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ANALYSIS OF THE ELECTRICITY CONSUMPTION FOR THE PRODUCTION OF ELECTRONIC-GRADE POLYSILICON

A study on behalf of Wacker Chemie AG

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Content

1 Motivation and Scope

The manufacturing of high-purity polysilicon is central to the photovoltaic (PV) and electronics industries. As the industry shifts to decarbonize and reduce costs, the electricity demand for producing solar-grade (SoG) and electronic-grade (EG) polysilicon has become a critical benchmark for sustainability and competitiveness. This report provides a comprehensive analysis of electricity consumption in the production of EG polysilicon, focusing on process-level breakdowns, specific energy learning rates, and industry benchmarks. Figures and tables throughout the report illustrate key data, trends, and process comparisons, drawing on sources such as the China PV Industry Development Roadmaps (CPIA 2018–2025), W. Si et al. (2024), Bernreuter Research Polysilicon Market Outlooks (2020, 2029), and sustainability/annual reports from leading EG polysilicon producers (Wacker, REC Silicon, Hemlock and Tokuyama).

2 Technology Description

This section describes the main industrial technology for EG polysilicon production, with an overview of the Siemens route processes. Table 1 summarizes the process flow and main reactions, while Figure 1 provides a schematic of the standard process.

Table 1: Overview of Standard Siemens Processes ***(Yadav et al., 2017, Jungbluth et al. 2012).***

Step	Process	Main Reaction	Typical Conditions
1	Trichlorosilane (TCS) Synthesis	$Si + 3.1\ HCl \rightarrow 0.9\ SiHCl_3 + 0.1\ SiCl_4 + 1.1\ H_2$	300°C, fluidized bed
2	TCS/STC (Silicon tetrachloride) Distillation	Separation/purification of $SiHCl_3$ and $SiCl_4$	30–60°C, multi-stage. See Table 2
3	CVD Deposition	$SiHCl_3 + H_2 \rightarrow Si + 3\ HCl$	~1100°C, bell reactor
4	Off-gas recovery	H2 is recovered and reused in the CVD Deposition (reduction of TCS) HCl is recovered and reused in the TCS Synthesis STC is recovered as byproduct	See Table 2
5	Polysilicon rod crushing and etching	Acid etching: mixtures of nitric acid and hydrofluoric acid or Alkaline etching: mixtures of oxidizing agent, strong base (KOH, NaOH) and HCl/HF for base metal removal	Room temperature for acid etching, 70-80°C for alkaline etching

Table 2: Boiling temperatures for TCS/STC distillation and off-gas recovery *(NIST Chemistry WebBook, 2018 and Chase, M.W. 1998).*

Components		Boiling temperature [°C]
Chlorine	$Cl_2(g)$	-33,6
	HCl	-85,1 Very low, but highly soluble in water
STC	$SiCl_4$	56,8
TCS	$SiHCl_3$	31,8
	H_2	-252,8 and low solubility in water
DCS	SiH_2Cl_2	8,1
MCS	SiH_3Cl	-30,4

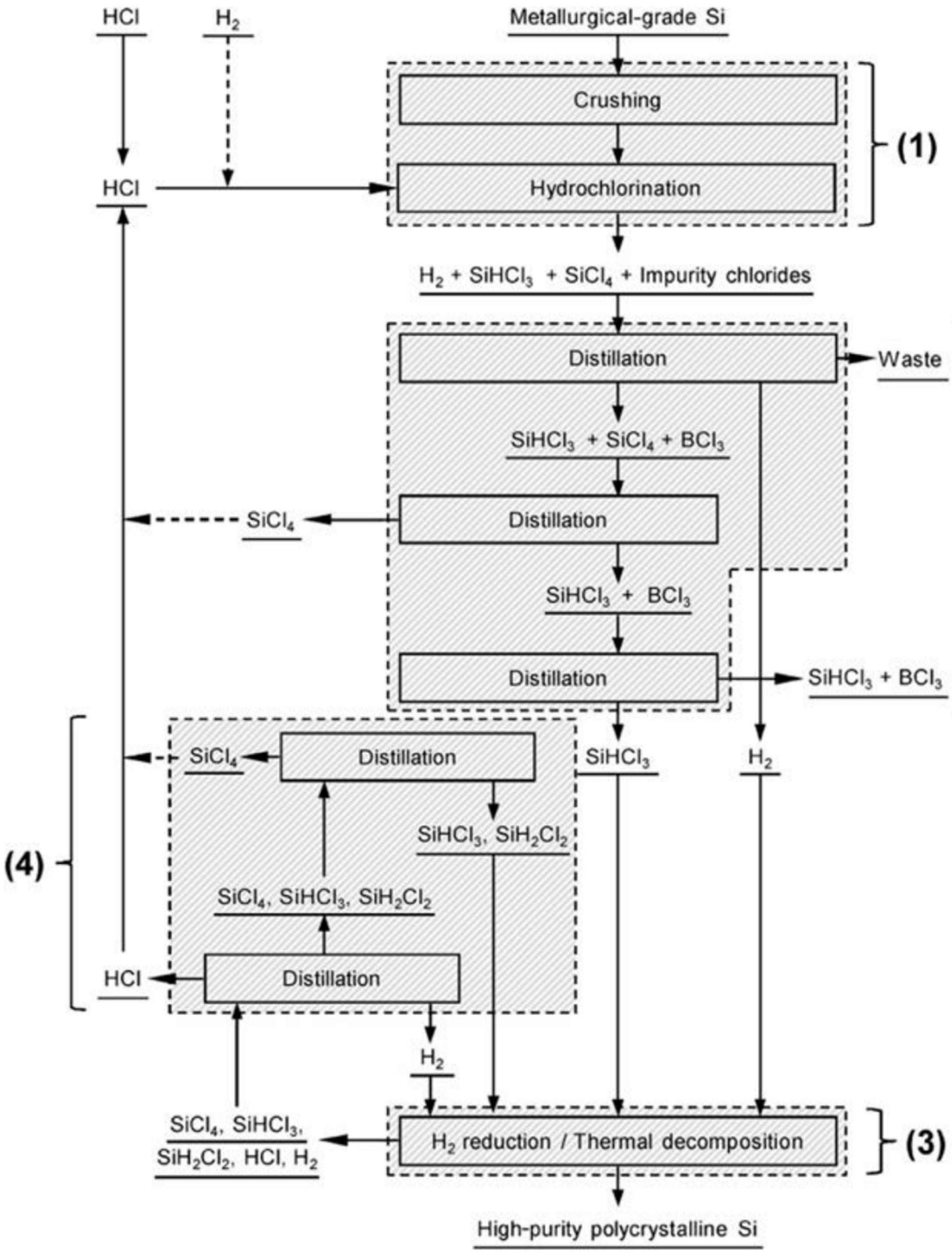


Figure 1: Detailed process flowchart of the Siemens process for polysilicon production. (1) Production of TCS from MG-Si (2) Purification of TCS (3) Reduction/deposition of TCS into polysilicon (4) Recovery and recycle of byproducts. (Reprinted from *Renewable and Sustainable Energy Reviews, Vol. 78, S. Yadav, K. Chattopadhyay, C. Veer Singh, "Solar grade silicon production: A review of kinetic, thermodynamic and fluid dynamics based continuum scale modeling", Pages 1288-1314, 2017*, with permission from Elsevier.)

The main process elements are further described as follows:

- **TCS Synthesis:** MG-Si is reacted with HCl in a fluidized bed to form TCS and STC. The Siemens process begins with the synthesis of trichlorosilane (TCS) through the reaction of metallurgical-grades silicon (MG-Si) with hydrochloric acid (HCl) at approximately 300°C. This reaction generates TCS and silicon tetrachloride (STC) as by-products. The TCS is then purified through a distillation process to remove impurities, which is critical for achieving the ultra-high purity required for EG polysilicon.
- **Distillation:** Multi-stage distillation separates and purifies TCS from STC and by-products chlorides.
- **CVD:** TCS is reduced with H_2 at ~1100°C, depositing high-purity polysilicon on rods.
  - Following purification, TCS undergoes thermal decomposition in a chemical vapor deposition (CVD) reactor, where it is deposited onto electrically heated silicon rods. The deposition occurs at high temperatures, typically around 1100°C, resulting in the formation of polysilicon.
  - Slim rods have an initial diameter of 20 mm. The final silicon rod thickness is set between 150 mm and 180 mm. Silicon rod growing is varied up to 1.9 mm/h depending on the desired rod uniformity.
  - Decreasing TCS mole fraction reduces the density of the gas phase and the convective heat transfer taking place at the rods surface. This improves the temperature uniformity at the rod surface and of rod deposition rate. HCl mole concentration need to be kept low for uniformity as well. These process requirements are crucial for EG polysilicon production.
- **Off-gas Handling and recovery:** H_2, HCl and STC are recovered and recycled. Condensation VCR (Vacuum Gas Recovery) units are used to separate the H_2 and HCl from the chlorosilanes stream. The H_2 is returned to the CVD inlet feed. HCl to the TCS Synthesis. The chlorosilane stream is then distillated to recover TCS/DCS (Dichlorosilane) for the CVD reactor feed. STC is a byproduct and precursor for silicones, silica-based products and for SoG polysilicon production by a modified Siemens route with hydrochlorination of STC.
- **Auxiliary Steps: Crushing, etching, and packaging.**
  - The etching of polysilicon surfaces reduces their roughness and allow the removal of surface metals. It can be performed with acid mixtures of HNO_3/HF or with alkaline etching. The auxiliary steps are relevant for the polysilicon quality but only the etching process is relevant for its electricity consumption.

3 Product Specifications for SoG and EG polysilicon

Product specifications for SoG and EG polysilicon are directly provided by manufacturing companies or referenced to national standards. There are no international standards in place at present. Table 3 compares the key impurity limits for each grade, referencing the Chinese national standard GB/T 12963-2022 and Fraunhofer ISE data from technology transfer projects. EG polysilicon, especially "Special EG" has much stricter specifications in terms of impurities. It can be assumed that higher grades of MG-Si are used to produce EG polysilicon. But from a process perspective, the selection of MG-Si grade does not impact the requirements for polysilicon production.

The polysilicon is either sold as block (irregular shape of chunks distributed along 6 mm to 150 mm) or rod (diameter established between supplier and purchaser).

Polysilicon surface should be dense and smooth (particle size at the edge of cross-sections <3 mm).

Table 3: Product Specifications of SoG and EG polysilicon. ***(Adapted from GB/T 12963-2022, National CN Standard for EG and Fraunhofer ISE data for SoG).***

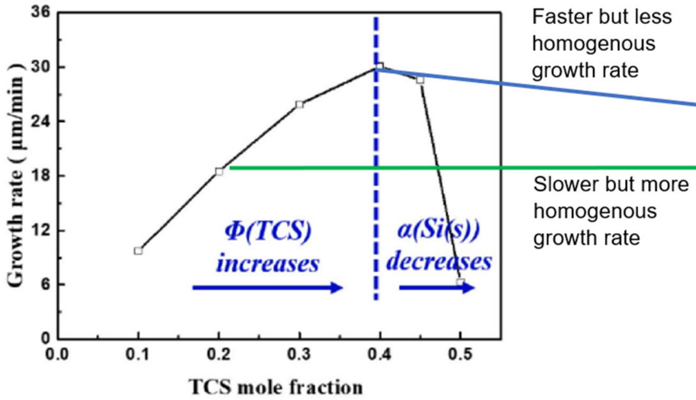
Impurity (total content by atomic number cm^{-3} or ng/g)	**Special EG**	**EG1**	**EG2**	**EG3**	**SoG**	**SoG vs EG3**
Donors (P, As, Sb) (cm^{-3})	≤1.5e12	≤2.5e12	≤5e12	≤1.5e13	≤2.5e14	17× higher
Acceptors (B, Al) (cm^{-3})	≤5e11	≤1.5e12	≤2.5e12	≤5e12	≤5e13	10× higher
Carbon (cm^{-3})	≤1e15	≤2.5e15	≤2.5e15	≤5e15	≤1.5e11	4 orders of magnitude higher
Base metals (total contents of Fe, Cr, Ni, Cu, Zn and Na) (ng/g) (ppbw)	≤0.1	≤0.3	≤0.5	≤2.0	≤1.0	Similar to lower EG. 10x higher than Special EG
Surface metals (total contents of Fe, Cr, Ni, Cu, Zn, Al, K, Na, Ti, Mo, W, Co) (ng/g) (ppbw)	≤0.1	≤0.5	≤1.0	≤5.0	≤1.0	Similar to lower EG. 10x higher than Special EG

4 Processing Differences for Different Polysilicon Grades

This section discusses the process adaptations required for EG polysilicon compared to SoG polysilicon, referencing W. Si et al. (2024), specification norms and industrial expertise. Table 4 summarizes the main differences. The energy intensive CVD reactor process has a significant difference for the production of SoG and EG polysilicon. Slower growing rates on the CVD reactor are used for EG production as an homogenous growth of the rod is desired, this is achievable with a uniform H_2:TCS molar ratio, low concentration of HCl and uniform temperature.
At reduced TCS mole fractions the growth rate of the silicon growth is slower; this has a direct proportional impact on the production cycle time as shown in Figure 2. For SoG polysilicon growing rates of 1.9 mm/h are achievable (Fraunhofer ISE data from technology transfer projects), while for EG polysilicon growing rates of 1 mm/h are plausible (Yang et al. 2025, growing rate to an inlet components mole fraction of H_2 0.8 / TCS 0.2).

Table 4: Processing Differences—SoG vs. EG polysilicon.

Parameter	SoG polysilicon	EG polysilicon	Reference
MG-Si raw material purity	98.5%	99.5%	Fraunhofer ISE internal data from technology transfer projects
Distillation cycles	3	5	Verlinden, 2022; Si et al., 2024
CVD reactor size	Large	Small	Si et al., 2024; Yang et al., 2025
CVD cycle time	Shorter	Longer	Si et al., 2024, Yang et al., 2025
Rod surface smoothness	Lower	Higher	Si et al., 2024, Yang et al., 2025
Surface etching	Less	More	GB/T 12963-2022



Parameters	SoG polysilicon		EG polysilicon	
Cycle time	3,5	Days	6,7	Days
	84	hours	160	hours
silicon rod growing rate	1,9	mm/h	1	mm/h
Initial rod thickness, diameter	20	mm	20	mm
Initial rod height, straight	3000	mm	3000	mm
Initial rod height, U Shaped	200	mm	200	mm
Final rod thickness, diameter	180	mm	180	mm
Rod thickness growth	160	mm	160	mm

Figure 2: Illustration of rod growth rate at different H2:TCS molar ratio and effect on CVD reactor cycle time (Table on the right side: *Fraunhofer ISE calculation*, Graph on the left side: Reprinted from *Chemical Engineering Science, Vol. 295 (120162), W. Si et al., "A revisit from CVD kinetics to CVD reactor: Investigating uniform growth mechanism of polysilicon in a reduction furnace", 2024,* with permission from Elsevier.)

Key Process Adaptations

- **Raw material:** higher grade of MG-Si used for EG polysilicon
- **Distillation:** 1.66× more cycles for EG polysilicon, increasing thermal energy use.
- **CVD:** Smaller reactors, longer cycles, and stricter controls for impurity and uniformity. Silver-plated deposition reactors should be used especially for production of EG polysilicon applications.
- **Etching:** EG polysilicon requires more extensive surface treatment.

5 Resource Consumption for SoG polysilicon: Detailed Analysis of Electricity Consumption per Process, Learning Rate

This chapter presents process-related as well as integrated electricity consumption data for SoG polysilicon production. The information is based on Fraunhofer ISE internal models, CPIA roadmaps 2018 - 2025 and Bernreuter Research Polysilicon outlooks (2020,2029). Table 5 shows an overview of the electricity use per process for the production of SoG polysilicon. For SoG polysilicon, about 60% of the power demand is required by the CVD Deposition process, 15% for the TCS Synthesis and the remaining power demand is distributed along the facilities and VGR condensation units. Table 6 shows the integrated specific electricity demand reported by the SoG polysilicon industry in China. When comparing the "Total (2023)" results in Table 5 with historic numbers in Table 6, it can be stated, that the sum of process specific power demand calculated in Table 5 is consistent with industrial data presented in Table 6.

From the year 2018 to the year 2024 the industry reduced its electricity demand at a learning rate of 2.75 kWh/kg/year. It is expected that until the year 2030 this learning will be reduced, resulting an overall expected learning rate of 1.83 kWh/kg for the period 2018 to 2030. One driver for the SoG polysilicon electricity consumption reduction in the last five years was the increment of FBR (Fluidized Bed Reactor) polysilicon share in the SoG polysilicon market. According to Bernreuter Research Polysilicon Market Outlook 2029, the share of FBR polysilicon increased from a mere 2% in 2020 to 15% for the year 2024.

Considering both the process-wise and integrated specific electricity industry statistics, for the reference year 2023 the specific electricity demand for SoG production was on the range 60-71 kWh/kg.

Table 5: Process-wise Electricity Consumption for SoG polysilicon.

Process Step	**Specific electricity consumption (kWh/kg SoG polysilicon)**	**Reference**
TCS Synthesis	~9 kWh/kg	Verlinden, 2022
Distillation (3 cycles)	0 kWh/kg (Energy provided by CVD reactor wasteheat recovery	Verlinden, 2022 and Yadav et al., 2017.
CVD Deposition	~35-45 kWh/kg (70-85% recoverable as wasteheat)	TaiyangNews, 2017. Yuan et al., 2025. Fraunhofer ISE data from technology transfer projects
Others	16 kWh/kg (for VGR condensation units, Proton Exchange Membranes (PEM) electrolysis to produce H_2, scrubber systems, facilities and ancillary services)	Fraunhofer ISE data from technology transfer projects
Total (2023)	**60-70 kWh/kg**	CPIA 2025, Bernreuter Research Polysilicon Market Outlook 2029 and Fraunhofer ISE data from technology transfer projects

Table 6: Integrated Electricity Consumption for SoG polysilicon *(CPIA 2018–2025 and Fraunhofer ISE technology transfer projects).*

Year	Specific electricity (kWh/kg SoG polysilicon)
2018	71
2019	70
2020	66.5
2021	63
2022	60
2023	60–71 (Fraunhofer ISE technology transfer projects)
2024	54.5
2028	51 (prediction)
2030	49 (prediction)

Expected learning rate:
~-1.83 kWh/kg SoG polysilicon/year between the years 2018 and 2030.

6 Industry Electricity Benchmarks for SoG and EG polysilicon

This chapter presents company-level and industry-wide benchmarks, with Table 7 summarizing recent production data from Bernreuter Research polysilicon market outlooks and annual/sustainability company reports for electricity demand. The specific electricity is calculated by dividing the production data of polysilicon and chlorosilane gases (only available for REC Silicon) by the annual electricity demand reported by the companies. Trends and information for recent years is evaluated in section 7c of this report. The information from Tokuyama is no further used in section 7 as the available energy data is for their broad product portfolio and is also not clear on the share of electricity in the total energy demand.

Table 7: Industry Benchmarks for Polysilicon Production Electricity Consumption.

Company	Year	Product Mix	Specific Electricity (kWh/kg)	Reference
Tokuyama	2019	SoG/EG	274 (all energy types)	Bernreuter Polysilicon Market Outlook 2020 for production data, Tokuyama for energy data.
Wacker	2020	Multi-product	91.9	Bernreuter Polysilicon Market Outlook 2020 for production data, Wacker, Sustainability Report 2019/2020 for electricity data.
REC Silicon	2020	Multi-product	123	REC Silicon, Annual Report 2022 for both production and electricity data
Hemlock	2019	Multi-product	126	Bernreuter Polysilicon Market Outlook 2020 for production data, Hemlock Semiconductor, Sustainability Report 2024 for energy data.
Wacker	2002	EG only	150	Jungbluth et al., 2012

SoG-only values (2023, CPIA and Fraunhofer ISE data): 60–71 kWh/kg.

7 Estimation of Electricity Demand for EG Polysilicon Production

This section presents three methods to estimate the EG polysilicon specific electricity demand: (a) learning curve extrapolation from SoG polysilicon, (b) process-based modeling, and (c) industry benchmarks.

7.1 (a) Learning Curve Extrapolation

The specific electricity consumption for SoG polysilicon presented in Table 6 are used to construct a linear regression of the type Y=a*X+b, where the independent variable X is the year of evaluation, and the dependent variable Y is the specific electricity consumption. The resulting equation and its graphical representation are shown in Figure 3.
As a second step the regression equation was used to estimate the specific electricity for SoG polysilicon for the year 2002. For this year a reliable data point for EG polysilicon is available in the literature as shown in Table 8. The difference of the specific electricity of EG and SoG polysilicon for the year 2002 was used to scale the origin coefficient of the regression equation of SoG polysilicon specific electricity to produce an analogous equation for EG polysilicon. This resulted in the following equation:

$$\text{Spec. Elec.}_{\text{EGpolysilicon}} = -1.9054 \times (\text{Year}) + 3964.62$$

This equation was then used to extrapolate the specific electricity consumption for EG polysilicon for the year 2023. Table 8 shows the historic and predicted values for SoG and EG polysilicon specific electricity demand. The EG polysilicon specific electricity results in an approximately **50 kWh/kg higher electricity consumption for the production of EG polysilicon than for SoG polysilicon** for the year 2023.

Table 8: Historic and extrapolated values for specific electricity demand per kg of EG polysilicon using the electricity consumption learning rate of SoG polysilicon.

Year	SoG (kWh/kg)	EG (kWh/kg)	Reference
2002	100 (predicted)	150	Jungbluth et al., 2012
2023	60	110 (predicted)	CPIA, Fraunhofer ISE

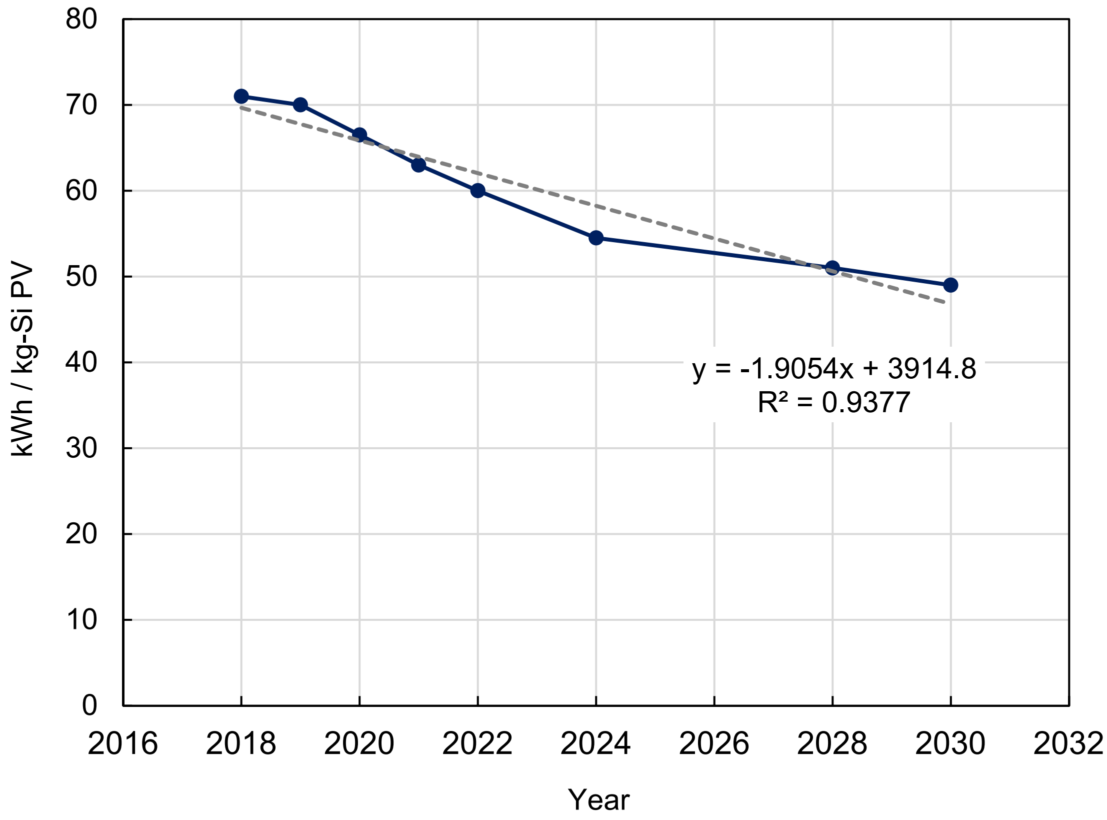


Figure 3. Integrated electricity consumption learning curve for SoG polysilicon from 2016 to 2030.

7.2 (b) Process-Based Estimate

As second estimation method, the processing differences between SoG and EG polysilicon production described in section 4 of this report are considered. Here, the resulting electricity consumption differences between the production of SoG and EG polysilicon are highlighted:

- **CVD step for EG polysilicon:** For the SoG polysilicon a faster growth rate of 1.9 mm/h allows a specific electricity consumption of just 35 kWh/kg. The slower growing rate of 1 mm/h for the EG polysilicon rods results in a specific electricity requirement of ~66 kWh/kg of EG polysilicon. **Thus, the CVD reactor specific electricity consumption for the production of EG polysilicon is ~31 kWh/kg higher than for SoG polysilicon.** It is important to note that polysilicon producers have invested in energy recovery systems that allow them to recover between 70% and 85% of the energy provided to the CVD reactor in from of useful heat. This heat is used to operate the distillation columns and reduces the requirements of primary energy sources, in form of fuels or electricity, for the factories.
- **Distillation:** EG polysilicon production uses five distillation steps, while the SoG polysilicon only requires three distillation steps (Verlinden, 2022). Nonetheless, due to the significant waste heat recovery measures implemented by the industry, the requirements for the distillation steps are provided by the heat recovered from the CVD and TCS synthesis reactors. Therefore, no additional electricity consumption is needed for EG polysilicon production.
- **Etching:** EG polysilicon has stricter surface impurity specifications, as reported in section 3 of this report. The **surface etching of EG polysilicon chunks requires a specific electricity consumption of ~1 kWh/kg** (Fraunhofer ISE internal models). This considers the etching of 1.5% of polysilicon chunks mass with an etching depth of 20 µm. Heat can be partially provided by waste heat recovery from the CVD reactor and TCS Synthesis reactors.
- The specific electricity requirements for the TCS synthesis, H_2 production, VGR condensation units, scrubber systems and facilities are similar for both SoG and EG polysilicon. These processes account for 25 kWh/kg of specific electricity.

The **cumulative process-wise differences in specific electricity consumption for EG polysilicon are 32 kWh/kg higher than for SoG polysilicon**. In absolute terms, this analysis estimates the **total specific electricity consumption of EG polysilicon to be 92 kWh/kg**. The reference SoG polysilicon specific electricity is 60 kWh/kg as reported in section 4 lower range.

7.3 (c) Industry Benchmarks

In this subsection the specific electricity consumption per kg of polysilicon mix grades (see Figure 4) is determined by the division of the reported electricity demand of the companies by their estimated annual polysilicon (see Table 9) and available silane gases (only available for REC Silicon) production figures. Estimates of production data were gathered from Bernreuter Research Polysilicon Market Outlooks 2020, 2029 and companies reports. Electricity consumption was gathered from the companies' annual and sustainability reports. The main conclusions of this analysis are the following ones:

- **Production and electricity consumption data has a poor availability and transparency:** Only REC Silicon reports both data sources. They even report an overall energy intensity of 178 kWh/kg silicon product mix (polysilicon and silane gases) for the year 2022. 76% of their total energy is electricity consumption (137 kWh/kg).
- **Multi-product plants specific electricity requirements:** 80–137 kWh/kg (mix, REC, Hemlock, Wacker) can be calculated allocating all the electricity consumption to their polysilicon production. Considering a specific electricity demand for the SoG polysilicon of 60 kWh/kg (reference value for the year 2023) and considering the production shares of EG and SoG polysilicon (available from Table 9) is possible to calculate a range of **124–166 kWh/kg for the EG polysilicon specific electricity for Hemlock and Wacker.**
- **Special EG products electricity consumption from REC Silicon:** 193 kWh/kg for EG special products can be determined by comparing annual production and electricity consumption between years.

- **Overall: EG polysilicon electricity demand from this analysis is 64–95 kWh/kg higher than the ones found for SoG (60-71 kWh/kg).** For special EG products even 133 kWh/kg higher.
    - It is crucial to highlight that these estimates for EG polysilicon specific electricity are methodologically overestimated, this is due to the required assumption of allocating all the companies' electricity demand to the production of polysilicon and the unknown plant utilization rates. If only 90% of the electricity is allocated to the polysilicon production the specific electricity range for EG polysilicon for Hemlock and Wacker decreases to **102-124 kWh/kg**.
    - Production figures for both SoG and EG polysilicon had been estimated by Bernreuter Research and have high uncertainty.

Table 9: EG and total polysilicon production (tonnes per year) for EG polysilicon producers ***(Bernreuter Research Polysilicon Market Outlooks 2020, 2029 and REC Silicon Annual Reports 2022, 2024).***

	Hemlock		Wacker		REC Silicon	
Year	EG	Total polysilicon	EG	Total polysilicon	EG	Total polysilicon
2019	ND	19000	ND	62000	ND	ND
2020	ND	17000	ND	64000	ND	969
2021	11000	ND	13000	ND	781	1307
2022	12500	ND	13500	ND	993	1453
2023	12000	32000	13500	72000	704	1101
2024	11500	29000	13000	65550	422	682

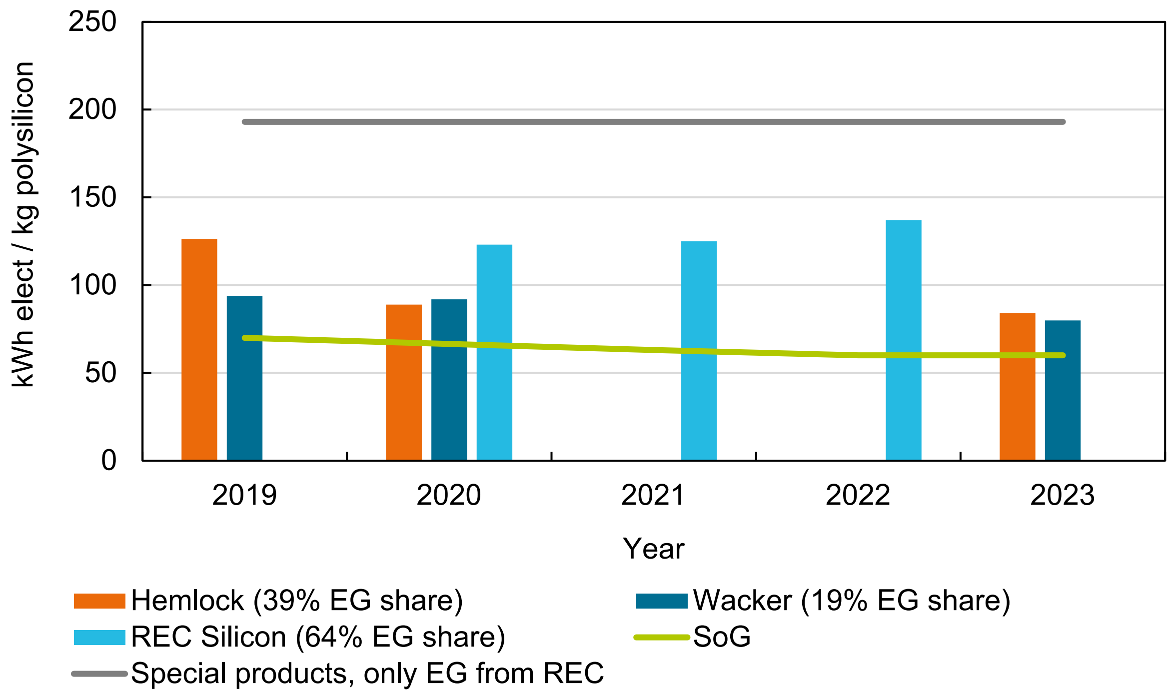


Figure 4. Specific electricity for polysilicon and silane gases production, electricity allocated to polysilicon. ***(Fraunhofer ISE models based on production data from Bernreuter Research Polysilicon Market Outlooks 2020, 2029 and companies' annual or sustainability reports. Mean EG polysilicon shares for the years 2023 and 2024 for Hemlock and Wacker, years 2021 to 2023 considered for REC silicon share. SoG polysilicon data from CPIA Roadmaps 2018-2025).***

7.4 Synthesis of analysis a,b and c

In this section the specific electricity estimates resulting from the analysis a, b and c are reported. Table 10 presents the results accompanied with a reliable historic data point for EG polysilicon production. A wide interval can be appreciated for the industry benchmarks as different EG polysilicon products and significant differences on production capacities exist between producers.

It is interesting that the CPIA learning curve analysis for the specific electricity for EG polysilicon production is within the range estimated with industry benchmarks. It is also foreseeable that the industry benchmarks are above the process-wise estimation, as they include factories utilization rates efficiency losses.

Table 10: EG polysilicon specific electricity estimations, synthesis of analysis a,b and c.

Source	EG (kWh/kg)	Notes
Historic (Wacker)	150	Reference year 2002, obsolete
CPIA learning curve	110	Reference year 2023, extrapolated
Process-wise model	92	Consistent with process steps
Industry benchmarks	102–124 kWh/kg 193 kWh/kg special EG polysilicon products	Recent REC Silicon, Hemlock, Wacker. 90% of electricity demand allocated to polysilicon production.

8 Summary and Conclusions

This section synthesizes findings, presents the plausible interval for EG polysilicon electricity demand, and highlights strategic implications.

Key Findings

- SoG polysilicon electricity demand has decreased to a current range of 60–71 kWh/kg (2023, CPIA and Fraunhofer ISE technology transfer projects). Lower specific electricity figures are expected in the future due to an increasing share of FBR polysilicon for the SoG polysilicon market.
- This study shows that EG polysilicon production specific electricity remains 32–53 kWh/kg higher than the SoG polysilicon one. Due to slower polysilicon rods growing rates on CVD reactor, smaller reactor size and additional etching requirements.

As result of the analyses in this study the electricity consumption for the production of EG polysilicon in the year 2025 is estimated to be in the range of:

92 – 124 kWh/kg$_{\text{EG polysilicon}}$

Special EG products require more resources and **up to 200 kWh/kg for the production of these special EG polysilicon products**.

All values are supported by Fraunhofer ISE internal models, CPIA roadmaps, Bernreuter Research Polysilicon market outlooks, EG polysilicon producers' sustainability or annual reports, and academic literature (Si et al., 2024; Yang et al., 2025, Yuan et al., 2025, Jungbluth et al., 2012; Laine et al., 2016; Verlinden, 2022, Yadav et al. 2017).

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