Effects of module performance and long-term degradation on economics and energy payback: Case study of two different photovoltaic technologies

Kristopher Davis, H. Moaveni
Florida Solar Energy Center, University of Central Florida
1679 Clearlake Road, Cocoa, FL

ABSTRACT

Both the economic viability and energy payback time of photovoltaic (PV) systems are inextricably tied to both the electrical performance and degradation rate of PV modules. Different module technologies exhibit different properties in response to varying environmental conditions over time. The purpose of this study is to quantify the effects of those differences on the life-cycle economical cost and energy payback time of two fielded PV systems; one system comprised of polycrystalline silicon (c-Si) modules and one featuring hydrogenated amorphous silicon (a-Si) modules. The DC operating current, DC operating voltage, AC power, and conversion efficiency of each system have been monitored for a period of over four years, along with plane-of-array (POA) irradiance, module temperature, and ambient temperature. Electrical performance is evaluated in terms of final PV system yield (Y_f), reference yield (Y_r), and performance ratio (PR), which are derived from the primary international standard used to evaluate PV system performance, IEC 61724[1]. Degradation rates were evaluated over the four year period using regression analysis. The empirically determined trends in long-term performance were then used to approximate the energy produced by both system types under the same environmental conditions; most importantly, the same levels of solar irradiation. Based on this modeled energy production and economic conditions specific to the state of Florida, comparisons have been carried out for life-cycle costs and energy payback time.

Keywords: PV, degradation, yield, economic assessment, energy payback time

1. INTRODUCTION

In this study, two grid-tied PV systems with different module technologies were compared. One of the systems consisted of a 3.96 kW array of traditional polycrystalline silicon modules (i.e. glass face, aluminum frame, polymer backsheet) installed using a tilted rack-mount configuration on a flat roof. The other system featured a 3.36 kW array of thin-film laminate modules (i.e. multiple-junction hydrogenated amorphous silicon, no glass or aluminum) bonded directly to a metal roof. The systems were installed in similar climatic zones, both in coastal areas of Florida (c-Si at Latitude:30.45 Longitude:-86.58 near the Gulf coast ,a-Si at Latitude:29.04 Longitude:-80.9 near the Atlantic coast). The c-Si system was installed in February of 2003, and the experimental data was collected between February 2005 and December 2008. The a-Si system, which was installed three years earlier, was analyzed between February 2002 and December 2005, which is to say the same time period relative to the date of installation. Both periods of time under investigation correspond to a 47 month period beginning two years after the finished installation date. Parameters were collected at five-second intervals and averaged at 15 minute intervals using Campbell Scientific dataloggers. Various transducers were used to measure the following parameters: irradiance (pyranometer), ambient and back-of-module temperature (thermocouples), DC current (shunt), DC voltage (voltage divider), and AC power output (watt-hour transducer). Data filtering techniques were used to mitigate the affect of communication and instrumentation error.

Non-ideal circumstances often arise when performing an observational experiment, as opposed to a designed experiment where one has full control all aspects of the experiment. There were two undesirable consequences stemming from the use of archived data in this study. First, because data wasn't collected during the time period immediately following the installation of the a-Si system, no measurements from the initial light degradation period were available for investigation. Consequently, all data presented

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corresponds to the stabilized output of this array. Also, the two systems under investigation featured different inverters with different wiring configurations. The extent to which this affected the comparison should be minimal based on the known stability of both inverters.

2. ANALYSIS OF EXPERIMENTAL DATA

The method of analysis used in this study provides a means of comparing the performance of PV systems with different designs, module and inverter technologies, and geographical locations[2]. Here, final PV system yield, Y_f, is given as the net AC energy output, E_{out}, divided by the DC nameplate power of the array under Standard Test Conditions, P_{STC}. Standard Test Conditions (STC) corresponds to an irradiance of 1000 Wm^{-2} incident on the modules, spectral distribution of AM1.5, and cell temperature of 25°C.

$$Y_f\left(\frac{kWh}{kW}\right)=\frac{E_{OUT}\ (kWh)}{P_{STC}\ (kW)} \tag{1}$$

Reference yield, Y_r, is given by the total plane-of-array (POA) solar irradiation incident on the array, H_{POA}, divided by the reference irradiance, G_{STC}, which is 1000 Wm^{-2}.

$$Y_r(hours)=\frac{H_{POA}\ (kWhm^{-2})}{G_{STC}\ (kWm^{-2})} \tag{2}$$

The performance ratio (PR), which is dimensionless, is simply the final PV system yield divided by the reference yield. This parameter allows for a more appropriate comparison of one PV system to another by normalizing the relative difference in irradiance incident on the individual arrays. Fig. 1 shows the PR of both systems along with the ambient temperature at each site over the four year period under investigation.

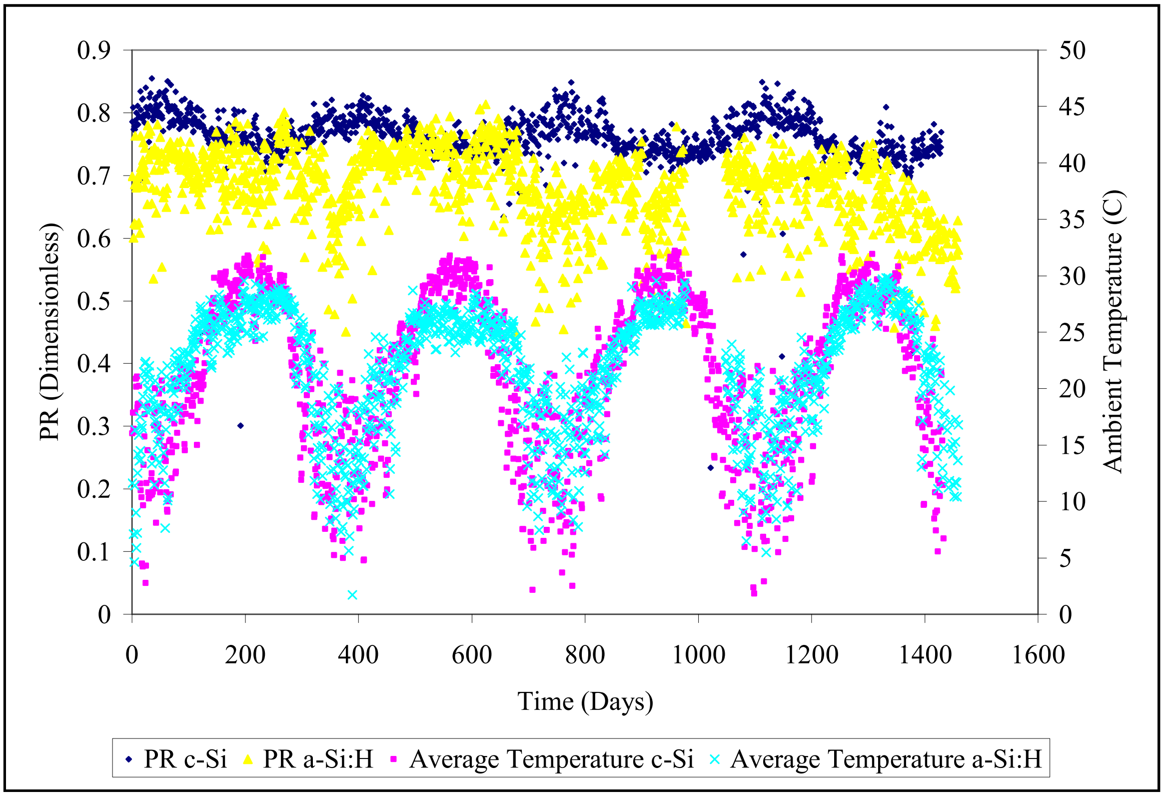

Fig. 1 PR and ambient temperature for both PV systems over 47 month period

While the c-Si system clearly exhibits a higher PR and lower degradation rate, the performance does appear to be rather comparable throughout the four year period. The well-known seasonal fluctuations are evident by the inverse nature of the two oscillating PR curves, illustrating the relatively higher performance of the a-Si system during the warmer months[3]. Linear degradation trends, which are given in terms of the annual decline with respect to the initial PR values, were established using regression analysis of monthly PR values over the course of the 47 month period. The degradation rates for the c-Si and a-Si systems were found to be -1.2%/year and -2.1%/year, respectively.

3. ESTIMATING ENERGY OUTPUT

The energy output of each system has been modeled on a monthly basis using a straightforward technique utilizing the nameplate power output of the array along with the PR values and degradation rates established from the experimental results. For this estimation, equivalent levels of incident solar irradiation are assumed for both arrays to allow for a fair comparison. This method, which is similar to one described by Takahashi et al.[4], is given by the following equation:

$$E_{AC}(kWh\ per\ month) = H\ (kWhm^{-2}\ per\ day) * N\ (days\ per\ month) *\ P_{STC} * PR \tag{3}$$

where E_{AC} represents the energy output of the system for a given month, H is the average incident solar irradiation per day which is assumed to be the same for both systems and is based on typical meteorological year data from the National Renewable Energy Lab's National Solar Radiation Database, N is simply the number of days in the month of interest, P_{STC} is again the STC nameplate power of the array, and finally PR is the performance ratio which has been modeled using the experimental results described above. PR was modeled using linear extrapolation of the degradation rates over the lifetime of the system (Fig. 2), which was assumed to be 20 years in this study.

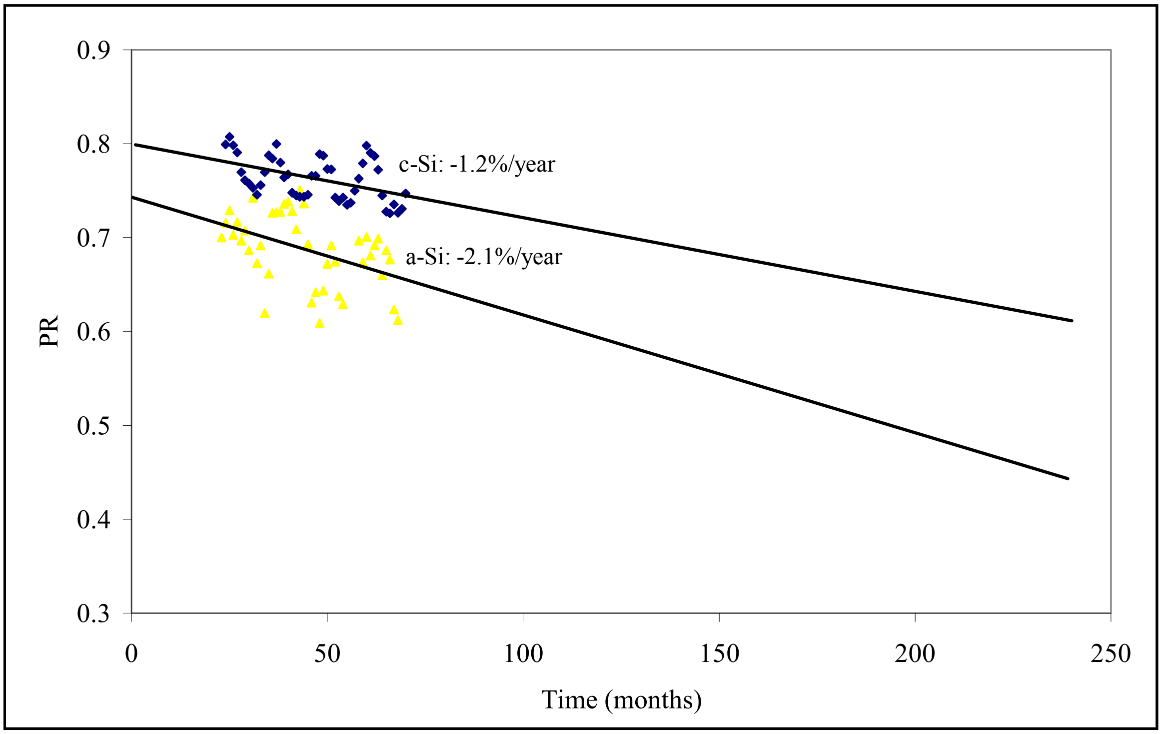

Fig. 2 Linear extrapolation of measured monthly PR values - 20 year system lifetime

Both the experimental and modeled performance of these systems seems to align with the commonly held assumption that c-Si is a better long-term performer. However, if the thin-film product is cheaper, then perhaps there is a trade-off between lower performance and reduced upfront capital cost. This is the primary reason for performing the economic and energy payback analysis; to quantify this relationship based on actual data from two PV systems.

4. ECONOMIC ANALYSIS AND ENERGY PAYBACK TIME

Life-cycle cost analysis was performed on each technology based on published cost data[5], cost data collected internally by the Florida Solar Energy Center (FSEC)[6], federal tax incentives, Florida state rebates, and the estimated energy output for each system. The total investment costs for each system are listed in Table 1 and are given in 2009 US dollars per peak Watt, referring again to the STC nameplate power of the array. A 20 year economic lifetime is assumed for the array and balance-of-system components (BOS) and a 10 year lifetime for the inverter. These numbers are based on warranty information from leading module and inverter manufacturers. Clearly the largest savings for the a-Si system come from reduced BOS cost and installation cost, which is a result of the direct laminate thin-film modules not requiring mounting hardware for roof attachment. This has the affect of both reducing upfront capital cost and installation time. Estimated annual costs of both systems are given in Table 2, which refers to operation and maintenance (O&M) costs and insurance costs. Based on the costs presented in both tables, the 3.96 kW c-Si has a total investment cost of $29,462 and a total annual cost of $139. The 3.36 kW a-Si has a $21,874 total investment cost and a $118 total annual cost.

Cost Breakdown	c-Si System		a-Si system		Economic Lifetime in Years
	Cost per Watt	% of Total	Cost per Watt	% of Total	
Module	$3.32	44.6	$3.2	49.2	20
Inverter	$1	13.4	$1	15.4	10
Balance-of-system	$0.61	8.2	$0.3	4.6	20
Installation, Design	$2.5	33.6	$2	30.7	20
Permitting	$0.01	0.1	$0.01	0.2	20
Total Investment	$7.44		$6.51		20

Table 1 Total investment cost of both systems

Cost Breakdown	Cost per Watt
O&M Cost	$0.02
Insurance	$0.015
Total Annual Cost	$0.035

Table 2 Total annual cost of both systems

To calculate annual benefit per year due to saved electricity expenses, an assumed annual rise in retail electricity rates has been set at 6%. The purchase of photovoltaic systems covered under the Florida Renewable Energy Technologies and Energy Efficiency Act qualifies consumers to receive a substantial rebate of $4.00 per Watt of the total array output based on the manufacturer's power rating at STC. This amount is capped at $20,000 for residential photovoltaic systems, which would only affect a system over 5 kW in size. The US federal government currently offers an investment tax credit for residential and commercial PV systems, which equates to a credit of 30% of the initial cost minus all other rebates and incentives.

Annual inflation is set to 3%. The coefficient that correlates a future cash flow with a present value is called the present value coefficient and is given by the following equation[7]:

$$CF_{t=0} = \frac{CF_{t=n}}{(1+r)^n} \tag{4}$$

The net present value (NPV), which is actually the present value of the total cash flow throughout the economic life-cycle of an investment is given next:

$$NPV = B_{t=0} - C_{t=0} = \sum_{i=0}^{n} \frac{B_{t=i}}{(1+r)^{i}} - \sum_{i=0}^{n} \frac{C_{t=i}}{(1+r)^{i}} \tag{5}$$

The benefit-to-cost ratio (BCR) is an index of the ratio of the present value of the benefit cash flow to the present value of the cash flow and is given by the following equation:

$$BCR = \frac{B_{t=0}}{C_{t=0}} = \frac{\sum_{i=1}^{n} \frac{B_{t=i}}{(1+r)^{i}}}{\sum_{i=1}^{n} \frac{C_{t=i}}{(1+r)^{i}}} \tag{6}$$

The pay-back period (PBP) is the number of years needed for the NPV to reach zero, and can be described as the amount of time before the investment pays for itself. PBP is found by solving equation (5) with NPV set equal to zero, using the following equation:

$$\sum_{i=0}^{PBP} \frac{B_{t=i}}{(1+r)^{i}} = \sum_{i=0}^{PBP} \frac{C_{t=i}}{(1+r)^{i}} \tag{7}$$

The BCR of the c-Si system is 1.059, while the a-Si system has a BCR of 1.055. In order for an investment to be efficient, the BCR should be larger than unity. Based on the PBP found for each technology, both systems will gain profit in year 19. This value for the both systems is very high and approaches the life-cycle of the systems.

In Fig. 3, the annual cash flow is illustrated for the 20 year life-cycle of both systems, including the damping value that occurs at year 10 which is due to the replacement of the inverter. Fig. 4 illustrates the NPV for the 20 year life-cycle of both systems. The PBP of both systems clearly converges around year 19, wherein the sum of the annual cash flow becomes positive for both systems.

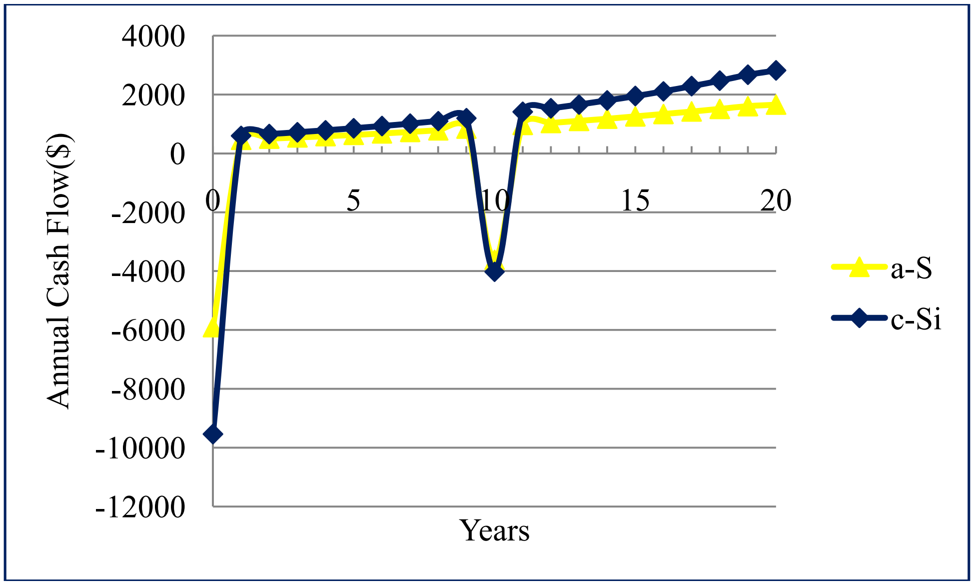

Fig. 3 Annual present value of the cash flows during the life-cycle of the systems

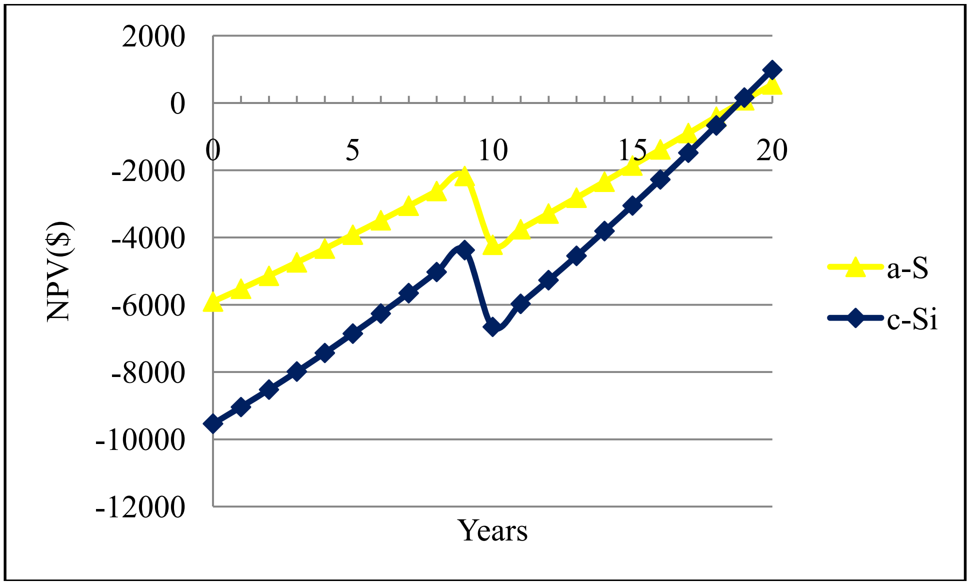

Fig. 4 NPV during the life-cycle of the systems

Finally, the energy payback time for both the c-Si and a-Si modules has been calculated. Energy payback time is the time necessary for a PV module to generate the energy equivalent used to produce it during the manufacturing process. The energy requirements for c-Si and a-Si module production with a present day technology has been taken from previous studies[8] (35 MJ per nameplate Watt at the low end and 96 MJ per Watt at the high end for c-Si modules, 20 MJ per Watt for the frameless a-Si module). The difference between energy requirements for c-Si and a-Si module production is mainly due to higher energy consumption for the c-Si crystallization process. According to two systems and insolation rate, the payback time for the c-Si module is between 1.8 to 5 years in high and approximately 1 year for the frameless a-Si module.

5. CONCLUSIONS

The intention of this paper is to utilize an observational case study approach to better under the operational differences in c-Si and a-Si PV modules from a system design perspective. As a result of this case study, the long-term performance and upfront costs for each technology balanced out to create two closely matched investment opportunities. Both systems exhibited predictable, stable behavior over the 47 month period of investigation, with a -1.2%/year degradation rate for the c-Si system and a -2.1%/year degradation rate for the a-Si system. In this study, the net present value of both systems approached zero near year 19, meaning both systems have a projected pay-back period smaller than the warranty life of each array. One potential scenario that would create a sizeable advantage for the c-Si system in this study would be a higher annual rise in the retail electricity rate (i.e. more than 6% annually). On the other hand, reducing the production cost of the thin-film laminate modules would give leverage to the a-Si system, which is possible since a-Si production isn't as mature as the c-Si manufacturing industry. Three areas that could significantly improve the economics of both systems would be reducing installation and design cost, increasing inverter lifetime, and driving down O&M cost.

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REFERENCES

[1] International Electrotechnical Commission, IEC 61724 Ed. 1.0
[2] B. Marion et al., “Performance parameters for grid-connected PV systems”, Proc. 31st IEEE Photovoltaic Specialist Conference and Exhibition, Orlando, (2005)
[3] R. Rüther, J. Livingstone, “Seasonal fluctuations in amorphous silicon solar module outputs and thin film characteristics”, Solar Energy Materials and Solar Cells, vol. 36, 29-43, (1994)
[4] H. Takahashi, S. Fukushige, T. Minemoto, H. Takakura, “Output estimation of Si-based photovoltaic modules with outdoor environment and output map”, Journal of Crystal Growth, vol. 311, 749-752, (2009)
[5] Module Price Index, Photon International, 76, 2009-05
[6] K. Lynn, J. Szaro, W. Wilson, M. Healey, “A review of PV system performance and life-cycle cost for the SunSmart school program”, Proceedings of the ASME International Solar Energy Conference 2006, Denver, (2006)
[7] J.Adnot, B.Duplessis, A.Marchio, A.Rabi, P.Riviere, “Cycle de vie des systémes énergétiques”, course notes, Ecole des Mines de Paris
[8] E. Alsema, P. Frankl, K. Kato, “Energy pay-back time of photovoltaic energy systems: present status and future prospects”, 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, (2006)
[9] L. Moore, H. Post, “Five-years of residential photovoltaic system experience at Tucson Electric Power”, Strategic Planning for Energy and the Environment, vol. 28, 58-73, (2008)
[10] M. Quintana, D. King, T. McMahon, C. Osterwald, Proc. 29th Photovoltaic Specialists Conference and Exhibition, New Orleans, (2002)