

Evaluating the Environmental Benefit of Residential Photovoltaic Modules Early Retirement in California

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Abstract— Over the past decade, the demand for photovoltaic (PV) cells and solar power in the United States has been steadily increasing. The standard lifetime of PV modules is expected to be 25-30 years but could be shorter due to repowering or early module failure, challenging the common assumption that PV systems always have a positive environmental impact. In this study, using installation and replacement data for California, PV system installations were evaluated to quantify an average carbon payback time (CPBT) of about three years and five zero carbon electricity production per system.

Keywords—photovoltaic cell (PV), life cycle assessment (LCA), repowering, life cycle assessment, carbon payback time

I. INTRODUCTION

The state of California is the foremost leader in solar photovoltaics (PV) installations in the United States, with 1,390,240 installations and 24.76% of the state's energy coming from solar [3]. In the United States, solar accounted for 3.3% of total generation and is the fastest-growing electricity source [5][8].

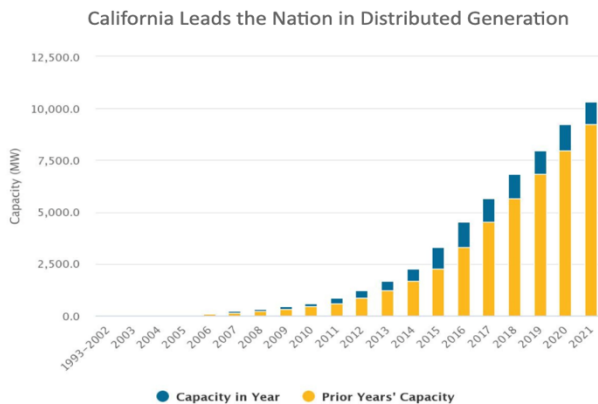


Fig. 1. NEM solar PV capacity in California. [1]

As the prices for PV have dropped 11% in the last 5 years [3] and a 17% capacity increase in 2021 [5], the market is undeniably increasing. Currently, most PV sustainability studies and life cycle assessments focus mainly on PV manufacturing and assume standard insolation (1700 kWh/m²) and system lifetime (years) to calculate the energy and carbon payback time (CPBT) [6]. This results in misleading information used by homeowners, policymakers, etc.

Another aspect not considered by current studies is the actual system design (system location, tilt and azimuth) and module choice, in particular the temperature coefficient which affects the electricity generation over time.

The other benefit of installing PV is avoiding the production of electricity from the grid. In regions with high proportion of fossil fuel generators (coal and natural gas), the avoided carbon footprint per kWh of electricity is very high, but in California, the electricity production is already more than 33.4% renewables [2] and the proportion of renewables is expected to further increase in the future, therefore reducing the avoided carbon benefit compared to other regions.

In this work, we wanted to ensure that modules that were retired early did produce electricity long enough to compensate for the carbon footprint associated with their manufacturing. In other words, we calculated the carbon payback time and based on the lifetime of the system, calculated the number of years the system produced zero carbon electricity.

II. METHODS

The objective of this study is to use the life cycle cumulative energy demand and greenhouse gases to evaluate the carbon payback time (CPBT) of PV systems in California. The four steps of this methodology are summarized in Fig 2.

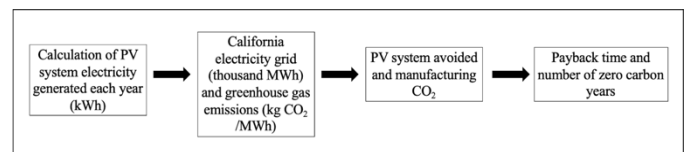


Fig. 2. Summary of methodology required to calculate payback time and the number of zero carbon years.

Residential PV installations were gathered from the California NEM database [1] from 2019 and the software SAM (System Advisor Model), created by the National Renewable Energy Laboratory [9], was used to model the PV systems electricity generation. System location, module numbers, tilt, and azimuth were inputted into SAM.

Module-specific data including nominal efficiency, temperature coefficients, maximum power (Wdc), maximum power voltage (Vdc), maximum power current (Adc), open circuit voltage (Voc), and short circuit current (Isc) were verified using module specification/information sheets. Each

system was run in SAM to receive annual energy generation in kWh.

Data on California’s electricity production was compiled and generation per sector [12] was calculated per year for 2001 to 2040. The custom mix for each year was then entered into the NETL Electricity LCI Explorer [11] to calculate the greenhouse gas emissions of the grid over time. GHG data was essential in determining the amount of avoided CO₂, by multiplying electricity generated by GHG data per year.

Multiplying module area by the number of modules per system by the carbon footprint of the modules, manufacturing CO₂ was found. The carbon footprint of all modules was kept constant at 303 kg/m² CO₂ based on the material inventory from IEA PVPS 2015 data [4]. By subtracting carbon from manufacturing (kg CO₂) from the avoided CO₂ multiplied by the number of kWh/year yielded the payback time for each system. Consequently, the number of years remaining after the payback time of each system resulted in the number of zero carbon years.

III. RESULTS AND ANALYSIS

Data from the EIA [12] in California was gathered and graphed below in terms of the percentage amount of electricity generation per sector from 2001 to 2044 along with calculated greenhouse gas emissions data.

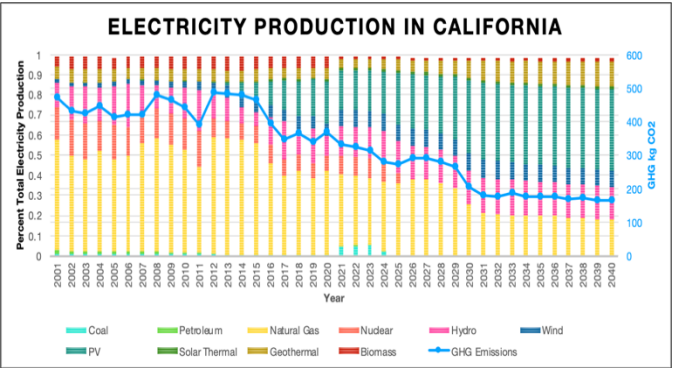


Fig. 3. Electricity production per energy source and associated greenhouse gas emissions for California over time.

Greenhouse gas emissions are expected to decrease significantly and plateau around 100 to 200 kg CO₂ over the next 25 years. Natural gas and hydropower followed a similar trend. PV did the opposite and dramatically increased projecting making up 50% of California’s electricity production by 2044.

Before analyzing CPBT, raw efficiency data from the NEM systems was evaluated to determine the relationship between

module efficiency and module manufacture year.

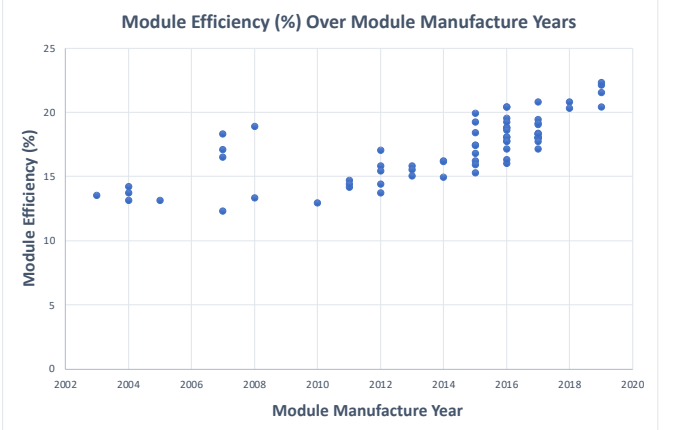


Fig. 4. Module efficiency of installed PV system from 2003-2019 in California.

As expected, as the manufacturing year increased, module efficiency followed. However even if more efficient modules are available, lower efficiency modules are often installed as shown for example in 2015 where efficiency range from 15 and 20%.

When modules are replaced, higher efficiency modules are installed. For example, a system with modules manufactured in 2005 had an efficiency of 13% and was replaced with modules made in 2017 with an efficiency of 18%. Additionally, from the systems modeled, the newest modules manufactured in 2019 had an efficiency of 21%.

Factoring in module models, system size, area, carbon footprint, and greenhouse gas emissions, CPBT is determined. Below is a sample system displaying modules before retirement.

PV System Lifetime (years)	Electricity Produced from PV System in kWh (Efficiency and Modules Adjusted)	GHG Emissions from California Grid (kg CO ₂ /mWh)	Avoided CO ₂ (kg CO ₂)	PV System Manufactured CO ₂	CO ₂ /year	PV System Carbon Payback Time (years)
2012	7473	487	3639	7839	4199	1 year
2013	7437	483	3592		607	2 years
2014	7401	480	3553		-2945	607/3553
2015	7365	463	3410			0.17
2016	7329	395	2895			Payback Time: 2.17 / 8
2017	7293	347	2531			Zero Carbon Years: 5.83
2018	7258	366	2656			
2019	7222	340	2455			

Fig. 5. CPBT and zero carbon years results from a sample pre-retirement system.

The average CPBT and number of zero carbon years across all 40 systems modeled were 2.8 and 4.9 respectively.

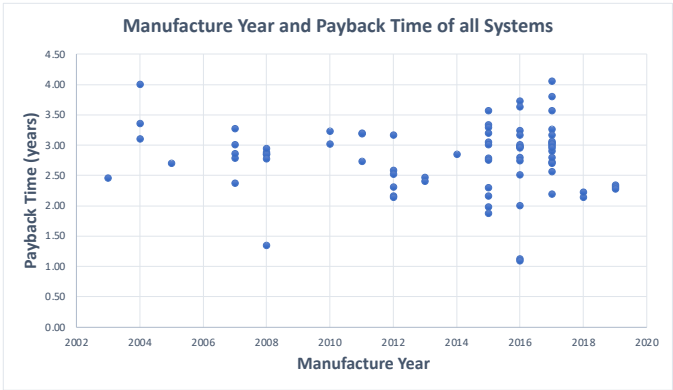


Fig. 6. Manufacture year for modules within each system compared to payback time.

All systems had a carbon payback time of approximately 4 years or lower, with a range of payback times corresponding to various modules released in the same year.

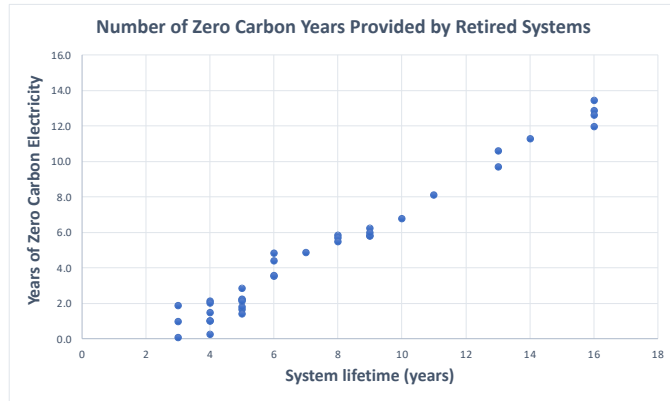


Fig. 7. The number of zero carbon years provided by retired and replaced systems.

The systems that were replaced had a strong correlation between system lifetime and the number of zero carbon years given. Since the payback time was around three years, intuitively, systems that lasted longer supplied more zero carbon years of electricity.

IV. DISCUSSION

Module efficiency is clearly increasing as time progresses, showing promise for new, ever-changing PV technology occurring today. Despite this, there is still a notable range of efficiencies between modules from the same year potential corresponding to consumer budget constraints, location constraints, etc.

The calculated CPBT of 2.8 years provided evidence to support the assumption that PV always has a positive environmental impact. No systems had a longer than average payback time, however, there was some variation between modules within the four-year time frame.

In Fig 6., there are systems with modules made in 2004 that have a similar payback time as modules made in 2014 to 2017. Though the efficiency of these modules was different, and newer modules generally have higher efficiency, they had similar payback times. This could be due to the location of the system, amount of sunlight, and azimuth and tilt data. Since residential solar has limited installation options to optimize sunlight received, the system could have been in or at an inefficient place. Furthermore, module quality and cleaning should be considered as a number of systems that were replaced contained modules that were recalled.

V. CONCLUSION AND FUTURE WORK

Current PV LCA studies don't provide the entire picture and make assumptions that cannot be overlooked. It's important to consider real PV systems with varying temperature coefficients and installation data to provide the most accurate information for workers or scientists to make informed and environmentally

beneficial decisions. The use of real installation and location-based data in this study provides significant results and a strong framework for PV research.

When continuing this study for future work, the carbon footprint assumption of 303 kg/m² CO₂ for every system should be adjusted to reflect the year of manufacturing and changing material intensity of PV modules over time.

Moreover, there is a wide range of module efficiency for modules made each year. When evaluating the NEM systems, consumers weren't always picking the most efficient modules to maximize their investment. More work should be done on the consumer decision-making process to determine what factors impact these choices.

As stated, residential PV has many restrictions in terms of ideal PV installation. Other systems, residential or not, with better installation data should be examined with a similar process as this study and results should be compared between ideal and nonideal systems.

ACKNOWLEDGMENTS

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