The 1MW photovoltaic array at the Flatirons Campus (FC) of the National Renewable Energy Laboratory (NREL). *Photo by Werner Slocum, NREL 65307*

Energy and Carbon Payback Times for Modern U.S. Utility Photovoltaic Systems

Solar photovoltaic (PV) technologies are helping decarbonize the U.S. electricity system by harnessing a renewable energy source—the sun. However, manufacturing and operating a PV system consumes non-renewable energy and produces carbon emissions, as does end-of-life handling when PV systems are eventually decommissioned. To fully account for PV's contribution toward decarbonization, these life cycle impacts must be quantified.

Impacts over the life of PV systems are quantified using life cycle assessment (LCA) methods and can be used to estimate energy and carbon payback times. Energy payback time (EPBT) is the time required for a PV system to generate the same amount of energy used during system manufacturing, operation, and disposal. Similarly, carbon payback time (CPBT) is the time required for a PV system to offset the amount of carbon emitted over its life cycle, by displacing more carbon-intensive electricity which would have otherwise been used locally.

Updated Life Cycle Assessment of U.S. Utility PV Systems

A recent LCA from the National Renewable Energy Laboratory (NREL) estimated energy and carbon payback times for utility-scale PV systems installed in the United States. Utility-scale systems account for two thirds of U.S. PV capacity installed annually and are typically tens to hundreds of megawatts in size. The study assessed a typical U.S. utility-scale PV system installed in 2023 with modern silicon modules, single-axis trackers, and central inverters. The effects of PV module manufacturing regions were considered for imported modules and domestic modules. Evaluating installation locations across multiple U.S. regions show the effects of local irradiation and grid characteristics on payback times.

Short Energy and Carbon Payback Times in Most Scenarios

The energy payback times from the NREL study are between 0.5 and 1.2 years for utility-scale PV systems in the United States, as shown in Figure 1. The features for the different system scenarios are reported in Table 1. EPBTs are primarily affected by the amount of solar radiation and the grid efficiency where a system is installed. In less than 1.2 years, these systems produce enough electricity to offset all the energy needed to manufacture them, operate them for 30 years, decommission them, and process wastes.

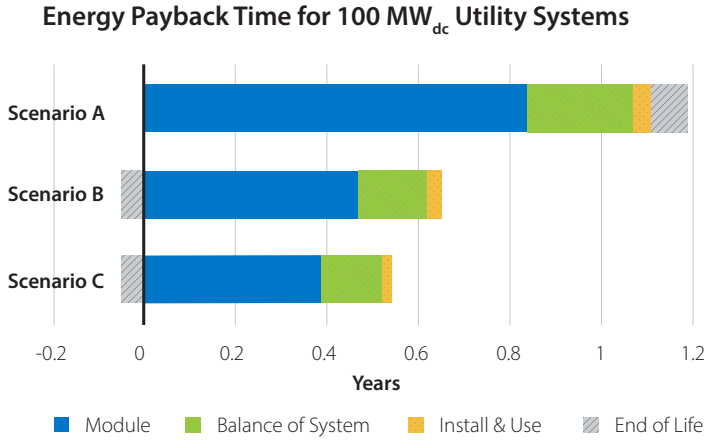

Figure 1. Energy Payback Times for Select Utility PV System Scenarios

Table 1. Select U.S. Utility PV Systems

		Scenario A	Scenario B	Scenario C
System Manufacturing & Disposal	**Source of PV Modules**	Imports from China & Southeast Asia		United States
	Carbon intensity of Module Manufacturing	High-carbon regions in China & Southeast Asia	Average-carbon regions in China & Southeast Asia	Low-carbon U.S. region
	End of Life Treatment	Landfill	Partial recycling	Hypothetical high-recovery recycling
Installation Location Characteristics	**Installation Location**	Seattle, WA	Fredonia, KS	Phoenix, AZ
	Solar Radiation	Low	Medium	High
	Local Grid Emissions (2022)	Low	High	Medium
	Local Grid Efficiency	High	Low	Medium
	Scenario for Projected Renewable Capacity Cost	Low	Medium	High
Results	**Energy Payback Time**	1.2 years	0.6 years	0.5 years
	Carbon Payback Time	20 years	2.1 years	0.8 years

The carbon payback times for these utility-scale PV systems in the United States range from 0.8 years to 20 years, with a benchmark CPBT of 2.1 years. Carbon payback time is also affected by the amount of local solar radiation but is much more significantly affected by the carbon-intensity of the local grid it offsets, as well as the future projected grid mix for the location it is installed. In all Fredonia and Phoenix scenarios, payback times are 2 years or less. However, because the Seattle location has a low-carbon grid and low solar radiation, the carbon payback time ranges from 7 to 20 years, depending on assumptions about carbon emissions due to equipment manufacturing and disposal.

These EPBT and CPBT benchmark values represent a significant update over previous values reported for PV systems. Energy payback times are often reported as longer than a year[1], especially in older studies.[2] Similarly, carbon payback times are often reported as longer than 2 years, even in high-irradiance locations.[3,4]

References

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More Information

For details, see the report, An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States, at **www.nrel.gov/docs/fy24osti/87372.pdf**

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National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
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