5230-10
Photovoltaics Program
Technology Development and Applications
Lead Center

DOE/JPL-1012-79A
Distribution Category UC63b

Polycrystalline Silicon Material Availability and Market Pricing Outlook Study for 1980 to 88

January 1983 Update

E. Costogue
R. Pollin - Consultant, Charlotte, NC

(NASA-CR-173123) POLYCRYSTALLINE SILICON MATERIAL AVAILABILITY AND MARKET PRICING OUTLOOK STUDY FOR 1980 TO 88: JANUARY 1983 UPDATE (Jet Propulsion Lab.) 45 p HC A03/MF A01 CSCL 11G G3/27
N83-35145
Unclas
42171

5230-10
Photovoltaics Program
Technology Development and Applications
Lead Center

DOE/JPL-1012-79A
Distribution Category UC63b

Polycrystalline Silicon Material Availability and Market Pricing Outlook Study for 1980 to 88

January 1983 Update

E. Costogue
R. Pellin - Consultant, Charlotte, NC

February 1983

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 83-9

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

ABSTRACT

Photovoltaic solar cell arrays which convert solar energy into electrical energy can become a cost-effective, alternative energy source provided that an adequate supply of low-priced materials and automated fabrication techniques are available. Presently, silicon is the most promising cell material for achieving the near-term cost goals of the Photovoltaics Program.

Electronic grade silicon is produced primarily for the semiconductor industry with the photovoltaic industry using, in most cases, the production rejects of slightly lower-grade material. Therefore, the future availability of adequate supplies of low cost silicon has been one of the major concerns of the Photovoltaics Program.

Two silicon material outlook reports have been published previously that track the status of the silicon material industry and predict the availability of the material. In November 1979, a report entitled Silicon Material Outlook for 1980-81 (Reference 1) was published which reported the results of a silicon survey conducted in July 1979. A second report entitled Industry Survey Report Status of Silicon Material and the Silicon Sheet Technologies (Reference 2) was published in May 1981. This report provided an update on the silicon material outlook through November 1980.

This current report updates the supply outlook for silicon with emphasis on pricing, and is based primarily on an industry survey conducted by a JPL consultant. This survey included interviews with polycrystalline silicon manufacturers, a large cross-section of silicon users and silicon solar cell manufacturers. The conclusions from this latest update on the status of silicon availability and market pricing outlook through 1988 are as follows:

(1) Polycrystalline silicon availability is now and will continue to be in excess of the users demands.

(2) Polycrystalline silicon material prices have decreased over the past year and will continue to drop.

(3) Refiners of silicon have greatly expanded plant capacity by addition of simple process improvements. The changes have been achieved with minimal capital expenditures.

(4) The present and projected overcapacity in the silicon industry has led to aggressive refining process cost reduction efforts.

(5) The world-wide recession, which began in summer 1980, has caused a slightly lower rate of growth of the semiconductor industry than was expected.

(6) New polycrystalline silicon low-cost refining processes, largely developed through DOE funding and administered by JPL, are reaching technology readiness. A number of new technology plant improvements expected to be available which will further reduce the polycrystalline silicon production cost.

CONTENTS

I. INTRODUCTION 1

II. POLYCRYSTALLINE SILICON OUTLOOK 3

III. SILICON INDUSTRY STATUS AND PLANS 11

IV. POLYCRYSTALLINE SILICON PRICING OUTLOOK 17

A. BACKGROUND 17

B. POLYCRYSTALLINE SILICON MANUFACTURING COST DRIVERS 18

C. MARKET PRICING OUTLOOK 20

V. POLYCRYSTALLINE SILICON AVAILABILITY FOR PHOTOVOLTAICS INDUSTRY . . 27

VI. CONCLUSIONS 31

VII. REFERENCES 33

APPENDIX. SEMICONDUCTOR DEVICE INDUSTRY MANUFACTURING COST DRIVERS . . . A-1

Figures

1. A Comparison of Polycrystalline Silicon Usage Versus Manufacturing Capacity 10

2. Union Carbide Process Polycrystalline Silicon Manufacturing Steps 15

3. Weighted Average Price History and Forecast, for Polycrystalline Silicon per Kilogram 26

Tables

1. Non-Soviet Block Usage of Semiconductor Grade Polycrystalline Silicon 4

2. A Forecast of Non-Soviet Block Usage of Semiconductor Grade Polycrystalline Silicon 5

Tables (Cont'd)

3. World Capacity to Manufacture Semiconductor Grade Polycrystalline Silicon 7

4. A Forecast of World Capacity to Manufacture Semiconductor Grade Polycrystalline Silicon 8

5. History and Forecast of Polycrystalline Silicon Production . . 9

6. Cost Estimates for the Manufacture of Polycrystalline Silicon Using Various Processes 12

7. Estimated Manufacturing Cost for Polycrystalline Silicon in 1982 19

8. Polycrystalline Silicon Used Internally by the Manufacturers 20

9. A Forecast of Polycrystalline Silicon Used Internally by Manufacturer 21

10. Purchases of Polycrystalline Silicon 22

11. A Forecast of Polycrystalline Silicon Purchases 23

12. Polycrystalline Silicon Sales 24

13. A Prediction of Polycrystalline Silicon Sales 24

14. Polycrystalline Silicon Prices 25

15. History and Forecast of Silicon Solar Cell Sales by Place of Origin 29

16. Historical Use and Forecast of Polycrystalline Silicon Required for Silicon Solar Cell Modules. 29

17. Weighted Average Prices of Off-Grade Polycrystalline Silicon 30

A-1. Silicon Device Manufacture By Company A-2

A-2. Free World Silicon Device Usage By Product A-3

A-3. A Forecast of Free World Silicon Usage A-4

SECTION I

INTRODUCTION

The use of photovoltaic (PV) arrays to generate electrical energy for the nation's energy needs depends upon availability of a large quantity of low-cost materials. Since polycrystalline silicon is presently the prime candidate material for these solar cell arrays, the array market price will depend in part on the price of this material.

Presently, the photovoltaics industry is dependent upon polycrystalline silicon which is produced primarily for integrated circuits, power devices, and the discrete semiconductor device industry. This is expected to be the primary source of supply until DOE-sponsored new technology polysilicon becomes available and the photovoltaics industry develops its own source of supply.

The Jet Propulsion Laboratory's Technology Development and Applications Lead Center therefore assumed the responsibility to track the status and projected refined silicon availability which is critical for the development of the photovoltaics industry and to report the survey results.

In November 1979, a report entitled Silicon Material Outlook for 1980-1985 (Reference 1) was published by the Jet Propulsion Laboratory (JPL) Technology Development and Applications (TD&A) Lead Center, DOE, JPL Publication 1012-33, which reported the results of a silicon industry survey conducted in July 1979. The survey team concluded:

(1) A limited supply of polycrystalline silicon material would likely develop early in 1980, and would result in a severe shortage. The shortage would develop because of increasing consumption forecast by the semiconductor products industry and by the needs of the emerging PV industry. During this period, minimal expansion of the refining industry was expected because new low cost refining technology was under development.

(2) A seller's market would be created and the price of silicon would be expected to increase.

In November 1980 (Reference 2), a silicon industry update survey conducted by a JPL consultant, Remo Pellin, found that the silicon supply situation had begun to change drastically although some large fluctuations in pricing had taken place. In April 1980, the spot market price for silicon was quoted as high as $140/kg (Reference 3), an increase of a factor of 2 from the spot market prices quoted in 1979. The conclusions of this survey were:

(1) There would be no shortage of semiconductor-grade polycrystalline silicon needed to meet the forecast market demands for the semiconductor products industry.

(2) Excess semiconductor-grade silicon and non-conforming (rejected from the semiconductor industry) silicon could be available for

the PV industry at the market price, which may be more than the PV industry could afford to pay if low cost PV products are to be produced.

Since the last survey, a number of additional significant events have taken place:

(1) The Administration has imposed new guidelines on the Photovoltaics Program.

(2) The DOE-sponsored new technology polysilicon refining development is slowly reaching maturity.

(3) A world-wide recession has slowed the growth rate of the semiconductor industry.

(4) The polysilicon industry has taken advantage of Siemens process improvements resulting in part from DOE-sponsored new technology developments and are expanding their capacity.

(5) China and Russia have begun production of polycrystalline and are now offering limited quantities to the free world.

The above events have changed the silicon availability outlook since the last study in 1980.

A recent brief survey was conducted by Dr. Remo Pellin. The results of this brief survey are summarized as a part of this report.

SECTION II

POLYCRYSTALLINE SILICON OUTLOOK

Silicon solar cells are manufactured from single crystal silicon wafers, polycrystalline silicon wafers, or from amorphous silicon thin films. Today, polycrystalline silicon constitutes about 10% of the cost for manufacturing of solar cell module ($0.60 out of $6.00 per peak watt). Pure semiconductor grade polycrystalline silicon allows for high efficient solar cells to be manufactured, reducing the overall cost of the module per peak watt.

The use of any special "solar grade" polycrystalline silicon which result in lower efficiency solar cells is probably not warranted at this time. Thus, the silicon solar cell industry is associated with the same polycrystalline silicon industry that supplies the silicon integrated circuit industry with its raw material. In the past, and probably for the near future (through 1988), the silicon solar cell industry will use "reject" polycrystalline silicon. This reject silicon consists of virgin material which does not meet integrated circuit specifications in some particular item, such as boron, phosphorus or carbon concentration. This deficiency does not degrade solar cell efficiency. As much as 5% of all semiconductor grade polycrystalline silicon manufactured is rejected because of tightened silicon crystal specifications for the integrated circuit industry, most silicon crystal growers, achieve single crystal yields of only 60%. Some 20% of crystal yield loss is recoverable and is eminently useful for growing crystal for silicon solar cells. In 1982, some 150 metric tons of virgin polycrystalline silicon and 300 metric tons of crystal scrap were available to the silicon solar cell industry. This was far more than was required for solar cell production. In 1988, it is expected that about 1700 metric tons of this "scrap" polycrystalline silicon will be available. Beyond 1988, new low-cost polycrystalline silicon manufacturing processes developed with DOE funding will be in place and will be capable of meeting economic targets of the Photovoltaics Program.

To predict quantitatively the availability of "scrap polycrystalline silicon" for the manufacture of solar cells, it is first necessary to forecast the polycrystalline silicon requirements of the silicon device industry.

Table 1 shows the usage of polycrystalline silicon by company for the years 1977-1982. The companies listed are primarily in the conversion of polycrystalline silicon to polished wafers. For most companies, growth has been monotonic.

Table 2 forecasts the expected use of semiconductor grade polycrystalline silicon for the manufacture of polished silicon wafers by company for the years 1983 through 1988. Projected growth is sufficient to allow all companies to expand. It is predicted that no company will gain a major technical or economic advantage. The forecast in Table 2 is based on industry experience and competitive technology approaches reported in the Appendix.

Table 1. Non-Soviet Block Usage of Prime Semiconductor Grade Polycrystalline Silicon, metric tons

	Company	1977	1978	1979	1980	1981	1982
1.	Wacker Chemetronic Gmbh	260	320	380	410	425	480
2.	Monsanto Co.	260	320	380	410	425	450
3.	Texas Instruments Inc.	130	150	190	200	210	230
4.	Osaka Titanium Mfg. Co.	100	130	200	210	220	235
5.	Motorola Inc.	65	90	130	140	150	150
6.	Shin-Etsu Handotai	60	100	140	150	160	170
7.	Siltec Corporation	60	80	100	100	110	110
8.	IBM	50	60	100	110	120	130
9.	General Motors	60	70	80	80	85	90
10.	Dynamit Nobel	40	60	80	90	110	200
11.	Western Electric	35	50	60	70	90	90
12.	Fairchild C & I Co.	30	50	80	85	90	90
13.	Komatsu Elect. Metals	30	40	50	50	50	50
14.	Philips	15	15	20	20	25	25
15.	Ametek Inc.	-	-	-	10	20	20
16.	Crystecc Inc.	10	10	10	10	20	20
17.	Pennsilco	10	10	15	20	20	25
18.	Cincinnati Milacron Inc.	-	-	-	5	15	20
19.	Topsil (Denmark)	15	15	15	15	15	15
20.	Peoples Republic of China	70	80	90	100	110	150
21.	All Others	26	18	28	27	23	17
	Annual Usage	1326	1668	2148	2312	2493	2767

Table 2. A Forecast of Non-Soviet Block Usage of Prime Semiconductor Grade Polycrystalline Silicon, metric tons

	Company	1983	1984	1985	1986	1987	1988
1.	Wacker Chemetronic Gmbh	450	570	740	960	1240	1630
2.	Monsanto Company	450	560	720	940	1220	1530
3.	Texas Instruments Inc.	170	200	250	330	420	500
4.	Osaka Titanium Mfg. Co.	470	560	670	810	1040	1250
5.	Motorola Inc.	120	130	170	210	260	300
6.	Shin-Etsu Handotai	470	560	670	810	1030	1250
7.	Siltec Corp.	80	100	130	160	200	250
8.	IBM	90	110	150	200	270	350
9.	General Motors	80	90	100	150	190	240
10.	Dynamit Nobel	200	230	270	320	400	500
11.	Western Electric	90	110	130	170	200	250
12.	Fairchild C & I Co.	80	90	100	120	150	180
13.	Komatsu Electronic Metals	120	150	180	220	270	350
14.	Philips	20	20	30	50	70	100
15.	Ametek Inc.	10	15	20	30	40	50
16.	Crysteco Inc.	20	25	30	40	60	80
17.	Pennsilco	25	30	40	50	70	90
18.	Cincinnati Milacron Inc.	20	30	40	60	80	100
19.	Topsil (Denmark)	15	15	15	15	15	15
20.	Peoples Republic of China	100	125	180	250	350	500
21.	Toshiba	50	150	220	300	340	400
22.	All Others	94	90	115	125	185	305
	Annual Usage	3224	3960	4970	6320	8100	10220

Table 3 records the history of the industries' capacity to manufacture polycrystalline silicon in the years 1977 through 1982, and Table 4 forecasts the expected capacity of the various plants to manufacture polycrystalline silicon in the years 1983 through 1988. It includes some modest production capacity increases based on the new DOE sponsored low cost polycrystalline processes. The total growth of refining capacity is impressive.

There are major variations between plant capacity, production, sales and usage. In 1982, all except 200 metric tons of polycrystalline silicon was sold on the basis of long-term (Five Year) contracts. Thus, sales depend upon what users thought they would need for the future based on experience. Users typically will buy more in recession years than they need and inventory the balance. Usage is based on many things, including such items as device yields and company fortunes. Production is based on what portion of plant capacity is used. In Table 5, world history and expected production volume for each of the polycrystalline silicon producer are shown. The production volume shown is always lower than plant capacity, but it is higher than the usage table and includes quantities for internal use and for purchases done for stockpiling and other market speculation.

Figure 1 shows the past, present, and future outlook, for silicon refining based on polycrystalline silicon plant capacity and usage. From the plots, it is apparent there should be sufficient polycrystalline silicon supply through 1988. The refiners production and plant capacity will remain in excess of the demand, which will result in price competition.

Table 3. World Capacity to Manufacture Prime Semiconductor Grade Polycrystalline Silicon, metric tons

	Company	1977	1978	1979	1980	1981	1982
1.	Wacker Chemetronic Gmbh	700	700	700	1200	1400	1800
2.	Hemlock Semiconductor Inc.	500	500	600	700	900	1000
3.	Osaka Titanium Mfg. Co.	150	150	200	400	400	450
4.	Texas Instruments Inc.	175	175	200	250	300	350
5.	Dynamit Nobel	150	175	190	220	300	350
6.	Monsanto Company	175	190	200	210	230	230
7.	Motorola Inc.	100	100	100	100	100	100
8.	Great Western (GE)	-	10	50	100	200	200
9.	Shin-Etsu Handotai	100	100	100	100	100	100
10.	Komatsu Elect. Metals	30	30	30	60	60	60
11.	Topsil (Pennsilco)	15	15	20	20	20	20
12.	Union Carbide Corp.	-	-	-	-	-	10
13.	Peoples Republic of China	100	100	150	200	200	300
14.	Russia	200	200	200	200	200	400
	Annual Capacity	2395	2445	2740	3760	4410	5370

Table 4. A Forecast of World Capacity to Manufacture Prime Semiconductor Grade Polycrystalline Silicon, metric tons

	Company	1983	1984	1985	1986	1987	1988
1.	Wacker Chemetronic Gmbh	2000	2500	2500	2500	2500	4000
2.	Hemlock Semiconductor Inc.	1200	1400	1500	2000	2500	3000
3.	Osaka Titanium Mfg. Co.	450	450	800	800	800	800
4.	Texas Instruments Inc.	350	350	450	450	450	600
5.	Dynamit Nobel	400	600	800	800	800	1600
6.	Monsanto Co.	230	230	230	230	230	230
7.	Motorola Inc.	100	100	100	100	100	100
8.	General Electric	300	400	400	400	600	800
9.	Shin-Etsu Handotai	100	100	100	100	100	100
10.	Komatsu Elect. Metals	60	60	60	60	-	-
11.	Pennsilco	20	20	20	20	20	20
12.	Union Carbide Corp.	100	200	800	1200	1200	1200
13.	Tokuyama Soda Co.	-	-	200	300	300	300
14.	Peoples Republic of China	300	300	600	600	600	800
15.	Russia & Satelites	500	600	600	800	800	1200
16.	New Manufacturers	-	100	400	1000	1500	2000
	Annual Capacity	6110	7410	9560	11360	12500	16750

Table 5. History and Forecast of World Polycrystalline Silicon Production Volume, metric tons

	Company	1980	1981	1982	1983	1984	1985	1986	1987	1988
1.	Wacker Chem. Gmbh	1200	1200	1400	1800	2300	2500	2500	2500	3000
2.	Hemlock Semi. Inc.	700	800	900	1000	1200	1400	1600	2000	2500
3.	Osaka	400	450	450	450	450	800	800	800	800
4.	Texas Inst. Inc.	250	250	300	350	350	450	450	450	600
5.	Dynamit Nobel	220	250	300	400	600	800	800	800	800
6.	Monsanto Co.	210	225	230	230	230	230	230	230	230
7.	Motorola Inc.	100	100	50	100	100	100	100	100	-
8.	General Electric	100	100	150	300	400	400	400	600	800
9.	Shin-Etsu	100	100	100	100	100	100	100	100	-
10.	Komatsu	60	60	60	60	60	60	60	-	-
11.	Pennsilco	20	20	20	20	20	20	20	-	-
12.	Union Carbide	-	-	-	-	100	300	1000	1200	1200
13.	Tokuyama	-	-	-	-	-	100	300	300	300
14.	Peoples Rep.of China	5	50	50	100	100	200	200	200	200
15.	Russia	-	-	-	100	100	200	200	200	200
15.	New Mfg.	-	-	-	-	-	200	700	1200	1200
	Annual Capacity	3410	3605	4010	4910	6110	7860	9460	10680	11830

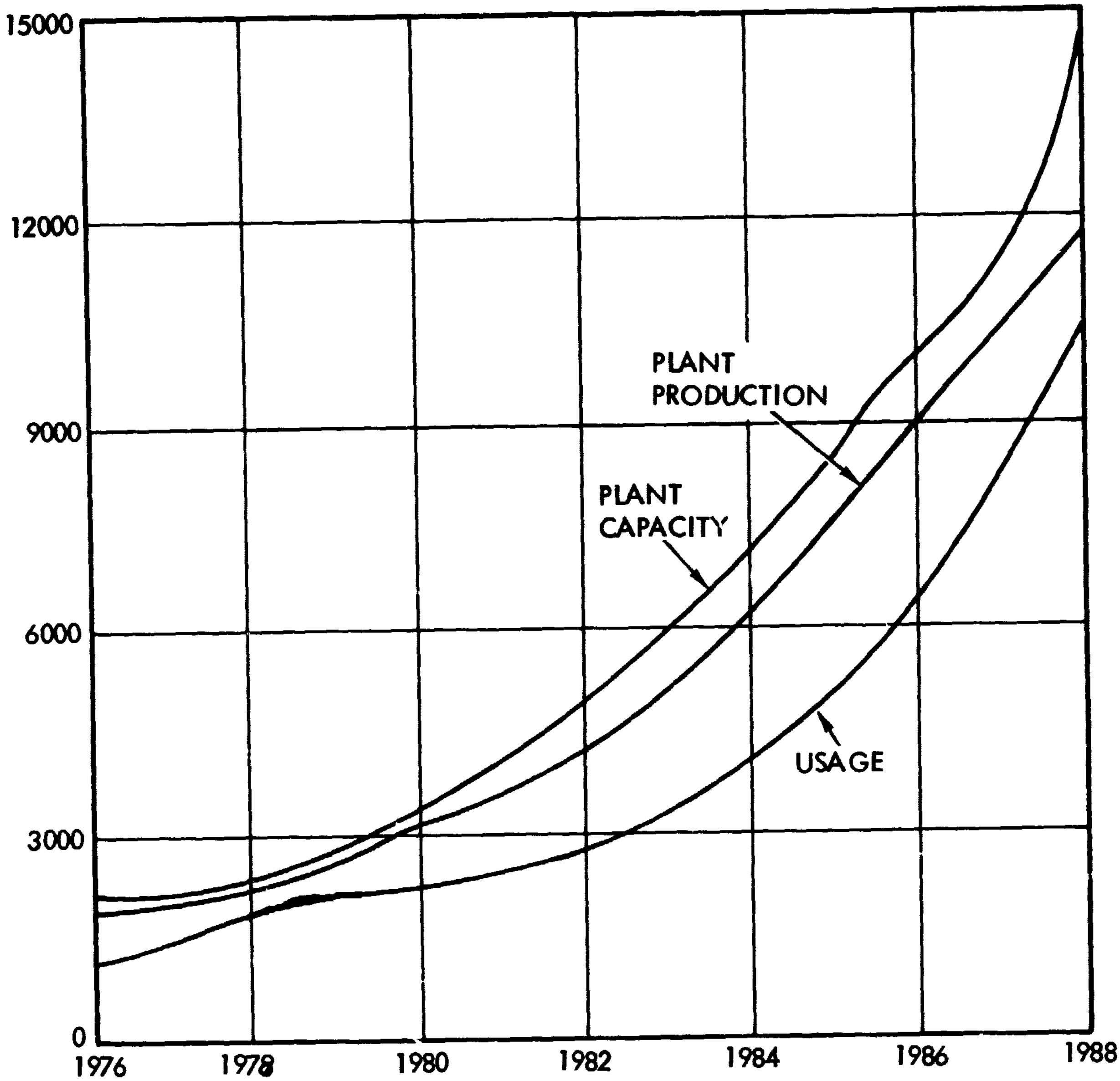

Figure 1. A Comparison of Polycrystalline Silicon Usage Versus Manufacturing and Capacity

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION III

SILICON INDUSTRY STATUS AND PLANS

This section reports on the latest information obtained from the industry through interviews and published information related to industry present posture and plans for the future.

The Wacker Chemetronic plant in Burghausen, West Germany, uses a Siemens process (Reference 4) and trichlorosilane to produce polycrystalline silicon. Between 1979 and 1980, plant capacity was increased 70% by simple process changes such as increasing final rod diameter. Between 1980 and 1982, the plant capacity was increased another 50% by new reactor installations. In 1982, a program of replacing quartz bell jars with water-cooled stainless-steel bell jars was initiated. The effect of such a replacement was described in the Industry Survey Report Status (Reference 2) published in May 1981, which stated that the stainless-steel bell jar is efficient in energy utilization. The stainless-steel bell jar reflects the heat from the hot silicon rods back to the rods. When a quartz bell jar is used, this heat is lost to the ambient by radiation. The same size power supply is thus capable of being used for growing larger size rods, and therefore greatly increasing plant capacity. In Table 6, a cost estimate is made for polycrystalline silicon at Wacker with a plant using quartz bell jars, Process No. 1, and stainless-steel bell jars, Process No. 2. The Wacker Plant enjoys at least three production cost advantages:

(1) Low cost internally produced electric power ($0.01/kWh).

(2) On-site manufacture of $SiHCl_3$ ($0.40/lb).

(3) A use for by-product $SiCl_4$ ($0.20/lb).

The Burghausen plant, when completely refitted with stainless-steel bell jars, could have an annual capacity of 4000 or more metric tons using trichlorosilane. Wacker believes that the safety risks involved in the use of silane or dichlorosilane are not now worth the effort and will stay with trichlorosilane feedstock. The construction of a polycrystalline silicon plant in Portland, Oregon, is still in the plans, but has been indefinitely delayed. The plant will be built when or if needed.

Hemlock Semiconductors Inc. of Hemlock, Michigan, increased plant capacity by 50% by a series of expansions in the 1979 through 1981 time period. A planned new plant at Carrollton, Kentucky, was cancelled (Reference 5). In 1982, plant capacity was further increased by simple process changes (Reference 6), it is expected that evolutionary plant improvement will continue into future years. These process changes include increasing the temperature of silicon rod surfaces and increasing the final rod diameter.

Hemlock Semiconductors Inc. continues to perform JPL-funded research for a process in which trichlorosilane is converted into dichlorosilane from trichlorosilane and decomposed to silicon in a Siemens-type reactor. The Hemlock plant capacity can be doubled any time dichlorosilane is substituted

Table 6. Cost Estimates for the Manufacture of Polycrystalline Silicon Using Various Processes, $/kg

Cost Item	Process No. 1	Process No. 2	Process No. 3	Process No. 4	Process No. 5	Process No. 6	Process No. 7	Process No. 8
Raw Material	x	x	x	x	x	x	x	x
Slim Rods	x	x	x	x	x	x	x	x
Seed Pellets	x	x	x	x	x	x	x	x
Personnel	x	x	x	x	x	x	x	x
Maintenance	x	x	x	x	x	x	x	x
Electricity	x	x	x	x	x	x	x	x
Gases	x	x	x	x	x	x	x	x
Taxes and Insurance	x	x	x	x	x	x	x	x
Depreciation	x	x	x	x	x	x	x	x
Manufacturing Cost	22.20	18.30	39.80	10.20	18.00	10.20	18.00	9.80

1. Depreciation is 10 year Straight Line
2. Costs are on a $ per kilogram basis
3. 1982 dollars
4. Plant process costs unless otherwise specified are based on 1000 annual metric ton capacity

Process 1 - Present Wacker
Process 2 - Wacker with stainless stell bell jars
Process 3 - Present Hemlock
Process 4 - Hemlock with SiH_2Cl_2
Process 5 - Present Texas Instruments
Process 6 - Texas Instruments with SiH_2Cl_2
Process 7 - Present Union Carbide
Process 8 - Union Carbide with Fluidized Bed

for the trichlorosilane now used. Process 3 in Table 6 represents a costing of the Hemlock plant process as it existed of early 1982. Process changes have continued during the past year.

Process 4 is an estimated cost of manufacture at Hemlock if the plant were converted to dichlorosilane, the bell jars changed to stainless steel and if on-site facilities were installed to convert byproduct $SiCl_4$ back to dichlorosilane via the mgSi-$SiCl_4$-H_2 reactor and redistribution of trichlorosilane. These changes are anticipated before 1988.

The Japanese Government has recognized that a huge Japanese electronics industry (Reference 7) was becoming dependent upon imported polycrystalline silicon. An understanding between MITI and the Osaka Titanium Manufacturing Company has been reached under which Osaka will increase its plant capacity to 800 annual metric tons in 1985 and to 1800 metric tons by 1990. Osaka Titanium Manufacturing Company of Japan and Rhone Poulenc in France have formed a joint venture to manufacture the metallurgical grade silicon feedstock for these expansions. The Osaka Titanium Manufacturing Company now uses the Siemens process (Reference 6), with trichlorosilane and water-cooled stainless-steel bell jar. The quality of the silicon is excellent, and the process is equivalent to that operating at Wacker Chemetronic, but with higher power product cost due to higher electric power cost.

The Texas Instruments Inc. fluidized bed silicon plant is running very well now after years of start-up troubles. This plant is very energy efficient and uses only 39 kWh per kilogram of polycrystalline silicon produced. A process cost estimate is shown as Process 5 of Table 6. The Texas Instruments Inc. will increase the capacity of their plant at Sherman, Texas, as needed, by adding more reactors. Should Texas Instruments decide to use dichlorosilane in the fluidized bed, and to set up facilities to convert byproduct $SiCl_4$ to SiH_2Cl_2, then polycrystalline silicon production costs could be improved as shown in Process No. 6, Table 6.

The Siemens plant of Dynamit Nobel plant at Merano, Italy, is now being expanded by process changes (Reference 8), and the installation of stainless-steel bell jars. It is expected that these improvements will expand the plant capacity to 800 metric tons a year. When further new capacity is required, a new plant will be built in Mobile, Alabama. It is expected that the new plant will be operational in the 1988 to 1990 time period. The Dynamit Nobel process is similar to the Wacker process; however, it is more costly because trichlorosilane is not produced on site and electrical power is somewhat more expensive than for Wacker.

The Motorola Inc. and Monsanto Company silicon refining plants use purchased trichlorosilane. Both companies have decided that they will purchase their future increased needs for polycrystalline silicon. Both companies have new plant designs that could be implemented.

The General Electric Company purchased the Siemens process plant of the Great Western Silicon Corporation (Reference 9), early in 1981. With the use of stainless-steel bell jars, the plant capacity can be expanded to 800 metric tons per year. The prediction is that the General Electric Company will expand to at least this level.

Shin-Etsu Handotai has a small plant in Japan that uses Hemlock Semiconductor Inc. technology. Shin-Etsu is proud of its wafer expertise and probably will expand this business using purchased polycrystalline silicon.

Komatsu Electronic Metals has licensed Union Carbide to use its advanced Siemens process decomposition of SiH_4. Komatsu has a good business in the manufacture of floating zone silicon crystal for use in nuclear and infrared detection and power devices. Komatsu will purchase Union Carbide polycrystalline silicon as it becomes available from the new Moses Lake, Washington plant.

Pennsilco of Bradford, Pennsylvania, purchased the Topsil Silicon Facility (Reference 10) located in Denmark from Motorola Inc. Topsil uses $SiCl_4$ in the Siemens process to produce a very dense polycrystalline silicon well suited to float zone crystal feedstock, which is used for state-of-the-art power devices. This material has found a niche, but usage probably will not increase greatly.

The Union Carbide Corporation, with the aid of JPL funding, developed an inexpensive method of converting metallurgical silicon to silane. This process is detailed in Figure 2. The Union Carbide Corporation has licensed the technical know-how from the Komatsu Electronic Metals Company to thermally decompose the silane to semiconductor grade polycrystalline silicon using a modified Siemens reactor. A pilot plant to test both processes is now operational at Washougal, Washington (Reference 6). Meanwhile, construction is underway at Moses Lake, Washington, on a 1200-metric-ton plant using the same processes. The Moses Lake plant is expected to be complete by late 1984 and in operation in 1985. Tests on polycrystalline silicon manufactured at the Komatsu plant, showed a product of remarkable purity. The boron levels were less than 0.01 ppba. A cost estimate for polycrystalline silicon manufactured by this process is shown in Table 6 as Process No. 7.

Union Carbide is also performing JPL-funded research on the thermal decomposition of silane in a fluidized bed reactor. The installation of fluidized bed reactors would reduce plant capital costs very substantially and should show a cost picture like the one shown as Process No. 8 in Table 6.

The Tokuyama Soda Company of Japan has licensed the technical know-how to build a polycrystalline silicon plant in Japan from the General Electric Company. This company will essentially duplicate the Great Western Silicon Corporation plant which is owned by General Electric.

The Peoples Republic of China now has 9 provincial polycrystalline silicon plants. The largest of these plants is only 25 metric tons in annual capacity. China is now expressing interest in expanding these plants for internal needs and for purchasing equipment for byproduct recovery. Seven of the plants use trichlorosilane, one plant uses silicon tetrachloride, and one plant uses silane. All plants are Siemens process in general methodology. China exported some 50 metric tons of polycrystalline silicon to the United States in 1982 and at least as much in 1980 and 1981. A similar U.S. import quantity can be expected in future years. Should polycrystalline silicon prices increase, then more will be exported. If prices drop substantially, the export will stop.

1. Si(Metallurgical Grade) + $3SiCl_4 + 2H_2 \longrightarrow 4SiHCl_3$

Conditions - Fluidized Bed Reactor
- 500°C + 300 lbs/in.^{2} Pressure
- CuCl Catalyst

2. $2SiHCl_3 \longrightarrow SiH_2Cl_2 + SiCl_4$

Conditions - Fixed Bed Reactor
- 80°C + Atmospheric Pressure
- Quarternary Ammonium Catalyst

3. $3SiH_2Cl_2 \longrightarrow 2SiHCl_3 + SiH_4$

Conditions - Fixed Bed Reactor
- 80°C + Atmospheric Pressure
- Quarternary Ammonium Catalyst

4. $SiH_4 \longrightarrow Si + H_2$

Conditions - 850°C + Atmospheric Pressure

Figure 2. Union Carbide Process Polycrystalline Silicon Manufacture Steps

In 1979, Russia and her satellites imported at least 150 metric tons of polycrystalline silicon or its equivalent in silicon wafers. In 1980, with the invasion of Afghanistan, this importation was totally stopped and the Russian electronics industry was hurt. Russia has increased their refining capacity and, in 1983, Russia will probably export some silicon to the free world market.

There is one U.S. company, new to the polycrystalline silicon business, which is building pilot plants preparatory to the erection of commercial plants. The company will use silane and will probably utilize fluidized bed deposition. It is expected to have 1000-metric-ton plant capacity on line by 1988.

SECTION IV

POLYCRYSTALLINE SILICON PRICING OUTLOOK

A. BACKGROUND

For an industry with 14 producing and 20 refined polysilicon using companies, the pricing history of semiconductor grade polycrystalline silicon has been unduly complex and mysterious. The price can be described as being very constant and very volatile at one and the same time. This is possible because polycrystalline silicon is sold on three different bases, and the general perception of shortage or glut is the major price setting factor. To date, the quality from all suppliers has been sufficiently high to eliminate quality as a price setting factor.

As much as 80% of all polycrystalline silicon is sold on the basis of long-term contracts (five year and Evergreen may be reopened regarding quality and price). The contracts specify maximum and minimum yearly sales quantities that can or must be delivered or accepted. Such contracts can be broken only upon payment of specified penalties. Further, these contracts specify yearly prices based on agreed escalation scales. Few polycrystalline silicon producers would dare build a new plant without such signed contracts. Year-to-year prices tend to be quite steady under such contracts and for many years have averaged around $65/kg.

As much as 10% of all polycrystalline silicon is sold on the basis of a 1-year contract where the silicon is bought one year for delivery the next year. During the past 4 years, silicon prices set on this basis have been far more volatile than those based on long-term contracts.

Less than 10% of all polycrystalline silicon sales take place on the spot market. Producers and long-term contractees take part as sellers in this market. During the past 4 years, prices on this market have been very volatile. For example, in July of 1978, SMIEL sold 40 metric tons of prime semiconductor grade polycrystalline silicon for $40/kg. In July 1980, the Great Western Silicon Corporation sold 30 metric tons of prime semiconductor grade polycrystalline silicon for $125/kg. In July 1982, Dynamit Nobel and the Great Western Silicon Corporation each sold 30 metric tons of polycrystalline silicon for prices between $38 and $42 per kilogram.

There are two types of "off-grade" polycrystalline silicon that are also sold on the spot market and tend to confuse the whole situation. This off-grade material, while not suitable for the most exacting uses such as manufacturing thyristors or random access memories, is emminently suitable for use in the manufacture of solar cells, auto rectifiers and as substrates for epitaxial wafers. This material comprises approximately 5% of all virgin polycrystalline silicon manufactured that does not meet the specifications of prime grade polycrystalline silicon because carbon, phosphorous, or boron levels are slightly too high. This material is sold as it is manufactured to whoever will purchase it. In addition, growing silicon single crystals, typically only 60% of the polycrystalline silicon ends up as usable single crystal wafers. The remaining 40% must be scrapped. At least 25% of this

PRECEDING PAGE BLANK NOT FILMED

crystal scrap can be recovered and is suitable for reconversion into single crystal for solar cells. Much of this crystal scrap is processed into wafers by the large crystal growing companies and is sold to the solar cell manufacturers at bargain prices.

The rest of the crystal scrap is made into wafers suitable for the manufacture of other semiconductor devices or is sold directly to solar cell manufacturers. The prices that have been prevalent for the sale of this scrap in the past have varied between one-quarter and one half of the price of prime semiconductor-grade polycrystalline silicon.

B. POLYCRYSTALLINE SILICON MANUFACTURING COST DRIVERS

The cost to produce polycrystalline silicon can be remarkably different from plant to plant, as estimated in Table 7. All production processes listed in Table 7 are based on Siemens with some modifications. At present, market competition is becoming severe, and manufacturers must minimize cost to stay in competition.

Each of these polycrystalline silicon manufacturers can examine the future and can perceive achievable manufacturing costs with plant modifications which can reduce their cost as much as 50 percent. For example, by changing reactor enclosures from quartz bell jars to water-cooled stainless-steel bell jars, larger diameter rods can be grown at higher average temperatures with far better trichlorosilane reaction yields. The stainless-steel bell jars are far more efficient in energy use and, therefore, existent power supplies are sufficient for at least doubling the capacity of existing plants. The coversion of trichlorosilane to dichlorosilane in a continuous and energy conservative process is now well known. The conversion of byproduct silicon tetrachloride to trichlorosilane in an energy efficient process is also now well known. The achievement of these production cost reductions is predicated upon plants producing at their capacities. This also suggests a very competitive battle for market, forcing substantial price reductions in the near future. This price battle has begun and has already resulted in some price reductions.

The price of polycrystalline silicon varies with form, vendor, quantity purchased, and foreign exchange equivalents. Polycrystalline silicon is sold in at least four different forms:

(1) Nuggets (pieces with a maximum dimension of 4 inches and a minimum dimension of 1 inch).

(2) One piece crucible charges.

(3) Broken pieces (collected prime-grade small pieces).

(4) Logs (rods as they come out of the reactor).

Nuggets are the most widely preferred form of product. One piece crucible charges are priced 5% higher than nuggets. The price of a 2-metric-ton quantity can be 10% more than the price per metric ton of a 20-metric-ton quantity delivered to the same location. Broken pieces are usually small in quantity, but sell for at least 3% less than nuggets. Logs are priced 10% less than nuggets.

ORIGINAL PAGE IS
OF POOR QUALITY

Table 7. Estimated Manufacturing Cost for Polycrystalline Silicon in 1982, 1982 $/kg

Cost Item	Wacker	Hemlock	Dynamit	Gen Elec	China	Osaka
$SiHCl_3$	8.40	22.40	13.00	17.00	17.60	18.20
Slim Rods	0.30	0.30	0.30	0.30	0.50	0.30
Maintenance	1.40	1.90	1.40	1.90	6.00	1.90
Personnel	2.50	3.00	2.50	2.50	3.00	3.00
Electricity	1.70	4.80	3.00	4.80	9.00	3.90
Gases	0.40	0.40	0.40	0.40	1.00	0.40
Taxes & Ins.	1.00	1.00	1.00	1.00	-	1.00
Depreciation	9.50	10.00	8.00	10.00	50.00	7.00
Manufacturing Cost	25.20	43.90	29.60	37.90	87.10	35.70

Parameter	Wacker	Hemlock	Dynamit	Gen Elec	China	Osaka
Investment $/kg of Capacity	95	100	80	100	500	70
Plant Capacity Metric Tons	1800	1000	300	200	20	450
Plant Production 1982	1400	900	300	150	15	450
Electric Power Usage kWh/kg	170	160	100	160	300	78
Electric Power Cost / kWh	0.01	0.03	0.03	0.03	0.03	0.05
TCS Usage per kg Si (lb)	28	32	20	20	44	28
$SiCl_4$ Generated /kg Si (lb)	14	16	10	10	20	14
TCS Cost/lb	0.40	0.80	0.70	0.90	0.40	0.70
Bell Jars	Quartz	Quartz	Quartz	Quartz	Stainless Steel	Stainless Steel

C. MARKET PRICING OUTLOOK

To understand polycrystalline silicon pricing, it is necessary to first understand the total market picture for polycrystalline silicon. With this understanding, it is believed that a realistic and fairly accurate forecast can be made for prices of polycrystalline silicon in future years. Polycrystalline silicon plant capacity and polycrystalline silicon usage in the past, present, and future, are shown in Figure 1.

Not all polycrystalline silicon manufactured, however, ever reaches the market for sale. Much of the material is manufactured and used within the same company. Table 8 gives a history of this internal usage of polycrystalline silicon. Table 9 predicts the growth of this polycrystalline silicon internal usage.

Table 10 presents a history of purchases of polycrystalline silicon. Table 11 predicts these purchases for the years 1983 through 1988. The Motorola Inc. purchases appear to be low. It is expected that Motorola will purchase much of its future needs in the form of polished wafers. Texas Instruments is shown to be increasing its purchases, primarily because their manufactured polycrystalline silicon is not pure enough for some of their semiconductor products.

A history of polycrystalline silicon sales is shown in Table 12. Between 1977 and 1982, only six companies manufactured and sold polycrystalline

Table 8. Polycrystalline Silicon Used Internally by the Manufacturers, metric tons

	Company	1977	1978	1979	1980	1981	1982
1.	Wacker Chemetronic	240	310	370	390	400	400
2.	Monsanto Company	175	190	200	210	230	230
3.	Osaka Titanium	100	126	190	220	280	390
4.	Texas Instruments	120	150	180	180	155	135
5.	Motorola Inc.	75	90	100	100	90	80
6.	Shin Etsu	90	100	100	100	100	100
7.	Dynamit Nobel	30	50	80	90	115	180
8.	Komatsu Electronic Metals	30	30	30	60	60	60
9.	Topsil	15	15	15	15	15	15
10.	Peoples Republic of China	40	50	60	70	80	90
	Total	915	1111	1325	1435	1525	1680

Table 9. A Forecast of Polycrystalline Silicon Used Internally by Manufacturer, metric tons

	Company	1983	1984	1985	1986	1987	1988
1.	Wacker Chemetronic	570	660	830	1060	1420	1800
2.	Monsanto Company	230	230	230	230	230	230
3.	Osaka Titanium	260	300	360	460	640	800
4.	Texas Instruments	236	270	350	440	450	600
5.	Motorola Inc.	100	100	100	100	100	100
6.	Shin-Etsu	100	100	100	100	100	100
7.	Dynamit Nobel	220	240	280	330	430	550
8.	Komatsu	50	60	60	60	-	-
9.	Topsil	15	15	15	15	15	15
10.	Peoples Republic of China	180	240	300	400	500	600
	Total	1961	2215	2575	3195	3885	4795

silicon. In Table 13, a prediction is made of polycrystalline silicon sales in the years between 1983 and 1988. Such factors as company determination, process quality and cost, and present market penetration and reputation were used as criteria for this forecast.

Wacker Chemetronic has always been the lowest price seller, and Hemlock Semiconductor has usually been the highest price seller of polycrystalline silicon. Dynamit Nobel (previously known as SMIEL, Montedison and Montecatini) usually prices its silicon between Wacker and Hemlock. Dynamit Nobel purchases the electricity it uses under long-term take- or pay-contract, and thus cannot economincally shut down its Merano, Italy. plant. At times, Dynamit Nobel sells at the lowest industry price to unload excess inventory. In general, Japan has been an importer of polycrystalline silicon because of high Japanese electricity costs. Between 1977 and 1982, Japan has manufactured about two-thirds of its silicon needs and has imported one-third of its needs from Hemlock, Wacker and Dynamit Nobel. The Osaka Titanium Manufacturing Company has sold only in Japan in the past. During the Fall of 1982, their salesmen visited all the United States polycrystalline silicon user companies and offered their product for $45/kg. The General Electric Company purchased the Great Western Silicon Corporation in early 1981. In general, it can be expected that, in pricing, General Electric will be competitive with the other manufacturers. The nine silicon plants in the Peoples Republic of China are tiny and high cost. It is doubtful whether China would be interested in selling prime grade polycrystalline silicon for

Table 10. Purchases of Polycrystalline Silicon, metric tons

	Company	1977	1978	1979	1980	1981	1982
1.	Monsanto Company	65	120	170	180	170	170
2.	Texas Instruments	-	-	-	-	20	30
3.	Motorola Inc.	-	-	30	30	30	30
4.	Shin-Etsu	-	30	100	130	180	280
5.	Siltec Corp.	35	50	70	70	75	70
6.	IBM	45	55	70	80	85	80
7.	General Motors	55	65	75	75	75	75
8.	Western Electric	45	50	60	70	75	80
9.	Fairchild	30	40	60	70	70	70
10.	Philips	15	15	20	20	20	20
11.	Ametek	-	-	-	5	10	10
12.	Crysteco	10	10	10	10	15	15
13.	Pennsilco	10	10	15	20	20	20
14.	Cincinnati Milacron	-	-	-	5	10	15
15.	Komatsu	-	20	20	-	10	30
16.	All Others	101	102	123	112	103	92
	Total	411	567	823	877	968	1087

less than $50/kg. China, however, will continue to sell scrap silicon to solar cell users. In the latter 1980s, as improved process know-how becomes extensively installed in China, she will resume exports. Russia will be in this market to a depth that will allow her to keep tabs on technology.

During the past year the dollar has been relatively strong versus the mark, lira or yen. This has placed Hemlock Semiconductors in a relatively bad position versus Wacker, Dynamit Nobel and Osaka Titanium. The current tariff on polycrystalline silicon entering the United States is 4.8% of sales value.

In Table 14, the semiconductor silicon price range and weighted average for (a) long-term contract, (b) spot market, and (c) sales for "off-grade"

Table 11. A Forecast of Polycrystalline Silicon Purchases, metric tons

	Company	1983	1984	1985	1986	1987	1988
1.	Monsanto Company	220	330	490	710	990	1300
2.	Texas Instruments	30	40	50	80	170	250
3.	Motorola Inc.	20	30	70	110	160	200
4.	Shin-Etsu	370	460	570	710	930	1150
5.	Siltec Corporation	80	100	130	160	200	250
6.	IBM	90	110	150	200	270	350
7.	General Motors	80	90	100	150	190	240
8.	Western Electric	90	110	130	170	200	250
9.	Fairchild	80	90	100	120	150	180
10.	Philips	20	20	30	50	70	100
11.	Ametek	10	15	20	30	40	50
12.	Crysteco	20	25	30	40	60	80
13.	Pennsilco	25	30	40	50	70	90
14.	Cincinnati Milacron	20	30	40	60	80	100
15.	Komatsu	60	90	120	160	270	350
16.	Osaka Titanium	20	110	110	110	240	450
17.	Toshiba	50	150	220	300	340	400
18.	All Others	94	90	115	125	185	305
	Total	1379	1920	2515	3335	4615	6095

semiconductor silicon are listed. As can be seen, the spot market prices vary substantially depending on the availability of the silicon. The prices actually skyrocketed during 1979, 1980, 1981 when the shortage of polycrystalline silicon began to develop.

There are a number of indicators (most of which have been pointed out in this report) that the price of pure semiconductor grade polycrystalline silicon will continue to drop beyond 1983. These indicators are:

Table 12. Polycrystalline Silicon Sales, metric tons

	Company	1977	1978	1979	1980	1981	1982
1.	Wacker Chemetronic	180	270	370	380	430	510
2.	Hemlock Semiconductor	190	244	333	340	368	410
3.	Osaka Titanium	21	30	40	37	60	57
4.	Dynamit Nobel	20	23	50	40	50	60
5.	Great Western Silicon	-	-	30	50	40	40
6.	Peoples Republic of China	-	-	-	30	20	10
	Total	411	567	823	877	968	1087

Table 13. A Prediction of Polycrystalline Silicon Sales, metric tons

	Company	1983	1984	1985	1986	1987	1988
1.	Wacker Chemetronic	651	875	990	1060	1330	1570
2.	Hemlock Semiconductors	458	620	775	875	925	1025
3.	Dynamit Nobel	100	150	200	250	300	400
4.	General Electric	100	150	200	250	300	400
5.	Union Carbide Corp.	-	-	100	300	560	900
6.	Tokuyama Soda Company	-	-	-	50	200	300
7.	Peoples Republic of China	20	25	50	50	100	200
8.	Russia and Satellites	50	100	100	100	100	100
9.	New Manufacturers	-	-	100	400	800	1200
	Total	1379	1920	2515	3335	4615	6095

(1) The spot market price has dropped from $125/kg in 1980 to $40/kg in 1982.

(2) The Monsanto Company is the largest contract purchaser of polycrystalline silicon. The Monsanto Company's long-range purchase contract with Hemlock ends in 1983. Wacker is making a determined effort to obtain this contract. Regardless of who gets the contract, polycrystalline silicon is predicted to be bought at a price of $50/kg or less.

Table 14. Polycrystalline Silicon Prices, $/kg

Year	Long-Term Contract		Spot Market		"Off-Grade" Semiconductor Material	
	Range	Weighted Average	Range	Weighted Average	Range	Weighted Average
1970	40-50	48	40-60	47	10-50	25
1971	40-55	49	40-50	47	10-30	25
1972	45-55	50	45-50	47	10-30	25
1973	50-60	55	50-80	54	-	-
1974	50-65	60	50-80	60	20-50	35
1975	50-60	55	50-60	61	25-35	32
1976	45-65	52	45-65	57	25-35	30
1977	40-60	50	40-65	53	20-40	30
1978	45-60	51	40-60	51	20-40	30
1979	45-60	55	40-100	60	20-40	35
1980	45-85	60	55-140	90	25-100	40
1981	55-80	65	51-147	51	25-50	30
1982	60-80	64	38-70	42	20-35	35

(3) Russia will probably attempt to sell up to 100 metric tons of polycrystalline silicon in the free world for less than $50/kg in 1983.

(4) The Osaka Titanium Manufacturing Company will sell excess polycrystalline silicon in the United States for less than $50/kg in 1983.

(5) Capacity at established polycrystalline silicon manufacturers is growing faster than market.

(6) Union Carbide and other United States manufacturers teams will enter the polycrystalline silicon market using new low cost processes. These plants will produce at low cost and will produce high quality product. The only way these new entries can enter the market is with lower prices than the competition.

Based on all these factors, it is forecast that the spot market price for prime grade polycrystalline silicon will monotonically be reduced to as low as $25/kg by 1988 and that long-range contract pricing will track the spot market pricing closely. The forecasted price reductions are shown in Figure 3 along with historical pricing.

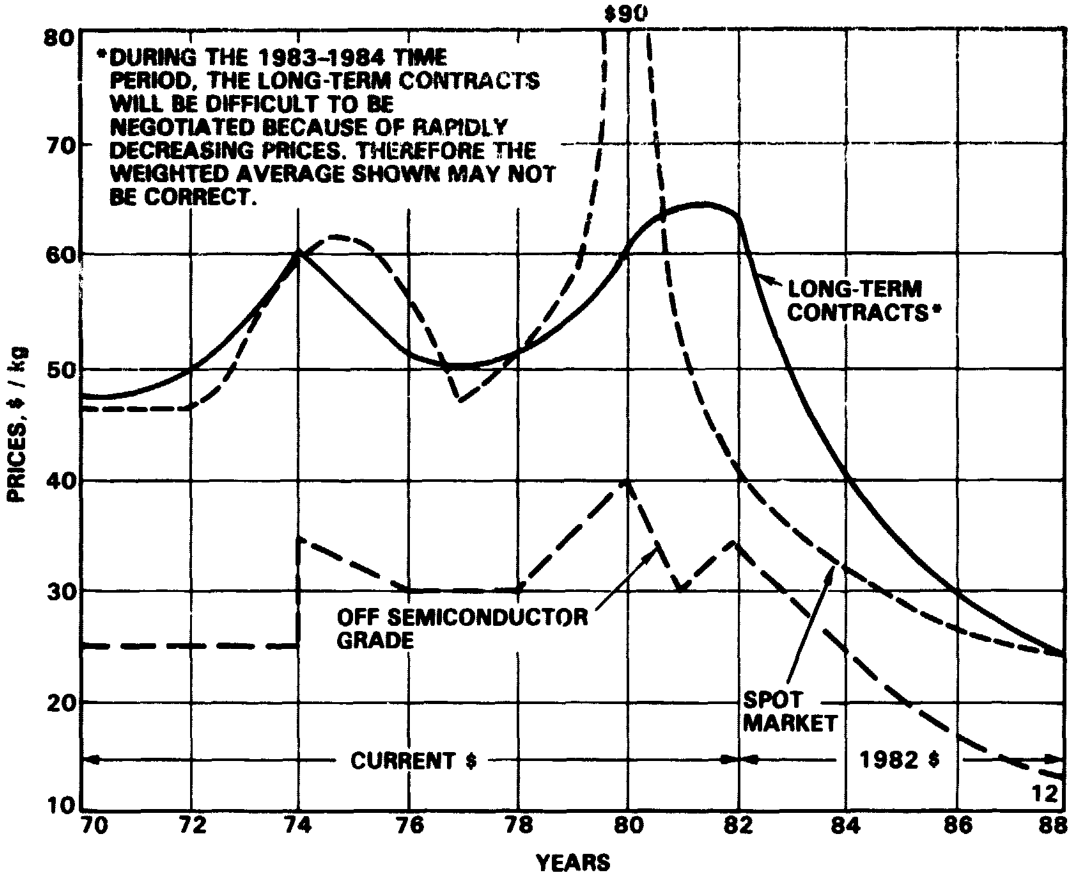

Figure 3. Weighted Average Price History and Forecast for Polycrystalline Silicon per Kilogram (1982 $)

SECTION V

POLYCRYSTALLINE SILICON AVAILABILITY FOR PHOTOVOLTAICS INDUSTRY

The major present and some future polysilicon users among U.S. manufacturers of silicon solar cells are listed below:

(1) Arco Solar.

(2) Solarex.

(3) Solar Power.

(4) Westinghouse.

(5) Motorola.

(6) Mobil Solar.

(7) Spectrolab.

(8) Photowatt.

(9) Solec.

(10) ASEC.

Arco Solar and Spectrolab buy polycrystalline silicon and grow their own Czochralski crystal. Westinghouse and Mobile Solar purchase polycrystalline silicon and grow silicon ribbons. Motorola. Photowatt and Solar Power buy silicon wafers. Solarex buys polycrystalline silicon and grows its own ingots. Scrapped out polycrystalline silicon is and will continue to be used to make efficient silicon solar cells. The solar cell is not as exacting a device as is a random access memory or a thyristor. In this report, only scrap silicon that contains impurities in the parts per billion range is considered, not the so called "solar grade" material with impurities in the parts per million.

In the growth of silicon single crystals, approximately 60% of the polycrystalline silicon ends up as usable crystal. The remaining 40% is scrapped. The losses related to crystal growth are:

(1) Crystal grinding, 3%.

(2) Nonsingle crystallinity. 2%.

(3) High O_2 and carbon content, 3%.

(4) Crucible leavings, 7%.

(5) Crystal bottoms and tops, 10%.

(6) Outside spec. resistivity, 15%.

The polycrystalline silicon left in the crucible after crystal growth and the grinding residue are a true loss. The remaining 30% is, however, perfectly usable for solar cells, diodes and as substrates for epitaxial wafers. At least two thirds of this scrap is available to the silicon solar cell industry. This availability can take the form of inexpensive wafers or polycrystalline silicon.

Approximately 5% of all virgin polycrystalline silicon produced does not meet the specifications required for the manufacture of integrated circuits or power devices. The level of phoshorus, boron or carbon is critical for integrated circuits, but not for solar cells. This off-grade product is available to the solar industry for a price that is usually less than one-half the spot price for prime grade polycrystalline silicon.

In Table 15, the dollar value history and a future estimate are made for silicon solar cells manufactured over the years. It seems that Japan could be on the threshold of capturing this industry also primarily because Japan will concentrate in volume production of amorphous silicon solar cells.

In Table 16, the silicon consumption history and an estimate of future needs are given for the manufacture of solar cells through 1988. Solar cells fabricated from Czochralski crystal and semiconductor grade polycrystalline silicon are normally at least 13 to 14% efficient. The efficiency should increase to 14.5 to 15% by 1983 and 15 to 15.5% by 1985. Solar cells fabricated for ribbon have demonstrated efficiency near 15% and are expected to be above 16% in the near future.

Slicing practices for ingots should improve in the next few years. The slice thicknesses should decrease from 375 to 250 micrometers (0.015 to 0.010 inch) and the kerf loss from 300 to 240 micrometers (0.0121 to 0.010 inch). Crystal yields, even with continuous pulling, should average 75% and crystal circumference grinding may be unnecessary. Using these assumptions, the amount of single crystal ingot and polycrystalline silicon required to manufacture wafers for fabrication into solar cells has been about 18-20 g/W. It is expected to be reduced to about 12 g/W with improved wafering techniques and higher efficiencies. With the ribbon technology the polycrystalline silicon for manufacturing solar cells is expected to be near 6 g/W. Table 17 shows the weighted average price of this scrap silicon and gives an estimate of future pricing.

Table 15. History and Forecast of Silicon Solar Cell Sales by Place of Origin, millions of dollars

Place of Origin	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
United States	9.0	12.0	15.0	17.0	24.0	39.6	39	47	55	70	100	120
Western Europe	2.8	3.9	4.6	3.9	10.2	12.7	22	26	30	40	60	80
Japan	0.9	6.0	7.0	8.0	9.9	12.5	23	37	55	77	120	150
Total	12.7	21.9	26.6	33.9	44.1	64.8	84	110	140	180	280	350

Table 16. Historical Use and Forecast of Polycrystalline Silicon Required for Silicon Solar Cell Modules

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Average Dollars Per Peak Watt	10.00	9.00	8.50	8.00	7.60	7.20	6.00	5.50	5.00	4.50	4.00	3.50
Mega Watts Peak	1.3	2.4	3.1	4.3	5.7	9.0	17	20	28	40	70	100
Polycrystalline Silicon Required (Metric Tons)	28	50	60	78	94	160	210	250	330	380*	630*	900*
Scrap High Grade Polycrystalline Silicon Available (Metric Tons)	225	280	250	400	425	470	550	675	830	1080	1360	1700

*50% of solar cell production will be using ribbons

Table 17. Weighted Average Prices of Off-Grade Polycrystalline Silicon, $/kg

Year	Weighted Average Price	Year	Weighted Average Price
1970	25	1980	40
1971	25	1981	30
1972	25	1982	35
1973	Product Not Available	Estimate	
1974	35	1983	18
1975	32	1984	16
1976	30	1985	14
1977	30	1986	13
1978	30	1987	12
1979	35	1988	12

SECTION VI

CONCLUSIONS

Over the past four years the outlook on the polycrystalline silicon material availability has changed drastically. In November 1979, a survey was conducted with the following conclusions:

(1) Limited supply of polycrystalline silicon material would develop beginning early in 1980, and would result in a severe shortage. The shortage would develop because of increasing demands forecasted by the semiconductor products industry and by the needs of the emerging photovoltaics (PV) industry.

(2) A seller's market would be created and the price of silicon would be expected to increase because of the predictions.

In November 1980, a silicon industry update survey was conducted which confirmed temporary tremendous increases in the spot market prices. In April 1980, the spot market price for the silicon material was quoted as high as $140/kg, an increase of a factor of 2 from the spot market prices quoted in 1979. The survey also found that the silicon supply situation was changing because of the industry activities to meet the forecasted demands. The conclusions of that survey were:

(1) Sufficient semiconductor-grade polycrystalline silicon will be available to meet the forecasted market demands for the semiconductor product industry.

(2) Excess semiconductor-grade silicon and non-conforming (rejected from the semiconductor industry) silicon material would be available for the PV industry.

The recent survey conducted by the JPL Consultant, Dr. Remo Pellin, indicates that the activities of the polycrystalline manufacturers to reduce production cost and to be highly competitive is continuing. Improvements to the basic Siemens process which can provide lower production cost in the existing plants and have been and are being included. The conclusions from this latest update on the status of silicon availability and market pricing are:

(1) Polycrystalline silicon availability is now and will continue to be in excess of the users demands.

(2) Polycrystalline silicon material prices have decreased over the past year and will continue to drop.

(3) Refiners of silicon have obtained greatly expanded plant capacity by simple process improvements. The changes have been achieved with minimal capital expenditures.

(4) The present and projected overcapacity in the silicon industry has led to more aggressive refining process cost reductions efforts, increased yield and competitive pricing.

(5) The worldwide recession which began in the summer of 1980, has caused a slightly lower rate of growth of the semiconductor industry than was expected.

(6) New polycrystalline silicon low-cost refining processes, largely developed through DOE funding and administered by JPL, are reaching technology readiness. A number of new technology plant improvements are expected to be available, which will further reduce the polycrystalline silicon production cost and hence the competitive selling prices.

The present outlook in silicon material availability and competitive pricing will provide for a healthy environment for the photovoltaic industry as well as for the semiconductor industry.

SECTION VII

REFERENCES

1. Silicon Material Outlook Study for 1980-1985, JPL Report 5230-1, Rev. A, Photovoltaics Program Technology and Application Lead Center, Jet Propulsion Laboratory, November 1, 1979.

2. Industry Survey Report Status of Silicon Material and Silicon Sheet Techniques, JPL Report 5230-5, Photovoltaics Program Technology and Application Lead Center, Jet Propulsion Laboratory, May 1, 1981.

3. Snyderman, Nat, Electronic News, March 31, 1980.

4. Snyderman, Nat, Electronic News, October 20, 1980.

5. Snyderman, Nat, Electronic News, March 17, 1975.

6. Snyderman, Nat, Electronic News, January 10, 1983.

7. Hataye, John, Electronic News, April 9, 1979.

8. Snyderman, Nat, Electronic News, April 26, 1982.

9. Snyderman, Nat, Electronic News, December 8, 1980

10. Snyderman, Nat, Electronic News, July 6, 1981.

APPENDIX

SEMICONDUCTOR DEVICE INDUSTRY MANUFACTURING COST DRIVERS

Table A-1 records the manufacture of silicon devices for the years 1977 through 1982 and forecasts the years 1983 and 1985. The standings for the 16 largest manufacturers are also shown. In Table A-2, the usage of the various device families for the years 1977 through 1982 is recorded; this usage is forecast for the years 1983 and 1985.

Table A-3 is a complex chart showing silicon device, silicon single crystal wafer, silicon single crystal, and polycrystalline silicon usage and forecasts usage from 1974 to 1990. In Column 2 of Table A-3 it should be noted that silicon device usage, in dollars, doubled from 1974 through 1979. It is predicted that this usage will double again between 1979 and 1984 even though 3 recession years are included in this period. It is expected that this usage will double again twice between 1984 and 1991. This forecast growth market is based upon use of a learning curve indicating that the silicon device industry can increase the computational power of a silicon device by a factor of 100 for a sales price increase of only a factor of two. Similar forecasts of silicon device market growth have been made by the Electronics Magazine, Dataquest Inc., and Semiconductor Equipment Manufacturers Institute.

The sales price of silicon devices varies enormously. A simple silicon device can be purchased for a few cents, while some microprocessors are priced at several hundred dollars. In general, the price of a device is related to the area of silicon wafer that is required to manufacture it and the processing yields achieved in production. Some devices require large silicon sheet area per device sold area because the yield of good devices is poor. Other devices require large areas of silicon wafer because the device uses a large area itself. The actual value per square inch of silicon wafer is listed below for several specific devices.

(1) Microprocessors, $36/square inch.

(2) 64K bit RAMs, $30/square inch.

(3) 16K bit RAMs, $25/square inch.

(4) Thyristors, $20/square inch.

(5) Photodiodes, $15/square inch.

(6) Autorectifiers, $12/square inch.

(7) Silicon Solar Cells, $0.50/square inch.

The industry average for silicon device manufacture has been $18 worth of silicon devices per square inch of silicon wafer for many years. In Column 3 of Table A-3, the 4.17% is simply the worth of a square inch of silicon wafer, $0.75, divided by the $18 average worth of devices. In 1983, this percentage begins to decrease as the total product mix of silicon devices

ORIGINAL PAGE IS
OF POOR QUALITY

Table A-1. Silicon Device Manufacture by Company, millions of dollars

Company	1977	1978	1979	1980	1981	1982	1983	1985
Texas Instruments	772	945	1210	1410	1400	1500	1725	2500
Motorola Inc.	572	718	920	1135	1350	1650	1900	2900
IBM*	550	625	750	940	980	1040	1200	1700
Philips	533	622	780	895	885	950	1040	1500
Western Electric*	520	600	700	800	880	980	[illegible]	1600
General Motors*	400	430	480	550	500	550	600	900
Nippon Electric	363	555	780	970	1050	1180	1400	2300
Nat. Semiconductor	300	420	620	780	750	780	880	1200
Fairchild	323	379	470	520	530	530	600	800
Siemens	250	292	410	460	440	450	510	850
Hitachi	271	455	728	900	980	1080	1260	1900
Toshiba	253	381	495	645	700	800	900	1500
RCA	206	236	270	300	290	280	300	400
Intel	200	300	430	680	750	800	1000	1600
Mostek	71	105	210	290	270	270	350	500
AMD	82	132	208	270	270	260	300	450
All Others	2944	2710	2439	2575	3075	3360	4055	5500
Total	8610	9905	11900	14120	15100	16460	19100	28100

*Estimated

Table A-2. Free World Silicon Device Usage by Product, millions of dollars

Device Type	1977	1978	1979	1980	1981	1982	1983	1985
Total Silicon Devices	8610	9905	11900	14120	15100	16460	19100	28100
Total Discrete Devices	3010	3280	3460	3720	3900	3870	4100	4920
Thyristors	334	365	405	447	479	490	519	700
Power Rectifiers	651	706	766	843	888	890	943	1240
Power Transistors	695	748	838	999	1076	1060	1124	1400
Zener Diodes	169	181	201	230	253	250	265	290
Signal Transistors	881	1023	1023	1001	960	900	900	900
Solar Cells	15	22	27	38	44	56	70	100
Other Devices	265	235	200	162	200	224	279	290
Total I.C.s	5600	6625	8440	10400	11200	12590	15000	23180
Bipolar ICs	1301	1487	1775	2119	2402	2660	3170	4700
MOS ICs	2037	2412	3457	4488	4791	5088	6370	10900
Linear ICs	1216	1373	1724	1993	1920	2491	2770	3740
Microprocessors	318	508	774	1159	1402	1749	2090	3230
Special Circuits	728	845	710	641	685	602	500	610

Table A-3. A Forecast of Free World Silicon Usage, millions of dollars and millions of square inches

Year	Silicon Device Usage $	% Material Value	Silicon Wafer Value $	Average Value Per Sq. Inch $	Silicon Wafers Square Inches	Average Diameter Of Crystal Inches	Grams of Polysilicon Per Square Inch of Wafer	Single Crystal In Metric Tons	Polysilicon In Metric Tons
1974	5,750	4.17	234	0.75	312	2.8	2.80	521	871
1975	5,170	4.17	230	0.75	307	2.9	2.80	553	921
1976	6,545	4.17	294	0.75	392	3.0	2.80	702	1170
1977	8,610	4.17	373	0.75	497	3.0	2.57	796	1326
1978	9,905	4.17	430	0.75	573	3.2	2.79	1001	1668
1979	11,900	4.17	519	0.77	674	3.5	3.10	1289	2148
1980	14,120	4.17	599	0.80	749	3.7	3.05	1387	2312
1981	15,100	4.17	644	0.82	785	3.9	3.12	1495	2493
1982	16,460	4.17	714	0.85	840	4.1	3.21	1660	2767
1983	19,100	4.15	838	0.90	927	4.3	3.30	1934	3224
1984	23,400	4.10	1009	0.90	1121	4.4	3.34	2377	3960
1985	28,100	4.05	1215	0.88	1381	4.5	3.39	2984	4970
1986	35,700	4.00	1517	0.88	1724	4.6	3.44	3795	6320
1987	44,600	3.95	1876	0.86	2181	4.7	3.49	4815	8100
1988	56,100	3.90	2336	0.85	2748	4.8	3.54	6130	10220
1989	67,300	3.80	2776	0.85	3265	4.9	3.59	7290	12150
1990	80,300	3.70	3184	0.85	3745	5.0	3.64	8460	14100

begins slowly to tilt toward the microprocessor type of device, which has more value per square inch of silicon. This trend toward ever more complex and powerful silicon devices will have an enormous effect on electronic systems. Eventually the entire component of a large computer will be contained in one silicon chip. The silicon chip will, at that point in time, be worth considerably more than the 2% of a computer that silicon devices are worth today. In Column 4 of Table A-3, the calculation of the worth of the required silicon wafers is made. In Column 5, of Table A-3, the average price per square inch of silicon wafer is presented for the years 1974 through 1982, and an estimate of the price of the wafer in future years is made. Beyond 1983, the price of wafers will decrease with decreasing polycrystalline silicon prices. In Column 6, of Table A-3 the amount of silicon wafer area is calculated. In Column 7, of Table A-3 the average diameter of silicon wafer used per year is recorded or estimated. As the crystal diameter increases, wafers must be cut thicker to prevent breakage and maintain flatness. An estimate of the actual number of wafers that can be theoretically cut per inch of crystal at varying diameters is shown below. This number of wafers is the result of saw kerf loss and required thickness.

Diameter of Crystal, inches	Number of Wafers Per Inch of Crystal
3	27
4	24
5	21
6	19

In Column 8 of Table A-3, a forecast of the expected material practice in the conversion of polycrystalline silicon to polished silicon wafer meeting all specifications is presented. There are at least seven steps in the process going from polycrystalline silicon to a finished acceptable polished wafer. These process steps are listed below along with an average industry yield for each step.

(1) Crystal Growth, 60%; Poly to Single Crystal.

(2) Crystal Grinding, 98%; Crystal to Ground Crystal.

(3) Crystal Slicing, 93%; Good Slices.

(4) Wafer Beveling, 97%; Good Slices.

(5) Lapping, 97%; Good Slices.

(6) Etching, 97%; Good Slices.

(7) Polishing, 93%; Good Slices.

Column 8 of Table A-3 is complex. When new plants come on line, wafer yields are poor and improve with time. Over the years, the crystal diameter increases. New specifications are constantly being imposed upon crystals and wafers. A learning process is involved in the manufacture of wafers any time the parameters of any device are changed.

In Column 9 of Table A-3, the amount of single crystal required is calculated; finally, in Column 10, of Table A-3 the requirement for polycrystalline silicon quantity by the silicon device industry is calculated.

A number of assumptions had to be made to arrive at the basic table of silicon material use represented in Table A-3. Although all the assumptions are warranted, they are assumptions nevertheless:

(1) The years 1980, 1981 and 1982 are considered recession years and that some of the years in the future will be more prosperous.

(2) In the crystallization process, only a 60% yield of saleable crystal will be attained. For Table A-3, it is assumed that this scrapped-out silicon is not reused for integrated circuits or power devices. This is not strictly true. Although most silicon wafer buyers specify virgin polycrystalline silicon, not all do. Certainly in times of polycrystalline silicon shortage, some of this material will find its way into integrated circuit wafers. When polycrystalline silicon is not in short supply, this crystal scrap finds its way into the silicon solar cell market.

(3) Silicon device manufacturers use a great many test wafers. These wafers are used to test device manufacturing processes and in no way ever produce saleable devices. As many as 10% of all wafers shown in Table A-3 are used as test wafers. These test wafers are selected out of the wafers rejected at the various process steps and sold at salvage value. Table A-3 is thus low in total wafers by as much as 10%.

(4) Table A-3 assumes a great deal of averaging occurs. When new silicon refining plants come on line, yields are poor for a time. When new silicon device plants come on line, the yield of devices is low for a time. When new devices such as the 256 K bit random access memory come on line, yield is poor. New plants and new devices are seldom brought on line in recession years. This tends to make recession years worse and boom years better for silicon materials houses.

(5) A considerable time lag occurs between the manufacture of polycrystalline silicon and the sale of a device made from it. It is assumed that 3 months occur between the manufacture of polycrystalline silicon and a polished wafer and that an additional 3 months occurs between the sale of a polished wafer and the sale of a device made from that wafer.

(6) Personnel are on a constant learning curve and get better at their job year by year. It is assumed that, as devices get smaller and

smaller, wafer specifications will get tighter and tighter and also that the tug of war remains a standoff. The silicon crystal and wafering yields have remained constant for the past 10 years. It is assumed these yields will remain constant for the next 10 years.

(7) The dollars referred to in Table A-3 are real dollars at the time of use and that the annual inflation over the next 8 years will range around 5% per year.

(8) That no new technology will come along in the next 8 years to seriously challenge the silicon technology.