When Subsidies Expire in 2016,” CNS News, Aug. 13, 2015. Available online: http://www.cnsnews.com/news/article/barbara-hollingsworth/report-danger-government-created-solar-bubble-bursting-when

[204] Cardwell, D., “Worry for Solar Projects After End of Tax Credits,” New York Times, Energy & Environment, Jan. 25, 2015. Available online: https://www.nytimes.com/2015/01/26/business/worry-for-solar-projects-after-end-of-tax-credits.html?_r=0

[205] Kisker, S., “Now is the Wrong Time for States to Reduce Solar Incentives,” Renewable Energy World, Feb. 19, 2016. Available online: http://www.renewableenergyworld.com/articles/2016/02/now-is-the-wrong-time-for-states-to-reduce-solar-incentives.html