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Methods to assess carbon payback times of utility PV systems in the United States

Brittany Smith, Ashok Sekar, Heather Mirletz, Garvin Heath, and Robert Margolis

National Renewable Energy Laboratory

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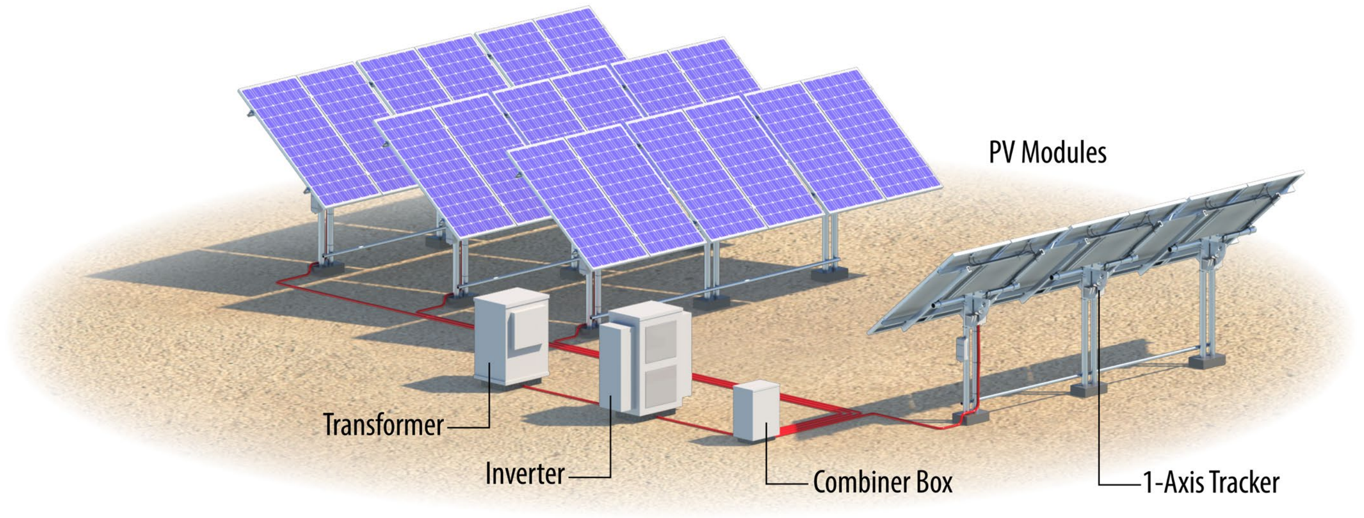
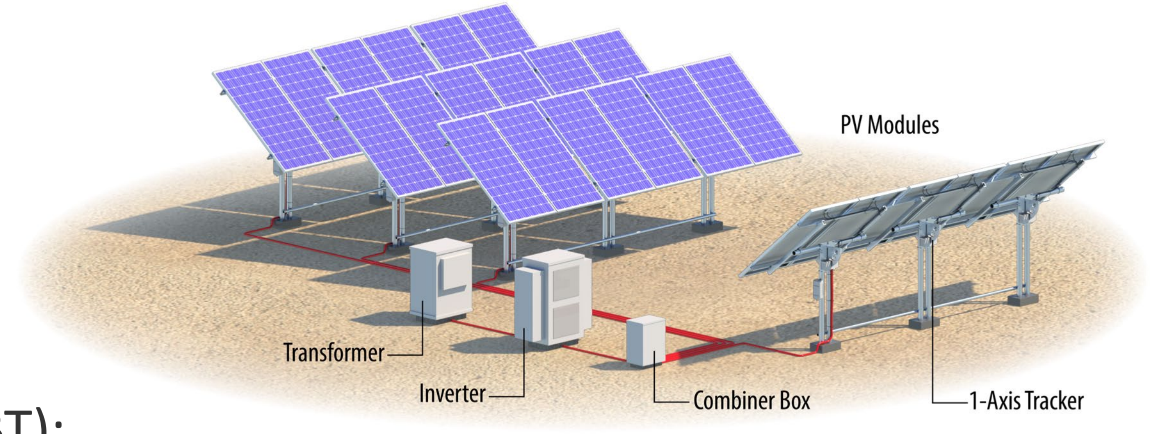
Overview

- Methods for estimating the carbon payback time (CPBT) and energy payback time (EPBT) of photovoltaic systems often use ***average*** annual energy generation in the calculation
- We examine tradeoffs for a 100-MW_{dc} utility PV system installed in the United States
- CPBT & EPBT methods presented here also apply to any other environmental assessments with non-linear temporal data



Definitions

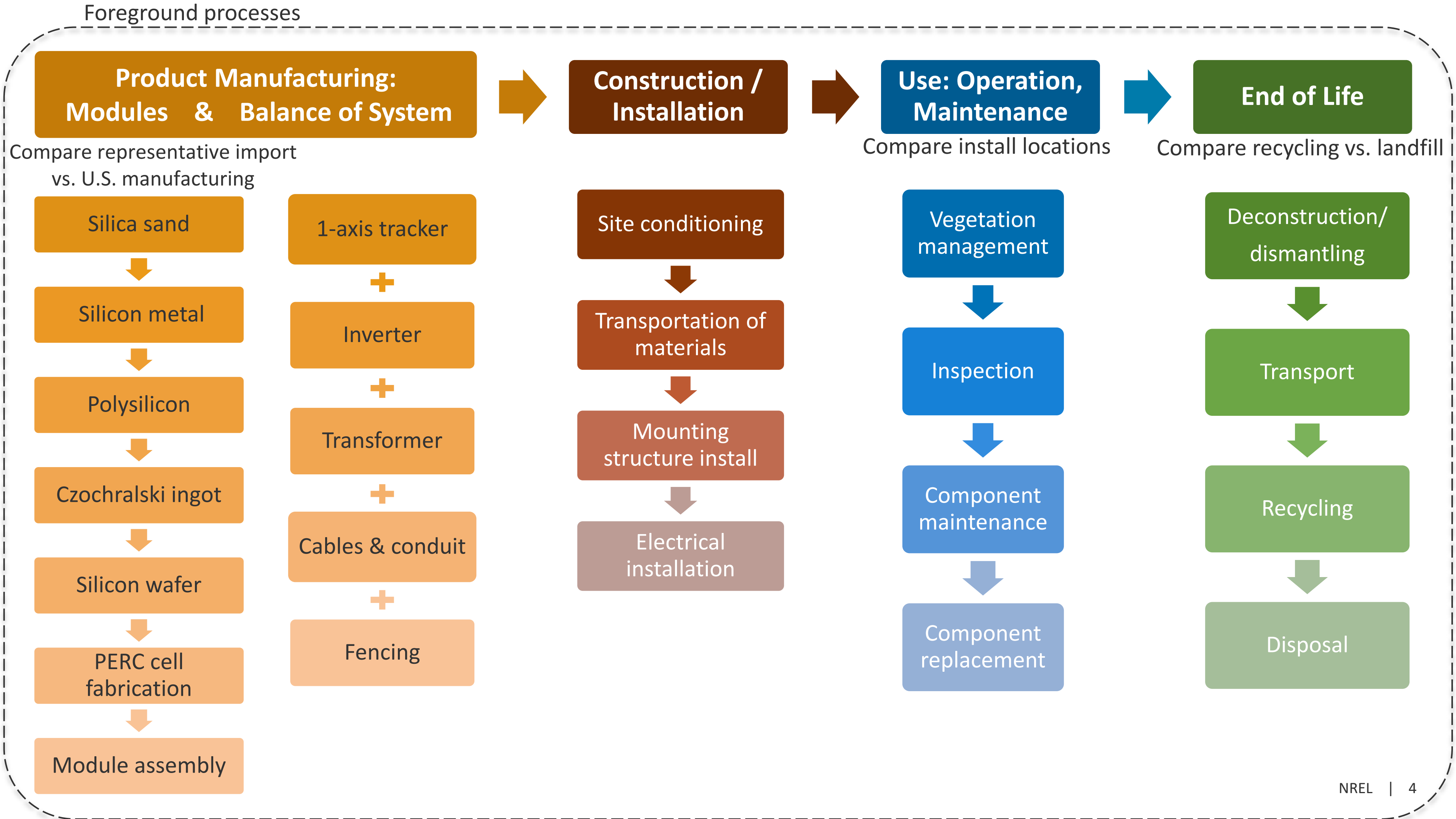


Energy payback time (EPBT):

the time required for a PV system to generate the same amount of energy used during system manufacturing, operation, and disposal

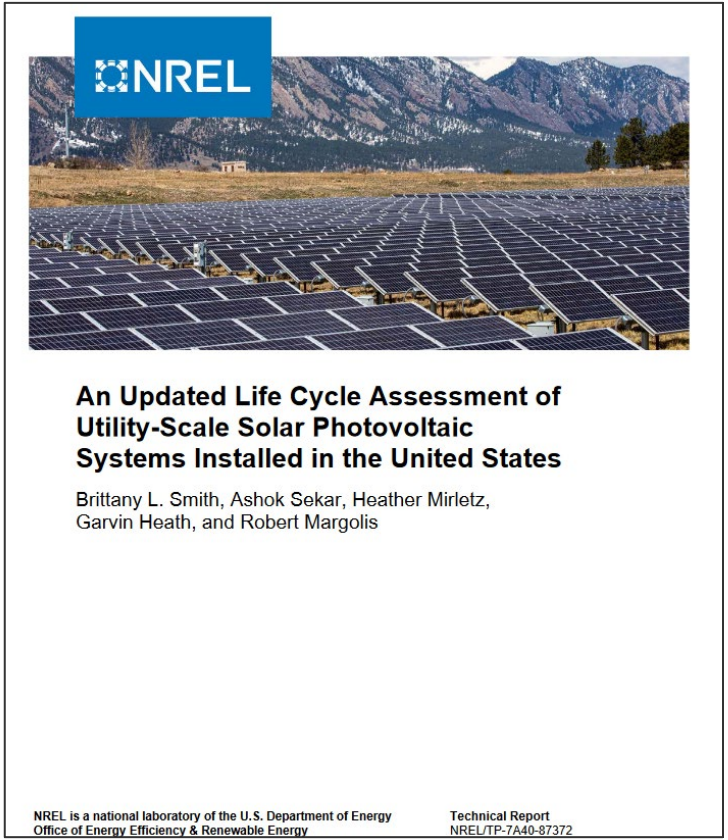
Carbon payback time (CPBT):

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


Foreground processes
Product Manufacturing:
Modules & Balance of System
Compare representative import vs. U.S. manufacturing
Silica sand
Silicon metal
Polysilicon
Czochralski ingot
Silicon wafer
PERC cell fabrication
Module assembly
1-axis tracker
Inverter
Transformer
Cables & conduit
Fencing
Construction / Installation
Site conditioning
Transportation of materials
Mounting structure install
Electrical installation
Use: Operation, Maintenance
Compare install locations
Vegetation management
Inspection
Component maintenance
Component replacement
End of Life
Compare recycling vs. landfill
Deconstruction/ dismantling
Transport
Recycling
Disposal

2024 U.S. Utility PV LCA Report

Scan QR code for the full technical report from NREL



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An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States

Brittany L. Smith, Ashok Sekar, Heather Mirletz, Garvin Heath, and Robert Margolis

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Technical Report
NREL/TP-7A40-87372

“Average Annual” method

$$CPBT = \frac{(C_{manuf} + C_{inst} + C_{use} + C_{EOL})}{\frac{(\sum_y (E_{agen,y} \times EF_{G,y}))}{Y}}$$

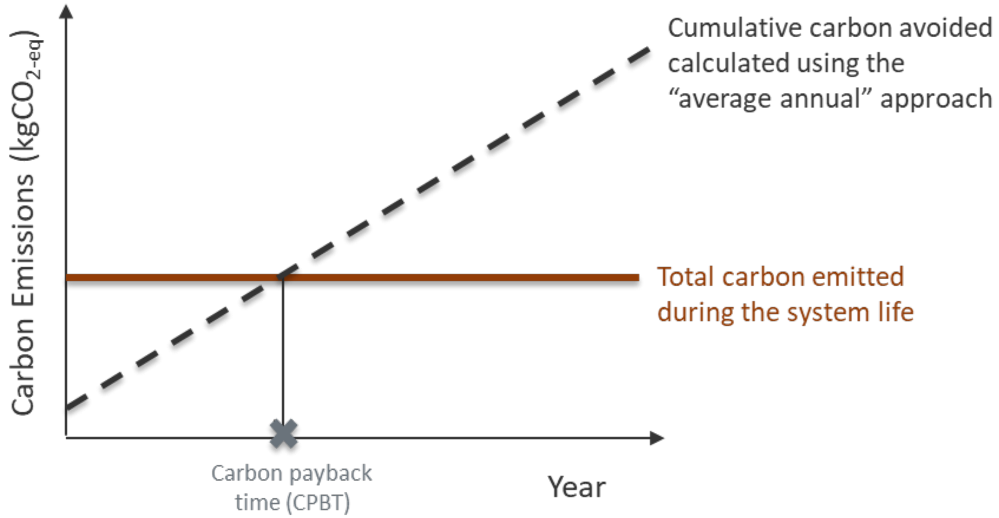
- C_{manuf} is GHG emitted (in g CO_2e) to manufacture PV system
- C_{inst} is GHG emitted (in g CO_2e) during construction and installation of the system
- C_{EOL} is GHG emitted (in g CO_2e) during end-of-life management
- C_{use} is GHG emitted (in g CO_2e) during operation and maintenance
- $E_{agen,y}$ is annual electricity generated by the plant (in kWh) each year of its life, y
- $EF_{G,y}$ is emission factor of the grid (g CO_2e per kilowatt-hour of electricity) for each year, y

Non-linear method

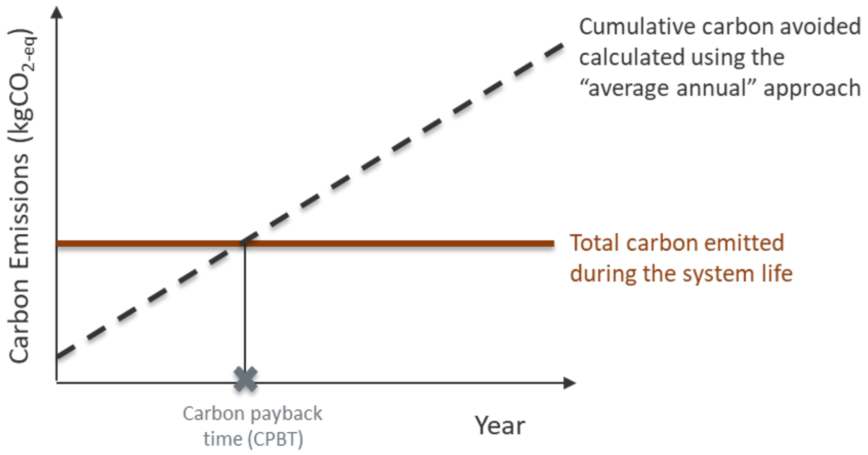
Solve for the minimum *y* value that satisfies the following inequality:

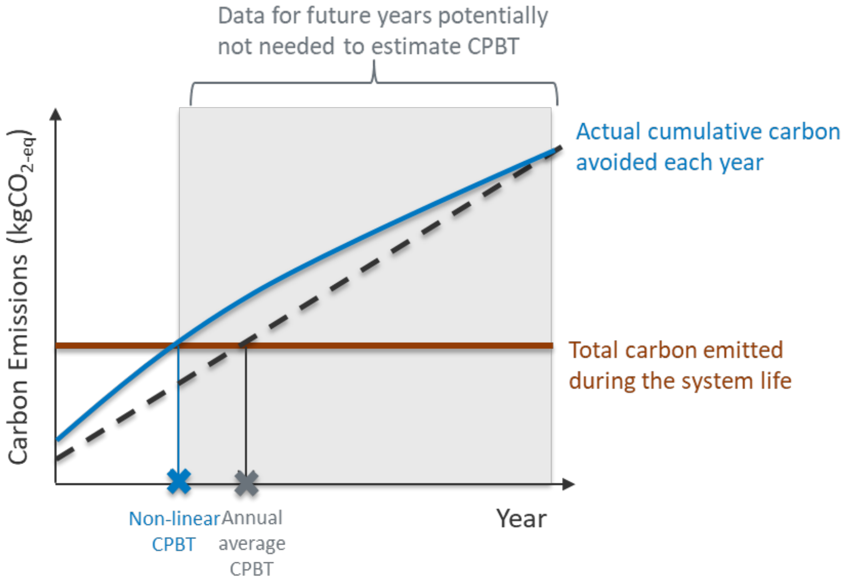
$$(C_{manuf} + C_{inst} + C_{use} + C_{EOL}) \leq \sum_y (E_{agen,y} \times EF_{G,y}), \qquad y = \{0, 1, 2, \ldots\}$$

Comparing methods



Comparing methods





Input Data & Scenarios

EPBT

Energy yield: NREL System Advisor Model (SAM)

Irradiation scenarios:

- Mid-case: **Fredonia, Kansas**
- Low irradiation: **Seattle, Washington**
- High irradiation: **Phoenix, Arizona**

CPBT

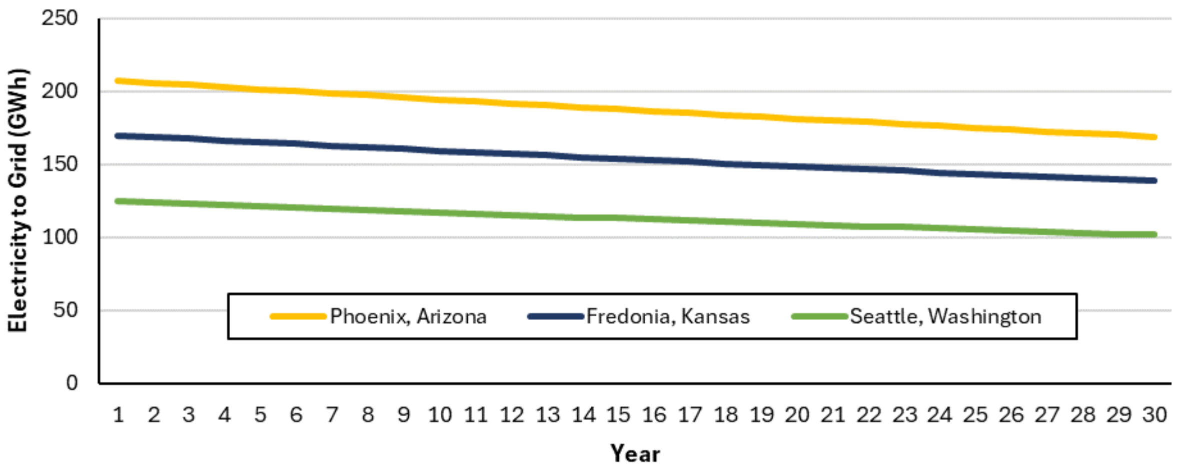
Grid emission factors: NETL Grid Mix Explorer

Grid mix projections: NREL Cambium Scenarios

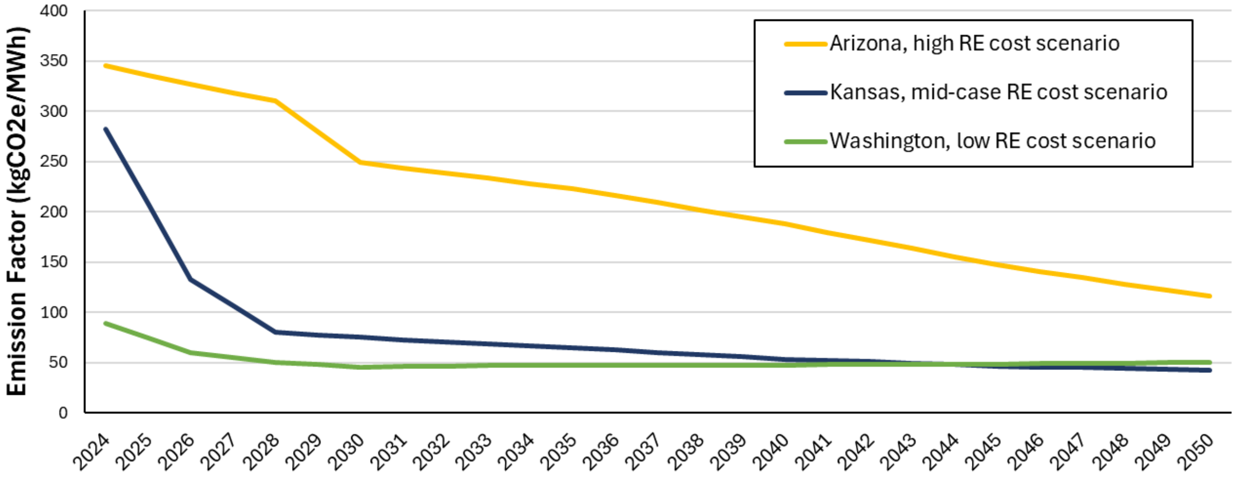
- Mid-case: **Fredonia, KS**
- High CPBT: **Seattle, WA**
  - Low irradiation
  - Low grid emission area (offsets low-emitting grid)
  - NREL Cambium Scenario: low renewable energy costs
- Low CPBT: **Phoenix, AZ**
  - High irradiation
  - High grid emission area (offsets high-emitting grid)
  - NREL Cambium Scenario: high renewable energy costs

Time-dependent data

Electricity generated by the PV system

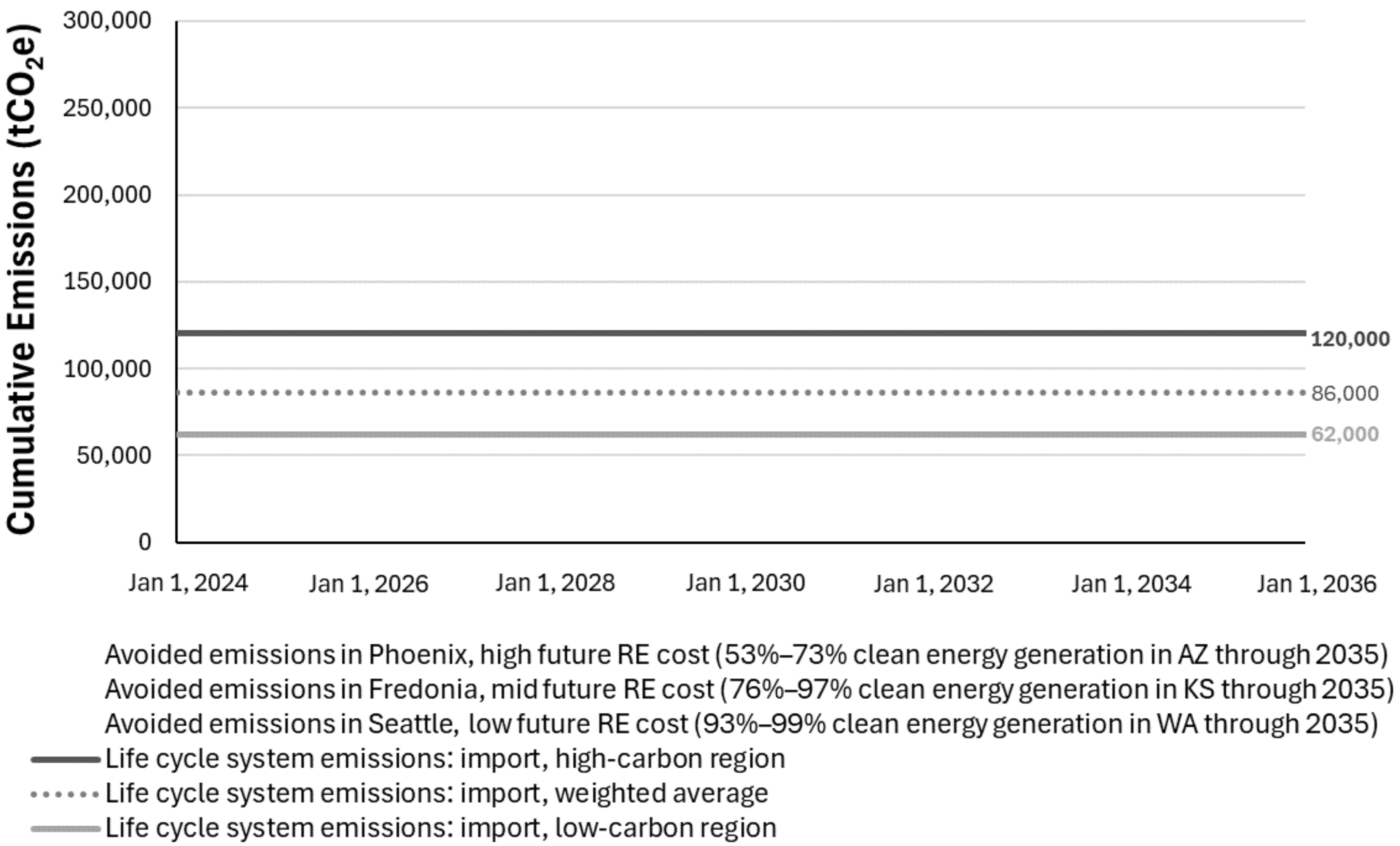


Emission factors of local grids



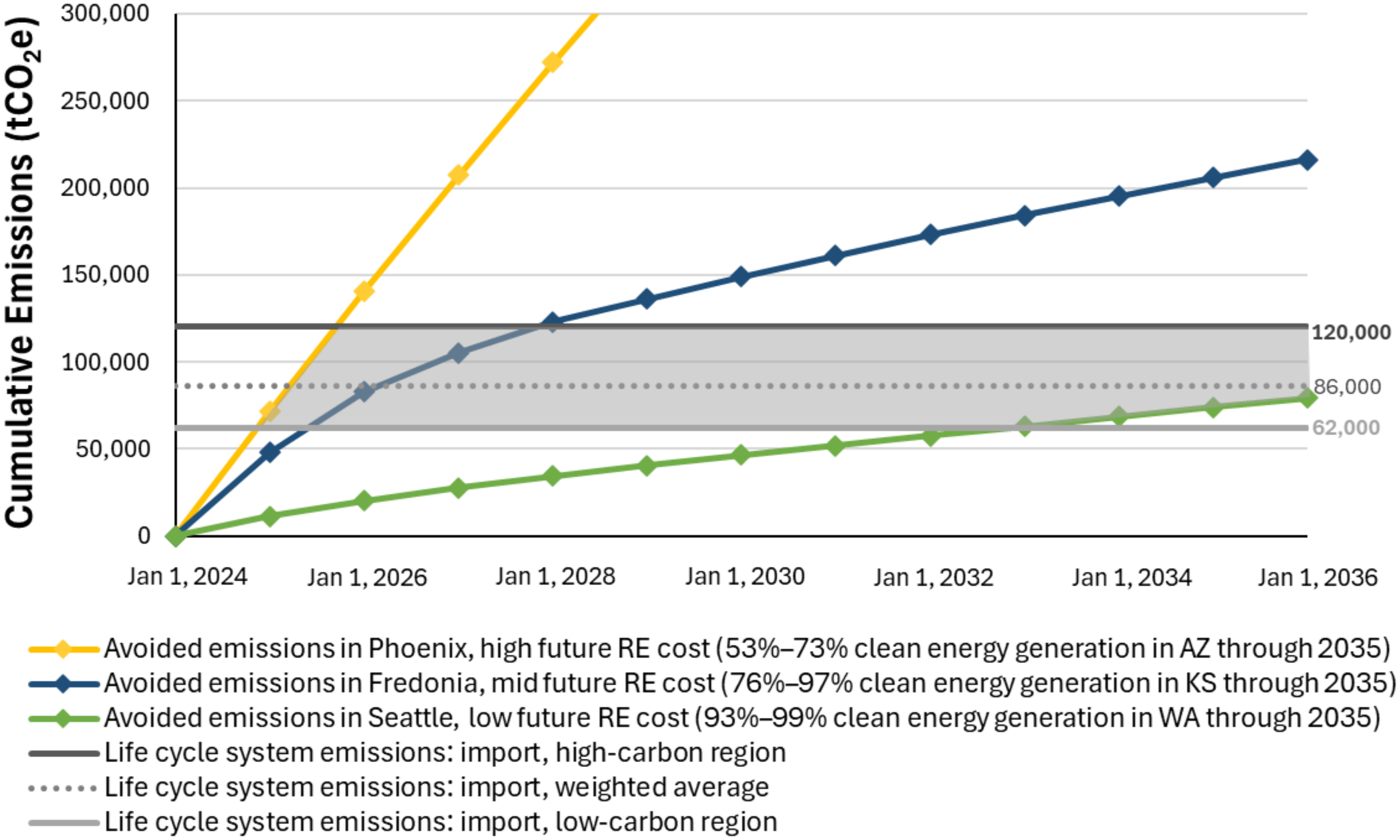
CPBT

PV system life-cycle emissions



CPBT

Add annual avoided emissions

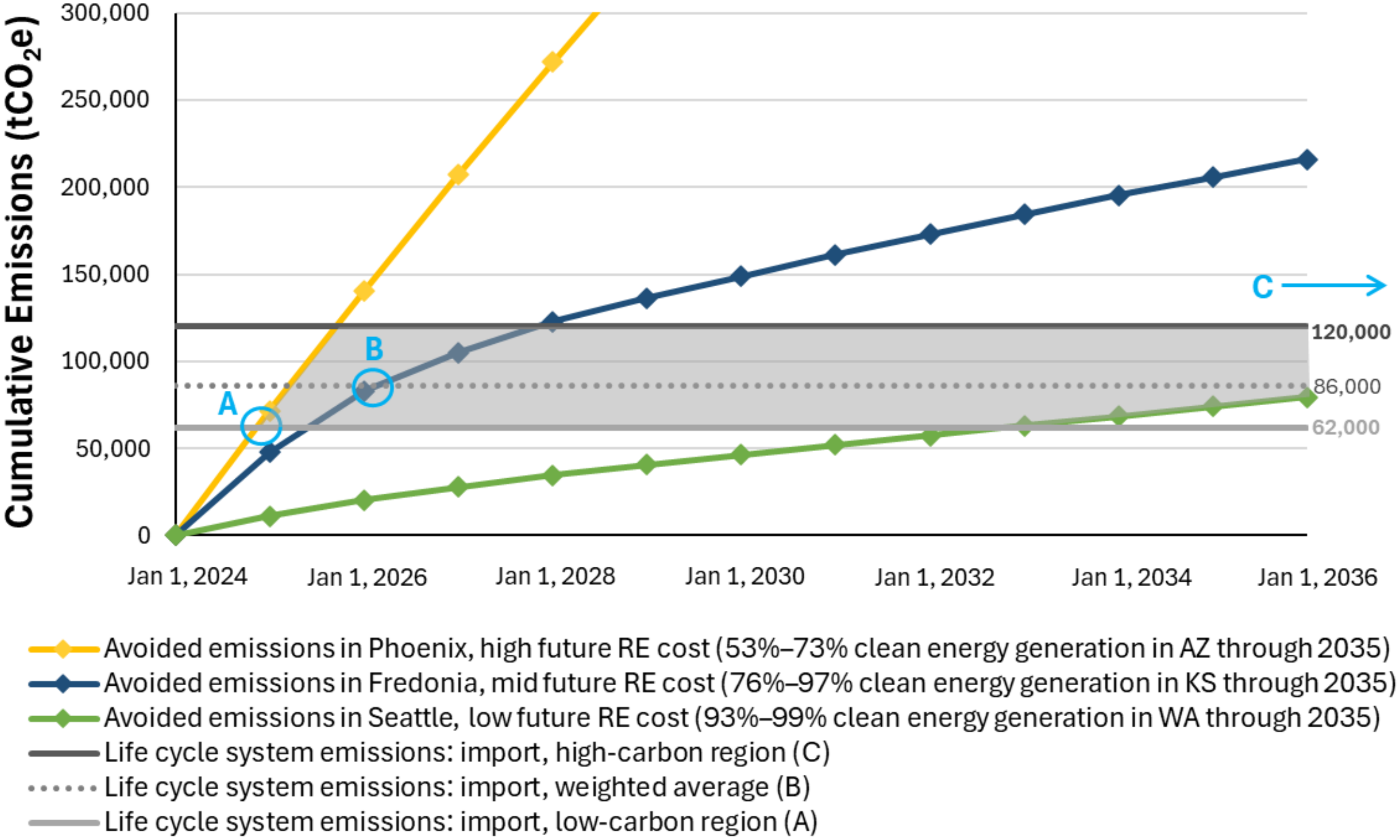


CPBT

A: 0.9 years

B: 2.1 years

C: 20 years

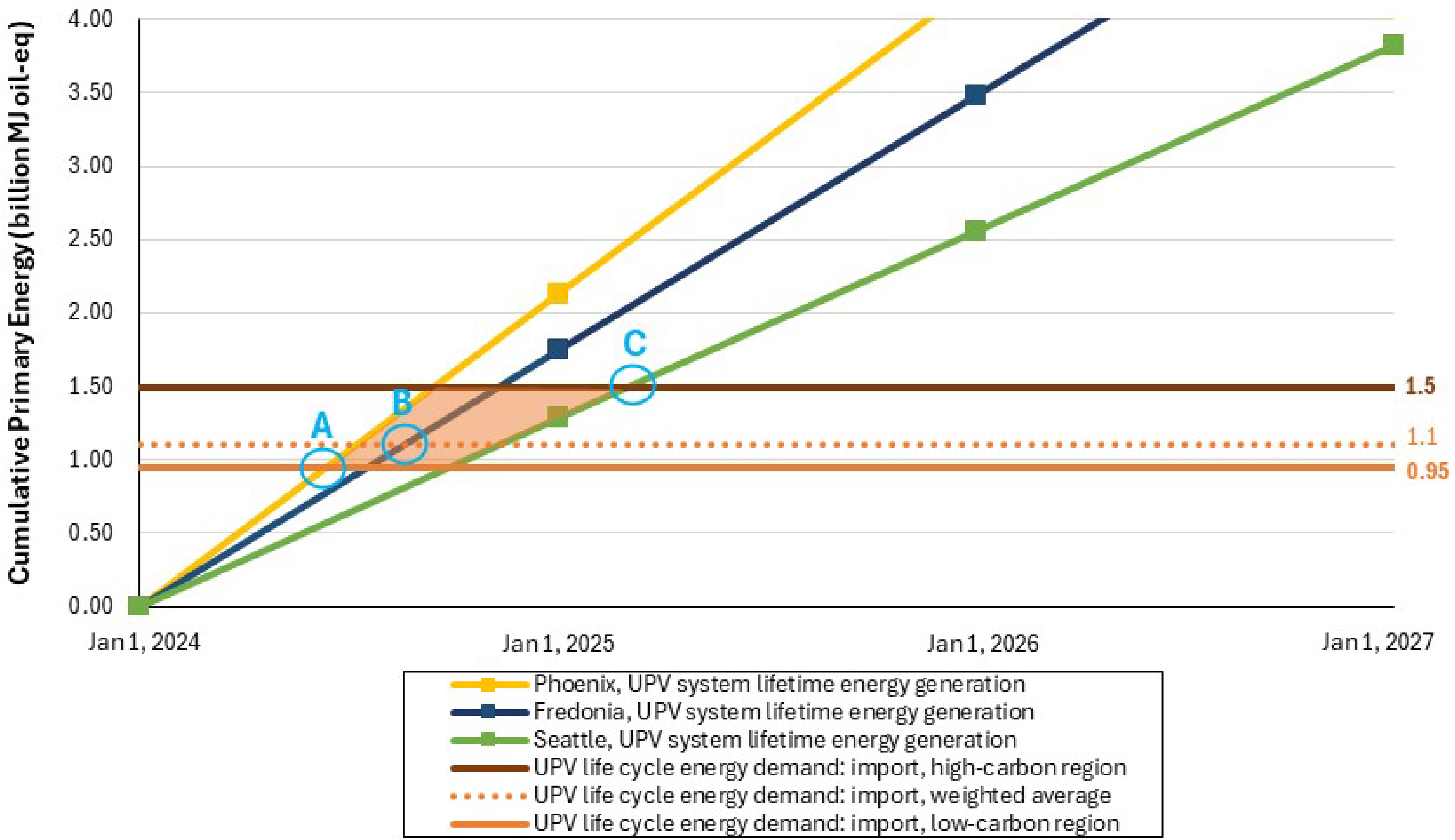


EPBT

A: 0.5 years

B: 0.6 years

C: 1.2 years



Scenario & method sensitivity analysis

For the Kansas mid-case, the “average annual” method gives a CPBT of **<u>7 years</u>**

- >3x the non-linear method CPBT of **<u>2.1 years</u>**

Importance of installation location effects on CPBT:

- PV systems with modules from high-carbon regions achieve CPBTs <4 years for both the high-irradiance/high-emission location (Phoenix) and the mid-irradiance/mid-emission location (Fredonia)
- The effects of the grid mix projection in Seattle were minimal: applying a high future renewable cost scenario for Seattle only reduced the CPBT of systems with high-carbon imported modules to 19 years (5% decrease)
- Conversely, applying a low future renewable cost for Phoenix increases the CPBT to 1.3 years (44% increase)

U.S. Utility PV EPBT & CPBT Fact Sheet

Scan QR code for the fact sheet from NREL

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.

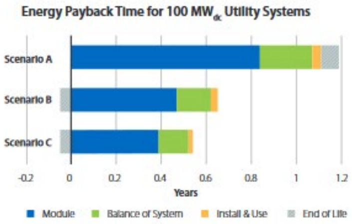


Figure 1. Energy Payback Times for Select Utility PV System Scenarios

Thank you

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