A Polysilicon Learning Curve and the Material Requirements for Broad Electrification with Photovoltaics by 2050

Brett Hallam,* Moonyong Kim, Robert Underwood, Storm Drury, Li Wang, and Pablo Dias

Herein, the current and future projected polysilicon demand for the photovoltaic (PV) industry toward broad electrification scenarios with 63.4 TW of PV installed by 2050 is studied. The current polysilicon demand by the PV industry in 2021 is equivalent to the consumption of 2.9–3.3 kt GW⁻¹. Depending on the physical constraints determining the lower limit for future polysilicon consumption, the annual demand can be 6–7 Mt year⁻¹ in 2050 under broad electrification, which requires 10–12 times more of the current production capacity. To achieve broad electrification by 2050, cumulative demand of 46–87 Mt is required. An electricity requirement for purification, ingot pulling, and wafering of ≈360–380 kWh kg⁻¹ for silicon wafers and carbon intensity can lead to a cumulative amount of ≈16.4–58.8 Gt of CO₂ eq emissions by 2050. To reduce the environmental impact, efficiencies are increased, thinner wafers are used, kerf loss reduced, alternative purification methods with low emission intensities are explored, and opportunities for polysilicon production with decarbonized electricity are explored.

1. Introduction

Extreme weather events are increasing in severity and frequency, and the world is on a trajectory to reach well over 1.5°C regardless of whether nations can reach their net-zero targets.[1] The primary cause of the temperature rise is due to increases in greenhouse gas (GHG) emissions, mainly carbon dioxide (CO₂). A significant source of GHG emissions is fossil fuel-based electricity generation, such as coal-fired power plants, which require almost 0.9 kg CO₂ eq kWh⁻¹.[2] The year 2020 experienced a 5% reduction in GHG emissions due to COVID-19; these recordbreaking events were shortlived, however, as global economies have been pouring stimulus cash into fossil fuels to aid the recovery from the Covid-19 recession, and in 2021, global CO₂ emissions jumped back to their highest emission levels in history.[3] This rapid regression to our prepandemic fossil fuel dependency demonstrates that fundamental change is necessary to reduce global GHG emissions.

Approximately 66% of electricity usage globally is generated from high-GHG emitting sources.[4] One critical approach to reducing GHG emissions is decarbonizing the electricity sector through renewable energy technologies like photovoltaics (PV) or hydropower. The cost of implementing renewable energy technologies has been declining rapidly; the cost of the crystalline PV on a utility scale was reported to be $0.03–0.041 kWh⁻¹.[5] This price level provides opportunities for sustainable development goals impacting society and economics, primarily access to clean and affordable energy. The cost of large-scale PV is well below that of any fossil fuel technologies.[6]

This year in 2022, the world finally reached 1 TW of cumulative PV installed capacity,[7] with the capability of generating the equivalent of around 2–4 PWh worth of electricity each year. Compared with the annual primary energy demand of 154.6 PWh and the generation from fossil fuel-based plants of 128.5 PWh[8] in 2020, the generation from PV is small but not insignificant at 0.86 PWh. Although PV has significantly lower energy production levels compared with fossil fuels, the PV industry has demonstrated sustained growth at 20–30% per annum for decades.[9] If such a significant growth rate is continued into the future, the PV industry may surpass fossil fuel energy generation, especially when considering the low annual energy demand growth rate of ≈1.9% for fossil fuels.[9] The world is projected to reach 1 TW year⁻¹ annual capacity by 2030,[10] which demonstrates the potential to decarbonize the electricity industry. Projections indicate that to head toward
net zero by 2050, the cumulative installed PV capacity could be in the range of 15–60 TW, depending on what capacity is assumed for other energy technologies such as wind and energy storage. The broad electrification scenario from the International Technology Roadmap for Photovoltaics (ITRPV), originally from a study by Ram et al., assumes that 69% of primary energy supply will be PV with 63.4 TW of cumulative installed capacity by 2050. The path along the way includes an expected 1.4 TW year−1 production by 2030 and 4.5 TW year−1 by 2050. Another key study by Verlinden highlighted that the annual production in 2030 may need to be substantially higher, at around 3 TW year−1, when accounting for the 25-year operational lifetime of PV modules and the subsequent impact on recycling, to ensure a stable long-term market size.

A key challenge for the PV industry is ensuring sustainable PV manufacturing and deployment at the TW scale. Given the significantly larger overall material requirements for PV compared with fossil fuels, achieving broad electrification will require substantial industry investment. The PV industry is expected to expand 7–15 times current PV annual production capacities by 2030, and annual growth rates in the range of 25–35% would be required to reach broad electrification. Further growth of 1.5–3 times in the subsequent 20 years to 2050 would also be required.

Concerns on sustainability for PV manufacturing are often focused on scarce and rare materials, given the limited amount of global mining, refining, and purification of such materials, and hence the risk of resource depletion. Scarc materials typically also have high costs, a factor that must be considered for deploying ultralow-cost PV, where each industrial large-area solar cell manufactured costs around $1 based on a module manufacturing cost of $0.2 W−1, including incorporating the cell into the finished module. Key scarce materials of concern include silver, indium, and bismuth where silver is common to all mainstream industrial silicon solar cell technologies, while indium and bismuth can be introduced with changes in solar cell technology such as silicon heterojunctions and future tandems, tellurium for thin film, and gallium when used as a key element in the solar absorber such as III–V materials and CIGS.

Vast quantities of abundant materials widely used for the deployment of TW scales of PV, such as aluminum and polysilicon (poly-Si), will be required, and their impact on the industry must be explored. Last year, the aluminum price spiked by more than 60%, and the poly-Si price increased almost 300% from $10 to $39 kg−1. The price surge was due to supply chain issues for poly-Si, similar to issues experienced almost 20 years ago. During the 2000s, the rapid growth of the PV industry resulted in a significant increase in poly-Si demand that the producers failed to meet. This increase in demand and inability to rapidly increase production capacity resulted in a price hike for PV, evident in the typical PV cost learning curve presented in the ITRPV. Around 2011–2013, a subsequent severe overcapacity and oversupply as new poly-Si plants came online led to rapid cost reductions. By 2014, PV prices had stabilized, and the PV industry used 90% of the global poly-Si supply.

The price of poly-Si rapidly increased since late 2020, primarily due to poly-Si demand outpacing production capacity. The recent price increases for aluminum and poly-Si, along with price increases of other key abundant materials for PV such as steel, glass, and copper, saw module manufacturing costs rise from $0.2 W−1 to $0.26–0.28 W−1 in 2021, putting the future of PV projects in jeopardy.

Overall, the emissions intensity from PV-generated electricity at 15–50 g CO2eq kWh−1 is more than an order of magnitude lower than the emissions per electricity from fossil fuel-based power plants such as coal at 700–910 g CO2eq kWh−1. Therefore, every 1 TW worth of PV deployed that can typically generate 2–3 PWh annually over the operation lifetime can avoid the generation of 1.4–2.6 Gt CO2eq year−1. Key features of PV in achieving this include the long operation lifetime of PV modules in the field of 25–30 years and the fact that little-to-no emissions are generated during operation in the field. For the broad electrification scenario with 60 TW of PV installed by 2050, this could equate to 71–89 Gt CO2eq of saved emissions, 15–17% of the global carbon budget toward net zero by 2050.

However, emissions generated during PV manufacturing and deployment must not be forgotten. The mining and purification process for many materials used for PV is emissions intensive, creating significant global warming potential (GWP) risk. Lennon et al. recently highlighted that by 2050, the aluminum demand could require 40% of primary Al supply, with a GWP of 1.1 Gt CO2eq, even with efforts to decarbonize Al production and reduce Al consumption in the PV industry significantly. If PV emissions are translated to a functional unit of tonnes CO2eq GW−1, the GWP is in the range of 0.26–1.20 Mt CO2eq GW−1. The introduction of a carbon tax at $40 tonne−1 CO2eq could increase the deployment cost of a 500 W module by $25, a 20% increase to the spot market prices of 0.36 AU$ W−1 for module costs in 2021.

Similar concerns can also be raised for silicon, the semiconducting absorber of choice for more than 95% of deployed PV. The mining and purification of solar-grade silicon and crystal growth process for Czochralski silicon wafers are energy and emission intensive to bring the material to the required quality. The life cycle assessment (LCA) method is also used to investigate the material, and electricity consumption, associated carbon dioxide equivalent (CO2eq) emissions, and opportunities to reduce the poly-Si-related emissions for deploying PV at the TW scale are also highlighted.

2. Estimates of Poly-Si Consumption for PV

2.1. Poly-Si Consumption Learning Curve

Over the past 8 years, the poly-Si required per watt in the PV industry has substantially reduced by a factor of 2.5. These rapid reductions in poly-Si are primarily due to the reduced wafer thickness, improved diamond wire sawing to reduce kerf-loss, and continual improvements in cell efficiency/module power output. From this work, we estimate a halving in poly-Si consumption from 2015 to 2020. The current value is aligned with
estimates of a midrange value for 2030 by Kavlak et al.,24 highlighting the rapid progress of the industry.

**Figure 1** shows the poly-Si consumption per unit of power (CPP) in units of g W⁻¹ and corresponding poly-Si remaining in a finished solar cell/module as a function of the cumulative installed PV capacity (P_total). The consumption based on the industry (CPP_industry) showed significantly higher values compared with the consumption in the cell and module level (CPP_cell/module). The values that are used to calculate CPP_industry and CPP_cell/module can be found in Table S1, Supporting Information. However, a more rapid trend of reduction in CPP_industry is shown, which had a learning rate (LR) using Equation (3) (LR_industry) of 29.3 ± 2.0%, which was higher than that of cell/module level (LR_cell/module) with a value of 7.6 ± 0.7%. While more investigation needs to be done to understand such difference, the gap between poly-Si demand by the PV industry and poly-Si utilized in finished solar cells is reducing, likely due to improved diamond-wire sawing with reduced kerf loss. For the overall poly-Si learning rate, we assume the learning rate of poly-Si consumption follows from LR_industry to LR_cell/module where the LR is equal to LR_cell/module when LR_industry ≥ LR_cell/module. It is important to note that, however, the calculated LR in this study does not necessarily account for any potential improvements in technology.

Based on the assumed values of dimension, usage, utilization, and efficiency, poly-Si consumptions can be estimated, which are shown in horizontal lines. With the cell thickness (t), efficiency (η), and utilization rate (U) of 170 μm, 20%, and 70%, respectively, for example, the poly-Si consumption is estimated to be 2.83 kt GW⁻¹. This is close to the most recent value of CPP_industry of 2.88 kt GW⁻¹. For the wider range of values of historical poly-Si consumption, please see Table S2, Supporting Information.

Ideally, a finished 166 mm solar cell with a thickness of 175 μm contains ~11.2 g of poly-Si. With an efficiency of 22.8% based on an industrial passivated emitter and rear contact (PERC) cell,30 the estimated poly-Si consumption is 1.79 kt GW⁻¹. EPDs25,26 have been utilized to find the poly-Si CPP at the module level, which is more representative of the environmental impact of PV deployment. The estimated CPP_cell/module is in the range of 1.51–1.9 kt GW⁻¹. Based on these values, at a bare minimum, the installation of 168–191 GW of PV in 2021 would have required 254–362 kt of silicon wafers and, therefore more than 30 billion solar cells manufactured. This solar cell production, however, does not account for the inefficiencies in poly-Si utilization throughout purification, ingot growth and wafering, and chemical processes during cell fabrication. This was considered by Kavlak et al. in 2015, with an estimated utilization factor of 45% (see Table S2, Supporting Information), giving an overall consumption of ≈6.63 kt GW⁻¹. By analyzing recent global poly-Si demand and PV deployment, the poly-Si consumption for 2020 was ≈3.6–3.9 kt GW⁻¹ (a total of 452 kt), providing an estimated utilization factor of 46–50%. This range of values is higher than the utilization rate reported from NorSUN’s EPD, from 33.7% to 41.9%. The value in the study, however, is the value of conversion directly from the ingot to wafers. In 2021, the estimated poly-Si demand continued to grow to 549 kt, with poly-Si consumption slightly reducing to 2.88–3.27 kt GW⁻¹.

**2.2. Estimates for Global Poly-Si Demand in PV Towards 2050**

This section discusses the global poly-Si demand and projected cumulative poly-Si demand. Based on the broad electrification scenario as proposed in ITPRV 20219 and the learning rate that was discussed in the previous section, **Figure 2a** shows annual poly-Si demand. The historical values are from different references, while the estimated values are based on linear interpolation. Projected poly-Si demand is based on the learning rates where the bottom uses the value of 29.3% while the upper range uses the LR from both LR_industry to LR_cell/module where LR = LR_cell/module when projected CPP_cell/module ≥ projected CPP_industry. The other lines use the examples from Figure 1. The value of annual poly-Si demand is expected to rise from 0.55 to 1.8–5.7 Mt year⁻¹ by 2050, which is close to a factor of about 3–11 increase when the learning from CPP_industry and CPP_cell/module is considered.

Using the learning rates and values for estimated CPP, **Figure 2b** shows the cumulative values of poly-Si demand. By the scale of broad electrification in 2050 with 63.4 TW, the projected cumulative demand is estimated to be 46–87 Mt of poly-Si. Compared with the historical value of the estimated cumulative poly-Si demand of 5.7 Mt, the estimated projected demand will be close to an order of magnitude more, which can be higher if poly-Si consumption is limited to the other examples that are shown in lines.

**3. Environmental Impact and Embodied Energy to Produce Silicon Wafers**

**3.1. LCA and Emission Intensity of Poly-Si Usage for PV**

While the emissions from PV production are considerably less compared with fossil fuel power plants, for every TW of production, the emissions from production can still contribute to global warming. Therefore, it is still inevitably important to reduce the carbon footprint. Using several EPDs and the LCA method for both cell and module production, it is evident that silicon wafer
production can contribute to over 37% of the CO$_2$-eq kWh$^{-1}$ produced.\textsuperscript{[25,26]}

Considering that 97% of wafers are produced in China,\textsuperscript{[27]} with a high penetration of fossil fuels in consumed electricity of 68%,\textsuperscript{[28]} there are significant GHG emissions and a high GWP factor associated with the production of silicon wafers from quartz from the mining stage. Figure 3 highlights the process flow of monocrystalline silicon wafer production, the breakdown of electricity consumed and GHG emitted for each step, and the material loss in each process. The figure demonstrates the material requirement, electricity usage, and the CO$_2$-eq emission for 1 kg of solar-grade poly-Si, which equates to 0.62 kg of silicon wafers. Based on the poly-Si consumption in 2021, such an amount is equivalent to $\approx$340 W. Therefore, for every 1 kg of silicon wafers (or 560 W of modules), it will require 6.5 kg of quartzite. Mining, furthermore, has social and environmental impacts: we want to reduce the poly-Si requirement and losses, to reduce those impacts.

Current estimates from LCA suggest that the silicon wafer, including mining, refining, poly-Si purification, ingot growth, and wafering, contributes $\approx$65% of the CO$_2$-eq emissions to fabricate a 20.3% efficiency Trina Duomax Twin (TSM-DEG17MC.20(II)) PERC module.\textsuperscript{[25]} Mining and production of metallurgical grade (MG) silicon require $\approx$18.2 kWh of electricity for each 1.4 kg of MG silicon,\textsuperscript{[12]} which in turn is used to make 1 kg of highly purified solar-grade poly-Si. It also requires 70–90 kWh of direct electricity in newer-generation Siemens reactors.\textsuperscript{[29]} Ingot growth from 1 kg of solar-grade poly-Si requires $\approx$41 kWh of electricity for crystal growth and wafering to produce 0.62 kg of Si wafers. The total value gives an estimated direct electricity requirement of $\approx$161–375 kWh kg$^{-1}$ Si wafer$^{-1}$. Electricity is primarily sourced from fossil fuels, such as coal (0.7–1 kg CO$_2$-eq kWh$^{-1}$ for Chinese electricity), and the emissions for direct electricity requirements for Si wafers are in the vicinity of 244–300 kg CO$_2$-eq kg$^{-1}$ Si wafer$^{-1}$. The emission is compared to a study by Fan et al.,\textsuperscript{[30]} which can be found in Figure S1, Supporting Information. The total emissions from processing and electricity demand are 360–680 kg CO$_2$-eq kg$^{-1}$ Si wafer$^{-1}$, which can be converted to 0.59–1.1 tonne CO$_2$-eq kW$^{-1}$ with 1.64 kg Si wafer kW$^{-1}$. Such estimation of GWP per power is similar to the values from another LCA study, which depended on where the PV was produced from.\textsuperscript{[31]} The study also reported that the emission from module manufacturing could also be significant, up to 26.7% from a monofacial module, which mainly comes from the aluminum frame or...
Nevertheless, using the emission intensity values from the wafer productions, 99–213 Mt CO$_{2eq}$ emission is estimated for 2021 production of 168–191 GW alone. Moreover, to achieve the broad electrification scenario of 63.4 TW by 2050, based on the cumulative silicon demand (see Section 3.2), the emission will lead to 16.4–58.8 Gt CO$_{2eq}$.

Although China produces the majority of silicon wafers, it is important to note that the emission intensity for electricity consumption varies worldwide. Countries such as Norway or the lower regions of Australia (Tasmania) experience high penetration from hydropower, which can significantly reduce the emission intensity of electricity to values closer to $\approx 0.013$ kg CO$_{2eq}$ kWh$^{-1}$. Such low intensity can also be achievable using PV energy, which can lower the emission intensity as low as 246–304 kg CO$_{2eq}$ kg Si wafer$^{-1}$ and would lead to only 11.3–26.5 Gt CO$_{2eq}$ for total electrification of 63.4 TW.

3.2. Outlook for Opportunities to Reduce the Emission Intensity from Poly-Si Production

There are a number of methods that can be done to reduce the environmental impact of silicon wafers. The primary method is to enhance the PV efficiency. Increasing the efficiency from 20% to 30%, for example, will lead to further reductions in the environmental impact by reducing the CO$_{2eq}$ per unit of power that is associated with the module and balance-of-systems components. Furthermore, the economies like levelized cost of energy and environmental impacts of other components can be greatly reduced.

Another method could be reducing the electricity requirements for purification in the vicinity of 25 kWh kg$^{-1}$ of SoG Si using a fluidized bed reactor (FBR) or upgraded metallurgical-grade (UMG) silicon. FBR is known to have significantly lower-carbon footprint and energy requirements compared with the Siemens process, which is widely used to produce pure poly-Si. GCL-Poly recently announced to demonstrate that their 10 000 MT FBR plant has achieved monocrystalline purity requirements. Furthermore, the company claimed to achieve 20 kWh kg$^{-1}$ with an emission reduction of at least 47.7%. However, it must be noted that using lower-quality silicon stock to produce silicon solar cells would expect to reduce the efficiency limit, which may or may not be a competitive option.

Recycling PV modules to extract silicone may also assist with reducing emissions intensity, depending on the energy requirements for treating recycled silicon material to a suitable quality for wafers. While recovering wafers from modules without contamination or breaking will be challenging, the wafer would generally have high purity, which can potentially be fed back into a molten ingot.

Thinning wafer thickness can also reduce the environmental impact. One study demonstrated a silicon heterojunction solar cell with an efficiency of 23.3% and thickness of only 56 $\mu$m. Another study demonstrated potential to achieve over 30% efficiency using ultrathin silicon in interdigitated back-contact (IBC) structure. While a high-performance cell is promising using a thin wafer, they will likely bring more technical challenges too. Thin wafers may reduce mechanical yield, which can mainly impact other manufacturing processes like screen printing or high-temperature processes. It must be managed to ensure high production yields. An increased utilization factor through epitaxial growth or lift-off approaches could greatly reduce the silicon requirements if performance is not adversely affected.

Another aspect of reducing the emission is hydrogen. Given hydrogen gas is required for silicon purification ($0.11$ kg H$_2$ kg$^{-1}$ solar-grade Si), using green hydrogen sourced from PV could reduce the carbon footprint. The emission is comparably less than the electricity required to produce Si wafers, with the electricity requirement of producing hydrogen at only 5 kWh kg$^{-1}$ H$_2$.

Reducing the consumption of poly-Si per unit of power and carbon footprint is crucial to ensure that PV technology is sustainable. Moreover, the growth of the PV market needs to be maximized to ensure the high-carbon-intensive electricity generation using fossil fuel-based power plants that can be placed with PV power plants ($\approx 0.9$ kg CO$_{2eq}$ kWh$^{-1}$). Maintaining a high learning rate of silicon consumption over cumulative PV installed capacity creates opportunities for PV to self-supply and sustainable silicon in the future if it can be appropriately recycled if warranted with the energy required for ensuring the appropriate quality of silicon.

4. Conclusion

In this study, we investigated the polysilicon learning rate in the PV industry. Approximately 63 TWp of cumulative PV installations are required to achieve the most ambitious scenario from ITRPV, the broad electrification scenario by 2050. Such an accelerated growth of the PV industry will significantly impact all PV materials, including those that are abundant in quantity. This article has studied the historical demands of poly-Si for the PV industry and PV production. Future poly-Si demands have been estimated through learning rates. Lower limits were estimated based upon combinations of wafer thicknesses, utilization factors for silicon (e.g., kerf-loss), and module powers. The current learning rate was estimated to be 29.3 $\pm$ 2.0%. However, based on the geometry of cells and modules and the current trend of their performances, the rate is expected to be reduced to 7.6 $\pm$ 0.7% when >3 TW of cumulative PV installed capacity is reached.

Using the learning rates and the broad electrification scenario, the annual and cumulative poly-Si demands by 2050 are expected to be 1.8–5.7 Mt of poly-Si year$^{-1}$ and 46–87 Mt of poly-Si, respectively. While silicon is an abundant element, it will still be a challenge to supply such a significant amount of poly-Si demand compared to the last year's demand and supply of only about 0.5 and 0.7 Mt, respectively.

From the environmental point of view, the LCA has been analyzed to ascertain the GHG emissions from poly-Si mining, refinement, and processing required if we reach broad electrification levels of PV. When carbon-intensive electricity sources are used, it can be equivalent to 360–680 kg CO$_{2eq}$ for 1 kg of silicon wafers or 0.59–1.1 tonne CO$_{2eq}$ kW$^{-1}$. Decarbonizing the electricity source using renewable energy like hydropower or PV, however, can reduce the total cumulative emission of GHG by 5.1–47.5 Gt of CO$_{2eq}$ for a broad electrification scenario.

Future deployment of low-cost PV requires close monitoring of silicon consumption to ensure poly-Si production can grow proportionately with poly-Si demand without the supply issue.
that we have seen in the past. Large expansions in the production capacity of poly-Si will be required in the near future, along with other supporting materials and infrastructure.

5. Experimental Section

Poly-Si Consumption and Learning Curve: Poly-Si consumption values for solar cells and modules were obtained from several sources. The poly-Si contained in recent production modules was obtained from Environmental Product Declaration (EPD) statements from leading panel manufacturers Trina and Jolywood, as well as estimates based on the wafer thickness and cell/module power from the ITRPV. Global solar-grade poly-Si demand was obtained from an analysis by Exawatt for 2018–2020, with estimates provided for 2021–2023. The annual PV production and cumulative PV installed capacity were obtained and averaged from several sources, including the IEA 2020 World Energy Outlook, International Renewable Energy Agency, and the IEA PVPS. Information from the Ecoinvent 3.8 database and the IEA Task 12 PVPS was used in the Life Cycle Inventory (LCI) for Life Cycle Analysis to estimate the CO2-equivalent (CO2-eq) emissions from silicon wafer production and cell/module production.

A learning curve for poly-Si consumption was presented based on global poly-Si demand and annual PV production, along with estimated learning curves based on wafer thickness and cell/module power from ITRPV data and industry sources and reported poly-Si consumption values, including estimates of poly-Si utilization where available. The learning curve and potential lower limits for the physically feasible poly-Si consumption values were then used to estimate future annual and cumulative poly-Si demand toward the broad electrification scenario with 63.4 TW of PV installed by 2050.

Poly-Si consumption per unit of power for the PV industry (CPPIndustry) could be estimated based on

\[
CPP_{\text{Industry}} = \frac{AMD}{\text{APP}} \tag{1}
\]

where

\[
AMD = \text{annual material demand of poly-Si and APP = annual PV production}
\]

In comparison, the value of poly-Si consumption at the cell and module level (CPPCell/Module) was based on PV cell efficiency and module power. Values were from ITRPV 2022, and the minimum poly-Si usage possible in a cell/module was based on the volume of silicon wafers, the density of poly-Si, and the number of cells per module (See Equation (2)).

\[
CPP_{\text{Cell/Module}} = \rho \times t \times \left( \frac{1}{\eta_{\text{Cell}}} + \frac{(A_{\text{Cell}}) \times n_{\text{Cell}}}{P_{\text{Module}}} \right) \tag{2}
\]

where

\[
\eta_{\text{Cell}} = \text{a stabilized cell efficiency of p-type mono PERC}
\]

\[
n_{\text{Cell}} = \text{number of cells for a module}
\]

\[
A_{\text{Cell}} = \text{a cell area}
\]

\[
P_{\text{Module}} = \text{a module power}
\]

\[
\rho = \text{silicon density, which is assumed to be } 2.329 \text{ g cm}^{-3}
\]

\[
t = \text{thickness of a silicon cell}
\]

For values of \(\eta_{\text{Cell}}\), they are based on different ITRPV editions from 2nd to 13th editions. For the ITRPV edition that did not explicitly state the p-type mono-PERC efficiency, p-type monoefficiency was used instead. Note that p-type mono was not necessarily the dominant PV technology in earlier years. However, for simplicity, the calculation was based on p-type mono values without considering the market share percentage and different poly-Si consumption. The values did not account for any utilization rate and were only based on geometry and the annually reported performance of cells or modules. They are based on the dimensions and stabilized efficiency only such that the value represents the 100% utilization scenario. Therefore, as the industry value accounts for any loss such as yield loss and kerf-loss from ingot-to-wafer to produce the corresponding annual PV capacity, the value is expected to be higher than the value of CPPCell/Module; hence, it represents the technological learning rate limit.

However, note that the learning rate can be enhanced when we account for a breakthrough technology that can yield significantly thicker silicon wafer or performance beyond the single-junction performance limit using a tandem structure, for example.

Based on the historical values of poly-Si consumption (CPP) and the cumulative installed PV capacity \(P_{\text{installed}}\), the learning curve can then be estimated, which can be fit using the Equation (3).

\[
CPP(P_{\text{installed}}) = C \cdot P_{\text{installed}}^{L} \tag{3}
\]

Where LR is a learning rate, and C is a prefactor.

Life Cycle Assessment for Poly-Si Production: A LCA was conducted using the software application OpenLCA. The LCA considered the life cycle stages from mining through to solar-grade (SoG) ingot production, with a functional unit of 1 kg of SoG silicon ingot produced. This metric was used to compare the study by Fan et al. These results could then be extrapolated outside of LCA to get an approximation for high-level values of global poly-Si usage in the PV industry.

Two key sources were used for the database to complete the LCA: First, the Ecoinvent 3.8 database was used as a baseline for key processes of silicon wafer production. However, through private correspondence, it was confirmed with Ecoinvent that this data had no recent major update for many processes. Therefore, where possible, LCI data inputs for the LCA were updated using the 2021 Fan et al. values for silicon wafer production.06

Once the LCI inputs were finalized, a life cycle impact assessment (LCIA) was conducted using the well-known ReCiPe hierarchical model to determine key midpoint environmental impacts. The environmental impact category of focus was climate change or global warming, which had LCI outputs measured in kg CO2-eq.

Following the results of the LCIA, methods to reduce the impacts on emission intensity can be addressed by first understanding the GHG emission per generated electricity in kg CO2-eq kWh−1, which can then be compared to methods in the literature for reducing the environmental impacts, such as decarbonization of the electricity used in the fabrication of silicon wafers in terms of kg CO2-eq kWh−1. The LCA was key in forming the basis for understanding the current environmental impacts of poly-Si production in the PV industry on a global scale.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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