The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

World Year of PHYSICS 2005

Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

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"Technology of Solar-grade Silicon"

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Silicon for the PV Industry

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Workshop on "Physics for Renewable Energy", Trieste

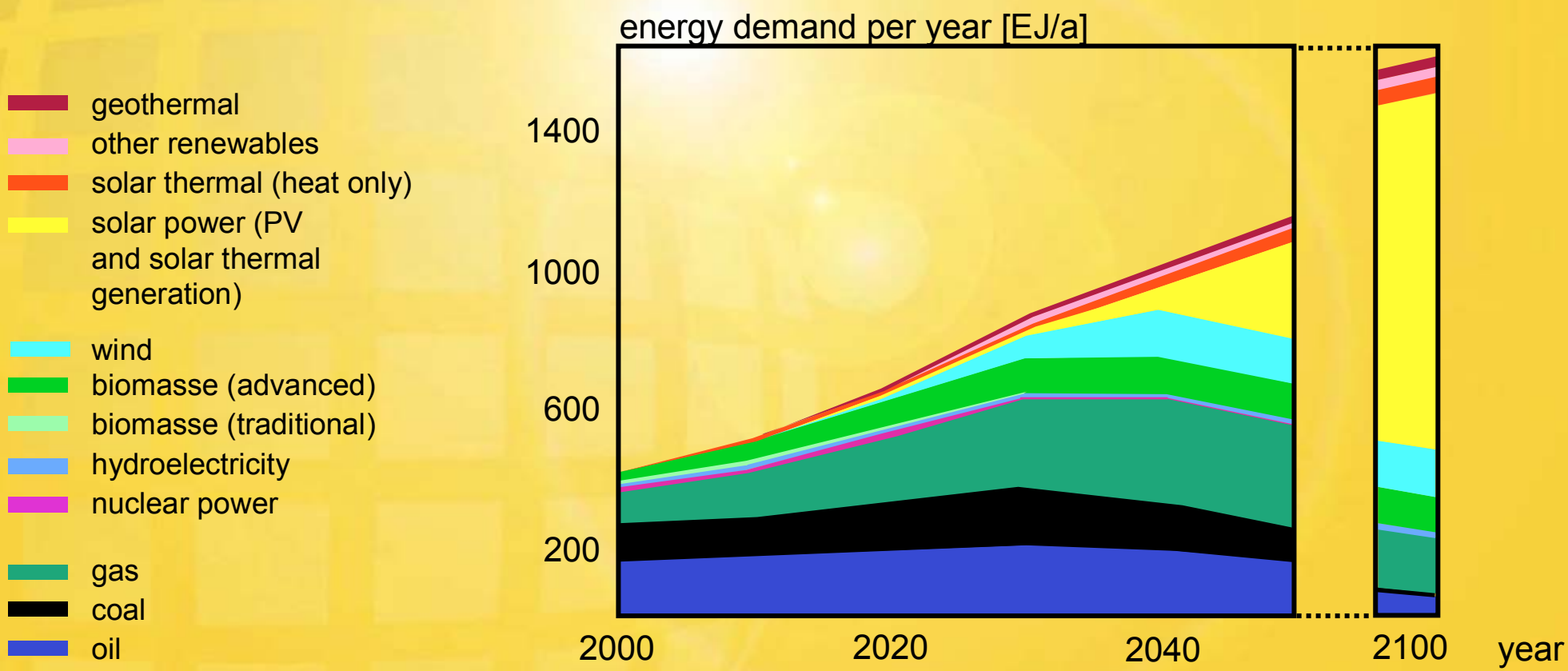
October 24, 2005

OVERVIEW PRESENTATION

- INTRODUCTION
- LONG-TERM SCENARIO
- REQUIREMENTS FOR DYNAMIC GROWTH
  - TECHNOLOGY
  - MARKETS
- CONCLUSIONS

Long-term Scenario

Solar power (PV and Thermal) will become the dominating energy source within this century

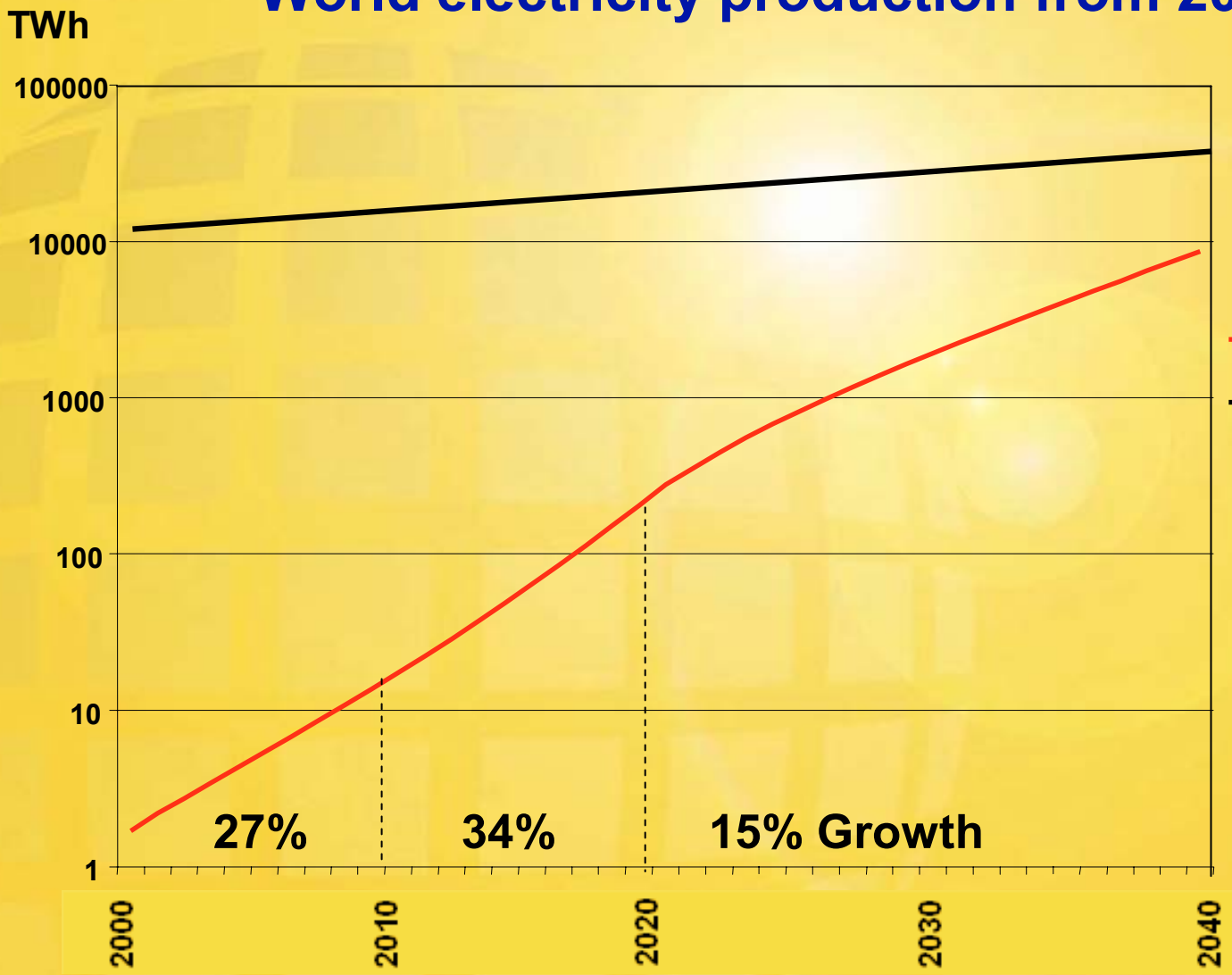


Source: German Advisory Council on Global Change, 2003

www.wbgu.de

- Time period considered 2000 – 2040
- Wafer-based technology
- No “quantum leaps“, steady progress, known physics
- Growth rate world-wide module shipment according EPIA-study
- Price-learning curve for competitiveness

World electricity production from 2000 to 2040



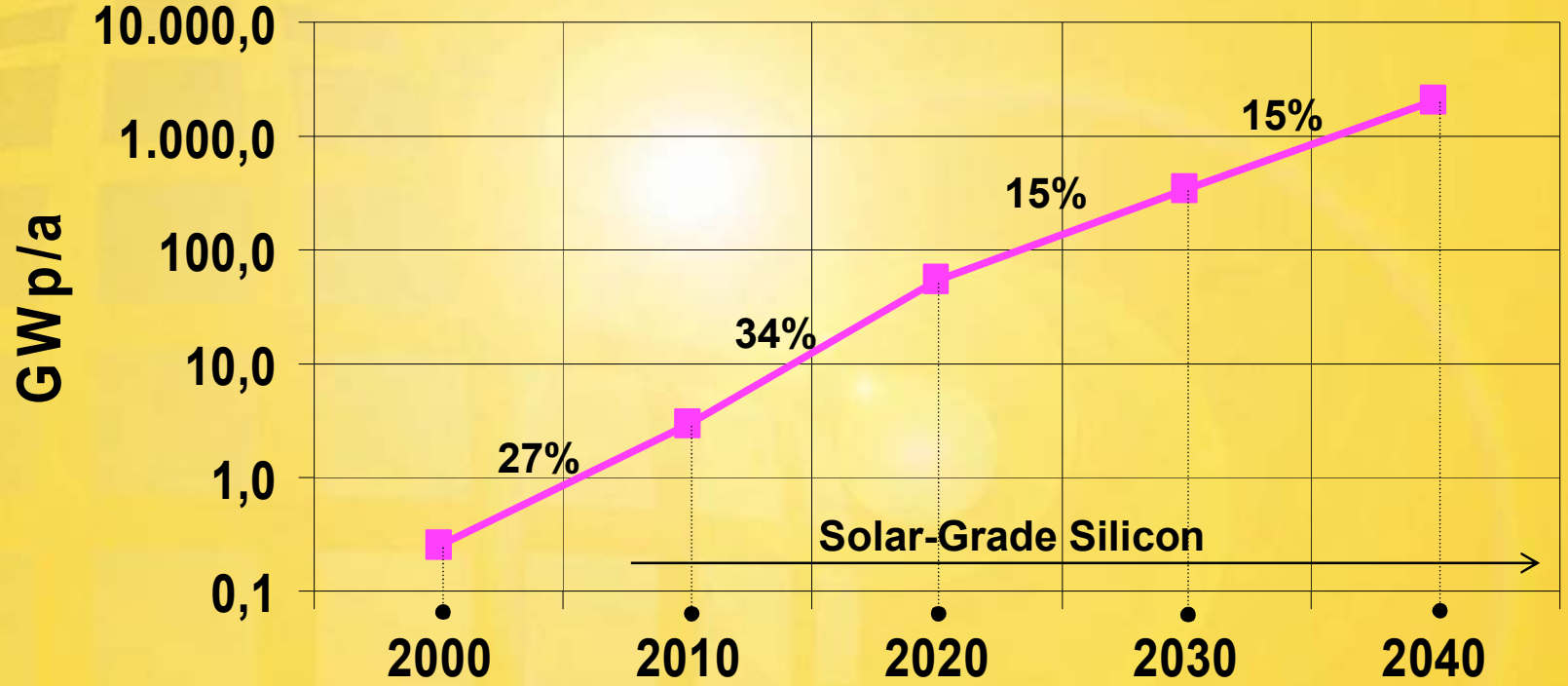
World Electricity from PV in TWh

World Electricity Generation in TWh

2020: PV 1% world electricity

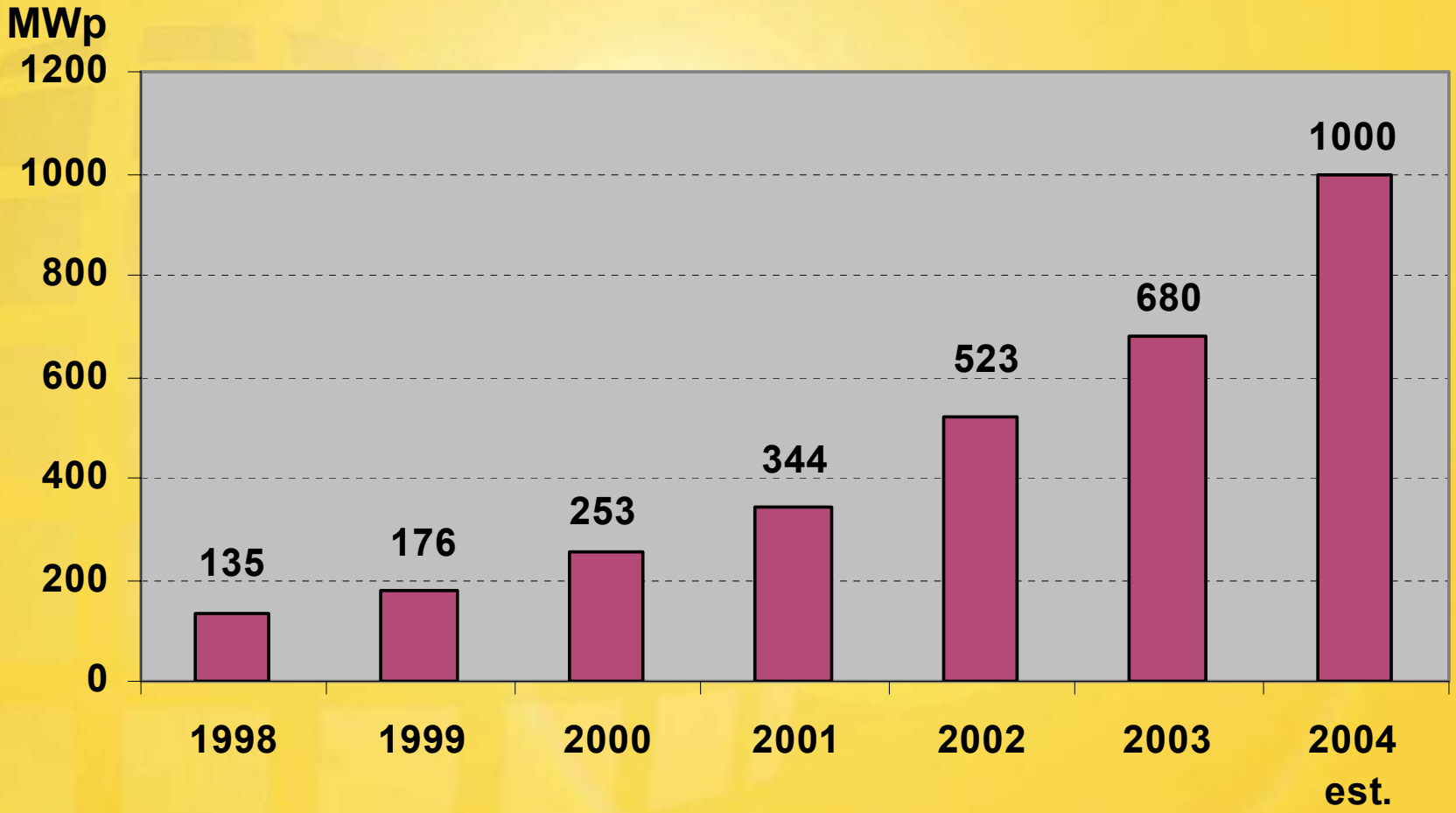
2040: PV 26% world electricity

Source :Solar Generation and IEA-PVPS



to/a	4.500	29.500	300.000	1.200.00	5.250.000
to/MWp	17,5	10,0	5,2	3,5	2,5

Installed Module Capacity and Silicon Consumption



Source: Strategies Unlimited, PVCS

World-Wide Cell & Module Shipments 1998-2004

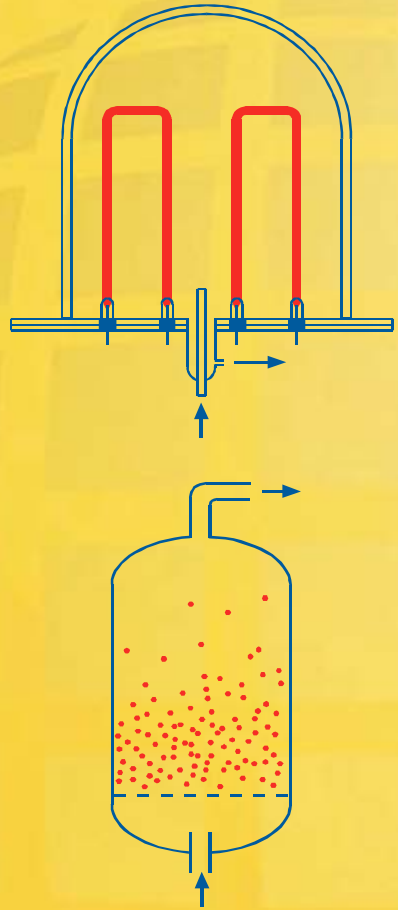
- No bottlenecks seen for long-term, large scale PV Solar Electricity generation using crystalline Si-wafer technology

- Major thrust high efficiency at low cost

Technology

To reduce cost in the long-term scenario technology advancements in all areas are necessary:

- Solar-grade silicon
- Crystallization
- Wafering
- Solar cells
- Modules



Production Capacity appr. 31,000 t/ p.a.

IC's

Off-spec poly-Si ≈ 2,000 t (2004)

Solar-grade Si ≈ 9,000 t (2004)

SOLAR-GRADE SILICON

- Gas phase deposition
- Purify MG-Silicon

SOLAR-GRADE SILICON

- No clear definition exists as to the purity level of solar-grade silicon
- Most frequent usage:

  p-type 0.5 – 10 Ω cm

  slight compensation acceptable

  carbon concentration $< 5 \times 10^{16}$ (Cz ≠ mc ≠ EFG)

  metal impurities < 1ppm

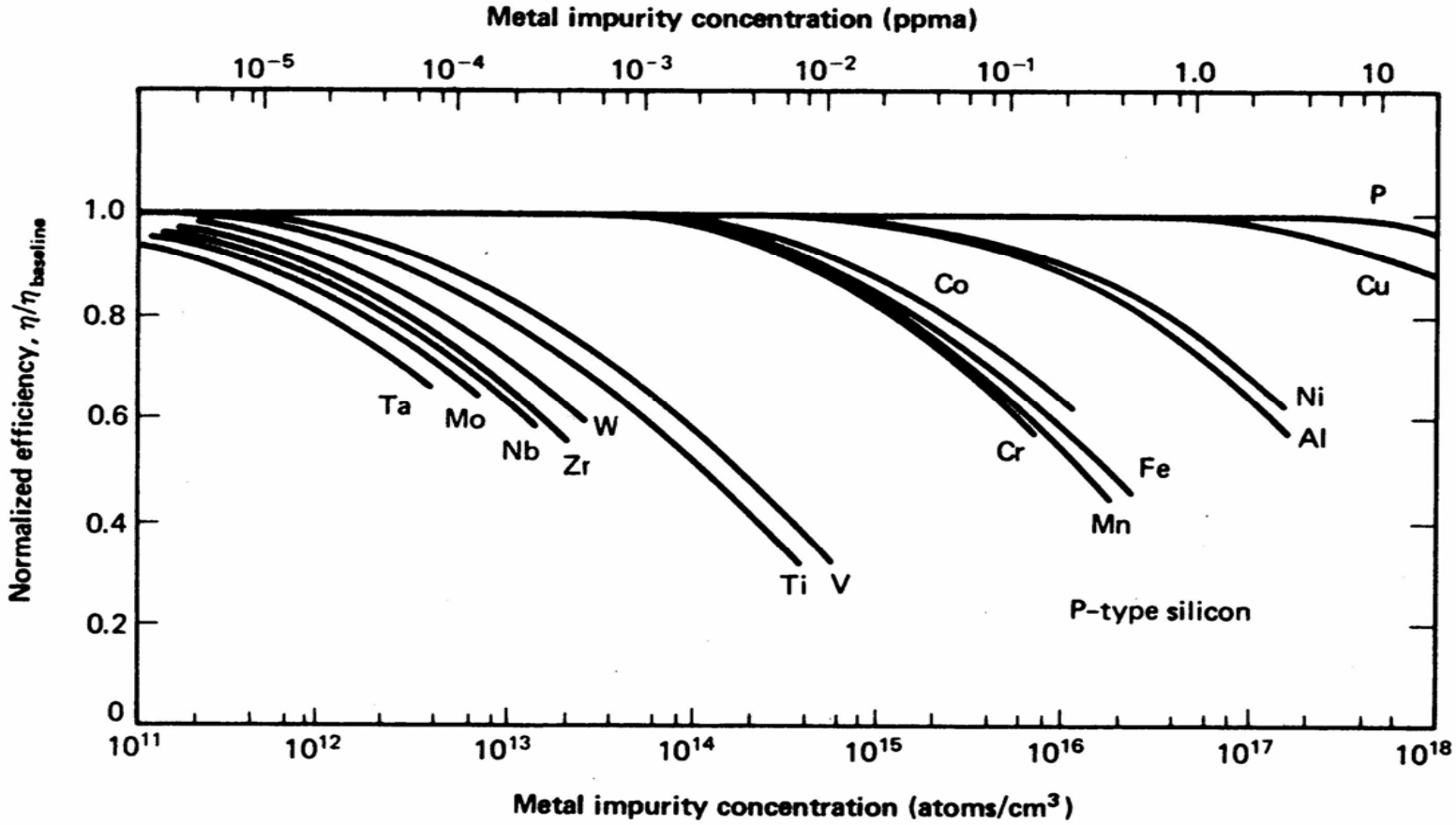
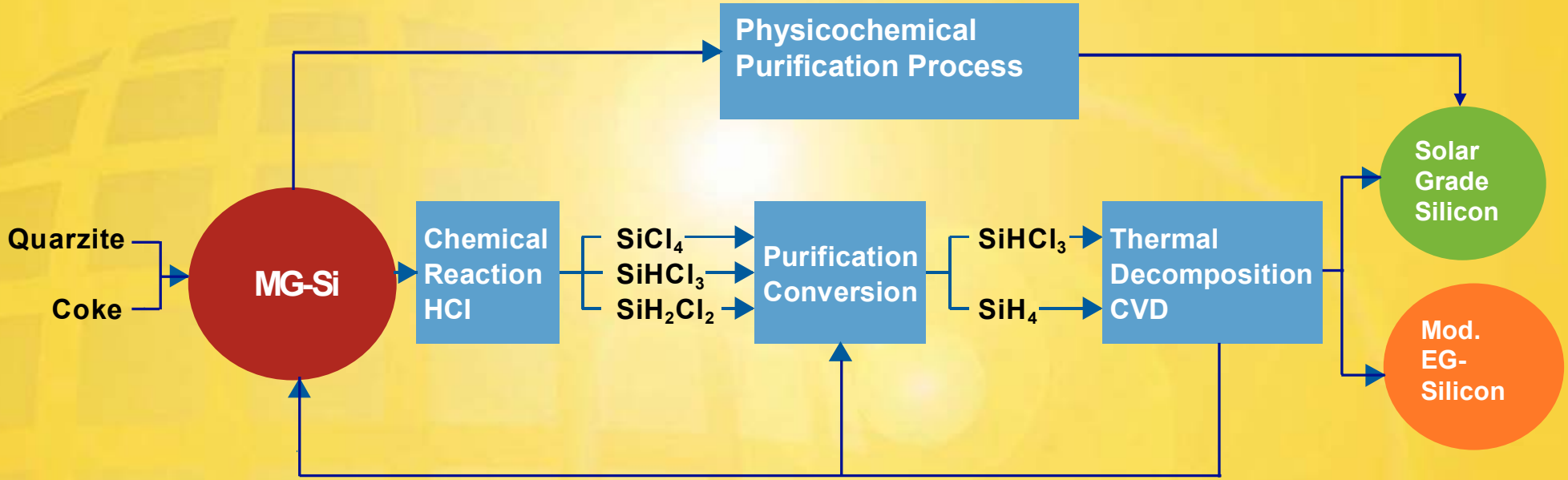


Figure 7.1. Effect of different secondary impurities on the performance of silicon solar cells (After Ref. 7.1, ©1978 IEEE.)



- Major new investment into conventional Siemens-type deposition, modified EG-Si. Capable semiconductor usage.
- Fluidized bed reactor appears to offer little price advantage
- Purified MG-Si usage not yet clear.

CONVENTIONAL BELL JAR GROWING OF POLYSILICON –

THE CONTINUOUS IMPROVEMENT GOES ON.

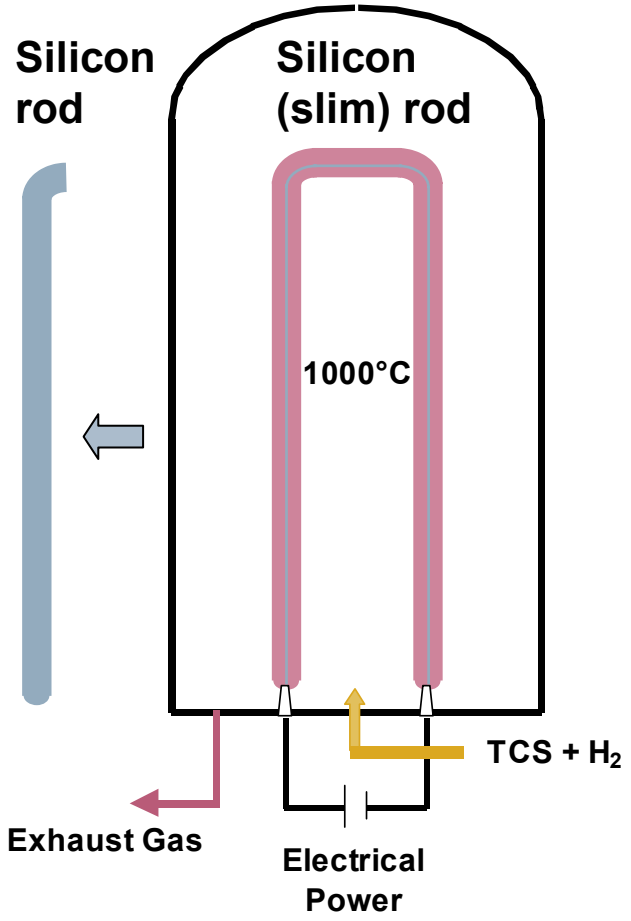
Solar-grade silicon

CRUSHING

CRUSHING

HF/HNO_3 ETCHING

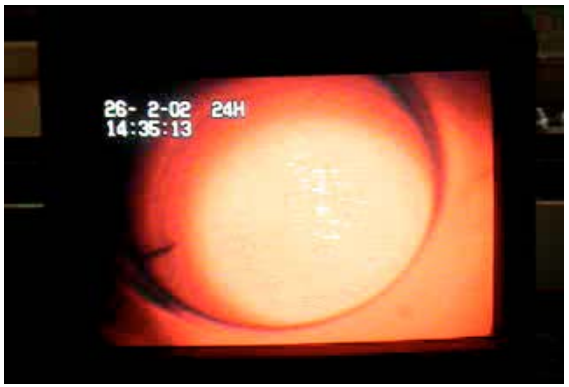
Prime polysilicon

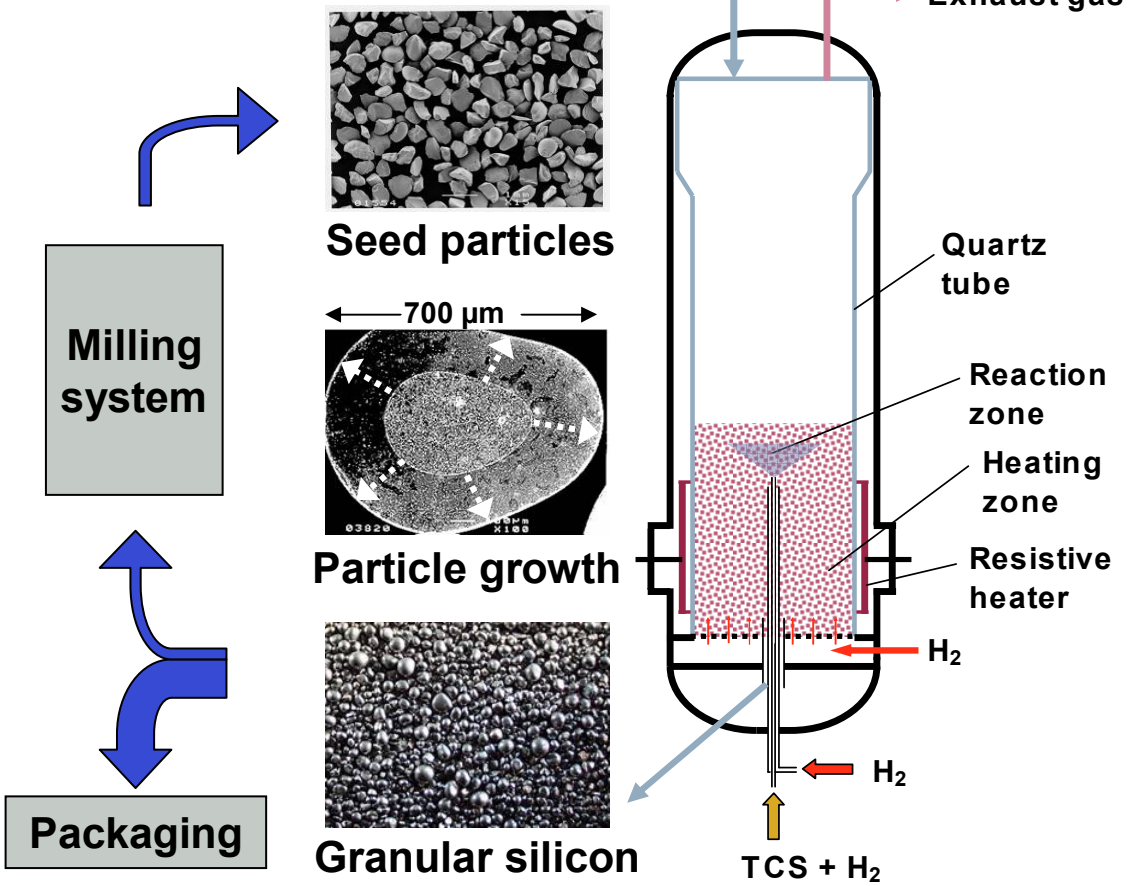


WACKER POLYSILICON

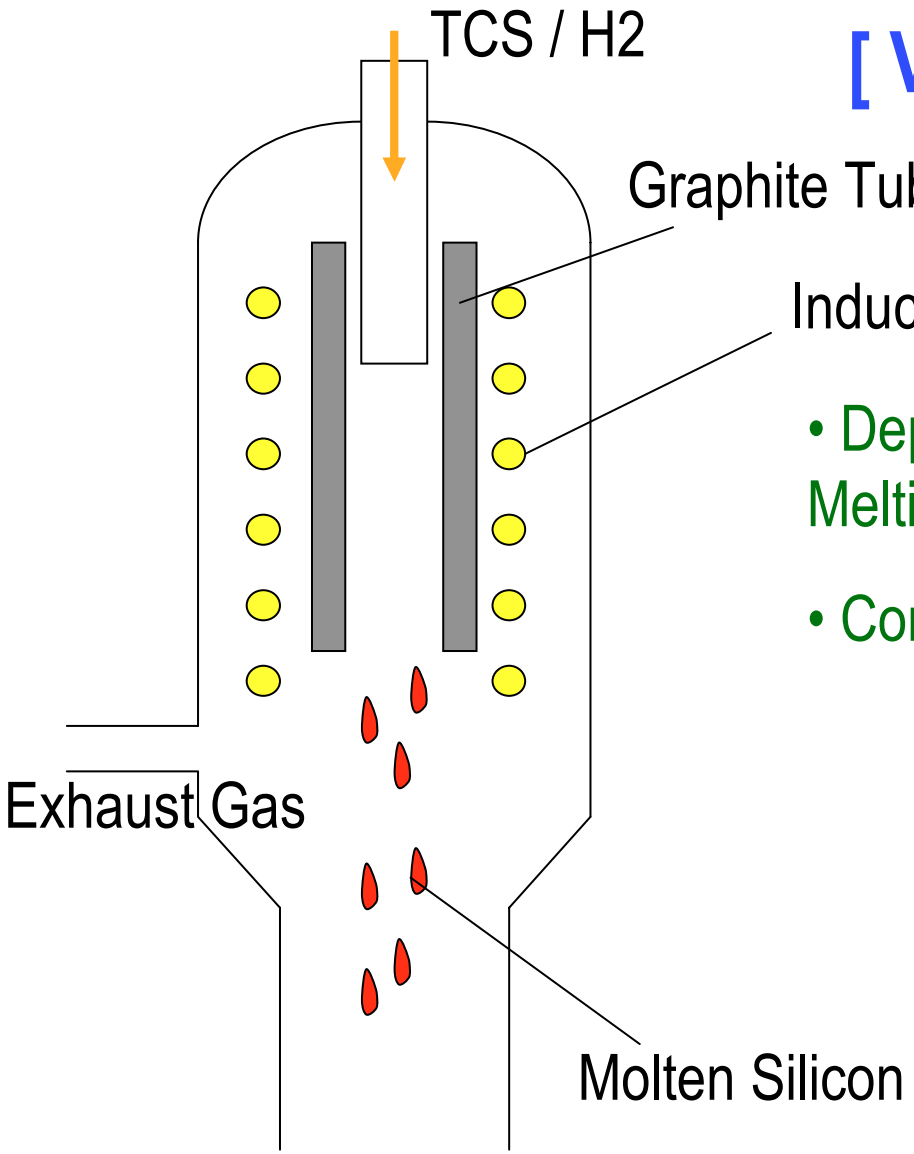
Feedstock for the PV Industry
Karl Hesse, Ewald Schindlbeck, April 11 2005

FLUIDIZED BED GRANULAR DEPOSITION: A CONTINUOS PROCESS





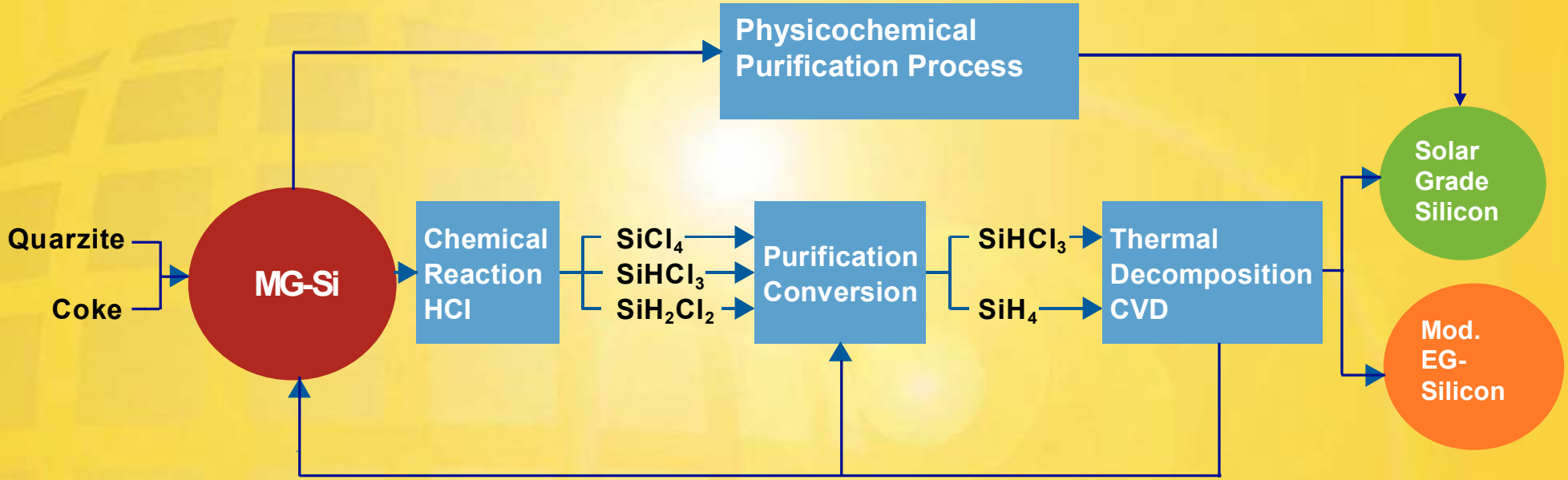
The Si Liquid runs from Reactor Tube just like a Tap Water



[Vapor to Liquid Deposition]

- Deposition Temperature is Higher than Si Melting Point
- Continuous Production of Granular Si

Chemistry with a Heart
TOKUYAMA



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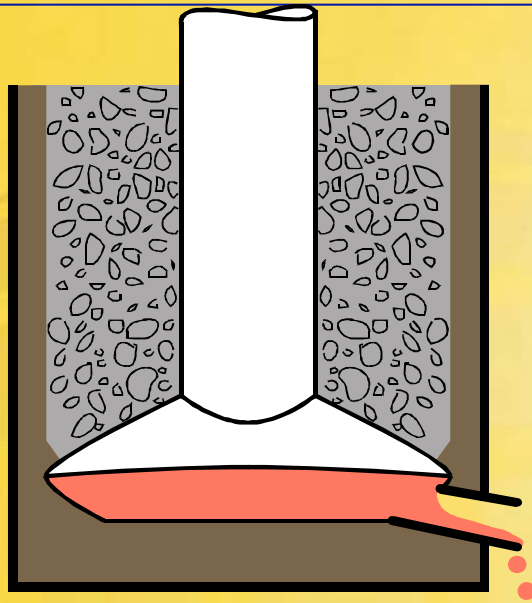
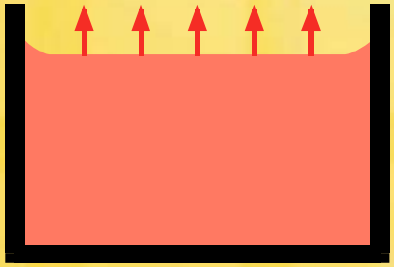
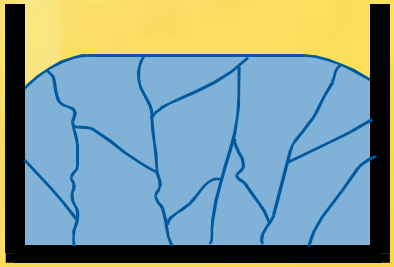


Arc furnace metallurgical grade silicon



chemical/physical treatment



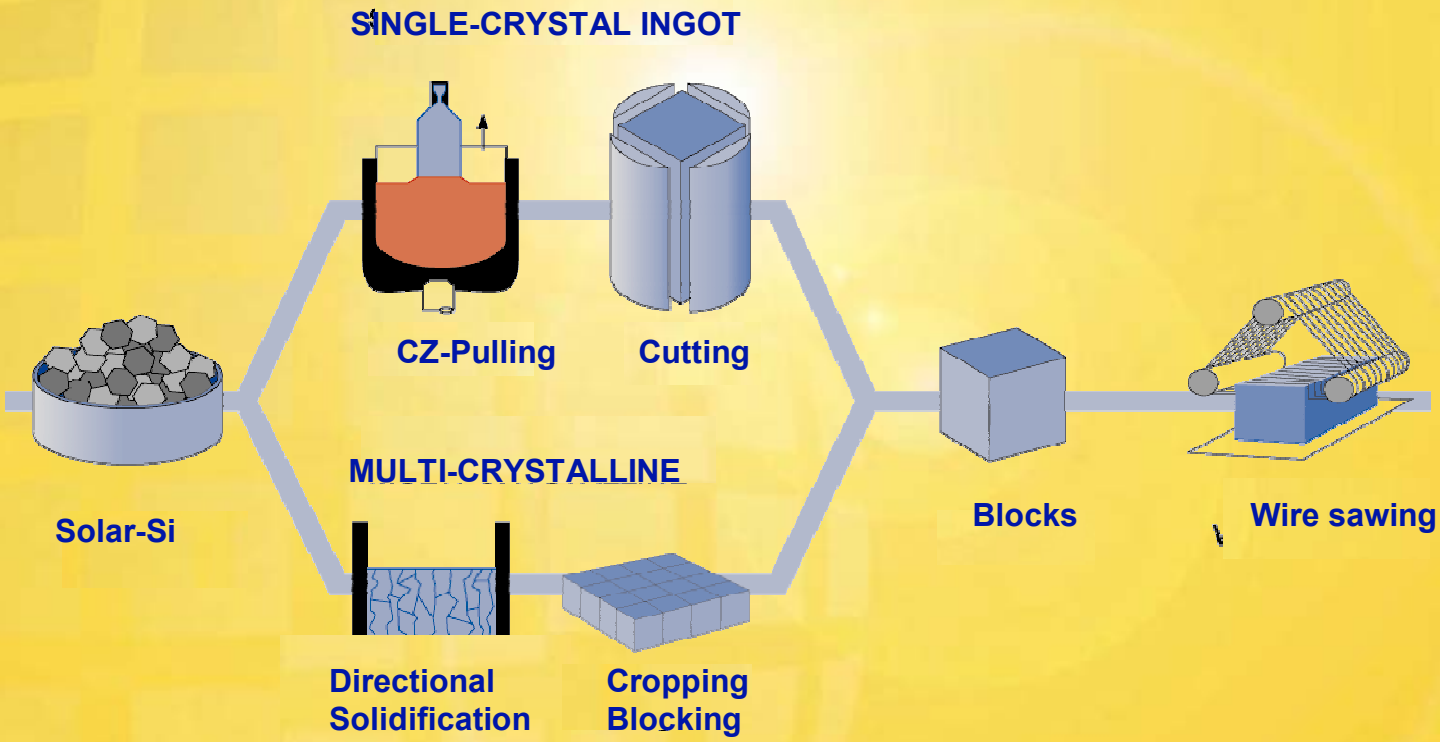
directional solidification

solar grade silicon feedstock

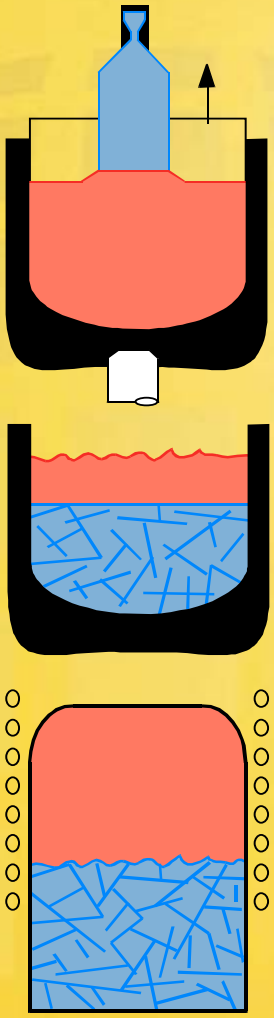
DECREASE SILICON CONSUMPTION

- Crystallization
- Wafering
- Solar Cell

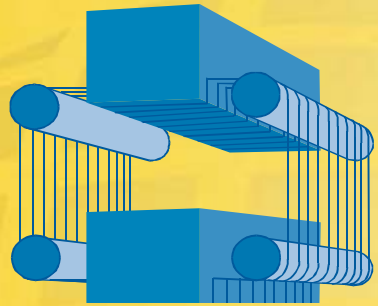
Total Silicon Yield From Feedstock To Wafer 32-54%



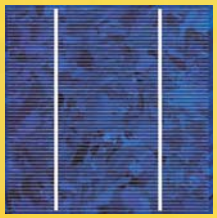
Silicon Yield:	**90%-95%**	**80%-95%**	**45%-60%**
Si-Recycle:	**Pot Scrap**	**Cropped Section (Tops and tails,slabs)**	**Broken Wafer**



- Multiple ingots from one crucible
- Taller and larger ingots
- “Continuos“ casting
- Low cost / Wp

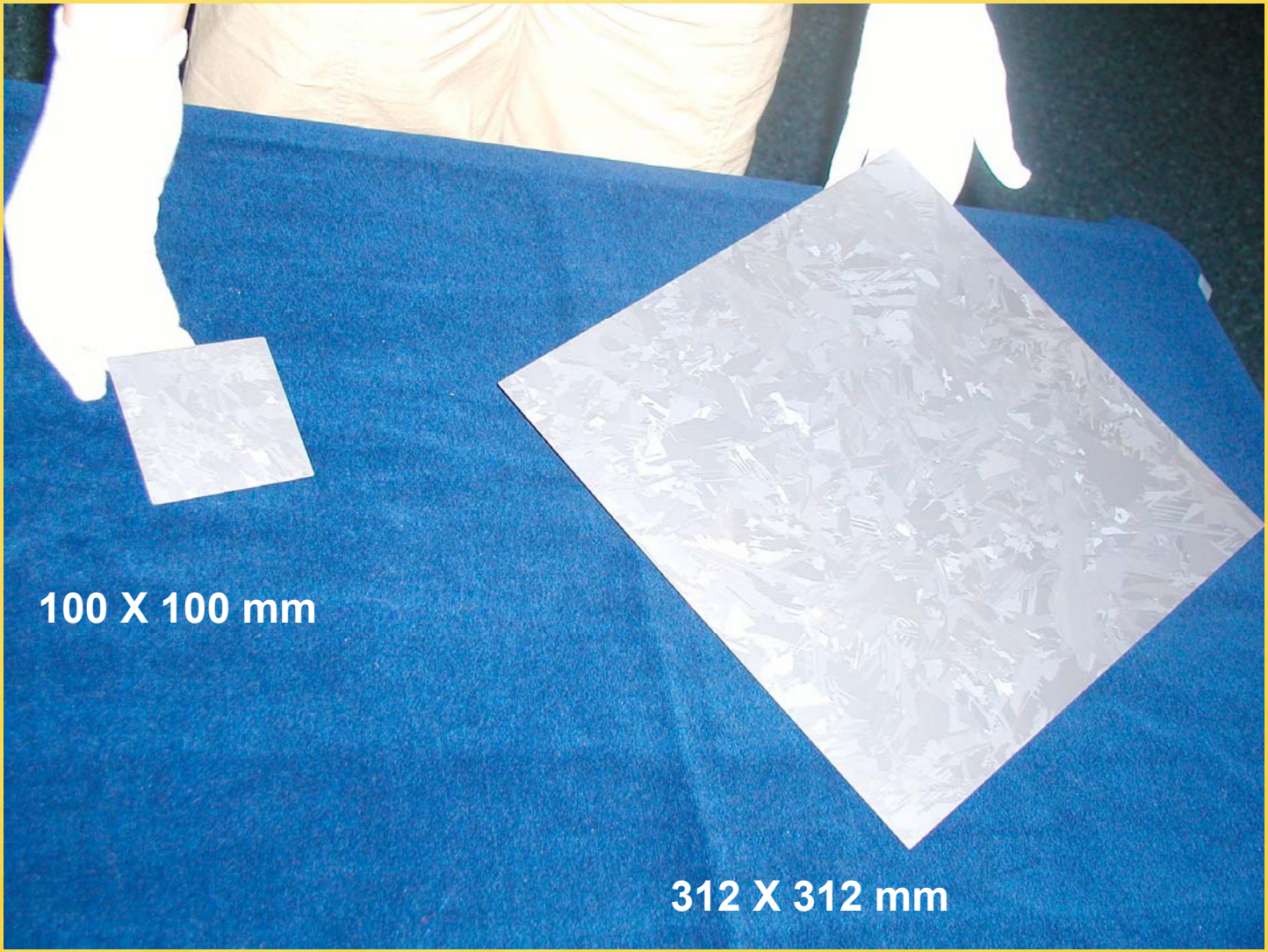


- Decrease spec. Silicon consumption from ca. 13 g/Wp to < 5 g/Wp



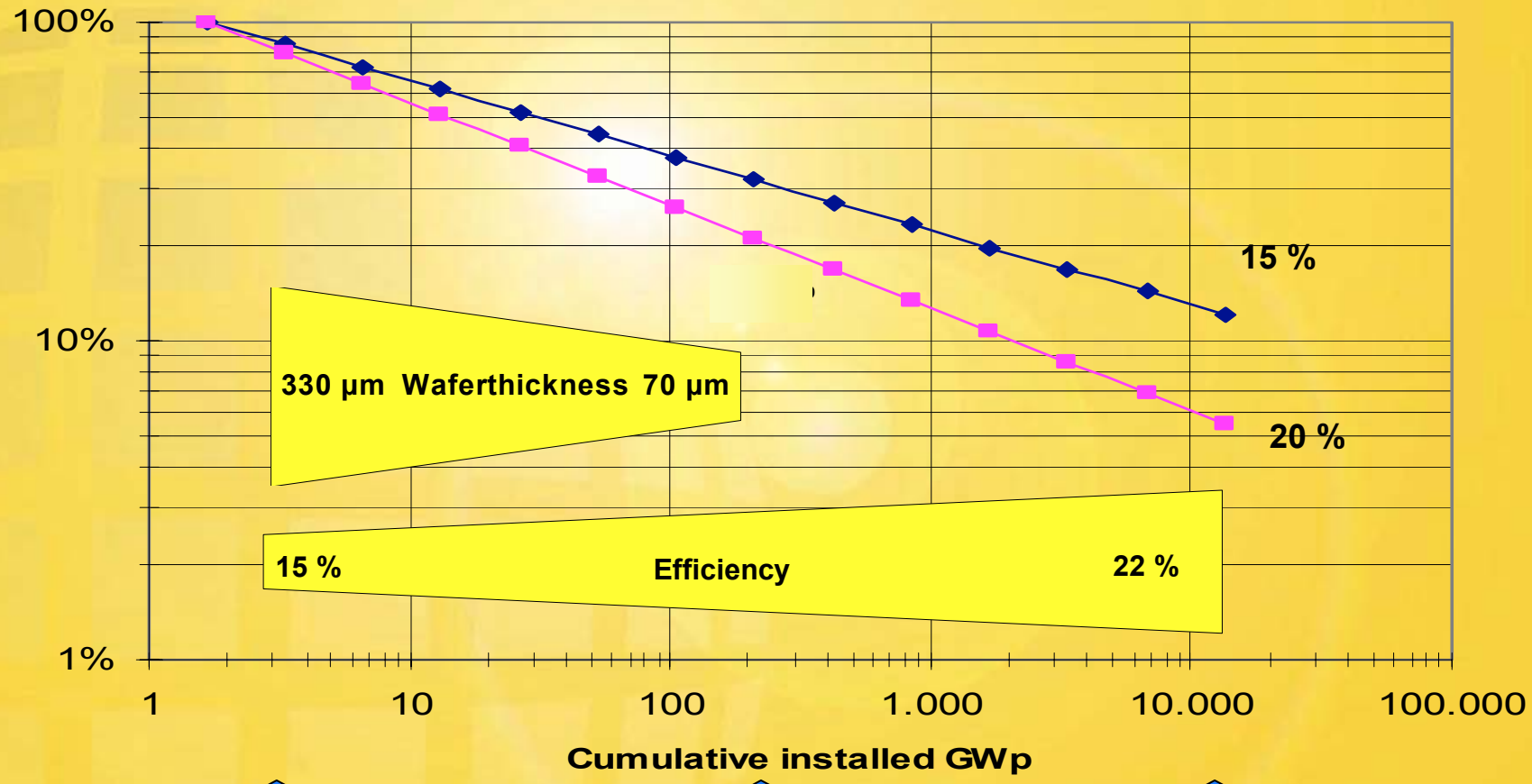
- Increase solar cell efficiency from av. 14.5 % up to 22 % and beyond

100 µm Thin and Flexible Wafer as Cut


100 X 100 mm
312 X 312 mm

- **Module efficiency up to 21 %**
- **Lifetime expectancy 35 years**
- **Building integrated**

Price-Experience Curve For PV Modules



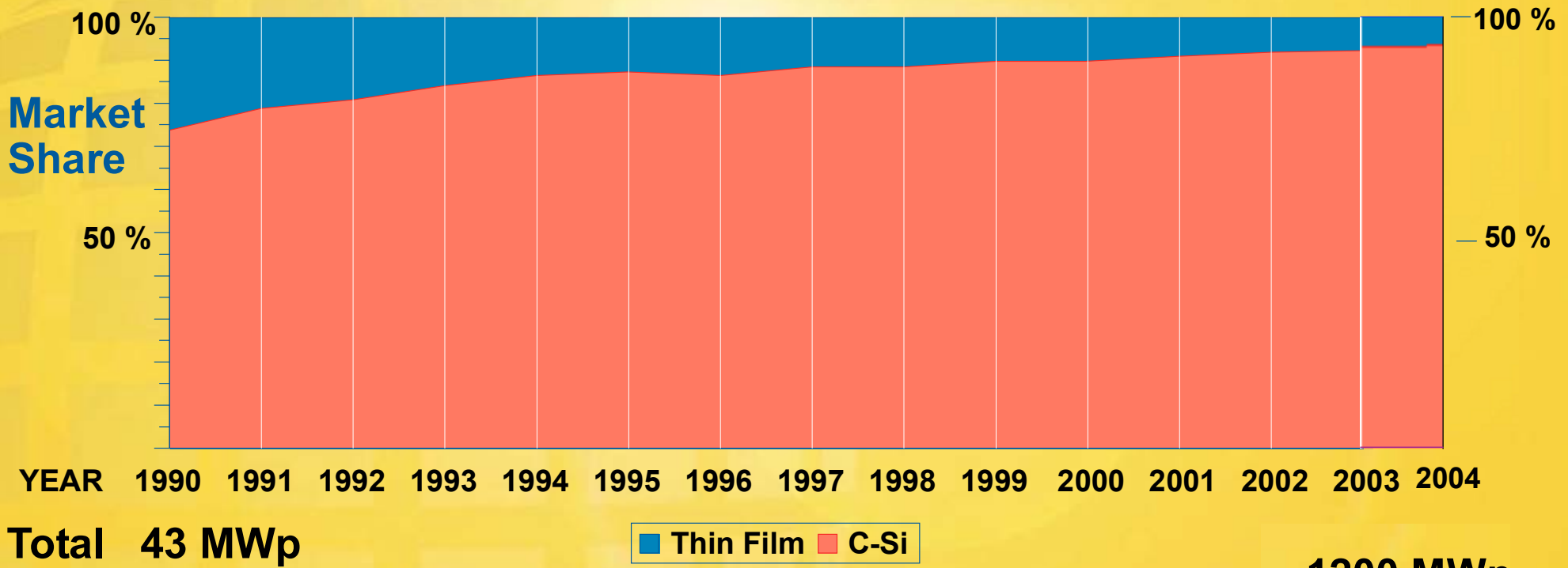
today

2020
1 %

2040
26 %

PV Contribution Total Electricity

THIN FILM TECHNOLOGY



Source: Strategies Unlimited

Development Market Share C-Si vs. Thin Film

Production Site PV Crystalox Solar

Markets

Off-Grid / remote industrial

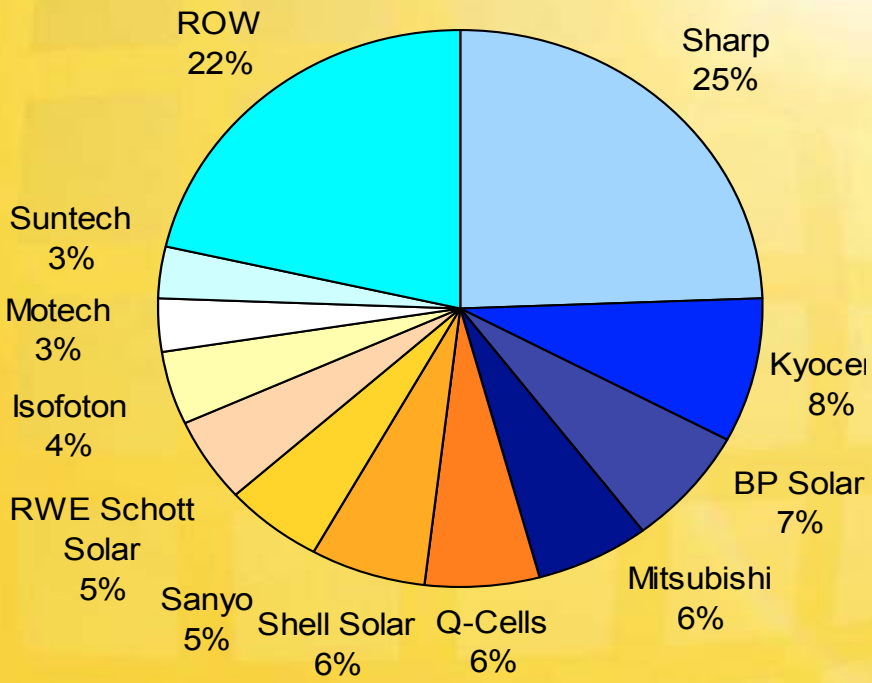
On-Grid

Off-Grid / rural electrification

Consumer

Solar cell producers worldwide

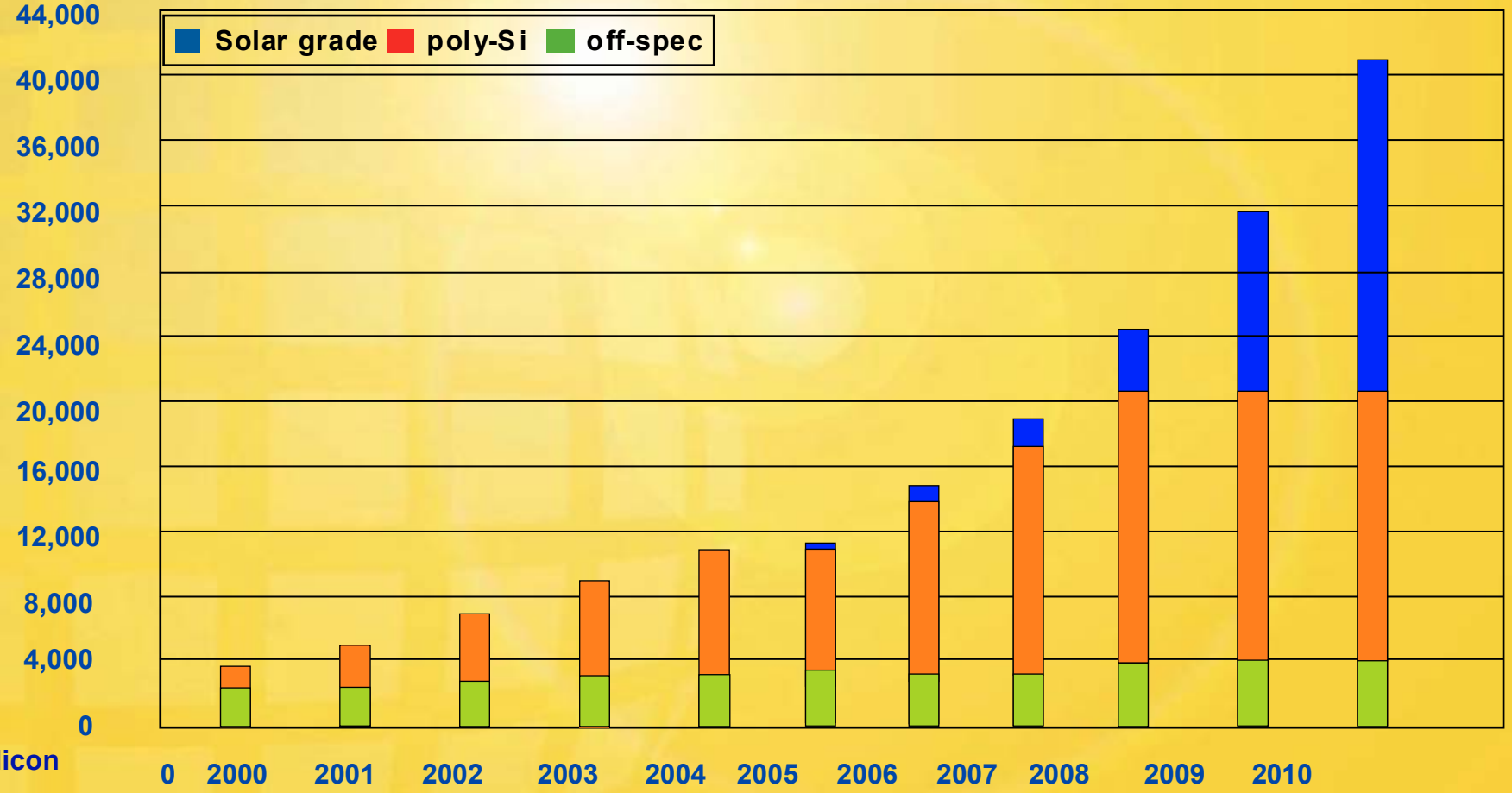
Market Share in Solar Cells in 2004 (1200 [MWp])



Source: Photon International, 2005, own estimates

- **Some of the large cell producers have wafering capacities but are increasingly outsourcing wafer production**
- **Some cell producers entirely outsource wafer production**
- **New solar cell producers mainly purchase wafers**

According to our estimate silicon production might grow by ca. 30 % p.a. Demand by our customers much higher



Source: PV Silicon

CONCLUSIONS

- Crystalline silicon wafer technology to dominate solar electricity for power applications in the foreseeable future

- Silicon likely to remain “the fuel“ of the future