Overview

The objective for this calculation is to determine the greenhouse gas payback time, in years, of a utility-scale solar PV installation. We assume 1.85 m^2 modern glass-backsheet solar PV modules of 366 Wp rated capacity assembled with single crystalline polysilicon PERC wafers (166mm x 166mm, 170um-thick wafers of M6 size), with a capacity per unit area of 197.84 Wp/m^2, and an efficiency of 19.79% produced in either China or Europe, and installed in either China or California.

California case: Panel is installed in California, a region with an average grid CO_2 intensity of 200 g CO_2eq/kWh

China case: Panel is installed in China, assuming a region with a grid CO_2 intensity averaging 620 g CO_2eq/kWh.

Solar PV module assumptions

To convert carbon intensity values of (kg CO_2eq per kg silicon wafer) and (kg CO_2eq per kWp) into (kg CO_2eq per m^2):

- We assume a polysilicon requirement of 2.69 kg/kW (Frischknecht et al., 2020), which compares to a competing value of 2.95 kg/kW in (Müller et al., 2021).
- We assume that the model solar PV module is 366 Wp and has an area of 1.85 square meters (197.84 Wp/m^2), featuring 60 cells using single crystalline polysilicon PERC p-type wafers (166mm x 166mm, 170um-thick wafers of M6 size).

Quartz mining to wafer slicing

The life cycle GHG emissions for quartz mining, MG-Si production, solar-grade polysilicon production, Cz single crystalline polysilicon ingot casting, and wafer slicing in Chinese manufacturing facilities is taken from (Fan et al., 2021).

For the same steps in Europe, we take the sum of carbon emissions for these steps in (Müller et al., 2021), from Figure 4: 32+110+77+13 = 232 kg CO_2eq per kWp (or ~46 kg CO_2eq/m^2)

A brief justification for utilizing values from Fan et al., 2021 for Chinese solar manufacturing chain steps (quartz mining to wafer slicing):

Fan et al., 2021

- Consulted Chinese factories in Shandong, Jiangsu, Ningxia, Yunnan directly and primarily reference Chinese literature sources.

- Primary energy used in production of MG-Si was converted into standard coal.
- Find the cradle-to-gate life cycle impact to be **775 kg CO2 per kg** mono-Si in 156mm x 156mm, 180 um wafers of M0 size (Table 7). Scope encompasses quartzite mining to wafer slicing.
- Assuming **2.69kg mono-Si per kWp**, this is **2085 kg CO2 per kWp**.

Müller et al., 2021

- Largely cites an unpublished paper (Friedrich et al., Global Warming Potential and Energy Payback Time Analysis of Photovoltaic Electricity by Passivated Emitter and Rear Cell (PERC) Solar Modules) and Ecoinvent 3.7 for life-cycle inventories.
- Calculated GHG emissions of **509 kg CO2 per kWp** from MG-Si production to Wafer production steps, not including upstream quartzite mining. Wafers are 166mm x 166mm, 170um wafers of M6 size.
    - From Table S5, it appears that MG-Si production is assumed to primarily use wood chips and petroleum coke for industrial heat needs, but in Xinjiang these heat requirements are likely supplied largely by coal, as assumed by Fan et al., 2021.
    - From Table S6, it appears that 1 kg Siemens solar-grade polysilicon production assumes considerably lower electricity needs (72 kWh versus 113 kWh in Fan et al., 2021), lower MG-Si needs (1.13 kg MG-Si per kg solar-grade poly-Si versus 1.4 kg MG-Si in Fan et al., 2021) and assumes that 70 MJ of process heat is provided by natural gas as opposed to coal.
    - From Table S7, it appears that inventory data are either mistyped or wrong entirely, as the table implies that 0.64 kg of solar-grade poly-Si are used to produce 1 kg of Cz sc-Si. Electricity and NaOH requirements for Czochralski ingot production and wafer-slicing closely match Fan et al., 2021, suggesting that technological assumptions are nearly identical.
    - Table S8 assumes natural gas rather than coal for industrial heat needs, but to be fair heat requirements for wafering and bricking are minimal (1.8 MJ/kg wafer).

Cell production, module production, transportation, and end-of-life

For both Chinese and European production, we take the sum of carbon emissions for these steps in (Müller et al., 2021), whose assumptions regarding regional electricity grid carbon intensities, shipping, and end-of-life recycling are appropriate for manufacturing plants in China versus Europe.

China: (69+196+25+13 = 303 kg CO_2eq per kWp or 60 kg CO_2eq/m^2)
Europe: (52+175+4+13 = 244 kg CO_2eq per kWp or 48 kg CO_2eq/m^2)

To account for the possibility of highly coal-intensive aluminum in Chinese solar PV module frames, we subtract 74 kg CO2/kWp solar from the above Chinese value, based on Figure 5 of Müller et al., 2021, to avoid double-counting. We assume 15 tons of aluminum per MW of solar PV capacity, based on a recent Bloomberg New Energy Finance analysis. This corresponds to 15 kg Al per kWp.

The dirtiest aluminum on the market is around 20 tons CO2 per ton of aluminum, based on a report from the International Aluminum Institute. This equates to 300 kg CO2 required to produce the 15 kg Al in 1 kWp of solar PV modules.

The new Chinese value for cell production, module production, transportation, and end-of-life becomes: 303 - 74 + 300 = **529 kg CO2 per kWp**.

Total life-cycle carbon intensity of solar PV

Adding together these three separate calculations of GHG impacts associated with three separate groups of steps in the solar PV life cycle, we obtain a lifetime carbon footprint of 2614 kg CO_2eq / kWp for a solar PV module manufactured in China, and 476kg CO_2eq / kWp for a module produced in Europe.

Life cycle stage	High Case (China) carbon intensity (kg CO_2eq / kWp)	High Case (China) Reference	Low Case (EU) carbon intensity (kg CO_2eq / kWp)	Low Case (EU) Reference
Quartz mining to wafer slicing	2085 [509]	Fan et al., 2021 [Müller et al., 2021, not used]	232	Müller et al., 2021
Cell production, module production, transport, and end-of-life	529	Müller et al., 2021	244	Müller et al., 2021
Total	2614		476	

Carbon payback period calculation

Although in practice operational factors like solar irradiance, lifetime, and performance ratio varies around the world, we make the following standardized assumptions.

California case: average current grid CO_2 intensity of 200 g CO_2eq/kWh
China case: average current grid CO_2 intensity of 620 g CO_2eq/kWh.

Let's assume 1 kWp of solar PV with 20% capacity factor in both cases, yielding 1752 full load hours per year. We further assume a 0.912 correction factor for average degradation over lifetime and a 0.944 correction factor for grid losses. This gives 1508 full load hours per year, or 1508 kWh annually.

Avoided grid emissions per year from 1 kWp of solar PV:
Case 1 (California): 301.6 kg CO_2eq/yr
Case 2 (China): 935.0 kg CO_2eq/yr

Lifetime emissions = 2614 kg CO_2eq / kWp for a solar PV module manufactured in China, and 476 kg CO_2eq / kWp for a module produced in Europe.

Case 1 California solar farm GHG payback time:

- **PV panel manufactured in China:** 8.7 years
- **PV panel manufactured in Europe:** 1.6 years

Case 2 China solar farm GHG payback time:

- **PV panel manufactured in China:** 2.8 years
- **PV panel manufactured in Europe:** 0.5 years

Over a 30-year generation lifetime, this implies a carbon intensity of 58 g CO_2eq / kWh for a Chinese-made solar PV module, and 11 g CO_2eq / kWh for a European-made panel.

We then conservatively assume that solar PV farm construction involves few differences between China and Europe or the United States. Neither Müller et al., 2021 nor Fan et al., 2021 calculate solar farm construction life-cycle impacts, so we derive the carbon intensity of these steps from UNECE, 2021, Figure 25. This figure implies that balance-of-system (BOS), inverters, grid connection, and operations and maintenance (O&M) life cycle impacts make up ~18% of the total footprint of 36.7 g CO2eq/kWh of solar PV electricity generation, or **6.6 g CO2/kWh**. A full half of these emissions are construction and O&M impacts, where most emissions will be transportation fossil fuels regardless of solar farm location. Thus, the carbon intensity of the inverter equipment is on the order of ~2 g CO2/kWh out of that amount.

More fossil-intensive Chinese-made inverters and grid equipment could increase this amount somewhat, but the addition is likely negligible. This is a relatively coarse addition that could be improved upon.

This increases the above per-kWh carbon intensities of Chinese-made and European-made solar PV modules to 65 g CO_2eq/kWh and 11 g CO_2eq/kWh, respectively.

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