BNL-52557

Photovoltaics and the Environment 1998

Report on the Workshop

Photovoltaics and the Environment 1998

July 23-24, 1998

Keystone Inn,

Keystone, Colorado

Organized by

Brookhaven National Laboratory (BNL)
and
National Renewable Energy Laboratory (NREL) Thin Film Partnership

Vasilis Fthenakis
Ken Zweibel
Paul Moskowitz

February 1999

DEPARTMENT OF ADVANCED TECHNOLOGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

Prepared for the U.S. Department of Energy
Photovoltaic Energy Division
Contract No. DE-AC02-98-CH10886

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Acknowledgment

We would like to thank all the workshop participants for their valuable input in the form of papers, presentations and discussions.

This workshop was organized by the Brookhaven National Laboratory and National Renewable Energy Laboratory Thin Film Partnership. It was supported by the US Department of Energy, Photovoltaic Energy Division, Conservation and Renewable Energy, under the leadership of Jim Rannels. We are grateful to the DOE program managers for their encouragement and support.

V.M. Fthenakis, K. Zweibel and P.D. Moskowitz

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Session 3. Million Roof Initiative: Potential EH&S Issues

WORKSHOP OBJECTIVE

The objective of the workshop "Photovoltaics and the Environment" was to bring together PV manufacturers and industry analysts to define EH&S issues related to the large-scale commercialization of PV technologies.

WORKSHOP BACKGROUND

The National Photovoltaic Environmental, Health and Safety (EH&S) Assistance Center

The National Photovoltaic EH&S Assistance Center is operated at BNL, under the auspices of the U.S. Department of Energy (DOE), to foster the safe and environmentally friendly operation of photovoltaic facilities and products, extending from R&D to manufacturing and use. The objectives of the Center are to prevent accidents, to reduce EH&S occupational and public risks, and lower the environmental- and safety-related costs.

The BNL Center undertakes the following types of activities:

1. It directly supports DOE Headquarters, the National Renewable Energy Laboratory (NREL), and Sandia National Laboratory (SNL) to ensure that their facilities and those of their contractors are operated in an environmentally responsible manner.

2. It conducts EH&S audits, safety reviews and incident investigations, as needed.

3. It assists the photovoltaic industry to identify and examine potential EH&S barriers and hazard-control strategies for new photovoltaic material, process and application options before their large-scale commercialization. To facilitate the transfer and application of knowledge derived from this work, BNL hosts workshops, tutorials and symposia, uses electronic mail and a web page, and publishes articles in the peer-reviewed journals. The current workshop is one of these "industry outreach" activities.

The Thin Film Partnership

The Thin Film PV Partnership is the main program funded by DOE to support R&D in thin film options, such as amorphous silicon, cadmium telluride, and copper indium diselenide. The Partnership funds in subcontracts to leading companies and universities to perform this research. Subcontractors are categorized as Technology Partners if they are companies with commercial or near-commercial thin films. Others are categorized as R&D Partners, and they undertake work that will keep further advances in the pipeline for the future. The members of the Partnership work on technology-specific National R&D Teams in collaboration with NREL in-house researchers; these teams are directed to solve critical fundamental and technological problems. An additional cross-cutting team, the Thin Film Partnership ES&H Team, is made up of the Technology Partners and others with commercial interests, as well as invitees, who address ES&H challenges together. The workshop in Keystone was one of their activities, planned jointly with BNL.

THE WORKSHOP

The workshop was opened by BNL's Paul Moskowitz who welcomed the participants and emphasized the need for open discussion and collaboration on EH&S issues among all industry players.

Executive Summaries

Session 1: Proactive Recycling: Near-term and Long-term Strategies

To safeguard the environmental friendliness of photovoltaics, the PV industry follows a pro-active, long-term environmental strategy involving a life-of-cycle approach to prevent environmental damage by its processes and products from "cradle to grave." Recycling manufacturing waste and spent PV-modules is examined as part of this strategy. Although the PV industry will not face this problem in a large scale before the year 2020, today's choices of materials and module designs may very well set a precedent for the future.

The session was chaired by Vasilis Fthenakis, BNL who briefly summarized the previous studies and work on recycling. The first workshop on recycling was organized by BNL and NREL and was held in March 1992 at Golden, CO. The 1992 workshop focused on Cd and Se and brought together interested parties from the PV industry, the metal-smelting industry, the utilities, the DOE, and the national laboratories. It established the state-of- current-affairs and provided a foundation for the infrastructure and technical feasibility studies, which were conducted by BNL, UNISUN, Solar Cells Inc. and Drinkard Metalox Inc. between 1993 and 1998. In April 1994, BNL and NREL hosted a workshop that focused on understanding and managing the health and environmental risks of CIS, CGS and CdTe module production and use. The 1994 workshop covered the toxicology of these new materials, and the pertinent implications to occupational health and the environment. This workshop identified the need to examine regulatory drivers and constraints to recycling.

The first session of the current workshop expanded on all these issues. The papers presented gave industry's perspectives and analyses of the collection and recycling infrastructure, regulatory concerns, technical feasibility, economic incentives, and costs. In the open discussion forum different opinions from the industry participants were heard and discussed.

Photovoltaic modules may contain small amounts of regulated materials, which vary from one technology to another. Environmental regulations can determine the cost and complexity of dealing with end-of-life PV modules. If they were classified as "hazardous" according to Federal or State criteria, then special requirements for material handling, disposal, record-keeping and reporting would escalate the cost of decommissioning modules. Chris Eberspacher, UNISUN, discussed such issues related to recycling of CdTe and crystalline Si PV modules. He showed that several of today's CdTe modules failed the US-EPA Toxicity Characteristic Leaching Procedure (TCLP) for potential leaching of Cd in landfills. Similarly, some of today's x-Si modules failed tests for leaching of Pb. Consequently, such modules may be classified as "hazardous" waste. The TCLP is the current EPA method to characterize the toxicity potential of wastes. It assumes a particular worst-case scenario of potential leaching of compounds in a landfill. However, many parameters that affect the leachability of contaminants in the field are not addressed in the current TCLP, and the EPA is investigating a more flexible approach that can be tailored to different types of waste. Danny Cunningham, BPSolar, discussed issues related to preparing PV scrap for TCLP testing. He showed that preparation of the sample can affect the results of the test and pointed out the need for preparation guidelines.

The PV industry may choose to recycle spent modules, even if there are no regulatory issues related with their disposal, because recycling may improve market penetration. Recycling is most cost-effective if is done collectively by the industry, and in high volumes. Jef Bagby, who presented the experience of the Rechargeable Battery Recycling Corporation (RBRC) discussed the benefits of a collective approach. Two hundred and fifty manufacturers of rechargeable products fund RBRC, representing about 75% of the world's rechargeable producers. Bagby described the difficulties in setting up the logistics and operating the collection and transport of products for recycling. These difficulties included allocating cost among participants, non-uniformity of state laws, restrictions from antitrust laws, national laws and international agreements affecting transportation, and additional overhead due to tax laws. The RBRC program became more effective when it was expanded beyond the manufacturers and involved distributors, retailers, end-users, and the government.

The technical feasibility of recycling was proved by work funded by the DOE small-business initiative research (SBIR). John Bohland presented the results of such research at Solar Cells Inc. (SSI), which demonstrated the feasibility of recycling the basic components of spent CdTe and x-Si modules. For CdTe, their technique entails crushing the module in a hammer-mill, screening EVA flakes, and stripping metals from the crushed glass in successive steps of chemical dissolution, mechanical separation, and precipitation or electrodeposition. The estimated cost for this process for a 2 MW process (about 40,000 modules) integrated with a manufacturing facility is 2-4 ¢/W, excluding transportation. For x-Si cells, SSI tries to recover the functioning cells which have a high value. So far, they worked with PV coupons (not complete modules), and recovered most of the Tedlar backsheet and the functioning x-Si cells, which have an electrical efficiency only slightly, lower than the original ones. Their method starts by gently heating and manually peeling off the backsheet. Then, inert atmosphere pyrolysis at about 500 °C vaporizes the EVA lamination layer. Si-cell recovery was estimated to cost about 13 ¢/W, for an operational scale of 150,000 x-Si cells per year. For comparison, a new x-Si cell costs at least $1.50/W to produce.

Bob Goozner, Drinkard Metalox (DMI) discussed the results of another DOE-SBIR project, dealing with recycling of CdTe and CIS modules. DMI's operations include chemical stripping of the metals and EVA, skimming off the EVA from solution, and successive steps of electrodeposition, precipitation, and evaporation to separate and recover the metals. DMI reports recovery of 95% or better of Te, and 96% or better of Pb from CdTe modules. Chemical stripping leaves the SnO_2-conducting layer intact on the glass substrate, potentially allowing the re-use of the substrates for PV deposition. They project a processing cost of 9 ¢/W or less for either CdTe or CIS modules. Goozner also showed some promising preliminary results of stripping x-Si coupons with an HNO_3 solution.

It has been shown that there is an economic incentive to design modules that will not be hazardous, or to design them in such a way that they can be recycled at a reasonable cost. This issue was discussed by Simon Tsuo, NREL, who presented alternatives in silicon solar-cell manufacturing that are friendlier to the environment than today's common practices. Tsuo started by referring to sources of information on environmentally benign semiconductor manufacturing, and continued with a step-by-step analysis of manufacturing and environmental improvements for x-Si PV. His major points were that alternatives exist that are both environmentally benign and cost-effective, and that the PV industry can benefit by coordinating efforts with the printed-circuit industries.

The following are some additional salient points from this session:

- Recycling makes sense because it conserves relatively rare minerals like tellerium, reduces the energy requirement in PV manufacturing, and preserves the environmentally friendliness of PV.
- Recycling can help market acceptance and penetration.
- Effective methods of recycling have been developed that can be used for both in-house and large-scale recycling.
- Currently, economic incentives may be inadequate to move the PV industry into voluntary recycling. However, this may change in future, as more economic incentives may be given to developing clean technologies, preventing pollution, and reducing CO_2 emissions.
- Also, in future, recycling costs are likely to decrease as the technologies mature, whereas the costs of landfill disposal are constantly increasing.
- The industry must keep an eye on regulatory developments related to TCLP, and similar waste-defining rules and exceptions as they affect the need for, and economics of, PV recycling.

Session 2: PV for Carbon Dioxide Reduction

Session II focused on the potential of PV to reduce emissions of carbon dioxide, and thus have an ameliorating effect on global climate change. The Chair of this session, Ken Zweibel, NREL opened the discussion with a synopsis of the fundamental terms used in analyzing PV energy payback and carbon dioxide mitigation. PV CO_2 emissions are zero during use because PV systems require little or no maintenance or oversight. Some CO_2 emissions can be attributed to manufacturing because it takes energy to manufacture a module. Thus, PV requires some input energy, which it pays back early in its lifetime. This energy pay back (EPB) was the focus of the paper by E. A. Alsema ("Energy Requirements and CO_2 Mitigation Potential of PV Systems") of the University of Utrecht. For PV to be useful, the energy payback must be reasonable. In the past, PV has had high EPB because technology was immature and burdened by energy-intensive processing. As Alsema points out, EPB for existing PV systems is in the 3-10 year range; and future technological options will likely allow system EPB to fall to the 1-3 year range. In this range, the amount of CO_2 displaced by PV over a thirty year lifetime outdoors is 90% to 97% as compared to the CO_2 of the energy it offsets. For example, if we assume the US mixture of energy generation causes 160 g carbon equivalent of CO_2 per kWh of electricity, then a 1 kW PV array in an average US location would produce about 1600 kWh each year, and 48,000 kWh in 30 years. That would avoid about (48,000*0.95)*160 g/kWh, or about 7 metric tons (MT) of carbon equivalent during its useful life. The "0.95" in the equation represents a reasonable guess about future energy payback at the system level. Clearly, certainty about the order-of-magnitude of this number is far more important than predicting it to three decimal places; and also more important than the expected absolute amount of carbon dioxide that PV will displace, since that is dependent on (1) the mix of energies with which PV will be manufactured and (2) the mix that it will displace (which will vary with location, application, and date).

Once it is established that substituting fossil-fuel energy generation with PV can prevent substantial CO_2 emissions, it is then necessary to establish that PV can become a large-scale source of electricity. The major barrier to PV becoming a large-scale energy source is PV electricity cost. Today's PV systems sell for about $6-$10 per peak Watt, with an implied electricity price of about $0.4 to $0.7/kWh. This is much higher than conventional sources, which sell for about 8 cents/kWh in the US. However, PV technologies are making rapid progress toward improved output per unit cost. Existing technologies are improving, and new technologies are coming on line. Projections of future costs based on progress in PV technologies are consistent with module costs below $0.5/W (compared to $3/W today) and reduced balance of system (BOS) costs as volume and design sophistication increase. Thus the competitive economic future of PV is quite promising.

However, PV faces several other hurdles before it can be a source of energy on a global scale. Two of them are covered in two other papers delivered during the session: "Materials Availability and Waste Streams for Large Scale PV" by Bjorn Andersson of Goteborg University and "The Competition Facing PV in a Greenhouse Gas (GHG) Emissions-Constrained World" by Robert Williams of Princeton. Andersson discusses the various potential constraints on the use of several thin film PV technologies that are expected to have excellent cost potential. However, each of these technologies uses a rare raw material: germanium in amorphous silicon; tellurium in cadmium telluride; and indium and gallium in copper indium diselenide. Andersson provides some sobering parametric insights into the potential of these technologies to be used on a global scale, i.e., at volumes per year of 10-100 GW. Each of these technologies must address the materials availability issue in order to be viable at these volumes. Fortunately, research avenues such as making thinner layers, increasing device output per unit area, increasing the materials utilization of processes, recycling, and substituting other materials for the rare ones, provide excellent avenues for meeting the materials availability challenges. These challenges will not impede the near-term adoption of these technologies (prior to 2010 or 2020, depending on growth), but will need to be addressed during this grace period.

Williams addresses the issue that PV must compete for markets that will have other choices, such as wind and biomass electric power. Indeed, such competition will always be a 'moving target' since all energy technologies will progress substantially during the time it will take PV to mature. If they have favorable cost, favorable environmental or infrastructure qualities, they will be hard competition for PV in developed and developing nations. The special uses of PV (e.g., for rural electrification in developing countries) means that some of this future market competition will out of necessity remain uncertain while markets and technologies develop.

Finally, our last paper "MARKAL-MACRO: A Computer Tool for Integrated Energy-Environmental-Economic Analysis", presented by Vasilis Fthenakis of Brookhaven National Laboratory (BNL), discussed the predictions of a BNL model (MARKAL-MACRO) on how PV will compete in the future 30 years, against other technologies in the US energy marketplace. Fthenakis used input data from NREL about future efficiencies and cost reductions of PV, and data from DOE on the expected performance of about 200 competitive technologies and administrative options, and produced estimates on PV penetration in the US and corresponding CO_2 emissions reduction. The model predicts that by the year 2020, if the targets of 15% PV module efficiency and \$0.71/W_p capital cost are attained, PV installations in the sunniest areas of the US (e.g., Arizona) will total 20 GW; if the price falls down to \$0.57/W_p, then PV's share in the US could jump to 140 GW (about 10% of the projected total 2030 US energy capacity). At that level, PV will be reducing carbon emissions by about 64 million metric tons per year, a very significant contribution by any single technology.

This workshop has addressed the effort to develop a framework for evaluating PV in relation to global CO_2 reduction. We have examined the issues of PV energy payback; PV CO_2 reduction; the potential of PV technologies to become cost competitive; competing technologies; and constraints such as materials availability and waste streams. This is only a first step. For example, we have not performed an in-depth study of PV with electric or chemical storage or other similar infrastructure issues unique to non-dispatchable sources like PV.

As PV matures and becomes a more widespread and practical energy option, we shall re-examine this question again and again. In the future, we hope to adequately characterize the value of PV in this endeavor so that the public and their representative organizations can properly weigh policy affecting PV development.

Session 3. Million-Roof Initiative: Potential EH&S Issues

President Clinton announced in June 1997 the ultimate goal for one million solar-energy systems to be installed on U.S. rooftops by 2010. He committed the federal government to installing 20,000 solar systems on its buildings' rooftops by then. This initiative was the Administration's response to the issue of Global Climate warming. As discussed in the previous session, PV can make a significant contribution in reducing carbon-dioxide emissions in the United States, and the Million-Roof Initiative is intended to jump-start the solar market and create the momentum for necessary price reductions to achieve this goal.

Christi Herig, NREL talked about the goals of the initiative and the role the administration envisions for the different partners (e.g., industry, states, municipalities, consumers, developers and builders). She presented some heartening statistics. In 1998, there were 8,500 solar buildings in the United

States, up from only 2,000 the previous year. The projected numbers of solar buildings for 2000, 2005, and 2010 are 51,000, 376,000 and 1,014,000 respectively. The DOE wants to identify potential EH&S concerns related to such a quick pace of development.

The most obvious issue relates to the hazards of electric shock and falls during the installation, connection, repair, and maintenance of PV roof systems. Ward Bower, Sandia gave an overview of codes, certification requirements, and guidelines issued by the IEEE, ANSI, ASTM, IEC and the UL. There are many guidelines and standards applicable to PV-system interconnects and current efforts at Sandia focus on ensuring that the National Electrical Code includes the PV-unique requirements for safe installation of PV building systems. Bower distributed copies of draft of NEC article 690 that covers photovoltaic systems, and discussed several considerations applicable to PV modules and arrays, (e.g., critical temperatures, voltage ratings, cable and insulation types, sizing for safe design, over-current protection, manual disconnects, grounding, anti-islanding protection, and in-surge and transient protection). An easy-to-read safety document, "IEEE Guide for Terrestrial Photovoltaic Systems Safety" will become available in early 1999. Other items that were touched upon by the audience included fire hazards to the buildings' occupants and to firefighters. Questions pending answers include: 1) How are arrays disabled so that firefighters are protected when using water on the roof? 2) Do firefighters need extra protection from potential toxic vapors emitted from a burning array? 3) Are there any environmental issues related to the disposal of roofing shingles and building-integrated modules? 4) Can the industry meet RCRA and state requirements for landfill disposal, or will treatment/recycling be necessary?

While these concerns are addressed by the industry and solutions are being worked out, it is imperative to emphasize the positive aspects of the upcoming scaling-up of building-integrated photovoltaics. Paolo Frankl, INSEAD showed that such systems could offer even greater benefits in lowering carbon dioxide emissions (on a MW basis) than large stand-alone systems. This conclusion is based on energy pay-back time, energy yield, and net CO_2 balance from a life-of-cycle analysis of current silicon-based photovoltaics. The main advantage of building-integrated systems vs. stand-alone ones comes from avoiding the expense and energy intensity needed for structural supports. Frankl also presented a parametric analysis of the effect of future system designs, showing that future hybrid PV/thermal roof systems are expected to further enhance the potential of PV to mitigate CO_2 emissions.

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PAPERS

Session 1. Proactive Recycling: Near-term and Long-term Strategies

1.1 Chris Eberspacher, Recycling of End-of-Life CdTe and Si PV Modules
1.2 John Bohland, Recycling as an Alternative to Disposal of PV Modules
1.3 Bob Goozner, Recycling Metals from CdTe and CIS PV Modules
1.4 Daniel Cunningham, Discussion about TCLP protocols
1.5 Simon Tsuo, Silicon Solar Cell and Module Manufacturing: Current and Alternative, More Environmentally Benign Processes
1.6 Jefferson Bagby, The Experience of the Rechargeable Recycling Battery Association
1.7 Hugh Morrow, International Cadmium Association, Worldwide Cadmium Recycling

Session 2. PV for Greenhouse Gas Reduction: Issues, Barriers and Potential Solutions

2.1 Eric Alsema, CO_2 and Energy Payback of PV
2.2 Bjorn Andersson, Materials Availability and Waste Streams for Large Scale PV
2.3 Robert Williams, PV and the Competition in 21st Century
2.4 Vasilis Fthenakis, MARKAL-MACRO: A Computer Tool for Integrated Energy-Environmental-Economic Analysis
2.5 Steve Johnson, Meeting Very Low Cost Goals for Cost-Effective PV

Session 3. Million Roof Initiative: Potential EH&S Issues

3.1 Ward Bower, PV Installations: Electrical Issues and Codes
3.2 Paolo Frankl, Analysis of Energy/CO_2 Aspects of Building Integration
3.3 Christi Herig, The Million Roof Initiative: Current Status

1.1 Chris Eberspacher

Recycling of End-of-Life CdTe and Si PV Modules

RECYCLING OF END-OF-LIFE CdTe and Si PV MODULES

Chris Eberspacher
UNISUN

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Photovoltaics and the Environment Workshop
Keystone, Colorado
July 1998

Introduction

Present

* x-Si dominates PV industry
* Some manufacturing byproducts recycled
* Un-usable x-Si PV cells & modules handled as trash
* CdTe PV emerging into commercial production

Future

* End-of-life modules = "wastes"?   "hazardous"?
* "Hazardous" waste disposal costs
* Recycling as cost-effective alternative to disposal

Recycling

* Recovery of valuable materials
* Mitigate waste disposal costs
* Green marketing

Materials Recovery

Minimal Scrap Value as Raw Materials

Al frame :	10 ¢/W new ;	1 ¢/W scrap
glass :	5 ¢/W new ;	0.2 ¢/W scrap
Ag grids :	15 ¢/W new ;	4 ¢/W scrap
CdTe, CdS :	10 ¢/W new ;	0 ¢/W scrap

* metals smelters use silica for fluxing and slagging
* smelter charge ca. 5 ¢/W excluding collection and transport

Salvage Value of Re-usable Components

* Si wafers :	2 US$/W new ;	0.65 US$/W salvage
* Si cells :	3 US$/W new ;	1.50 US$/W salvage

U.S. Law on Solid Wastes

National : Environmental Protection Agency (EPA)
Resource Conservation and Recovery Act (RCRA)

California : California Environmental Protection Agency (Cal-EPA)
Hazardous Waste Control Law (HWCL)

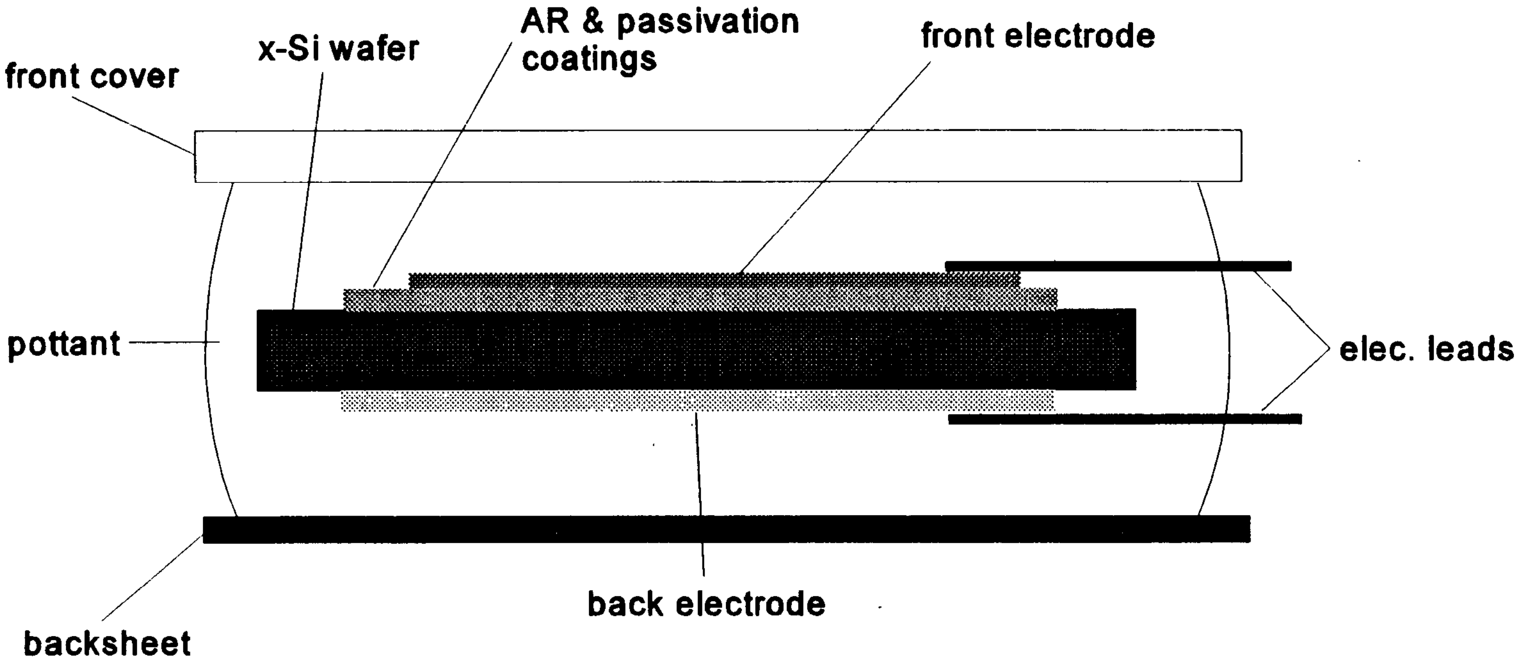
Solid wastes only.

Waste hazard classifications

Waste "characteristics," e.g. toxicity

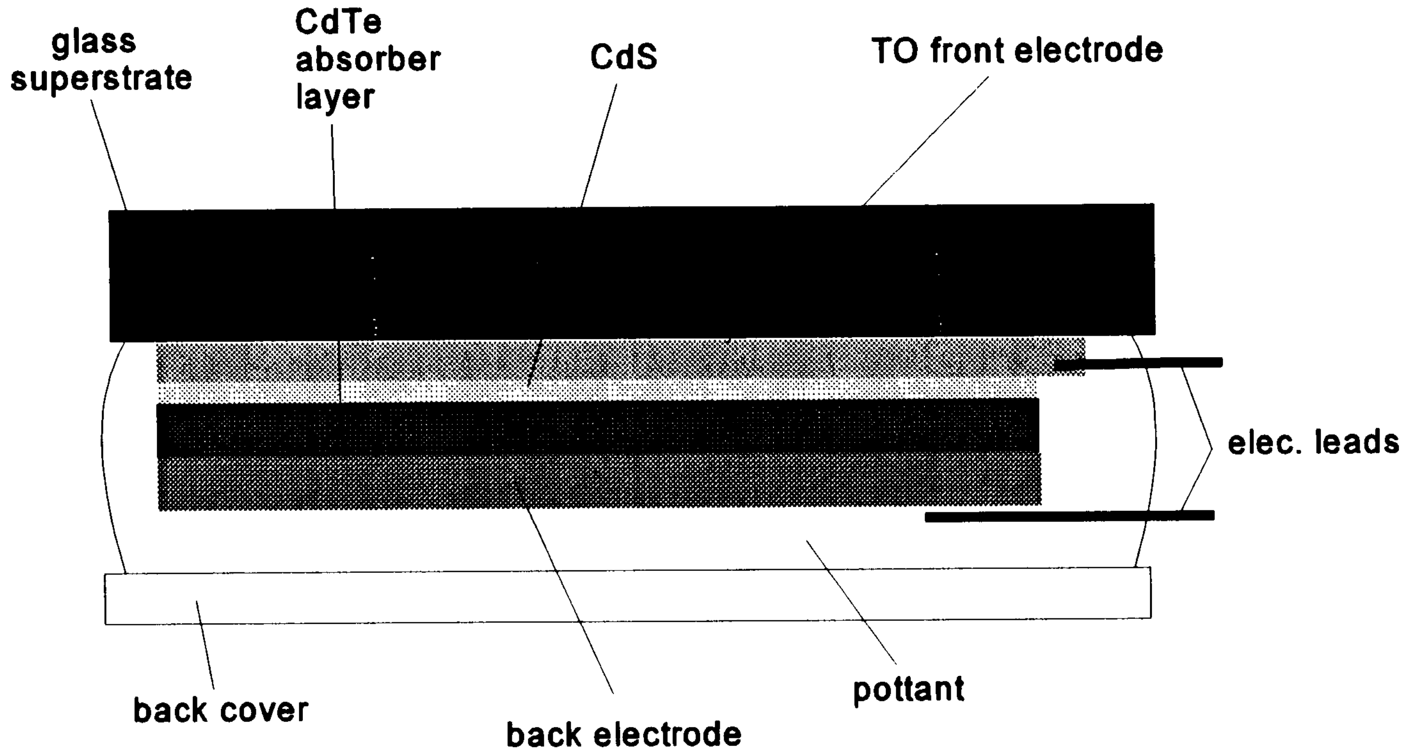
Certain exclusions if recycled.

Crystalline Si PV Modules



Relevant Materials :
U.S. EPA RCRA : Ag, Pb
Cal-EPA HWCL : Ag, Pb, Cu

Thin-Film CdTe PV Modules



Relevant Materials : U.S. EPA RCRA : Cd, (Pb?)
Cal-EPA HWCL : Cd, (Pb?), (Ni?)

Federal Toxicity Tests

TCLP = Toxicity Characteristic Leaching Procedure

Material	Calculated Estimates Cell g/kg	Calculated Estimates Module g/kg	Regulatory Limits Equivalent g/kg soluble	Regulatory Limits Limit mg/L	Measured TCLP Data Data mg/L	Measured TCLP Data Equivalent g/kg soluble
x-Si						
Ag	52	3.4	0.1	5	0 - 0.1	0 - 0.02
Pb		1	0.1	5	3 - 6.6	0.06 - 0.13
CdTe						
Cd		0.3	0.02	1	0.7 - 9.5	0.014 - 0.2
Pb		0.05	0.1	5	0.04 - 0.4	0.0008 - 0.008

➜ End-of-life x-Si and/or CdTe PV modules may be RCRA "hazardous" waste

California Toxicity Tests

STLC = Soluble Threshold Limit Concentration
TTLC = Total Threshold Limit Concentration

	Calc. Estimates		Regulatory Limits			
Material	Cell g/kg	Module g/kg	STLC Equivalent g/kg soluble	STLC Limit mg/L	TTLC Limit g/kg	
x-Si						
Ag	52	3.4	0.05	5	0.5	
Pb		1	0.05	5	1	
Cu (ribbon)		10	0.25	25	2.5	scrap metal?
CdTe						
Cd		0.3	0.01	1	0.1	
Pb		0.05	0.05	5	1	
Ni		0.02	0.20	20	2	

→ End-of-life x-Si and/or CdTe PV modules may be non-RCRA "hazardous" waste

Harmless Garbage or Hazardous Waste ?

Who is the responsible "Generator" ?

Manufacturers, distributors & users share common interests.

Economics of Waste Disposal & Recycling

- 0.02 US$/W	trash disposal
- 0.20 US$/W	hazardous waste disposal, e.g. 800 US$/MT
- 0.10 US$/W	scrap recycling, e.g. $200-400 US$/MT
+ 1. US$/W	x-Si wafer reclaim
+ 2. US$/W	x-Si cell re-use

Workable Recycling

Identify cost-effective strategy

Concentration is a key factor

- Materials & components reclaim
- Processing = refurbish, dismantle, recycle, smelt
- Collection costs / logistics
    - * large systems = system owners & installers, recyclers
    - * small / remote systems = mail, reverse retail, MSW, RLC's

Lessons From Other Industries

- "Product" / "waste" transition ; refurbishment isn't waste treatment
- Recycling can result in exclusions from haz. waste regulations
- Well-run recycling program can mitigate regulatory burden
- Modest incentive fees can motivate recycling
- Recycling useful even when materials recovery economics are poor
- Collective action can simplify recycling and improve economics

Exclusions by Recycling

If recycled , then maybe exempt from many Haz. Waste Regulations

recycled = used, reused or reclaimed
used or reused = employed as an ingredient or as an effective substitute for a commercial product
reclaimed = processed to recover a usable product

Recycled materials are not solid waste (ergo not hazardous waste) if :

- used or reused as an ingredient in an industrial process without being reclaimed
- used or reused as a safe and effective substitute for commercial products & not reclaimed
- returned to the original process from which was generated without first being reclaimed

Example of Exclusions

Thin-film PV structure: glass / PV layers / EVA / glass

Issues: amount & solubility of PV layers & solders; wrap-around; stray materials

Classifications :

garbage = regular trash > any disposal or recycling means is o.k.

RCRA hazardous waste = hazardous per CA-EPA and U.S. EPA
    * non-listed byproducts, e.g. various manufacturing scrap
    * unused off-spec. plates = "secondary" or "retrograde" materials
        -> recycle as non-listed commercial chemical products.
    * not solid wastes when sent for reclamation
    * pre-treatment allowed by certain techniques prior to recycling

non-RCRA hazardous waste = hazardous per CA-EPA, but not U.S. EPA
    * HWCL excludes certain recycled materials from solid waste
    * pre-treatment allowed by certain techniques prior to recycling

Conclusions

End-of-life PV modules may be "hazardous" waste

Product re-design may circumvent current regulations

Manufacturers, distributors and users share common interest

Recycling may be best business decision.

Recycling is most effective if collective and high-volume.

1.2 John Bohland

Recycling as an Alternative to Disposal of PV Modules

PHOTOVOLTAICS AS HAZARDOUS MATERIALS; THE RECYCLING SOLUTION

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ABSTRACT

Because traditional and newer PV technologies contain potentially hazardous materials, PV manufacturers are becoming increasingly aware that end-of-life modules and intermediate scrap materials must be managed according to environmentally sound practices and in compliance with international, national and regional regulations. Instead of disposal, we report methodologies to recycle both newer, thin-film PV technologies and conventional, crystalline silicon PV. This paper details these recycling processes; processes that reduce scrap material management costs, reduce regulatory and liability burdens, and increase global market acceptance of all PV technologies.

KEYWORDS: Recycling - 1: CdTe - 2: Silicon - 3

1. INTRODUCTION

Photovoltaic modules contain potentially hazardous materials such as cadmium, lead, selenium and silver. These metals demand prudent scrap material management practices throughout the PV module life cycle to avoid environmental and human heath risks and to comply with existing regulations.

Even now, PV manufacturers must comply with disposal restrictions (in the US) based on certain leachable metal concentrations. Metals of regulatory concern commonly present in PV modules include cadmium, lead, selenium and silver. For instance, a standardized leaching test resulting in greater than 1 mg/l cadmium, or greater than 5 mg/l lead, requires disposal management as a hazardous waste according to US federal law [1]. The implications of these regulations for PV manufacturers were discussed in more depth recently by Eberspacher and Fthenakis [2].

This work shows that several economic and environmentally benign reclamation methods to reclaim module scrap for both thin-film and crystalline silicon PV have already been developed and practiced.

2. RECYCLING TECHNOLOGY SUMMARY

To provide alternative end-of-life disposal options, and recover valuable raw materials such as glass PV substrates and semiconductor materials, Solar Cells, Inc. has developed three specific reclamation technologies applicable to both conventional crystalline silicon PV modules and newer thin-film materials. The technical details of these processes, their economics, and SCI's experience to-date follow.

For Solar Cells' cadmium telluride (CdTe) thin-film modules, two recycling technologies have been developed. The first was designed to address the end-of-life module issue. Solar Cells interprets "end-of-life" as the point at which a CdTe PV module can not be economically refurbished for any further use. For instance, if external electrical lead wires fail or are damaged, repair and further use in a secondary market may be possible. However, if the encapsulant fails or the front or back glass substrate breaks, repair is probably not viable and the module must be disassembled for reclamation. Glass breakage has been the largest contributor to the end-of-life condition at existing Solar Cells' arrays.

2.1 End-of-Life Thin-Film PV Recycling

Beginning with a broken module, disassembly commences. The external module power lead wires are removed at their termination in a reaction injection molded polyurethane potting disc using a wire cutting tool and salvaged for their copper scrap value. The module is then loaded into a "skip hoist" bucket elevator conveyor, currently up to three at a time, for delivery into a hammer mill. The hammer mill quickly (within seconds) reduces the module glass to between 4 and 60 mesh (4.76 mm to 0.25 mm) where it passes through the hammer mill sizing screen and onto a high speed, high incline belt conveyor. During the milling process, ethylene vinyl-acetate (EVA) encapsulant material is also fractured and freed from the module's front and back glass substrates. It is discharged from the mill in greater than 4 mesh (4.76 mm) pieces. The tin-coated copper buss bars used for current collection from the solar cell remains adhered to the EVA and follow this stream through the process. The belt conveyor transfers the crushed glass and EVA pieces to a neoprene-lined rotating conical barrel-finishing machine where the CdTe semiconductor and back metal electrode are dissolved using an acid etchant.

The friable glass and EVA leave the mill quickly, but the large elastomeric (about 8 cm in diameter) polyurethane potting and mounting discs that were chemically adhered to the module back-glass remain in the mill for about 30 seconds in order to completely free the mounts from glass. Then, an air-cylinder actuated trap door is opened and they are discharged into an isolated receptacle for recovery. Thus, one extremely simple and effective machine disassembles and separates all module components. Several uses are possible for the recovered polyurethane disks; grind them and use them as an impact modifier in new polymer formulations, use the mounts as packing material or fuel, or re-use them directly in the recycling process in the barrel-finishing machine as media to prevent glass clumping during the semiconductor etching process. This completes disassembly.

For CdS/CdTe thin-film modules, an etchant formula consisting of 2 to 4 N sulfuric acid, 1% to 2% by weight hydrogen peroxide, and a small percentage of an acid stable surfactant is added to the barrel-finishing machine. Complete removal of the semiconductor and metal electrode layers from the glass and EVA occurs at ambient temperature in 15 minutes or less (depending on ambient temperature) due to the aggressiveness of the acid and the vigorous glass on glass particle attrition caused by the barrel rotation. Under these process conditions, the tin from the tin-coated copper bus bar is removed but the copper is not itself significantly etched. No fume scrubbing equipment is required for this equipment.

After etching, the barrel is lowered and the spent etchant is decanted over a gyratory vibrating screen equipped with two screen decks; one at 4 mesh (4.76 mm) and one at 60 mesh (0.25 mm). After an on-screen water rinse, the EVA, with the copper buss-bar still adhered, is separated on the top (4 mesh screen) and is delivered to a receptacle. The next screen deck, at 60 mesh, separates all but the finest glass pieces and delivers them to another receptacle. The EVA, representing about 3% of the module weight, can be ground and used as an impact modifier in new polymer formulations, used directly as packaging material, or simply burned for its fuel value. The contamination of the copper buss-bar may reduce the applications of this material without further treatment.

About one percent by weight of the glass is smaller than 60 mesh and passes through the second screen deck, along with the spent etchant, in an etchant accumulation and glass fines settling sump tank. This glass is removed periodically and returned to the bulk glass cullet stream, all of which is suitable for recycling by a glass manufacturer. About 95% of inputted glass is recovered.

The spent etchant is pumped through a bag filter to remove any still suspended glass fines into a chemical precipitation tank where sodium carbonate is used to neutralize the acid etchant and precipitate all the dissolved metal species. Sodium carbonate is the preferred precipitation agent because cadmium carbonate, the precipitation reaction product, has less than 1 mg/l solubility at relatively low pH. The etchant is precipitated to between pH 8 and 9, acceptable to the Toledo, Ohio wastewater treatment works. After settling, the supernatant, containing only the sodium sulfate neutralization by-product, is pumped to the sanitary sewer discharge line after a cartridge filter polishing step. Cadmium concentrations in the discharged supernatant are consistently less than 0.1 mg/l; the discharge limit is 0.3 mg/l. The cadmium concentration in each batch of supernatant is measured and recorded before it is discharged. The precipitate sludge containing the cadmium, tellurium, tin, and other metals from the module back metal electrode contact is pumped to a sludge conditioning tank where lime or diatomaceous earth is added to bulk the sludge and allow more efficient de-watering when filter-pressed. A small (0.5 ft^3) plate and frame filter press is used to increase the metal laden sludge from about 4% solids to 60% solids. The effluent from the sludge press is returned to the precipitation tank instead of directly discharged because some metal-containing solids may pass through the filter cloths at the beginning of the filter press run.

Finally, the de-watered sludge is removed from the filter press and placed in a small alkali extraction vessel where tellurium, the one metal of commercial value from the CdTe PV modules, is extracted in concentrated potassium hydroxide. After extraction, the sludge is re-pressed in the filter press to separate the remaining undissolved metals, including the cadmium, from the resulting potassium tellurite extraction solution. This sodium tellurite electrolyte is electroplated in a custom electrowinning vessel and can be sold as commercial (99.7%) tellurium at market value. Recent evaluations show the tellurium recovery yield to be consistently above 80%. The remaining cadmium rich mixed-metal sludge is sent to INMETCO, a smelter in Ellwood City, Pennsylvania that has earned the United States Environmental Protection Agency's title of "Best Demonstrated Available Technology" for cadmium disposal. The cadmium is recovered in this process and can be used eventually for nickel-cadmium battery feedstock. The general arrangement elevation drawings in Figures 1 and 2 show the module disassembly and etching equipment, and effluent treatment equipment, respectively.

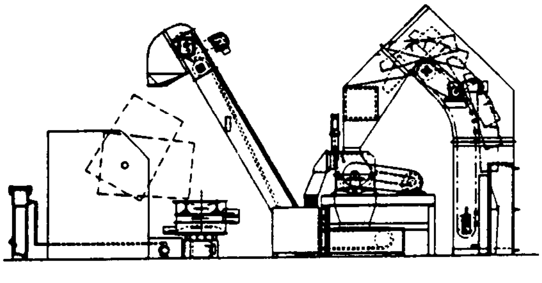

Figure 1: CdTe module recycling disassembly and etching equipment drawing

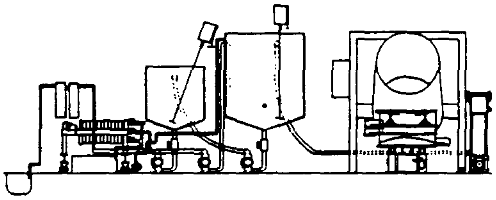

Figure 2: CdTe module recycling effluent treatment equipment drawing.

This reclamation technology is also applicable to copper indium diselenide (CIS) thin-film modules. A small-scale experiment has shown that the same etchant formulation used to etch CdTe modules is effective in removing the CIS film from its substrate glass. Though indium has significant reclaim value, recovery chemistry for it has not been investigated and may not be practical given the complex matrix of the CIS cell and the amount of indium available..

A more thorough description of the Solar Cells' CdTe module and review of the chemistry and equipment used in this patent-pending process were presented at the 26th IEEE PVSC [3].

2.2 Thin-Film Manufacturing Scrap Recycling

A second, proprietary technology was developed by Solar Cells for recovering early stage (unlaminated) manufacturing scrap. Early stage fall-off results mainly from start-up waste when a new coating run is begun.

This novel, proprietary process allows economic recovery and direct re-use (re-coating) of the solar cell substrate.

2.3 Crystalline Silicon PV Recycling

Solar Cells, Inc. is the first PV company to successfully apply the principles of inert gas pyrolysis to the problem of reclaiming intact and functioning silicon PV cells from encapsulated crystalline silicon (x-Si) PV modules. Though previous work has been done on x-Si module recycling it resulted only in recovery of the silicon wafer material itself, not functioning and potentially re-usable x-Si cells [4].

Study of a thermogravimetric analysis chart showing weight loss vs. temperature for EVA led to the hypothesis that using inert gas pyrolysis may be a cost efficient way to recover intact and functioning crystalline silicon cells from encapsulated x-Si module scrap [5]. Using pyrolysis, instead of combustion, results in controllable, (non-exothermic) polymer decomposition without creating carbonaceous by-products that render recovered silicon cells unusable.

To test this idea, crystalline silicon cell "coupons" were fixtured in a Lindberg quartz tube furnace and heated in a nitrogen atmosphere for about an hour at temperatures over 500°C. The coupons were fixtured to allow gravity drainage of intermediate liquid polymer decomposition products away from the delaminated wafer. The Tedlar® backsheet was removed prior to the pyrolysis step by gently heating the coupon then manually peeling the back sheet from the EVA encapsulant.

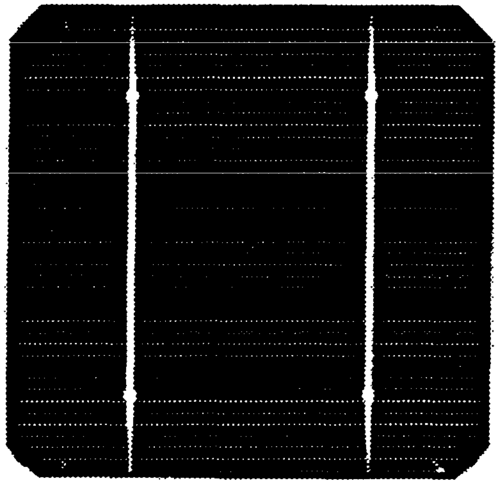

Figure 3: Pyrolytically de-laminated silicon cell.

Under these conditions, an unlaminated cell measuring 12.8% total efficiency was re-measured at 10.7% after delamination by the inert gas pyrolysis technique. The recovered cells were clean and nearly residue-free. Figure 3 shows a photograph of a cleanly recovered silicon cell.

Optimized process conditions, using equipment with faster temperature ramp-up capabilities, perhaps combined with directed convective nitrogen gas flows, or even heating under reduced pressure will result in even better recovered cell performance and appearance.

A patent application is underway for this process. A detailed technical report on this methodology was presented at the 26th IEEE PVSC [6].

3. RECYCLING ECONOMICS

We commissioned the world's only CdTe PV module recycling plant in March 1998. From this limited operating experience, economic analyses based on three cost scenarios have been developed.

3.1 Hazardous Waste Cost Avoidance Model

The first scenario is the break-even hazardous waste disposal cost avoidance model for in-house manufacturing scrap. Solar Cells has been quoted US \$360 per 55 gallon drum container of non-combustible hazardous waste disposal. About 720 pounds of crushed glass (modules) will fit in a 55 gallon drum. If end-of-life CdTe modules required disposal management as a hazardous waste, disposal at a permitted hazardous waste site would cost US \$0.35 per W_p, or US \$0.50 per pound. Based on actual capital equipment costs, labor requirements and other operating and overhead costs, the recycling cost break-even point is reached at an annual volume of 2,000 modules, assuming 35 pounds per module. In other words, the recycling facility can process this throughput of modules for US \$35,000 (the same cost as hazardous waste disposal of this quantity of modules) assuming capital equipment and installation costs are amortized over a ten year lifetime.

3.2 Maximum Throughput Model

The second scenario is the maximum throughput, in-house manufacturing scrap model. Here, if the recycling facility is run at its maximum annual recycling capacity of 2 MW (about 40,000 typical Solar Cells' modules), the cost is diluted to just over US $0.02 per W_p, or about US $0.03 per pound, comparable to the cost of disposal of trash in a non-regulated landfill.

3.3 Maximum Throughput, Stand-Alone Model

The third scenario, a stand-alone CdTe module recycling facility, again processing 2 MW of typical Solar Cells' CdTe modules, but now including costs incurred from facility burden and transportation, results in an estimated processing cost of US $0.12 per W_p, or US $0.17 per pound. A comparable estimate has been made by Eberspacher of UNISUN [7]. Though this cost may be a sizable fraction of the original manufacturing cost, recycling remains a much more cost effective option than disposal as a regulated waste.

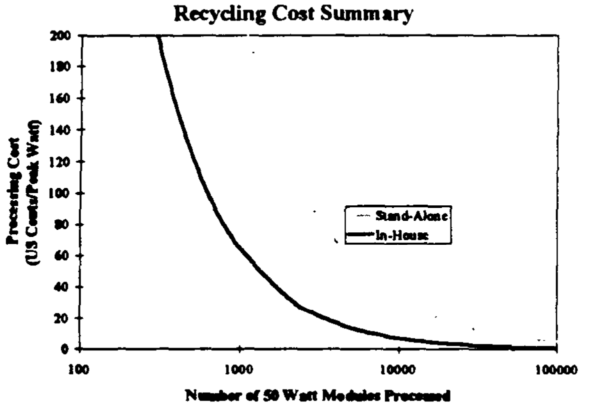

Figure 4: Graphical cost summary of Stand-Alone and In-House operating models Vs. Throughput.

3.3 Thin-Film Substrate Recovery Pay-Back

For early stage fall-off recycling, the whole value of the substrate glass is recovered and pay-back for installing and operating the recycling apparatus is estimated to occur after processing 2,100 current Solar Cells' CdTe substrates. This would occur in just over 3 months assuming 4% fall-off from a 10 MW coating line and certain operational, material and capital costs.

3.4 Crystalline Silicon Cell Recovery Pay-Back

Last, silicon cell recovery has been estimated to cost $0.13 per watt, based on reclaiming 250,000 x-Si cells annually, including labor, capital equipment and operating costs. However, this estimate does not include pollution control equipment to recover or combust the EVA pyrolysis by-products, transportation, facility costs, or the value of other recoverable components of the x-Si module such as the aluminum frame or Tedlar® backsheet. Even so, since silicon cells may cost at least US $1.50 per W_p to produce, a significant opportunity exists for recycling x-Si cells for its own economic merit, as well as to avoid environmental liabilities.

4. SOLAR CELLS EXPERIENCE

Solar Cells has recently completed the first full-out test of its recently commissioned CdTe module recycling line. In one eight hour period, 3,600 pounds of modules were recycled or 450 pounds per hour. This compares with a plant design throughput of 700 pounds per hour. With more experience and process optimization, full design throughput is expected.

Over 1,200 accumulated early stage manufacturing fall-off substrates have been reclaimed, already resulting in over 50% pay-back of the apparatus used for this process.

While the x-Si recycling technology has not been implemented, it remains an economic way to recycle scrap crystalline silicon PV modules as market or regulatory forces demand it.

5. SUMMARY

For many reasons, including preventing unlikely but possible environmental damage from irresponsible PV disposal practices, conserving relatively rare mineral resources like tellurium, reducing the energy component of PV life cycle assessments, complying with current and future regulatory requirements, and simply increasing market acceptance by keeping a "green" product "green", recycling makes sense.

Cost effective, environmentally benign and scaleable PV scrap management options that result in true recycling of the major module components instead of simply converting one type of waste into another have been developed and practiced. Photovoltaic products now enjoy recyclable status similar to other electronic devices such as nickel-cadmium batteries, circuit boards, computer chips, cathode ray tubes, and copier toner and printer ink cartridges.

6. ACKNOWLEDGMENT

This work was supported in part by a United States Department of Energy Small Business Innovation Research Grant (DE-FG02-95ER82068). Such support does not indicate an endorsement by USDOE of the views expressed herein.

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1.3 Bob Goozner

Recycling Metals from CdTe and CIS PV Modules

RECYCLING THIN FILM PHOTOVOLTAIC MATERIALS

Robert Goozner, Christi Byrd, Mark Long, William F. Drinkard

Drinkard Metalox, Inc.

PV AND THE ENVIRONMENT 1998

Keystone, Colorado July 23, 1998

TCLP

US EPA Toxicity Characteristic Leaching Procedure

40CFR Ch.1 Pt.261, App. II (7-1-91 Edition)

1. Extract sample with DI water to check for pH change caused by sample.
2. Based on step #1, extract a sample with pH=4.93 or pH=2.88 solution (5% for 18hours bottle roll).
3. Analyze leachate for toxic materials.

http://www.epa.gov/docs/epacfr40/chapt-I.info/subch-I/40P0261.pdf

TCLP FOR CdTe CELLS

No.	Cd (mg/L)	Se(mg/L)	Ag(mg/L)	Pb(mg/L)
108	0.915	0.206	0.039	0.038
121	0.025	0.260	0.043	0.082
122	0.013	0.196	0.064	0.108
001	0.093			
EPA	<1	<1	<5	<5

DRINKARD METALOX

TCLP FOR CIS CELLS

No.	Manufacturer	Cd (mg/L)	Se(mg/L)	Pb(mg/L)
109	A	0.079	0.283	37.50
110	A	0.098	0.404	0.503
111	A	0.016	0.419	0.073
159	B	0.213	0.254	0.107
EPA LIMITS		<1	<1	<5

TCLP FOR Si MODULES

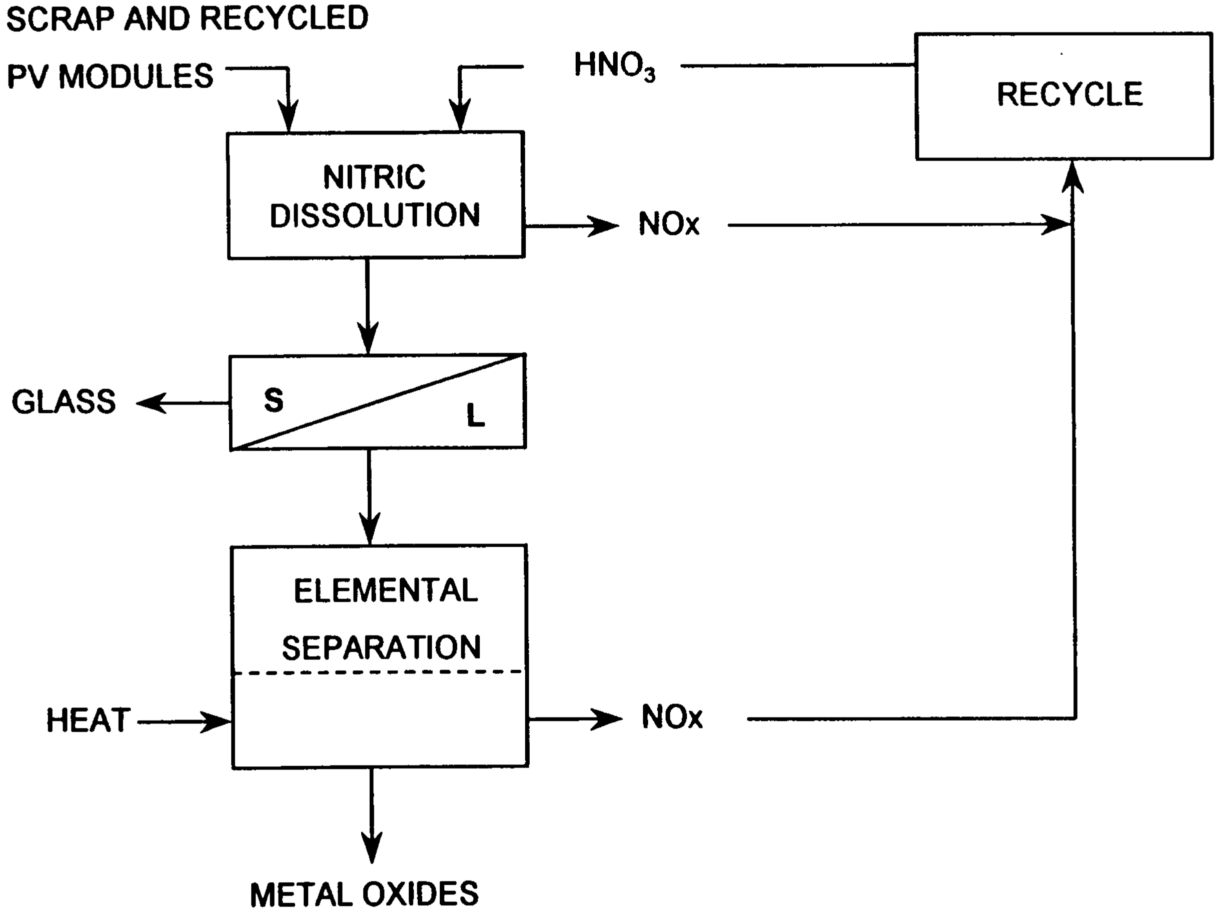
No.	Cd (mg/L)	Cr(mg/L)	Ag(mg/L)	Pb(mg/L)	Se(mg/L)	Cu(mg/L)
333*	0.014	0.047	0.074	5.355	0.408	0.073
334*	0.016	0.049	0.078	5.072	0.428	0.045
335**	0.014	0.036	0.029	6.516	0.273	0.112
336**	0.012	0.041	0.101	4.274	0.326	0.188
EPA LIMIT	<1	<5	<5	<5	<1	-

***glass and laminate**

**** glass, laminate, frame and junction box**

DRINKARD METALOX

INITIAL PROCESS DESIGN



SCRAP AND RECYCLED PV MODULES

HNO_3

RECYCLE

NITRIC DISSOLUTION

NOx

GLASS

S

L

ELEMENTAL SEPARATION

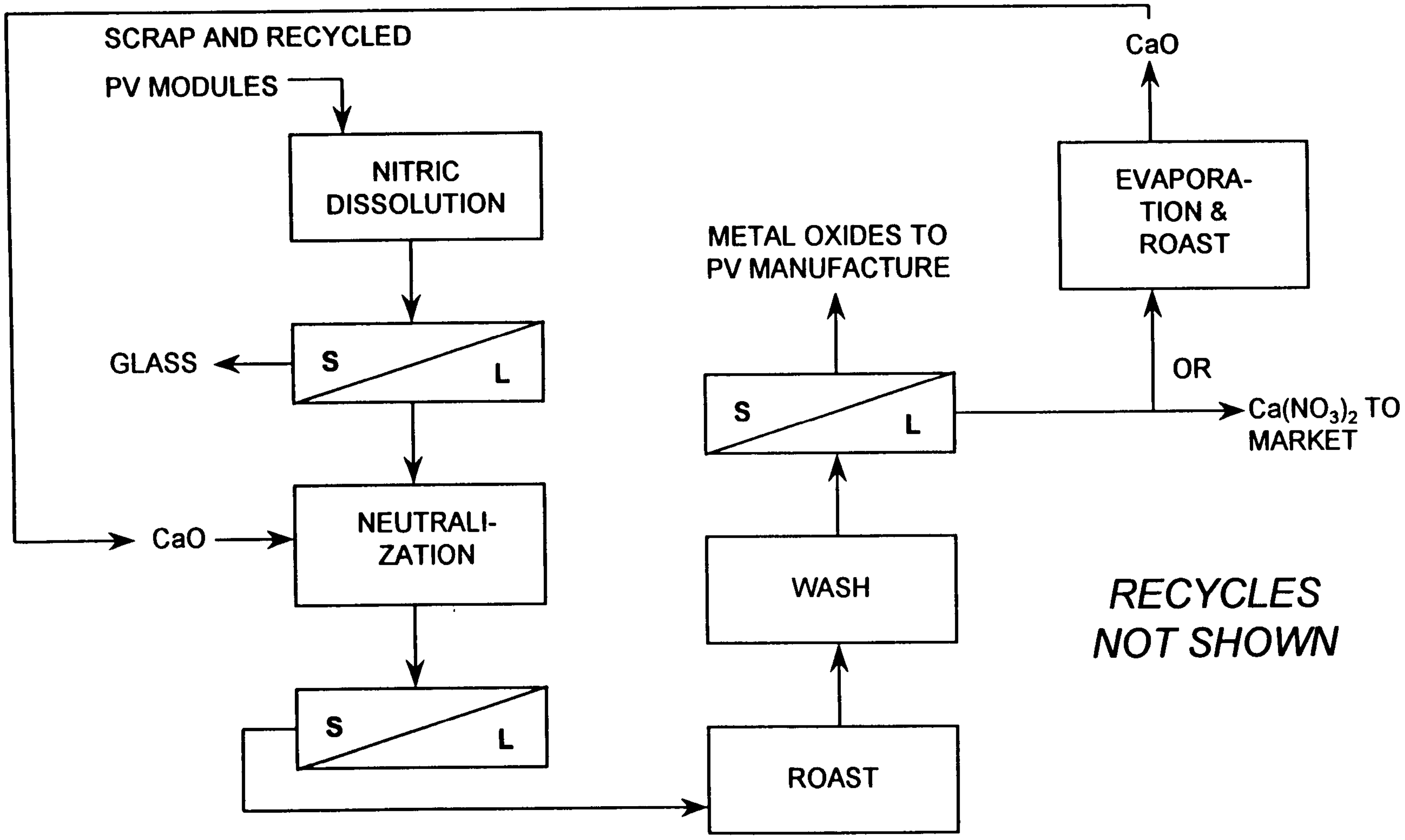
HEAT

NOx

METAL OXIDES

DRINKARD METALOX

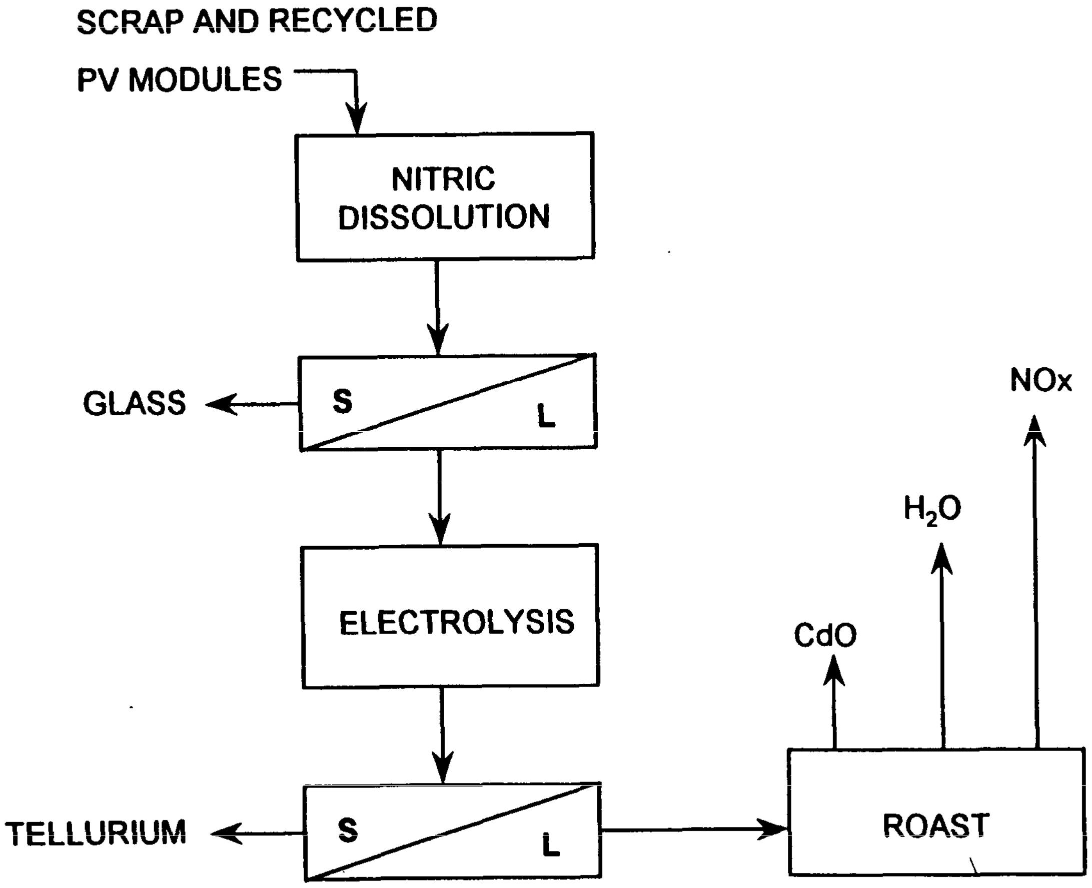
Cd-Te PROCESS I



RECYCLES NOT SHOWN

DRINKARD METALOX

Cd-Te PROCESS II (PREFERRED)



SCRAP AND RECYCLED PV MODULES

NITRIC DISSOLUTION

S L

GLASS

ELECTROLYSIS

S L

TELLURIUM

ROAST

CdO

H_2O

NOx

RECYCLES NOT SHOWN

DRINKARD METALOX

Cd-Te PROCESS

STEP: NITRIC DISSOLUTION

Typical Run: 3000.9 g (combined top & bottom layer) of cells are refluxed with 1300.7 g of 25% HNO_3 for 1 hour residence time. (ref. PV-23)

Results: Filtrate Analysis

	Al	Cd	Cr	Te	Sn
ppm	75.53	1277.02	6.95	1313.48	11.29

Cd-Te PROCESS

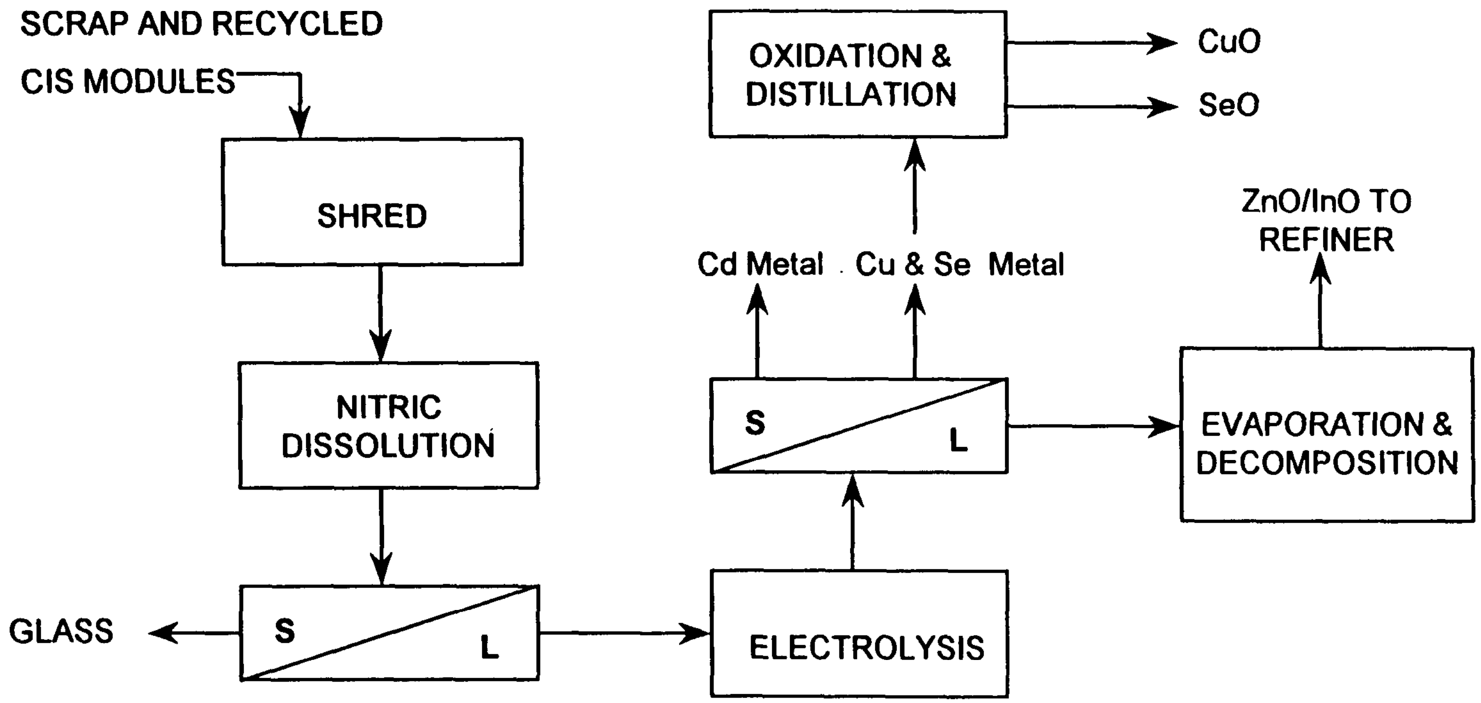
STEP: ELECTROLYSIS

Typical Run: 250 g of 1% (10,000 ppm) Cd and 1% Te solution dissolved in 2M HNO_3 are electrolyzed at 3.4A and 2.25V using Pt electrodes for 2 hours.

Results (for 3 runs):

Sample ID	Filtrate Conc. (ppm)		% Metals Recovered	
	Cd	Te	Cd	Te
PV-49	10,001	499	0	95
PV-50	10,763	226	0	98
PV-51	9,648	369	4	96

CIS PROCESS



SCRAP AND RECYCLED
CIS MODULES

SHRED

NITRIC
DISSOLUTION

GLASS

S

L

ELECTROLYSIS

S

L

Cd Metal

Cu & Se Metal

OXIDATION &
DISTILLATION

CuO

SeO

EVAPORATION &
DECOMPOSITION

ZnO/InO TO
REFINER

*RECYCLES
NOT SHOWN*

US Patent 5,779,877

DRINKARD METALOX

CIS ELECTROLYSIS RESULTS

Sample ID	% Metals Removed From Solution				
	Cadmium	Copper	Indium	Selenium	Zinc
PV66	0	94	0	88	0
PV67	16	99	0	89	0
PV68	20	99	0	90	0

LEAD REMOVAL

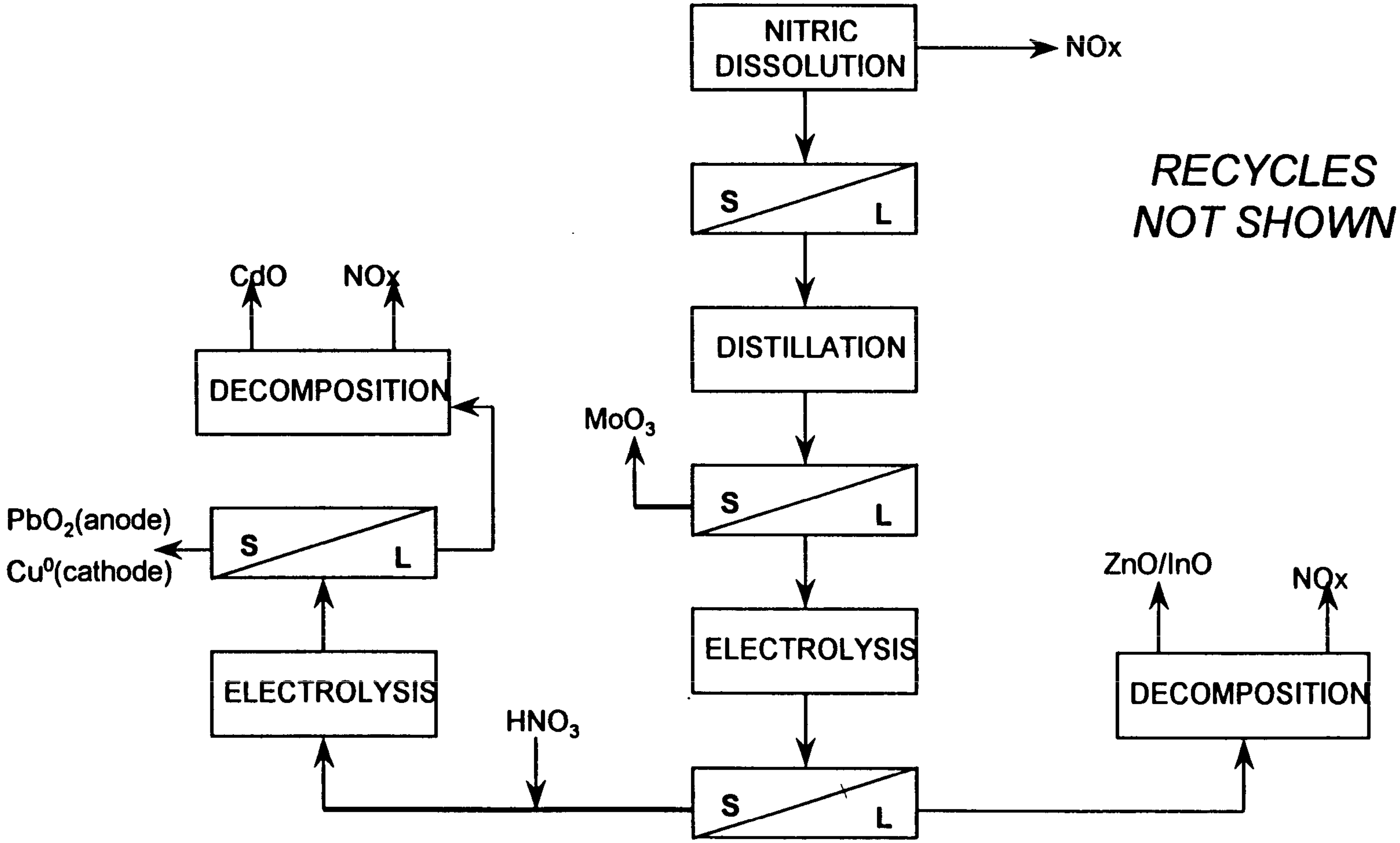
Electrolysis of lead containing CdTe solution precipitates Pb on the cathode.

SAMPLE ID	FILTRATE CONC. (PPM)			% METALS RECOVERED		
	Cd	Pb	Te	Cd	Pb	Te
PV-260	2225	952	52	9	96	99
PV-261	2525	395	109	0	98	97

From 0.25% solution of Cd, Te, Pb.

DRINKARD METALOX

Combined CIS/CdTe Process



RECYCLES NOT SHOWN

DRINKARD METALOX

PLANT COST ESTIMATE

Comapratiave Study: 10,000 tpa EAF Dust Plant Designed by Kvaerner Metals (greenfields design)

Equipment costs:	$2,773,733
Labor Cost:	$775,775
Building & Service Supply	
Material	$3,378,394
Labor Cost	$1,336,752
Direct Total	$8,264,655
Engineering & Start-Up	$2,389,008
Sub-Total + Indirects	$10,656,602
Contingentcy + Insurance	$2,195,338
TOTAL	**$12,852,000**

10,000 tpa
@20kg/module
= 500,000
module/year

DRINKARD METALOX

OPERATING COSTS

Comparatiave Study: 10,000 tpa EAF Dust Plant
Designed by Kvaerner Metals

Labor	39.60/ton
Reagents	15.00/ton
Office & Maintenance Supplies	33.25/ton
Power	5.19/ton
TOTAL	$93.04/ton

TOTAL COSTS

10 Year Plant Amortization	$128.52/ton
Operating Costs:	$93.04/ton
TOTAL	$221.56/ton
Recycling cost per 20kg module:	$4.43
Recycling cost @ 50W/module:	$0.09/W

At a selling price of $8-10/W, Recycling cost = 1% of selling price

DRINKARD METALOX

DISCUSSION TOPICS

- Incorporating recyclability into process and module design
- Recycling Strategies
  - Centralized Recycling
  - Localized Recycling

1.4 Daniel Cunningham

Discussion about TCLP protocols

BP SOLAR

Introduction to EPA TCLP

- What is TCLP?
- Why does it need to performed?
- What does it say about the product?
- Contaminants and regulatory levels?

Contaminants and limit levels

- The following show inorganics only:

– Arsenic	5.0ppm
– Barium	5.0ppm
– Cadmium	1.0ppm
– Chromium	5.0ppm
– Lead	5.0ppm
– Mercury	0.2ppm
– Selenium	1.0ppm

BP SOLAR

Summary

◆ TCLP levels are dependant on sample procedure.

◆ A more detail sample procedure is required

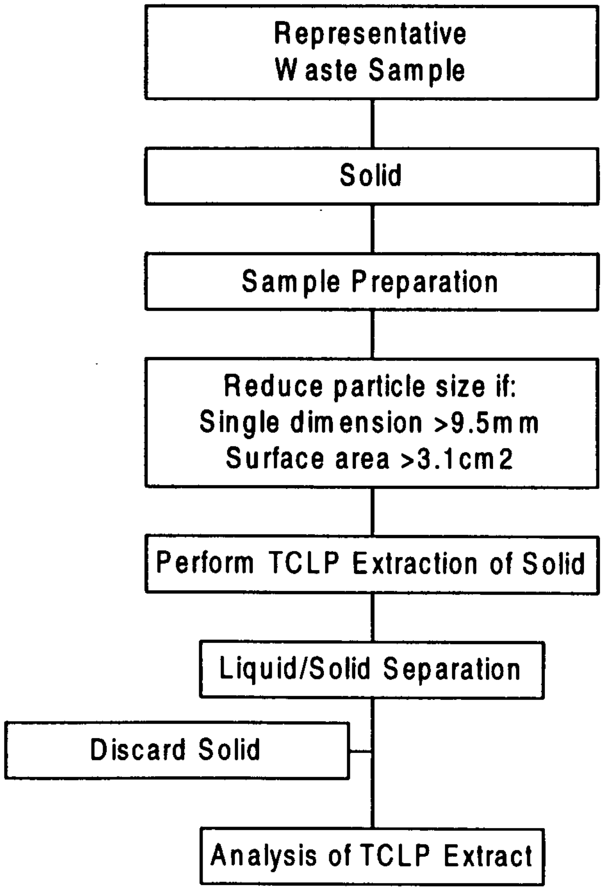
◆ Possible parameters might include:

  - Guidelines on sample composition.
  - A defined method for milling/reducing.
  - A more stringent definition of particle sizes

Sample Preparation

- No detail in procedure SW846
- Only two dimensional parameters given
- Metal concentration in extract depends on:
  - Construction of product
  - Compound exposure (post preparation)
  - Sample particle size

Summary of EPA Method 1311



Representative
Waste Sample

Solid

Sample Preparation

Reduce particle size if:
Single dimension >9.5mm
Surface area >3.1cm2

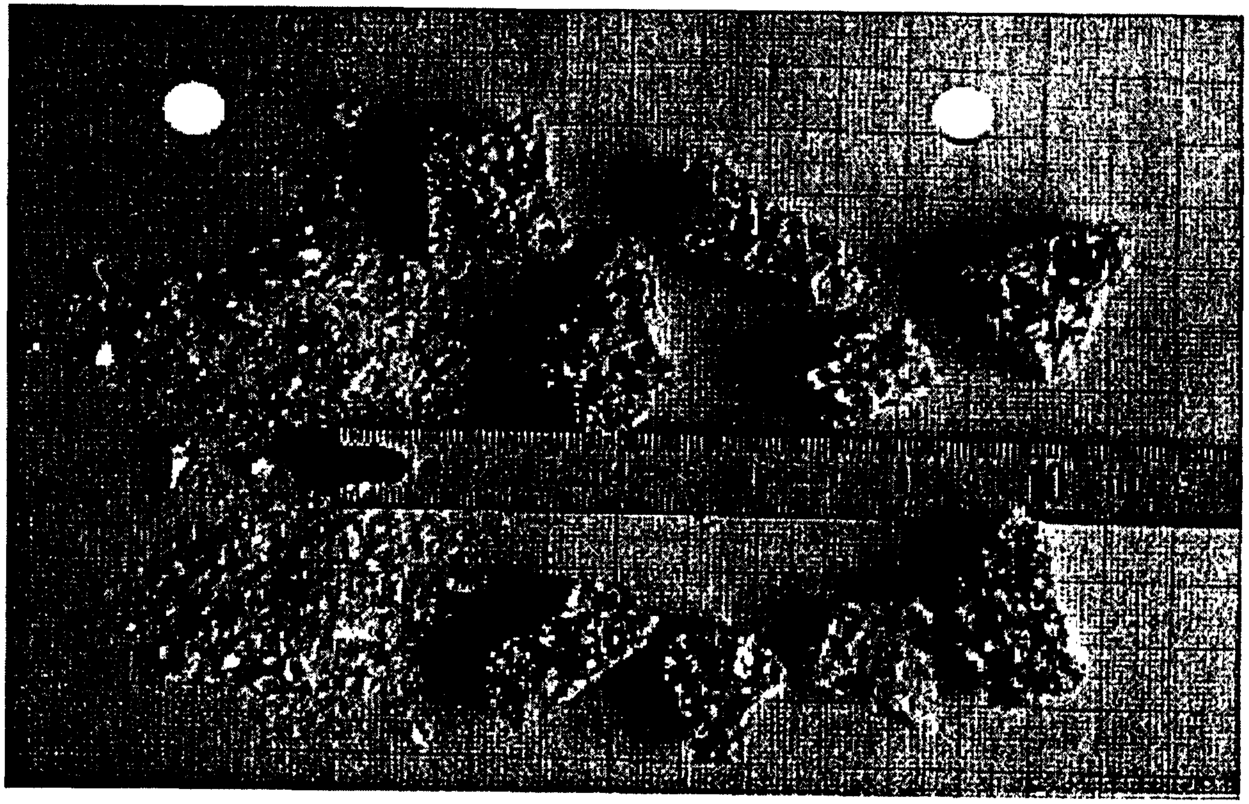
Perform TCLP Extraction of Solid

Liquid/Solid Separation

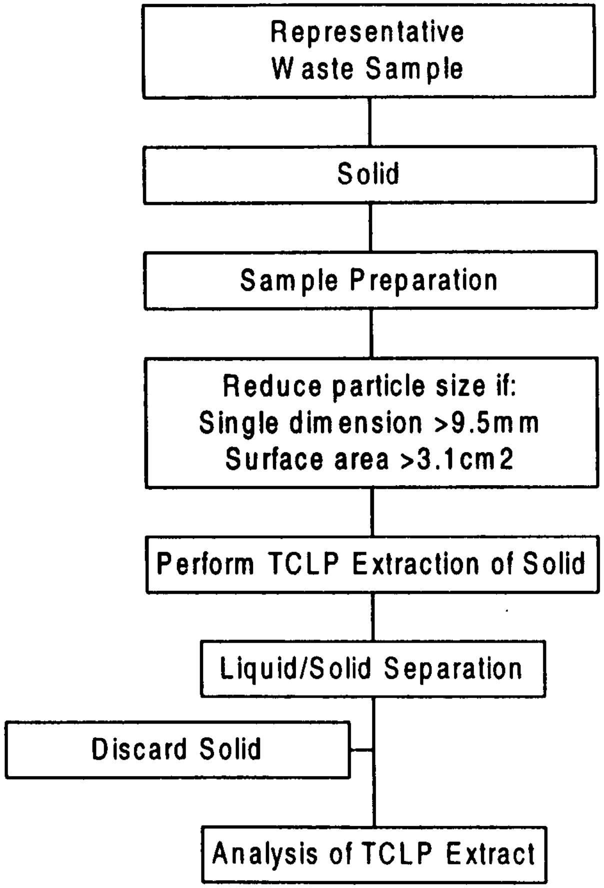
Discard Solid

Analysis of TCLP Extract

TCLP Sample Preparation



Summary of EPA Method 1311



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Analysis of TCLP Extract

Sample Preparation

- No detail in procedure SW846
- Only two dimensional parameters given
- Metal concentration in extract depends on:
  - Construction of product
  - Compound exposure (post preparation)
  - Sample particle size

Effect of Sample Size

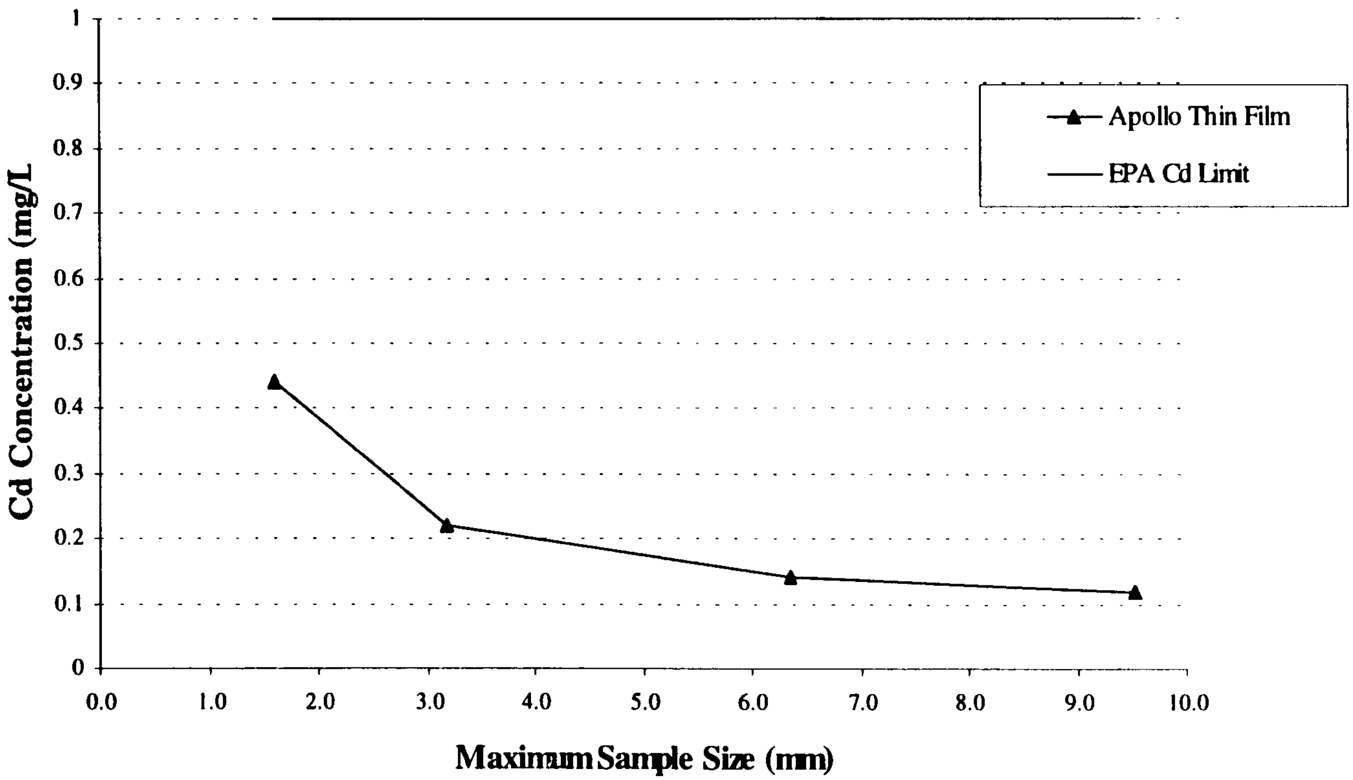
- Sample sizes used in tests

Long dimension (mm)	Surface area(cm2)
9.5	4.1
6.4	2.4
3.2	1.0
1.5	0.4

- Inert module material was not added in this test.
- Extraction and analysis performed by California DHS-ELAP certified lab.

BP SOLAR

Cd TCLP level vs. Sample Size



1.5 Simon Tsuo

Silicon Solar Cell and Module Manufacturing: Current and Alternative, More Environmentally Benign Processes

ENVIRONMENTALLY BENIGN SILICON SOLAR CELL MANUFACTURING

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ABSTRACT: The manufacturing of silicon devices - from polysilicon production, crystal growth, ingot slicing, wafer cleaning, device processing, to encapsulation - requires many steps that are energy intensive and use large amounts of water and toxic chemicals. In the past two years, the silicon integrated-circuit (IC) industry has initiated several programs to promote environmentally benign manufacturing, i.e., *manufacturing practices that recover, recycle, and reuse materials resources with a minimal consumption of energy*. Crystalline-silicon solar photovoltaic (PV) modules, which accounted for 87% of the worldwide module shipments in 1997, are large-area devices with many manufacturing steps similar to those used in the IC industry. Obviously, there are significant opportunities for the PV industry to implement more environmentally benign manufacturing approaches. Such approaches often have the potential for significant cost reduction by reducing energy use and/or the purchase volume of new chemicals and by cutting the amount of used chemicals that must be discarded. This paper will review recent accomplishments of the IC industry initiatives and discuss new processes for environmentally benign silicon solar-cell manufacturing.
Keywords: c-Si - 1: Manufacturing and Processing - 2: Environmental Effect - 3

1. INTRODUCTION

With the worldwide photovoltaic (PV) solar energy market expanding rapidly and the demand outpacing supply, the crystalline-silicon solar PV module is finally becoming a commercially viable product. Most of the newcomers and the capacity expansions of existing producers are based on either single-crystal silicon grown by the Czochralski (Cz) method or polycrystalline silicon by casting. There are also increasing numbers of suppliers who are developing production equipment for the industry based on best-known practices (BKPs) of silicon solar cell and module processing. Because solar electricity generation is a large-area application, it is likely the PV industry will eventually use more silicon than even the integrated-circuits (IC) industry. It is important at this stage to review the environmental impact of the rapidly growing silicon PV industry and to find opportunities for improving energy efficiency and productivity and reducing environmental impact.

The manufacturing of semiconductor silicon devices - from polysilicon production, crystal growth, ingot slicing, wafer cleaning, device processing, to encapsulation - requires many steps that are energy intensive and use large amounts of water and toxic chemicals. In the past two years, the IC industry has initiated several programs to promote environmentally benign manufacturing, i.e., manufacturing practices that recover, recycle, and reuse materials resources with a minimal consumption of energy. One of the programs is the establishment of the *Engineering Research Center for Environmentally Benign Semiconductor Manufacturing* on April 15, 1996, with an initial funding of US$10 million from the United States National Science Foundation (NSF) and Semiconductor Research Corporation (SRC). Crystalline-silicon modules accounted for 87% of the worldwide PV module shipments in 1997 and 93% of those modules shipped for outdoor applications [1]. Silicon PV module manufacturing has many steps similar to those used in the IC industry. Although the annual sales of the worldwide silicon PV module industry is about 400 times smaller than that of the IC industry, the PV industry consumes about 10% of the worldwide polysilicon production. Obviously, there are significant opportunities for the silicon PV industry to learn from new developments in the IC industry and to implement more environmentally benign manufacturing approaches. Such approaches often have the potential for significant cost reduction by reducing the purchase volume of new chemicals and by cutting the amount of used chemicals that must be discarded. Because PV manufacturing has lower semiconductor material-quality requirements than IC manufacturing, some lower cost and more environmentally sound processes may be acceptable for PV manufacturing even though they don't meet the stricter requirements of IC manufacturing.

It is not possible to review here in detail all the steps involved in the manufacturing of silicon PV modules. We will simply highlight some areas where we think opportunities exist to make the module manufacturing process more environmentally benign.

2. INDUSTRY INITIATIVES AND RESOURCES

Three recent initiatives by the semiconductor industry in the environmentally benign manufacturing area could produce results that also benefit the PV industry: (1) The National Science Foundation and the Semiconductor Research Corporation jointly established the *NSF-SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing* on April 15, 1996 [2]. SRC is a consortium of 65 corporations and government agencies that plans, directs, and funds the semiconductor industry's pre-competitive, long-term research [3]. (2) In April 1997, the international trade association for the semiconductor industry, Semiconductor Equipment and Materials International (SEMI), created a new *Environmental Health and Safety Division* that will explore worldwide environmental priorities for the industry [4]. (3) In October 1997, the Electric Power Research Institute (EPRI) and SEMATECH Corp. formed a new center, the *EPRI Center for Electronics Manufacturing*, to address productivity, environmental, and energy issues in the electronics industry [5]. SEMATECH is a non-profit R&D consortium of U.S. semiconductor manufacturers.

The NSF-SRC Center carries out research in six areas of semiconductor manufacturing: water conservation, plasma processes, wet chemicals, chemical-mechanical polishing, emission of organics, and risk-assessment studies. Some of these research results are presented in a weekly teleconference seminar series hosted by the four participating universities: University of Arizona, Massachusetts Institute of Technology, Stanford University, and University of California-Berkeley [6]. A good source of information on the Environmental, Safety, and Health (ES&H) goals of the semiconductor industry is the ES&H Section of the United States National Roadmap for Semiconductors [7]. In addition to these semiconductor industry organizations, the United States National Photovoltaic Environmental, Health and Safety Information Center [8] regularly publishes information on PV ES&H-related issues [9].

3. POLYSILICON PRODUCTION

For the feedstock material used in crystal growth, the silicon PV industry has been relying on rejected materials from the IC industry. These rejected materials, about 2,100 metric tons in 1997, amount to about 10% of the semiconductor-grade polysilicon used by the IC industry. This arrangement worked well until 1995 when a shortage of polysilicon feedstock began to drive up the cost and limit the growth of the silicon PV industry. If the PV industry continues to grow at the present rate, which in recent years has been higher than the growth rate of the IC industry, and if crystalline silicon continues to be the dominant technology of the PV industry, then we must develop new sources of solar-grade polysilicon. There are two possibilities: (1) build new factories dedicated to the production of low-cost (< US$10/kg), solar-grade polysilicon, and (2) find new ways to use the rejected silicon that is not currently being used, for example, purifying the about 30% of silicon lost from wafer-cutting operations (kerf loss) of semiconductor-grade polysilicon into solar-grade polysilicon. The purity requirements for solar-grade polysilicon, according to the Solar-Grade Silicon Stakeholders Group, are the following: it is preferred that polysilicon have either B or P doping, with no compensation; resistivity at 25°C should be greater than 1 ohm-cm; oxygen and carbon should not exceed the saturation limits in the melt; and the total non-dopant impurity concentration should be less than 1 ppma [10].

More than 98% of semiconductor-grade polysilicon is produced by the trichlorosilane ($SiHCl_3$) distillation and reduction method [11,12]. The trichlorosilane is manufactured by fluidizing a bed of fine pulverized metallurgical-grade silicon (MG-Si), which is more than 98% silicon, with hydrogen chloride in the presence of a copper-containing catalyst. The MG-Si, which costs about US$1/kg, is produced by the reduction of natural quartzite (silica) with coke (carbon) in an electric arc furnace. This method of polysilicon production is very energy intensive [13], and it produces large amounts of wastes, including a mix of environmentally damaging chlorinated compounds. About 80% of the initial metallurgical-grade silicon material is wasted during the process. In addition, the semiconductor-grade polysilicon material produced by this method far exceeds the purity requirement of the PV industry, and the cost (over US$50/kg, with most of it attributable to the $SiHCl_3$ processes) is several times higher than what the PV industry can afford [14]. Every watt of crystalline silicon PV module generating capacity requires roughly 20 g of polysilicon. Thus, if the cost of solar-grade polysilicon is US$20/kg, the cost of polysilicon per watt of a crystalline-silicon PV module is US$0.40. It is obvious that less complicated, less energy intensive, more efficient, and more environmentally benign methods need to be developed to meet the cost and quality requirements of the PV industry. New methods of producing solar-grade polysilicon should either be chlorine free or recycle chlorine internally to reduce cost and avoid damage to the environment.

3.1 Low-Temperature, Chlorine-free Processes for Polysilicon Feedstock Production

The National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), with funding from the Initiative for Proliferation Prevention (IPP) Program, has initiated a joint research program with the Intersolarcenter to study new chlorine-free methods of producing solar-grade polysilicon. So far, the most promising method developed by this project is one that uses MG-Si and absolute alcohol as the starting materials. This new process requires only 15 to 30 kWh of energy per kg of polysilicon produced vs. about 250 kWh/kg of the trichlorosilane method. The silicon yield (polysilicon and the main by-product, silica sol) is in the 80% to 95% range vs. 6% to 20% for the trichlorosilane method. The eventual cost goal is US$10 per kg of solar-grade polysilicon.

The basic processing stages of this chlorine-free polysilicon production process are the following:

1. The reaction of metallurgical-grade silicon with alcohol proceeds at 280°C in the presence of a catalyst:

$$Si + 3\,C_2H_5OH \xrightarrow{catalyst} Si(OC_2H_5)_3H + H_2\,. \tag{1}$$

2. The disproportion (i.e., simultaneous oxidation and reduction) of triethoxysilane in the presence of a catalyst will lead to the production of silane and tetraethoxysilane:

$$4\,Si(OC_2H_5)_3H \xrightarrow{catalyst} SiH_4 + 3\,Si(OC_2H_5)_4\,. \tag{2}$$

3. Dry ethanol and such secondary products as high-purity SiO_2 or silica sol can be extracted by hydrolysis of tetraethoxysilane. The alcohol will be returned to Stage 1.

$$Si(OC_2H_5)_4 + 2\,H_2O \text{ ---- } SiO_2 + 4\,C_2H_5OH\,. \tag{3}$$

4. Silane is decomposed pyrolytically to pure silicon and hydrogen at a temperature of about 900°C:

$$SiH_4 \xrightarrow{850^\circ - 900^\circ C} Si + 2\,H_2\,. \tag{4}$$

The purity requirements for solar-grade silicon are not as high as those for electronic applications. Thus, the silane will undergo a simplified cycle of purification, and at Stage 4 the less expensive and less energy-consuming process of a fluidized bed reactor can be used, instead of the well-known Siemens Process [11].

3.2 Purification of Metallurgical Silicon

NREL and ENEA (National Agency for New Technologies Energy & Environment) have proposed a novel method of producing solar-grade polysilicon by directly purifying MG-Si pellets. The process uses the very large surface areas, produced by porous silicon etch on the surfaces of the silicon wafer, as sites for gettering impurities in the subsequent high-temperature annealing. The details of this process will be presented seperately at this conference [15].

3.3 New Sources of Silicon Waste from the Electronic Industry

When wafers are sliced from silicon ingots using a multiple-wire saw, a layer of silicon about 250 micrometers thick is lost per wafer. This kerf loss is higher for inner-diameter (ID) saws. Depending on the wafer thickness, this kerf loss represents from 25% to 50% of the ingot material, several times the quantity of the material that is presently used by the PV industry. Presently, the solar industry uses mainly Cz ingot top and tails, pot scrap, and rejected wafers from the IC industry [14]. If a method can be developed to produce solar-grade polysilicon by purifying the kerf remains of semiconductor-grade ingots, enough polysilicon would be generated for over 300 MW/year of crystalline-silicon solar cells, i.e., more than two times the size of the current silicon solar-cell production.

4. CRYSTAL GROWTH

There are four types of crystalline-silicon solar cells: single-crystal, polycrystalline, ribbon, and silicon film deposited on low-cost substrates. In 1997, market share of the worldwide PV cell and module shipment for the four types of crystalline-silicon solar cells were 49.6% for single-crystal, 34.0% for polycrystalline, 3.2% for ribbon, and 0.4% for silicon film [1]. Crystal growth from a silicon melt generates relatively little waste. The main concern is the energy required and the amount of argon gas used during crystal growth. Electricity and argon needed for Cz growth are the highest among the four types of silicon materials [13]. Recently, however, the world's largest manufacturer of Cz silicon solar cells, Siemens Solar, Industries, announced a joint project with the Northwest Energy Efficiency Alliance to cut the amount of electricity used to grow crystals and yield savings of 40% to 50% [16].

5. WAFER SLICING AND CLEANING

5.1 Wafer Slicing

In the last six years or so, the PV industry has made the transition from using ID saws for wafer slicing to using multiple-wire saws. Multiple-wire saws can improve wafer yield per unit length of ingots by over 50% because of lower kerf loss and thinner wafers. However, wafer slicing is still one of the most expensive processes in silicon solar-cell manufacturing because of the large quantities of consumables (stainless-steel wire and abrasive slurry) and the kerf loss. During wafer slicing, ingots are bonded to a ceramic submount with hot-melt adhesive and sliced into wafers using multiple steel wires to which an abrasive slurry is fed. The slurry is composed of silicon carbide (SiC) and mineral-oil-based or glycol-based slurry vehicle. Oil-based slurry is commonly used by the PV industry. Compared to the water-soluble, glycol-based slurries more commonly used by the IC industry, oil-based slurries produce more environmentally damaging wastes and require more extensive wafer cleaning. The added cost and the process changes needed for the PV industry to switch over to glycol-based slurry need to be investigated. Methods of proper disposal or recycling of the stainless-steel cutting wire also need be studied, as does the effective recovery of the SiC in the slurry. The development of water-base slurries will also help reduce cost and environmental damage.

5.2 Wafer Cleaning and Etching

The cost of chemical waste disposal is high. It is important for the PV industry to find ways to reduce chemical consumption and waste generation through *source reduction, recovery, recycle, reuse, and substitution*. Because wafer cleanliness for PV is not as critical as for IC manufacturing, a safe choice, in terms of making sure the highest quality and most extensive cleaning procedures are used, is not necessarily the right choice in terms of cost reduction and environmental safety. Certain methods, such as dry cleaning processes, although not adequate for the IC industry standards, may be sufficient for the PV industry. For example, centrifugal shear carbon dioxide cleaning [17] is worth considering as an alternative to organic solvent and/or hot detergent cleaning methods for wafer degreasing and cleaning after slicing. This process uses carbon dioxide in three coexisting phases: liquid, supercritical, and dense-gas. Operating temperature ranges from 298 K to 310 K, and pressure ranges from 56 ATM to 100 ATM. CO_2 gas is non-flammable, non-combustible, and non-corrosive, and is abundant, inexpensive, and reusable. Compressing CO_2 at about 70 ATM and at temperatures below its critical temperature (305 K) liquefies the gas. Compressing CO_2 above its critical temperature and pressure (72.9 ATM) does not cause a phase change, yet the density of the gas may be liquid-like. Static and dynamic cleaning processes employing the multi-phase CO_2 system have been developed. The excellent cleaning abilities derive from a combination of solvent cleaning power and, in the dynamic processes, by physical cleaning action. Although CO_2 at these pressure and temperature conditions presents densities comparable to other cleaning agents (about 500 g/L), it has a viscosity comparable to gases. For instance, it is from 10 to 30 times smaller than 1,1,1-trichloroethane (TCA).

For texture etching and/or surface damage removal, most of the PV industry has been using sodium hydroxide etchant. NaOH etchant is considerably cheaper and easier to dispose of than the conventional hydrofluoric-nitric-acetic acid etchant. In an NREL-funded program, Siemens Solar Industries found that the caustic waste per wafer generated by the saw-damage-removal etching process was reduced by about 20% after the switch from ID saws for wafer slicing to multiple-wire saws [18]. This is because the wire-sawn wafers require less etching to remove saw damage.

The Photovoltaic Device Fabrication Laboratory (PDFL) at Sandia National Laboratories has had a program to continuously monitor and reduce chemical usage since the laboratory began operations in 1989. The chemical waste generation has been reduced by nearly 75% since 1990 by using three procedures: (1) eliminate and/or replace hazardous chemicals, (2) recycle chemicals, and (3) reduce usage of remaining hazardous chemicals. A key feature of this effort was the use of statistical experimental designs to screen chemicals for their effectiveness in wafer cleaning and statistical process control to ensure that chemical-reduction changes did not impact the manufacturing process. An experiment was performed that used statistical designs to examine the effect of 22 different parameters associated with chemical cleaning of wafers. The experiment was able to eliminate a popular, but expensive, chemical (hydrogen peroxide) that is widely used in the IC industry for cleaning silicon wafers. Subsequent experiments and changes in procedure have eliminated sulfuric and phosphoric acids from PDFL.

Hydrofluoric (HF) acid solution is used for wafer cleaning, dopant oxide removal, and diffusion tube and quartzare cleaning. It accounts for a very large percentage of the total hazardous waste generated by silicon solar-cell manufacturing. It is possible to reprocess used HF solutions using reverse osmosis [19]. A cost-benefit analysis indicates that, for a system with a capacity of 1000 gal/day, about one US dollar is the net savings for every gallon of HF solution reprocessed [20].

5.3 Optimizing Water Use and Reuse

The semiconductor industry worldwide spends as much on ultrapure water as on wet chemicals for wafer processing, about US$700 million each in 1996 [21]. The net-feed water use by the IC industry averages about 30 gallons per square inch of wafer processed in 1997. The current United States National Roadmap for Semiconductors recommends decreasing the net-feed water use to 10 gallons/in^2 in 2000 and 2 gallons/in^2 in 2012 [22]. The NSF/SRC Center is studying methods to decrease water usage by more efficient rinse processes, water conservation in cooling, scrubbing and washing, and by lowering idle flows [23].

The silicon PV industry, of course, uses significantly less water per wafer than the IC industry. However, the value of the final product per wafer of the PV industry is orders of magnitude less than that of the IC industry. Obviously, water use by the PV industry is a significant cost factor that needs to be carefully studied. It is also not clear whether the PV industry really needs to use the same high-purity deionized water as that used by the IC industry. Water purity in the semiconductor process is typically measured in a bath with a resistivity monitor. The resistivity is inversely proportional to the ionic concentration of chemicals. At 25°C, water can exhibit a resistivity of 18.2 megaohm-cm if no impurities are present. The American Society for Testing and Materials (ASTM) has set four types of requirements for electronic water [24]. The resistivity (in megaohm-cm) at 25°C for the highest-grade electronic water, Type E-1, should be above 18.0 for 95% of the time and never less than 17.0. Type E-2 should be above 17.5 for 90% of the time and not less than 16.0. Type E-3 should be above 12.0. Type E-4 should be above 0.5. Type E-1 water, which costs 1 to 2 US dollars per 100 gallons, is intended for use in the production of devices having line widths below 1.0 micrometer. Type E-2 water is for line widths below 5 micrometers and is probably more than adequate for even the most critical wafer-cleaning needs of the PV industry. Even Type E-3 may be adequate in most cases.

Reclaiming water is also an important issue to be investigated by the PV industry. For every dollar spent to generate and process ultra-purity water by the IC industry, about $0.60 is spent treating the industrial wastewater. According to SEMATECH, 70% of its members are reclaiming at least some of their water. Careful design of the methods of recycling used water back to the feed makeup for the water purification plant and the methods of reclaiming water for use in support processes, such as cooling and gas scrubbing, is important for reducing the cost of PV manufacturing.

6. SOLAR CELL PROCESSING

For junction diffusion, either a belt furnace or a tube furnace is typically used. Tube furnaces traditionally use a $POCl_3$ liquid source dopant, which generates toxic P_2O_5 and Cl_2 effluents and requires frequent cleaning of diffusion tubes using HF solutions. Belt furnaces are more environmentally benign because they can use water-soluble, non-toxic, spin-on or spray-on dopants or vapor dopants and do not require HF cleaning. Optically enhanced doping methods, such as the solar furnace doping proposed by NREL [25], are also environmentally benign alternatives.

Edge trimming to remove electrical shorts between the front and back junction can be done either by laser cutting or plasma etching. Because of its very high throughput, $CF_4 + O_2$ plasma etching is commonly used by the PV industry. However, CF_4 is one of the perfluorinated compounds (PFCs) that has no known natural destruction mechanisms, and thus, has a large global-warming potential [26]. The PV industry needs to either find an alternative to the CF_4 and O_2 plasma etch or improve the effluent treatment to include PFC capture and recycling.

Antireflection coatings can be deposited by vacuum evaporation, plasma deposition, atmospheric-pressure chemical vapor deposition, and spin-on liquids. Silane, which is pyrophoric, is commonly used in depositing silicon nitride antireflection coatings [27]. A safer alternative, chlorosilane, which is non-pyrophoric, has been used successfully by the IC industry for silicon nitride depositions [9].

For metal electrodes on the solar cells, it is not desirable to use silver-tin-lead solder baths after screen printing to enhance the conductivity of the metal grids because of the added lead content to the cells.

7. MODULE ASSEMBLY

7.1 No-Clean Flux

Flux, typically a derivative of pine resin, is applied to cell interconnection strips before soldering to act as a deoxidizer and to ensure better adhesion between the solder and solar cells. Conventional flux leaves residues on the cell surfaces that need to be cleaned with a chlorofluorocarbon (CFC) compound. CFCs are known to cause ozone depletion in the atmosphere [28]. Recently, water-soluble fluxes and no-clean fluxes, low-residue fluxes that could be left on the solar cell after soldering have become widely available [29]. In an NREL-funded program, Siemens Solar was able to eliminate the CFC usage in the manufacturing facility by switching from conventional solder paste to a "no-clean" solder paste [18]. The no-clean process both eliminates the environmental damaging CFC emissions and reduces costs. Siemens Solar also found that, by using a water-soluble flux, the CFC usage can be reduced by about 60% over a conventional flux. However, it appeared that water rinse of the cells retained moisture during the lamination sequence and caused module reliability problems.

7.2 Lead-Free Solder

Lead is a well-known hazard to human health. When disposed of in landfills, it can leach into soils and pollute ground water. It is important for the PV industry to remove or minimize the use of lead in modules so that proper disposal at the end of module life will not become a problem [30]. For example, some European countries have proposed a ban on the landfill disposal of electronic products containing lead. There are two sources of lead in a crystalline-silicon PV module: solder-dipped electrodes and solder-coated copper ribbons. The practice of dip-coating solar-cell contact electrodes is no longer necessary with modern screen-printed electrodes, but it is still used by a significant number of module manufacturers. The lead-tin solder that coats the surfaces of copper ribbons for tabbing strips is needed to prevent the oxidation of the copper and to improve the solderability of the ribbons. However, lead-free alternatives to lead-tin solder have been investigated extensively by the printed-circuit-board industry [31]. For example, the National Center for Manufacturing Sciences in Ann Arbor, Michigan, has recently completed a US$10-million project that evaluated 79 lead-free solder alloys and found seven promising replacement candidates [32]. The International Tin Research Institute (ITRI) in Middlesex, England, has also done extensive studies on lead-free solder alloys [33].

A very promising alternative for the tin-36% lead-2% silver ribbon coatings commonly used by the PV industry is the tin-3.5% silver alloy. It is identified as a promising alternative for the standard tin-37% lead alloy by both NCMS and ITRI. The silver in the alloy is needed to increase the pull strength of the ribbon. The 221°C melting temperature, although higher than the 183°C for the standard lead-tin alloy, is acceptable. Because it is a binary alloy, it should have excellent stability. Its resistance to high-temperature fatigue is also good. The present cost of the alloy, at US$0.10 per cubic centimeter, is about twice the standard lead-tin alloy, which is the cheapest of the tin alloys. The cost difference between the silver-tin alloy and the lead-tin-silver alloy is small.

8. CONCLUSIONS

As the silicon PV industry continues to rapidly expand, the environmental impact of its manufacturing processes and products will receive increasing attention. It is particularly important for a renewable energy technology to address its environmental impact during manufacturing because one of the primary benefits of renewable energy generation is its low environmental impact. We have discussed several alternative approaches in this paper that are both cost effective and environmentally benign. However, the manufacturability and reliability of most of these alternative approaches need further investigation. We propose that the silicon PV industry form an association of government laboratories, equipment suppliers, and cell and module manufacturers to promote more environmentally benign manufacturing approaches. This association can also coordinate the PV industry's interactions with the environmental associations of the integrated-circuit and printed-circuit-board industries mentioned in this paper.

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1.6 Jefferson Bagby

The Experience of the Rechargeable Recycling Battery Association

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BARRIERS TO PRODUCT STEWARDSHIP

by Jefferson C. Bagby[1] and Robert L. Guyer[2]
for The Rechargeable Battery Recycling Corporation

Introduction

The experience of rechargeable product manufacturers in the collection and recycling of used small dry cell rechargeable nickel-cadmium (Ni-Cd) batteries in the United States and Canada has shown that product stewardship programs are likely to encounter several unexpected barriers. Organizations establishing product stewardship programs may benefit from considering these barriers in their program design.

The specific barriers to product stewardship discussed in this paper are:

- inartfully drafted laws that fail to match the logistics of product stewardship with the realities of the international marketplace;
- the complexities of establishing a funding mechanism that fairly apportions the costs and responsibilities of product stewardship among all of the necessary participants;
- the impact of national laws and international agreements regarding antitrust and tax laws upon a non-profit public service company; and
- the impact of national laws and international agreements on the transboundary movements of recyclable, yet hazardous, materials.

But first, a description of the RBRC battery collection program:

RBRC Program Overview

The Rechargeable Battery Recycling Corporation (RBRC) is a non-profit public service company managing the collection and recycling of small dry cell rechargeable nickel-cadmium batteries (Ni-Cds) in the United States (US) and Canada. Originally established in response to individual US state laws requiring "Extended Producer Responsibility" (EPR) for Ni-Cds, the RBRC collection program has overcome several unforeseen significant barriers to product stewardship. As a result, today the RBRC program may be more accurately characterized as a program of "Shared Product Responsibility" (SPR).

Ni-Cd batteries power portable electric products commonly found in the workplace and home including camcorders, power tools, kitchen appliances, cellular and cordless telephones, toys, and a host of other modern conveniences.

Ni-Cds can be recharged several hundred times. Depending on application, the total lifespan of a Ni-Cd battery ranges from a few months (commercial use power tools) to ten years (home camcorder) with the average life being four years. Annually, 900-1,200 million Ni-Cd cells are being manufactured with an expected growth rate of 4-6 percent through 2002. These batteries, when spent, may be classified as a hazardous waste under the laws of most nations due to their cadmium content.

RBRC's Charge Up to Recycle/Recharge et Recycle Ni-Cd collection program (program) operates in the United States (US) and Canada. Currently, over 22,000 retail stores and scores of industrial, commercial, and institutional/governmental (ICI) facilities voluntarily participate as RBRC collection centers. Participation allows retailers to demonstrate environmental regard while requiring no out-of-pocket costs. RBRC subsidizes ICI participants, partially or completely, depending on several variables.

Over 250 manufacturers of rechargeable products, representing about 75 percent of the world's rechargeable product producers, voluntarily fund RBRC. They do so by paying RBRC a license fee to display the RBRC seal, a symbol similar in meaning to the German Green Dot. The RBRC seal is always displayed on the Ni-Cd and normally on the instruction manual and retail package. Display of the seal indicates that the manufacturer has provided for future collection and recycling of the Ni-Cd in the US and Canada.

Inartfully Drafted Laws, or "EPR" versus "SPR"

The RBRC program began in response to some US states mandating that battery manufacturers collect used Ni-Cds in order to lessen heavy metals in the municipal solid waste stream. This was early Extended Producer Responsibility legislation.

The "battery manufacturers do it all" approach was destined for failure because most battery manufacturers have little direct contact with the consumer. Experience, accompanied by an extensive industry lobbying effort, helped lawmakers realize that participation by a much broader group than battery manufacturers alone would be necessary for successful Ni-Cd collection.

Second-generation legislation calling for battery "marketers" or those in the stream of commerce to share responsibility broadened participation by bringing in product manufacturers and distributors. Lawmakers recognized that others besides manufacturers must share in the responsibility for the collection and recycling of the used product. However, without retailer participation, even the broadened shared responsibility group could not meet battery collection mandates.

Retailer participation is critical because retailers, not manufacturers, have direct contact with consumers.[3] The consumer holding the used Ni-Cd is most likely to discard it into the municipal solid waste stream. Consumers will bring into the retail store their used Ni-Cd in order to get the exact replacement battery. At that point the consumer can be educated about recycling and their used Ni-Cd easily captured.

Participation by the retailers and associated consumer advertising conveys a sense of presence and collects many batteries. However, the ICI sector overall uses most of the world's Ni-Cds. Individual entities in this sector, such as electric utilities, public safety (fire, police) departments, manufacturers, and the military, often use Ni-Cds in large numbers and are capable of collecting and properly managing them.

Today authors of most modern battery collection and recycling legislation recognize that imposing collection requirements on battery manufacturers alone is unworkable. Instead of focusing on the "producer" of the product to collect and recycle the product, enlightened legislators understand that shared responsibility among all parties involved with a product is necessary if the product is to be successfully moved from the solid waste to the recycling stream.

Equitable Allocation of Financial Responsibility

Equitably assigning funding obligations to those benefiting from the manufacture, sale, and use of products is philosophically and mechanically difficult. Should any product beneficiary be exempted from responsibility? And if so, why? Of those to be assessed, how should costs be allocated? If a product stewardship program crosses state or national boundaries, how should the recycling monies be shared or allocated between states and nations? None of these are easy questions, but they have been answered to some extent in the context of the RBRC program.

Rechargeable product manufacturers around the world discussed these issues over a period of several years at various trade association meetings. It was generally agreed that the goal should be to conduct battery collection and recycling in as cost effective and efficient a manner as possible. The program should not be an expensive "public works" program, as the costs of the program will eventually be included in the costs of products sold to consumers. Increasing product costs to consumers by any substantial degree would distort the economics of the marketplace, and could result in damaging environmental consequences. For example, if rechargeable batteries became too expensive, consumers might switch to single use primary batteries, thus dramatically increasing the number of primary batteries entering the waste stream.

Cost allocation among battery and product manufacturers, distributors, and retailers was a second major consideration. It was agreed that as the costs of the program would end up in the final price to the consumer, that collection of the program costs be as close as possible to the consumer in the distribution chain was desirable. This would prevent additional price mark ups for program costs as the product moved through commerce. In addition, since often only the final distributor or retailer actually knows whether the product is to be sold in the US or Canada, collection of the recycling program costs at a point close to the consumer helps assure that recycling fees are not imposed on products destined for other nations.

RBRC resolved these issues by charging rechargeable product manufacturers a license fee to place the RBRC seal on batteries that are sold into the US or Canadian markets. This fee is usually collected from the final product assembler, distributor, or retailer that has actual knowledge that the product is to be sold into the US or Canada.

Would it have been easier to collect the recycling fee from the handful of Ni-Cd battery manufacturers in the world, instead of from over 250 companies selling products into the US and Canada? Of course, but none of the Ni-Cd manufacturers had any idea of the quantity of their batteries that were ending up in the US and Canada. A worldwide study of electronic product markets might generate this data, but it is certainly impractical to undertake such a study.

Antitrust and Tax Law Problems

Two types of legal issues that are usually not thought of in the context of product stewardship have a very real bearing on how such programs are operated. Antitrust considerations, in both US law and international law, make the collection of information as to market share for the purpose of program cost allocation extremely difficult if not impossible. In the US and many nations, collection of market share information can quickly lead to lawsuits about anticompetitive conduct. For example, if manufacturers collect market share data and use this data to impose recycling fees on competitors, some of the competitors are likely to allege that they are being illegally overcharged. This may be discriminatory pricing, forcing some companies out of the market.

Further, if manufacturers agree to raise the price of their product across the board for the purpose of paying collection program costs, they are likely to be charged with "*per se*" price fixing. This can result in severe criminal and civil penalties.

Thus, any legislation that requires cost allocation based on market share must contain provisions dealing with antitrust laws. And, as these laws exist at the national and international levels, it may not be possible for any nation or state to unilaterally relieve manufacturers from their antitrust law obligations.

Once a funding source is acquired, tax authorities are quick to claim their share. As noted above, RBRC was established as a non-profit public service corporation. This was to eliminate the payment of income tax on recycling program funds existing at the end of the fiscal year. The amount of such funds may become substantial over time, especially if the program collects money today for products to be recycled several months or years hence. For products such as Ni-Cds, front-end collection of substantial funds is necessary as Ni-Cds will still need to be collected and recycled far into the future, even after Ni-Cds are no longer being manufactured. Other battery technologies will likely eventually replace Ni-Cds.

When the RBRC program moved from the US into Canada, RBRC discovered that simply being a non-profit corporation in the US did not mean it was non-profit in Canada. In fact, Canadian tax law did not explicitly provide for the situation where a US non-profit would conduct operations in Canada. Revenue Canada finally required RBRC to incorporate a Canadian subsidiary, complete with all the corporate overhead that entails, within Canada. A for-profit corporation would not have been required to do this to conduct business in Canada. So, to protect the RBRC recycling program funds from end of year taxes, and thus to keep the costs of the program down for consumers, RBRC had to spend additional money for unneeded corporate overhead.

The non-profit tax issue needs to be addressed in the larger context of product stewardship programs worldwide.

Transboundary Movement of Recyclable Hazardous Materials

Many used products, including Ni-Cd batteries, are technically "hazardous waste" when they are sent to recycling. Recently national governments and international non-governmental organizations have recognized that laws impede product stewardship when they treat relatively harmless post-consumer products destined for recycling as hazardous wastes or dangerous goods. Where multiple jurisdictions make up what could otherwise be an economically viable area for product stewardship, the jurisdiction or jurisdictional subdivision with the most restrictive laws, determines the viability of collection and recycling.

In the US, the Environmental Protection Agency (EPA) recently promulgated the "Universal Waste Rule," essentially deregulating certain common hazardous wastes such as used batteries, mercury thermostats, and certain pesticides when they are shipped for recycling. This allowed the collection of these wastes at the same locations where they are sold new to the public, and allowed shipment of these wastes to recycling without use of a manifest or hazardous waste hauler. It was only after the adoption of this new rule that the RBRC program was able to expand to over 22,000 drop-off locations.

Changing US law to treat used Ni-Cds as used consumer products or a common good rather than a hazardous waste for purposes of collection, storage, and transportation enabled the transformation of RBRC's formerly anemic US patchwork program into a model for successful collection.

Current Canadian laws, similar to US laws before US EPA changed its rules, also inadvertently impede Ni-Cd recycling by treating Ni-Cds as a dangerous good and hazardous waste. Such regulation unnecessarily burdens recycling with unproductive costs for such things as mandatory storage in a permitted hazardous waste facility and shipping as a dangerous good rather than as common good. Again, as in the US, Canadian regulators do not intend to frustrate collection efforts but are themselves tied up by existing regulations which treat used consumer products as toxic or hazardous waste.

International proponents of product stewardship must recognize that it is neither economically feasible, nor perhaps desirable, for recycling operations for all types of hazardous wastes to be located in every nation of the world. Pending international restrictions on the transboundary movement of certain hazardous wastes for recycling, such as used batteries, may ultimately prove counterproductive to worldwide efforts for product stewardship.

Conclusions

Based on the RBRC experience in the US and Canada, Extended Producer Responsibility programs would be better characterized as Shared Product Responsibility programs, at least if they are to be effective. All participants in the global marketplace must be engaged in product stewardship for any program to be effective. This includes component manufacturers, product assemblers, distributors, retailers, consumers, and all end users of products. An additional yet most critical participant in SPR is government.

Government can contribute most by drafting legislation and regulations that recognize the many players in the international marketplace. Product "producers," on their own, cannot take on the entire task of stewardship. SPR laws must take into account the realities of cost allocation, including restrictions from antitrust laws and the additional overhead caused by tax laws. Finally, once there is a plan for cost allocation, the environmental and transportation laws, at the local, national, and international level must be reviewed to assure they do not impede efficient collection and transportation to recycling.

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[2] Robert L. Guyer is a partner in the Washington law firm of *Guyer, Bagby & Zimmerman, P.C.* As an Electric Systems Environmental Engineer with the Gainesville Florida Regional Utilities, and later as Senior Engineer with Environmental Science and Engineering, he has extensive experience in power plant permits, contracts, and environmental compliance. As Legislative Affairs Manager with Energizer Power Systems, he represented EPS before legislatures, regulatory agencies, and private organizations. He served as Legislative Committee Chair for the Portable Rechargeable Battery Association, the national trade association for the rechargeable product industry. He is currently the Director of Legislative and Regulatory Affairs for the Rechargeable Battery Recycling Corporation. He routinely practices before state and provincial legislatures and regulatory agencies in the US and Canada, and on Capitol Hill.

Messrs. Bagby and Guyer were principal drafters and lobbyists for *The Mercury Containing and Rechargeable Battery Management Act (PL 104-142)*, one of only two federal environmental bills signed into law in 1996.

[3] Retailer participation for collection of some types of products may be different than found in the RBRC program. For example, the national program for collection of used mercury thermostats operated by the Mercury Thermostat Recycling Corporation (modeled on RBRC) uses electric equipment wholesalers as the point of "retail" collection. Contractors installing new mercury thermostats are asked to return the used thermostats to the electric wholesaler, where they are then packaged and shipped to recycling. The thermostat installation contractor is the "consumer" and the electric wholesaler is the "retailer."

1.7 Hugh Morrow

International Cadmium Association, Worldwide Cadmium Recycling

Worldwide Cadmium Recycling

Hugh Morrow
International Cadmium Association

SOURCES OF CADMIUM EXPOSURE

- NATURAL
- ANTHROPOGENIC

Production, Use & Disposal of
  - Cadmium Products
  - Products Containing Cadmium as an Impurity

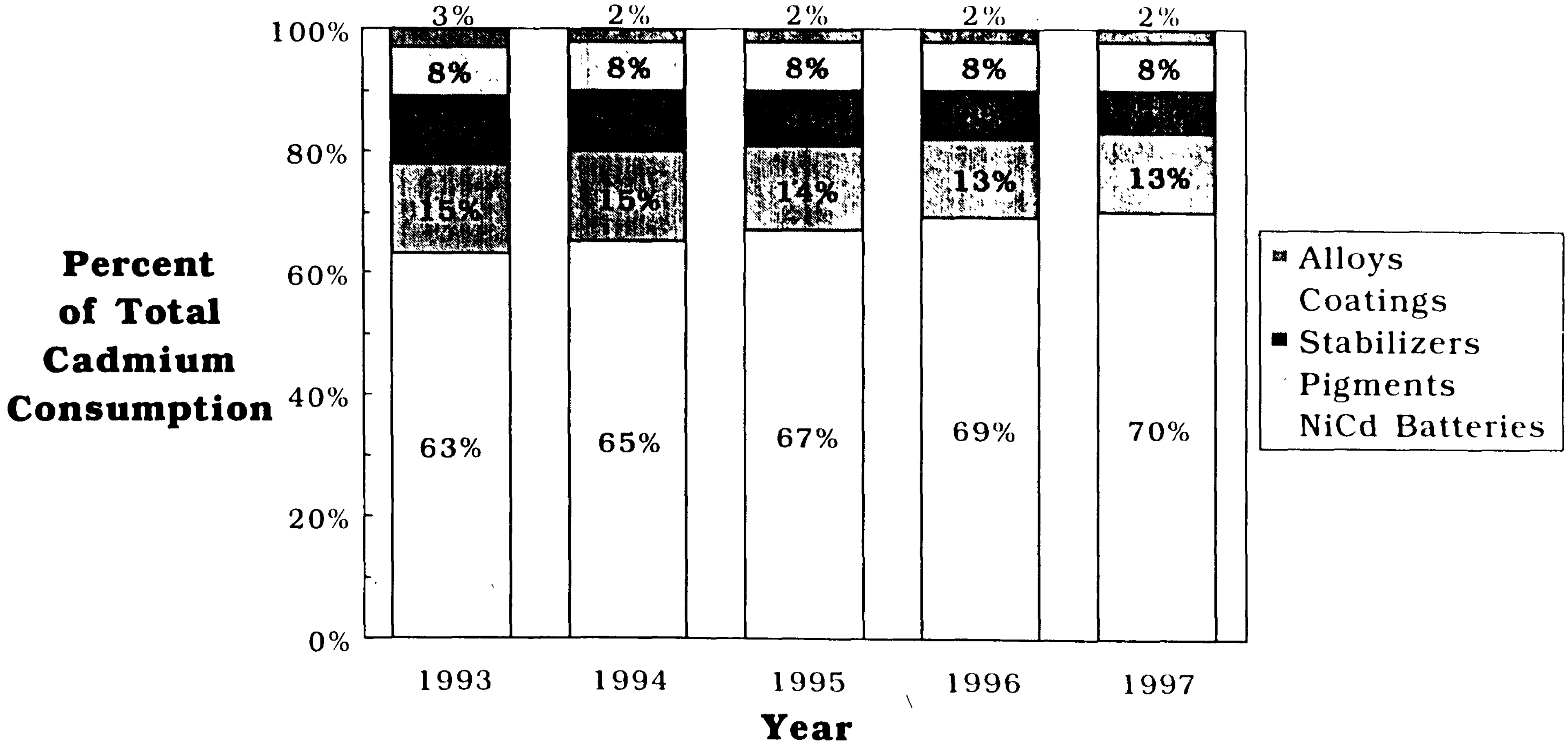
PRODUCTS WITH CADMIUM IMPURITIES

- **Nonferrous Metals**
  - **Zinc, Lead & Copper**
- **Ferrous Metals**
  - **Iron & Steel**
- **Fossil Fuels**
  - **Coal, Oil, Peat, Wood**
- **Fertilizers**
  - **Phosphates, Sewage Sludge & Composts**
- **Cement**

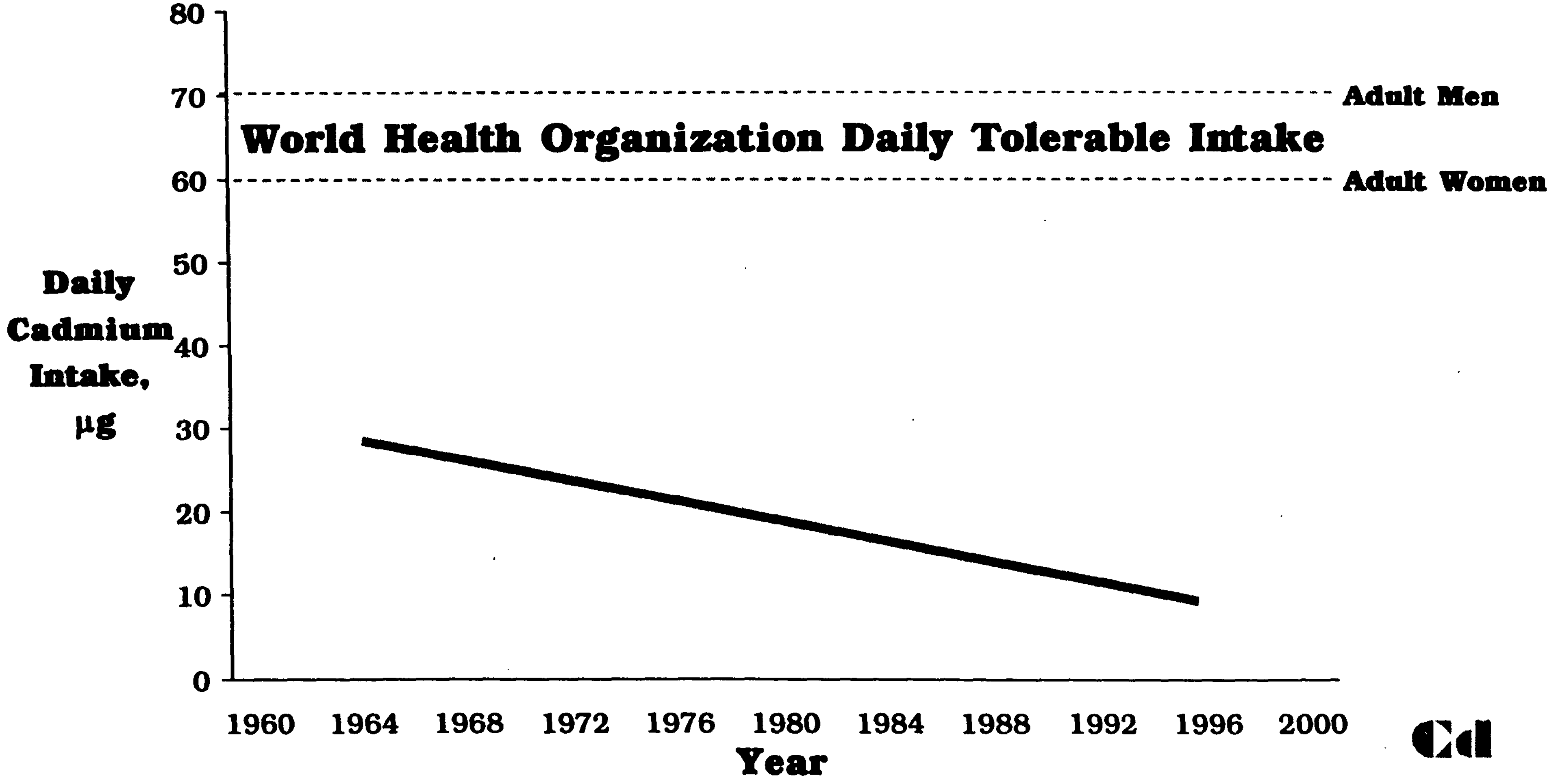
CADMIUM PRODUCTS

Product	% Cd	% of Market
NiCd Batteries	10-30	70
Cadmium Pigments	≈1	13
Cadmium Stabilizers	≈ 1	7
Cadmium Coatings	≈ 0.2	8
Cadmium in Alloys	1-20	2

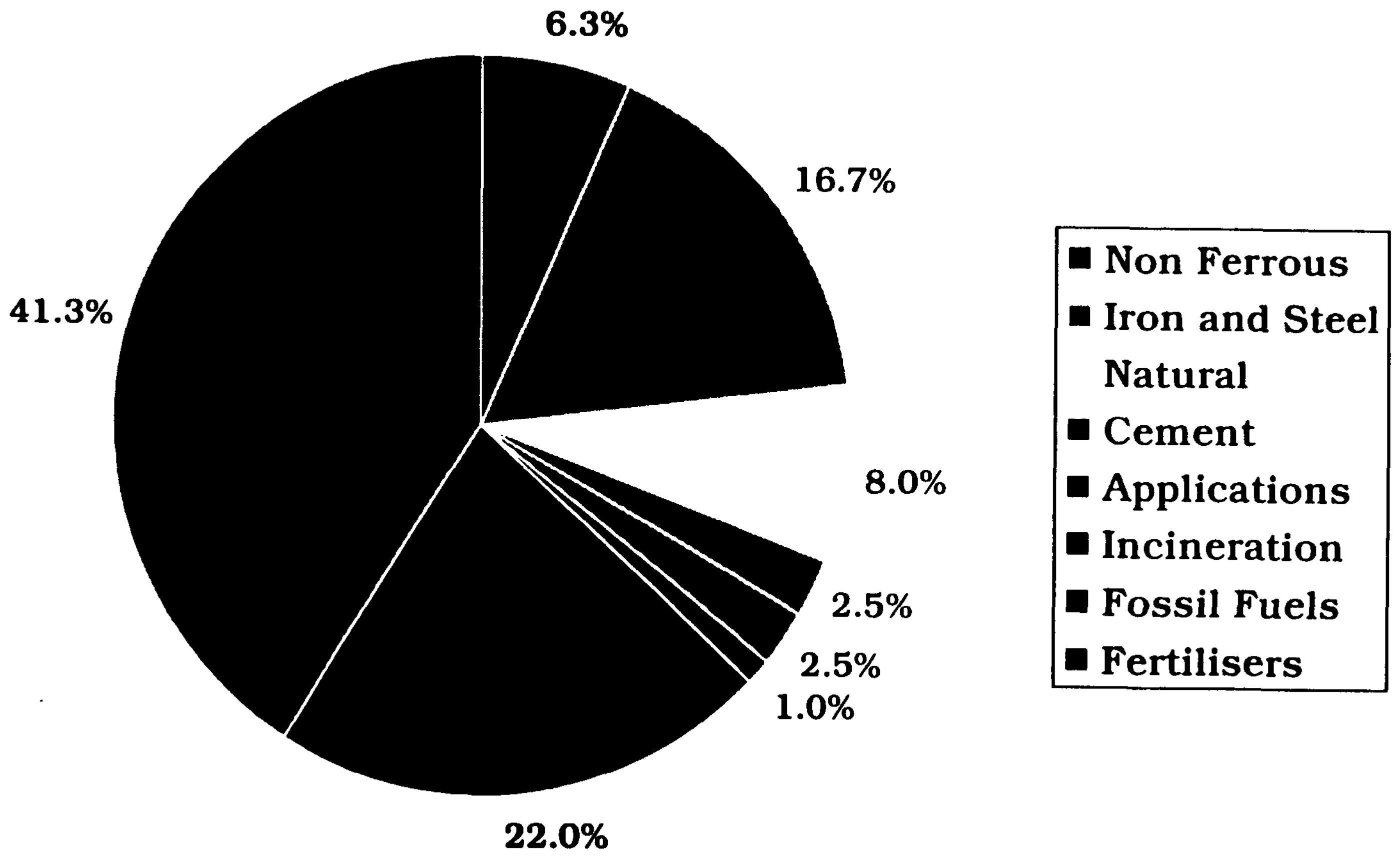
CADMIUM CONSUMPTION PATTERNS



DAILY CADMIUM INTAKE FOR GENERAL POPULATION



SOURCES OF HUMAN CADMIUM EXPOSURE

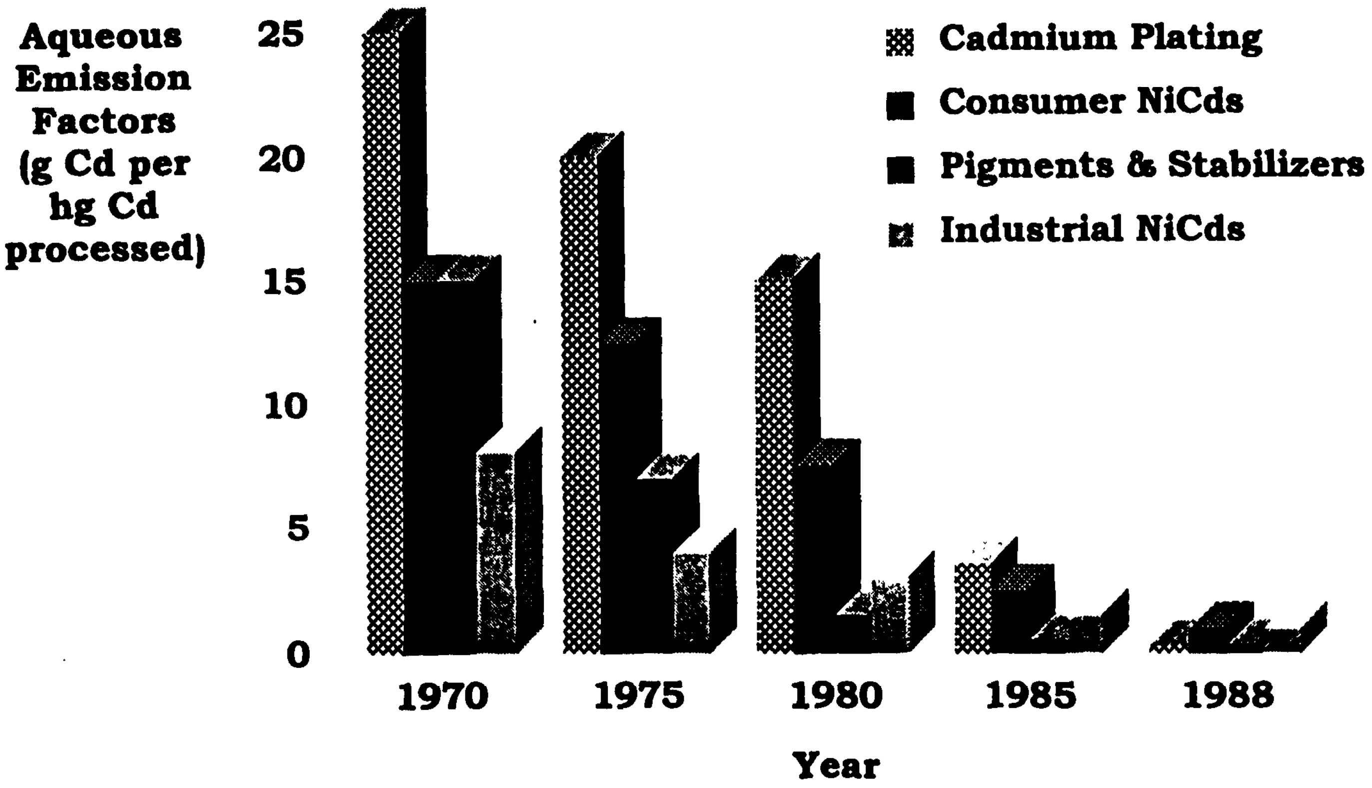


PARTITIONING OF CADMIUM IN PRODUCT MANUFACTURING

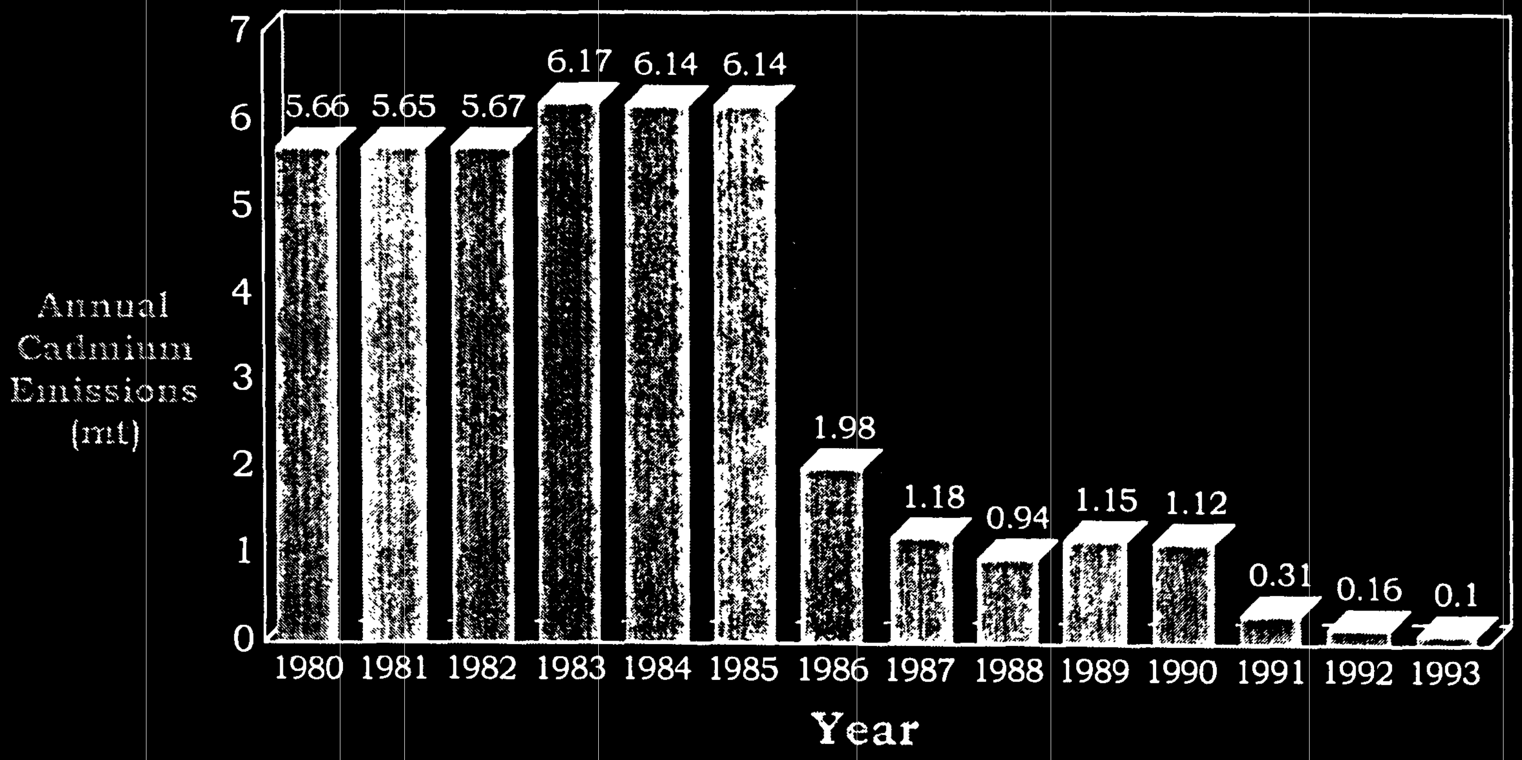
	Percent of Total Cadmium			
Product	**Air**	**Water**	**Soil**	**Product**
NiCd Batteries				
Industrial	0.01–0.10*	0.03–0.15*	0.50–2.75*	97.00*–99.46
Consumer	0.00*–0.01	0.03–0.05*	0.50–2.45*	97.50*–99.46
Pigments	0.05*	0.20*	2.25*	97.50*
Stabilizers	0.01*	0.20*	2.04*	97.75*
Coatings	0.00	0.02–1.25*	0.08–3.75*	95.00*–99.90
Alloys	0.50*	0.00*	0.00*	99.50*

*Stockholm Environmental Institute (1994)
Other Data: OECD Monograph on Cadmium & ICdA Estimates

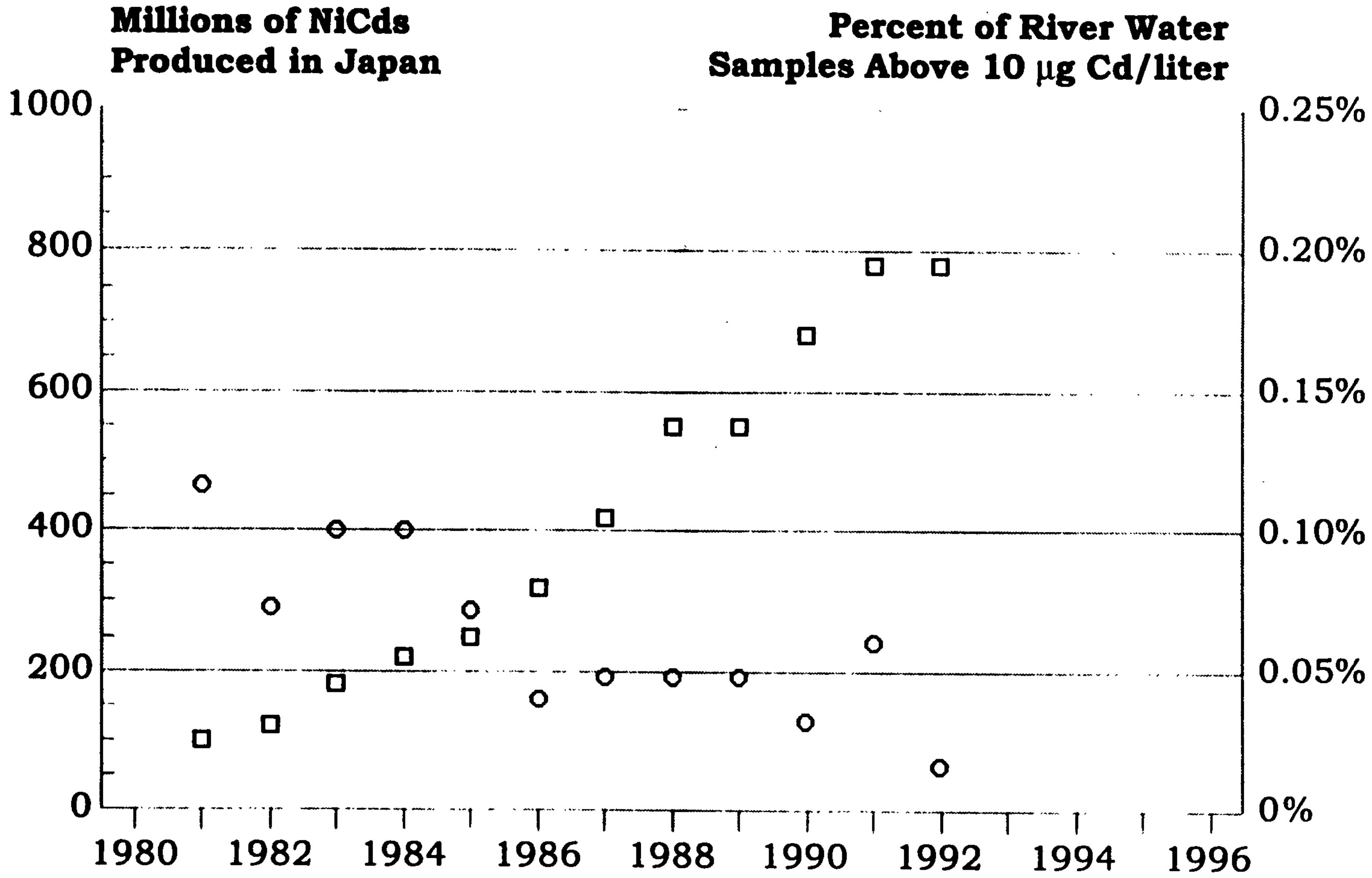
Aqueous Emission Factors
Rhine River Basin: 1970 - 1990



ANNUAL EMISSIONS OF CADMIUM TO GREATER MONTREAL SEWER SYSTEM

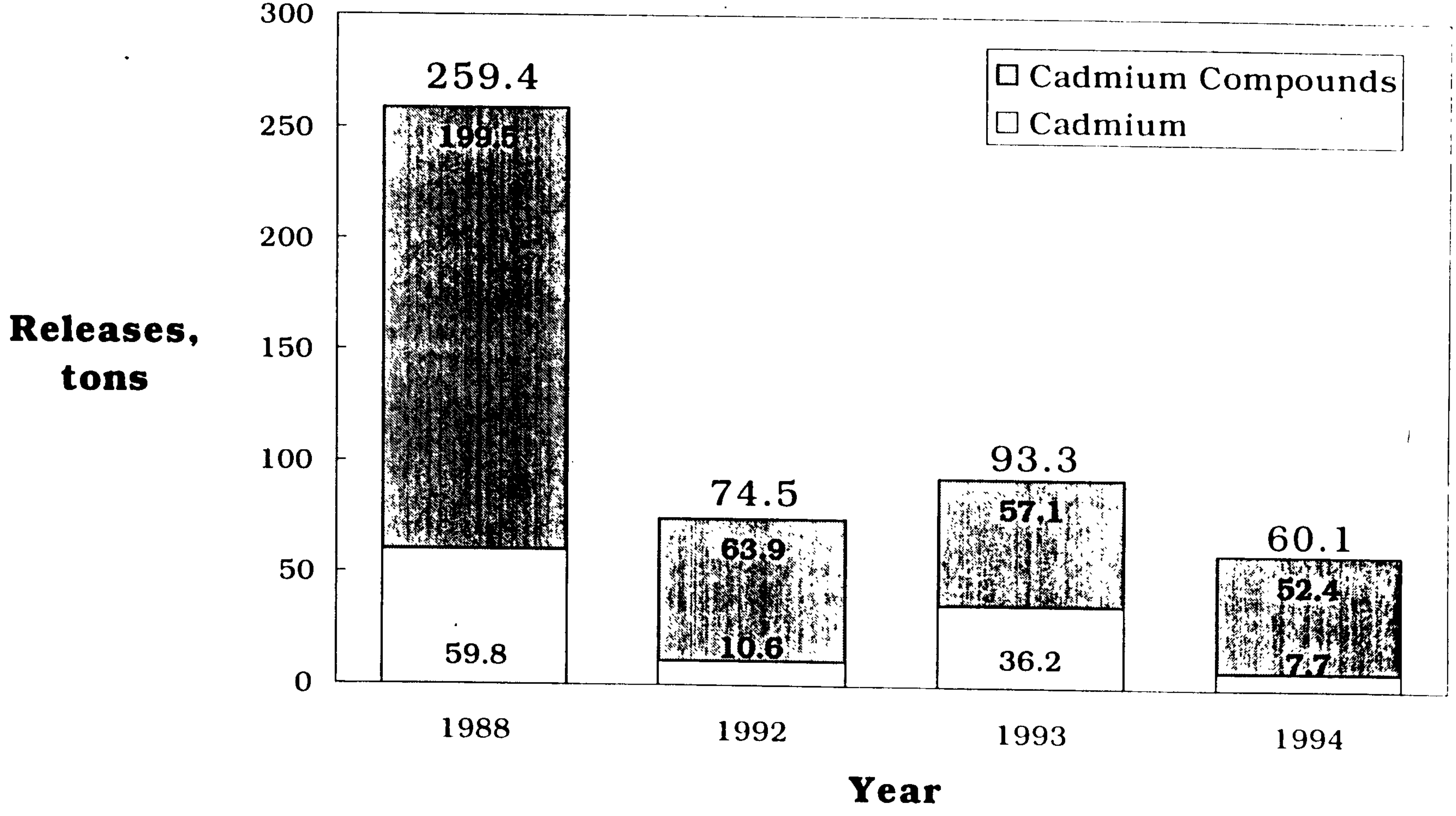


Source: Environment Canada (1996)


Millions of NiCds
Produced in Japan
Percent of River Water
Samples Above 10 µg Cd/liter
1000
800
600
400
200
0
0.25%
0.20%
0.15%
0.10%
0.05%
0%
1980
1982
1984
1986
1988
1990
1992
1994
1996
Year

Source: JSBA

USA CADMIUM TOXIC RELEASE INVENTORY



USE OF CADMIUM PRODUCTS

Product	**Life (yrs)**	**Dissipation (% per year)**	**Recycling (%)**
NiCd Batteries			
- Industrial	25	0.01(0.00)	50(85)
- Consumer	5	0.01(0.00)	4(15)
Pigments	10	0.01	0(0)
Stabilizers	25	0.01	0(0)
Coatings	10(20)	2.00(1.00)	35(50)
Alloys	15	1.00	35(35)

Source: Stockholm Environmental Institute (1994)
Figures in Parentheses are ICdA Estimates

NiCd BATTERY DISPOSAL

- INCINERATION (WORST)
- COMPOSTING (NOT USED)
- LANDFILL (BETTER)
- RECYCLING (BEST)

RECYCLED CADMIUM PRODUCTS

- **NiCd BATTERIES**
  - **Industrial, Consumer, Waste**
- **CADMIUM COATINGS**
  - **Sludges, EAF Dust, Anodes**
- **CADMIUM ALLOYS**
- **CdTe SOLAR CELLS**

RECYCLING PROCESSES

- PYROMETALLURGICAL
  - Distillation/Condensation
  - Distillation/Oxidation
- HYDROMETALLURGICAL
  - Chemical
  - Electrochemical

CADMIUM RECYCLING PLANTS

- **Dedicated NiCd Recyclers**
  - SNAM, SAFT, Kansai Catalyst, Japan Recycling Center
- **Stainless Steel Recycler**
  - INMETCO
- **Zinc Refineries**
  - Toho Zinc, Mitsui Mining & Smelting
- **Nonferrous Metals Recyclers**
  - TNO, Esdex, Hydrometal, Uniniquel, Drinkard Metalox

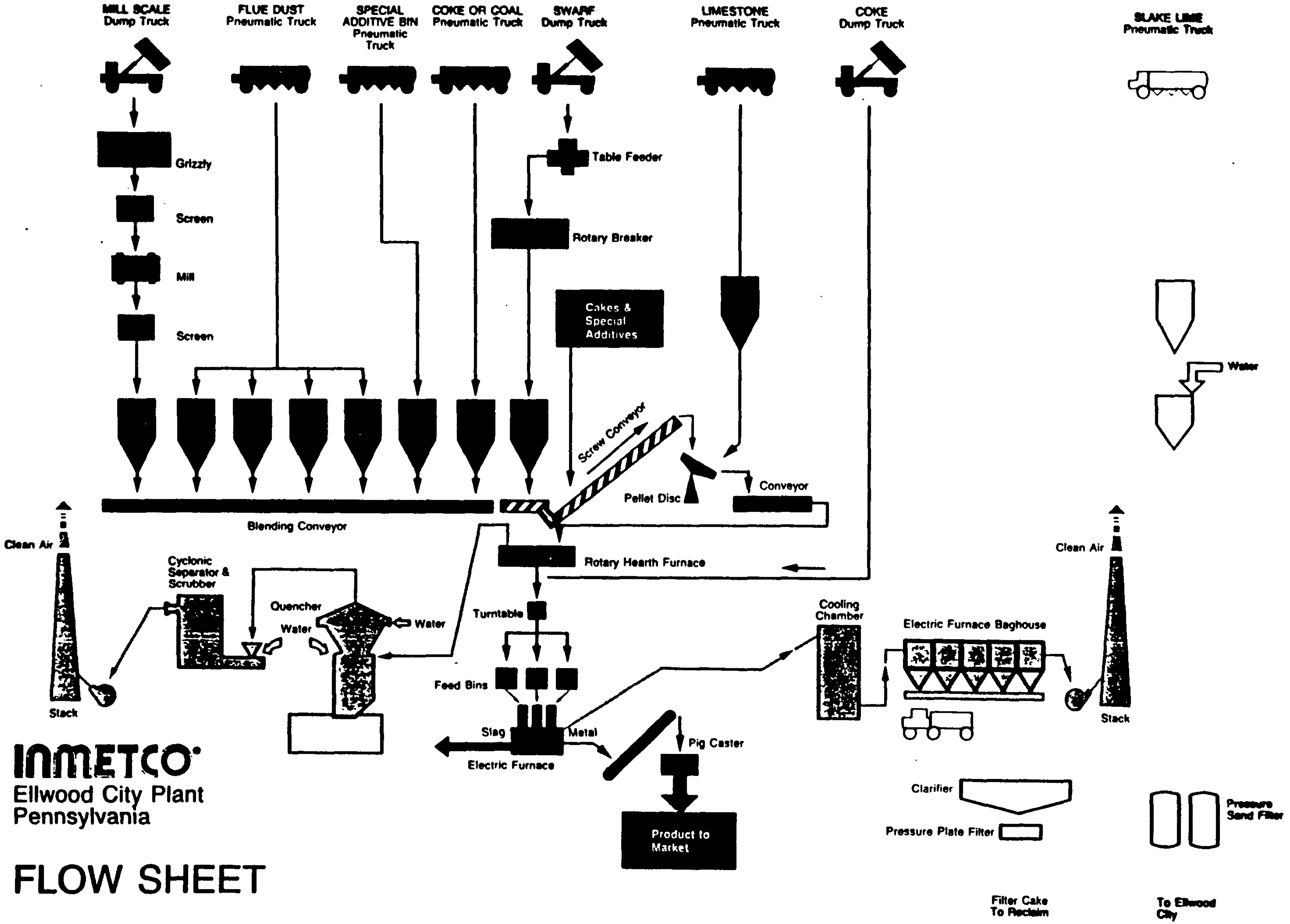
World's Major Cadmium Recycling Plants

Company	**Location**	**Type**	**Capacity (mt)**
INMETCO	USA	Stainless Steel	3,000
Japan Recycle Center	Japan/Korea	Dedicated NiCd Facility	3,000
Mitsui Mining & Smelting	Japan	Zinc Refinery	1,800
Toho Zinc Co., Ltd.	Japan	Zinc Refinery	1,700
Kansai Catalyst	Japan	Dedicated NiCd Facility	500
Hydrometal S.A.	Belgium	Hydrometallurgical	1,300
SAFT	Sweden	Dedicated NiCd Facility	1,500
SNAM	France	Dedicated NiCd Facility	5,400
TNO/Esdex/Leto	Netherlands	Hydrometallurgical	200
Uniniquel, S.A.	Spain	Hydrometallurgical	2,400*

* Planned Capacity

CADMIUM WASTES RECYCLED AT INMETCO

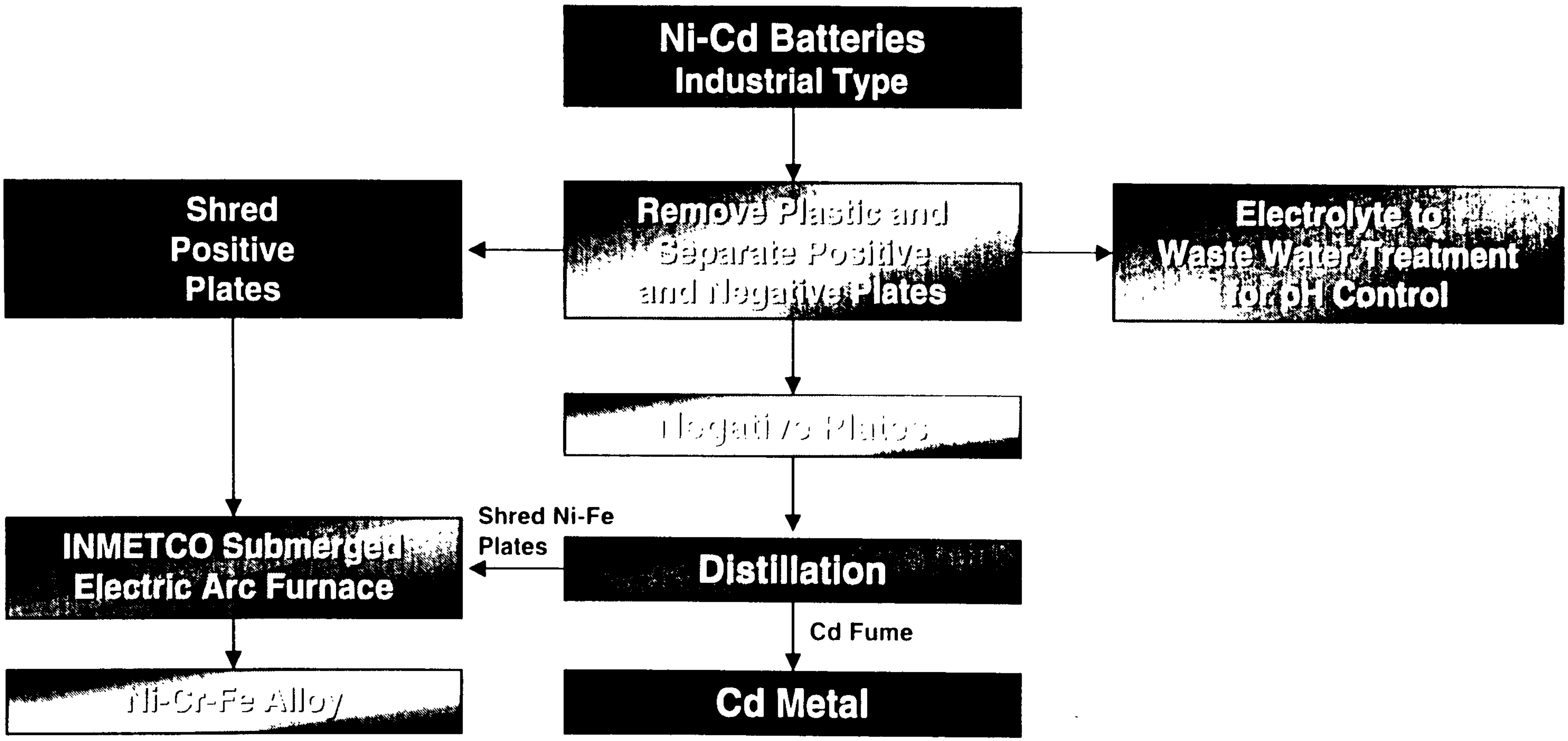
- K061 - EAF Dust
- F006 - Plating Sludges
- D006 - Cadmium Wastes
  - Wastewater
  - Non-wastewater
  - NiCd Batteries



INMETCO®
Ellwood City Plant
Pennsylvania

FLOW SHEET

INMETCO - INDUSTRIAL NiCds



Ni-Cd Batteries Industrial Type

Remove Plastic and Separate Positive and Negative Plates

Electrolyte to Waste Water Treatment for pH Control

Shred Positive Plates

Negative Plates

Distillation

Shred Ni-Fe Plates

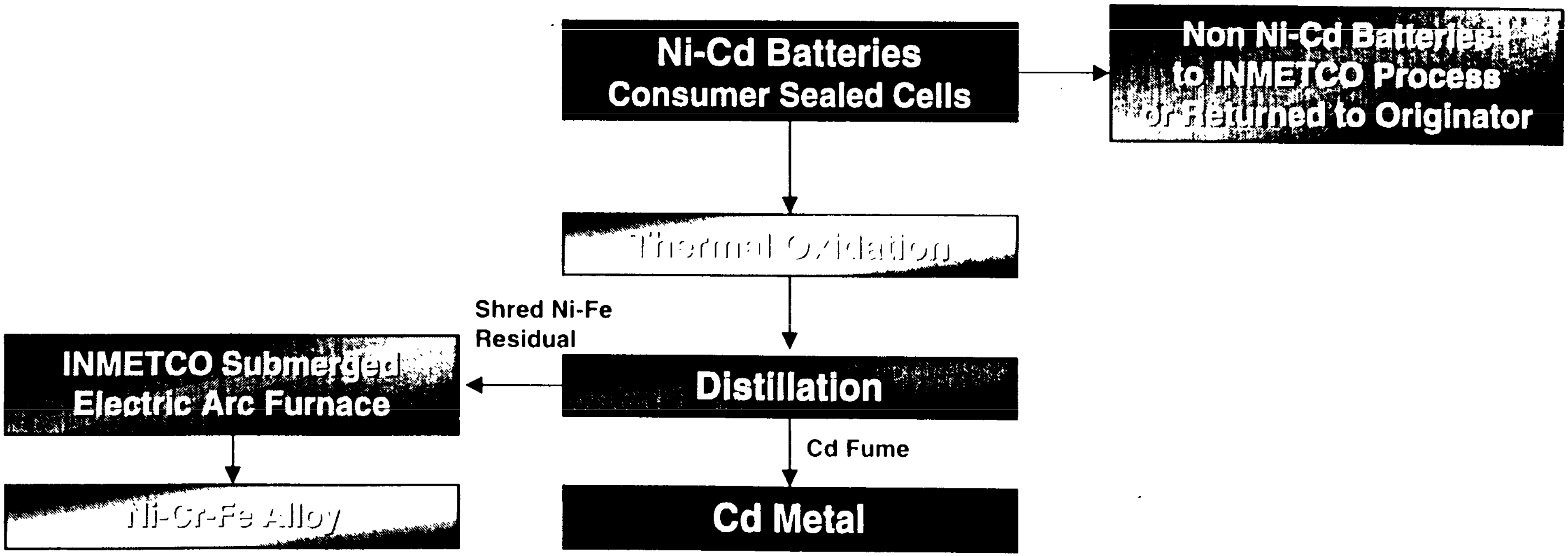
Cd Fume

Cd Metal

INMETCO Submerged Electric Arc Furnace

Ni-Cr-Fe Alloy

INMETCO - CONSUMER NiCds



Ni-Cd Batteries
Consumer Sealed Cells

Non Ni-Cd Batteries
to INMETCO Process
or Returned to Originator

Thermal Oxidation

Distillation

Cd Fume

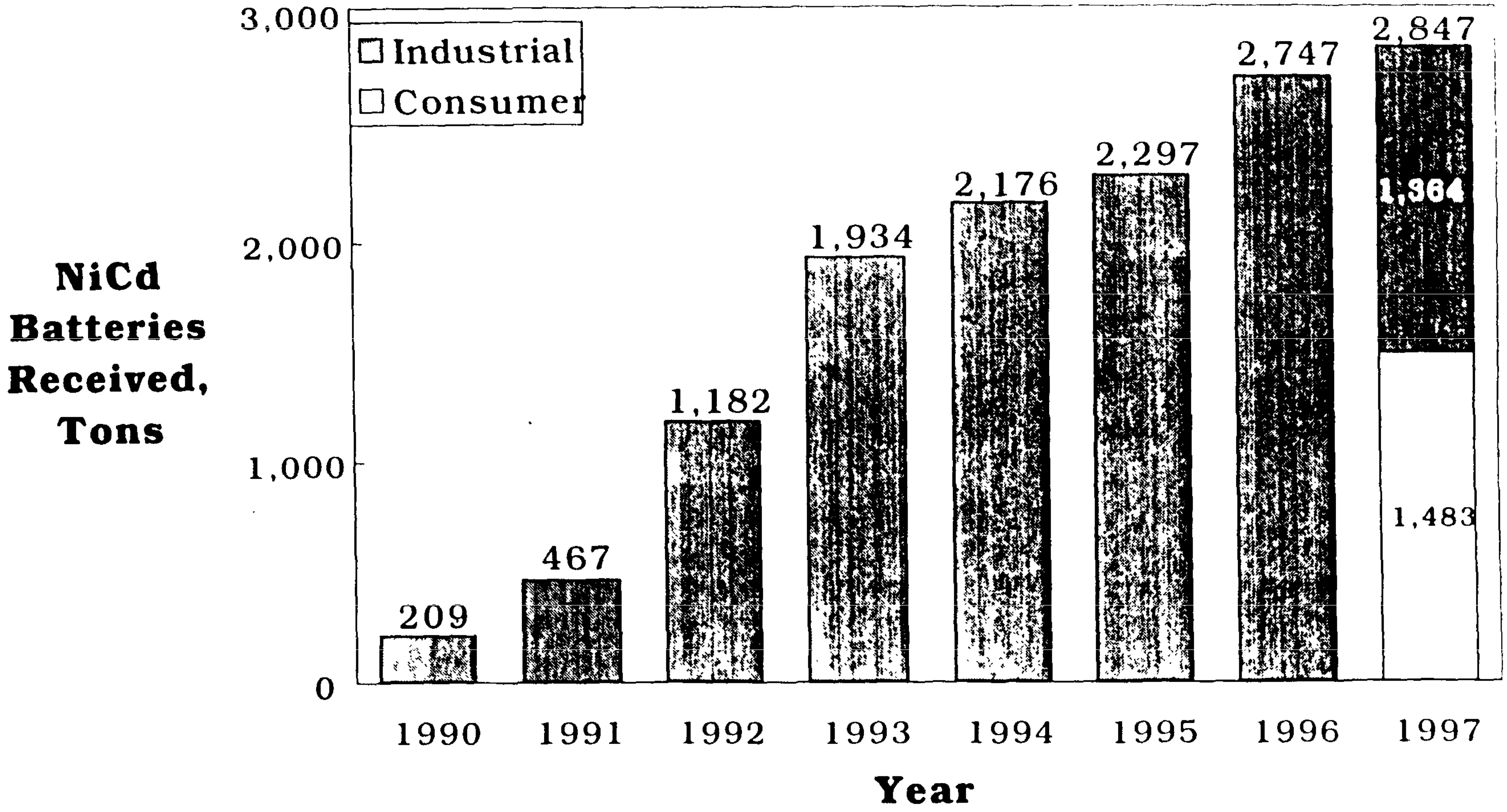
Cd Metal

Shred Ni-Fe
Residual

INMETCO Submerged
Electric Arc Furnace

Ni-Cr-Fe Alloy

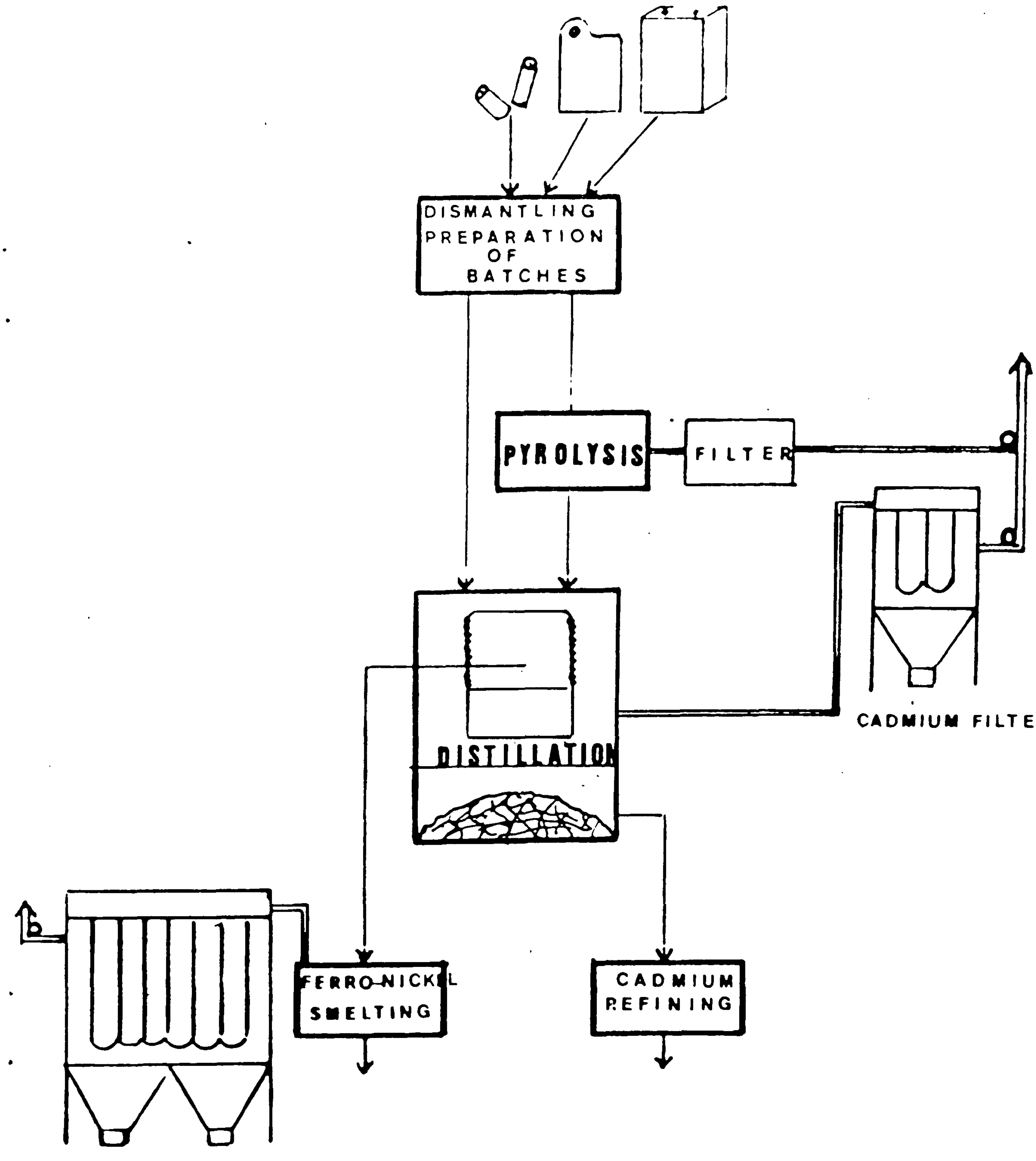
INMETCO - USA


NiCd Batteries Received, Tons
3,000
2,000
1,000
0
☐ Industrial
☐ Consumer
209
467
1,182
1,934
2,176
2,297
2,747
2,847
1,364
1,483
1990
1991
1992
1993
1994
1995
1996
1997
Year

Ni/Cr FILTER CAKES RECYCLED AT INMETCO

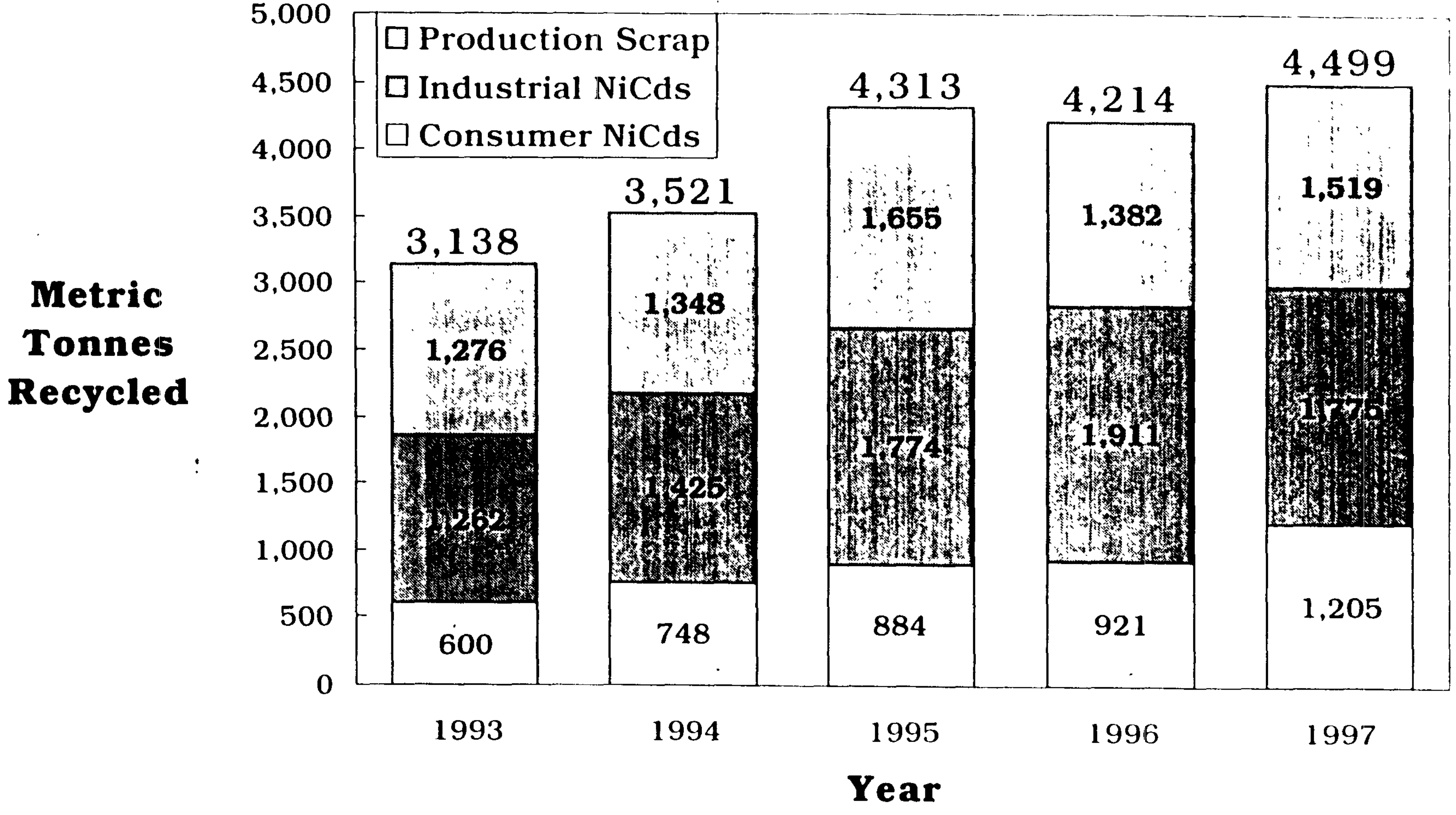
Client #	Cd	Mo	Pb	Zn	Cu	MgO	Ni	Co
1	0.03	0.12	0.04	0.02	0.11	0.50	2.29	0.08
2	0.07	0.22	0.10	0.16	0.33	7.12	4.66	0.16
3	0.07	0.35	0.19	0.50	0.44	2.02	3.74	0.37

Source: R.H. Hanewald, M.E. Schweers, J.C. Onuska, "Recycling Metal Bearing Wastes Through Pyrometallurgical Technology"

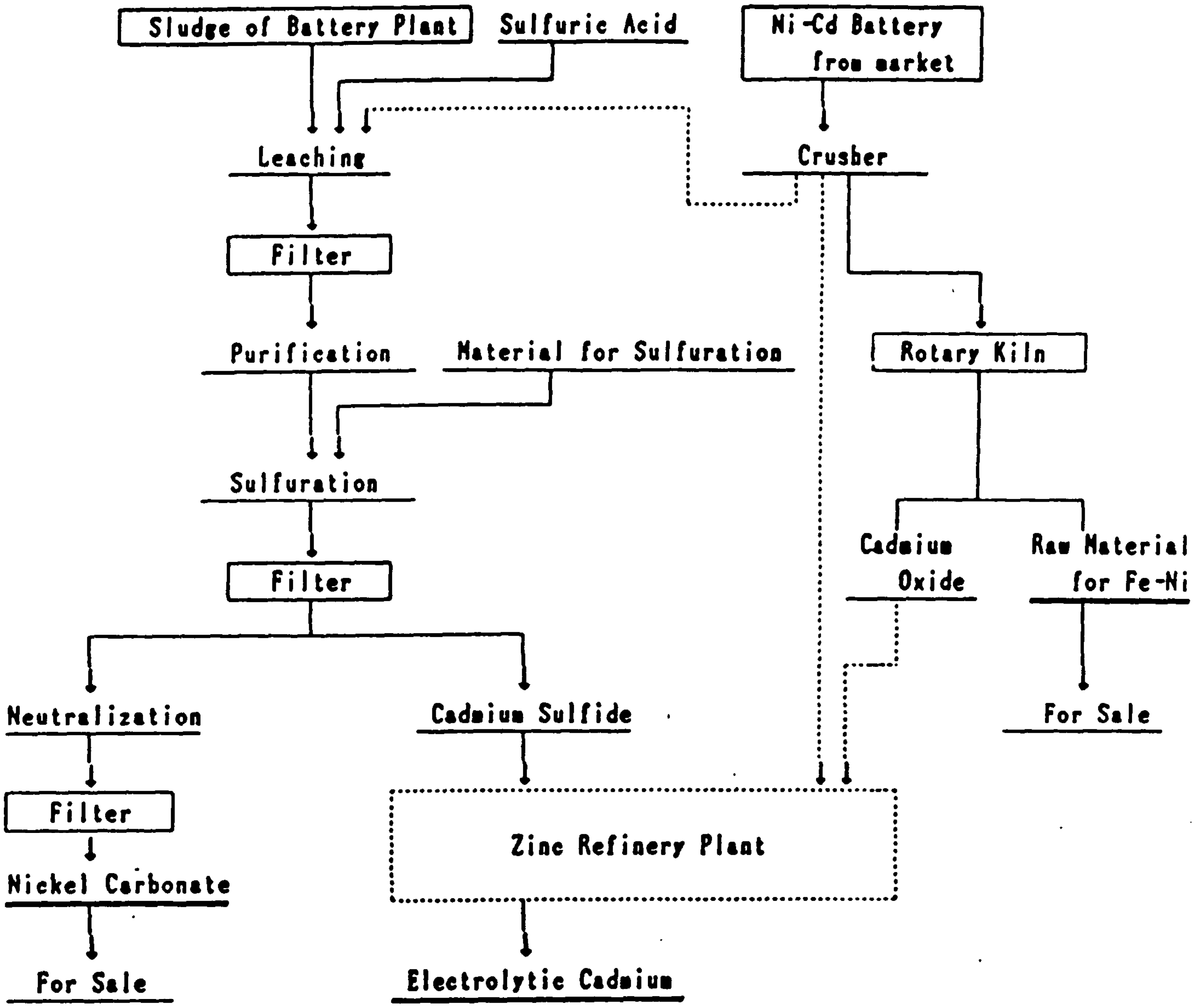

DISMANTLING PREPARATION OF BATCHES
PYROLYSIS
FILTER
CADMIUM FILTER
DISTILLATION
FERRO-NICKEL SMELTING
CADMIUM REFINING
NICKEL FILTER

SNAM

S.N.A.M. - FRANCE

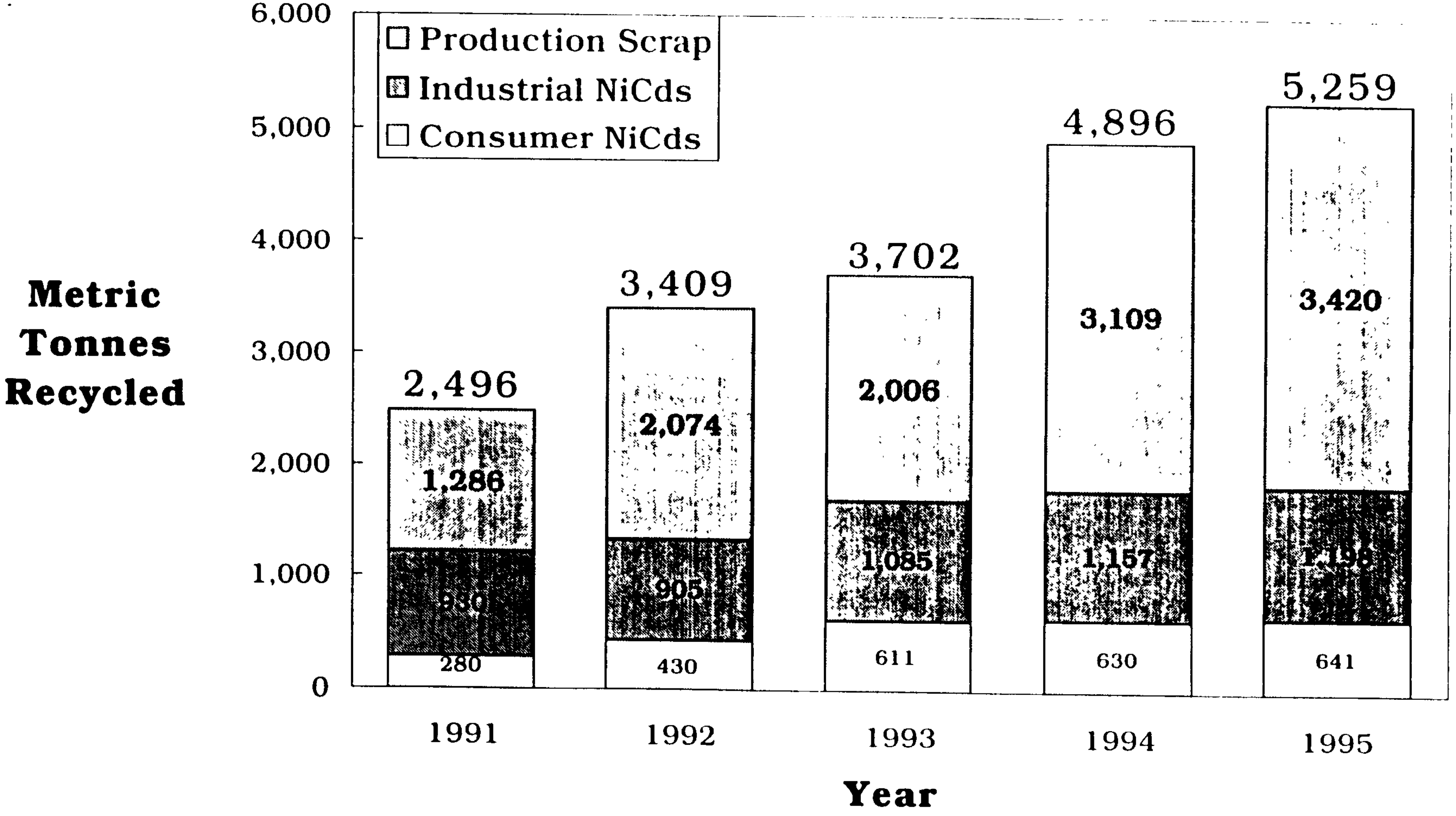


☐ Production Scrap
☐ Industrial NiCds
☐ Consumer NiCds
Metric Tonnes Recycled
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
3,138
1,276
1,262
600
3,521
1,348
1,425
748
4,313
1,655
1,774
884
4,214
1,382
1,911
921
4,499
1,519
1,775
1,205
1993
1994
1995
1996
1997
Year


Sludge of Battery Plant
Sulfuric Acid
Ni-Cd Battery from market
Leaching
Crusher
Filter
Purification
Material for Sulfuration
Rotary Kiln
Sulfuration
Cadmium Oxide
Raw Material for Fe-Ni
Filter
Neutralization
Cadmium Sulfide
For Sale
Filter
Zinc Refinery Plant
Nickel Carbonate
For Sale
Electrolytic Cadmium

TOHO ZINC

JAPAN


Metric Tonnes Recycled
6,000
5,000
4,000
3,000
2,000
1,000
0
☐ Production Scrap
▨ Industrial NiCds
☐ Consumer NiCds
2,496
1,286
930
280
3,409
2,074
905
430
3,702
2,006
1,085
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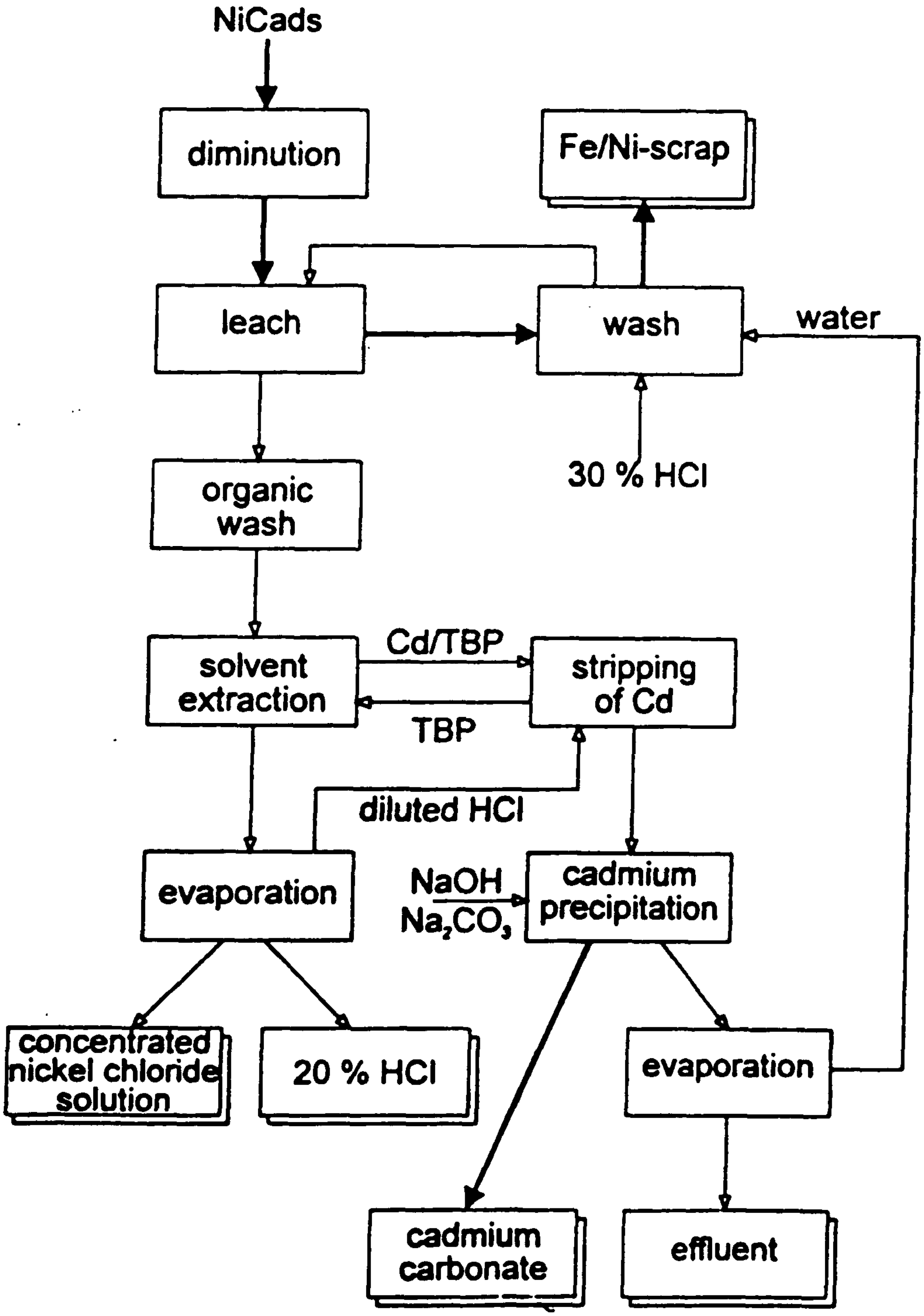
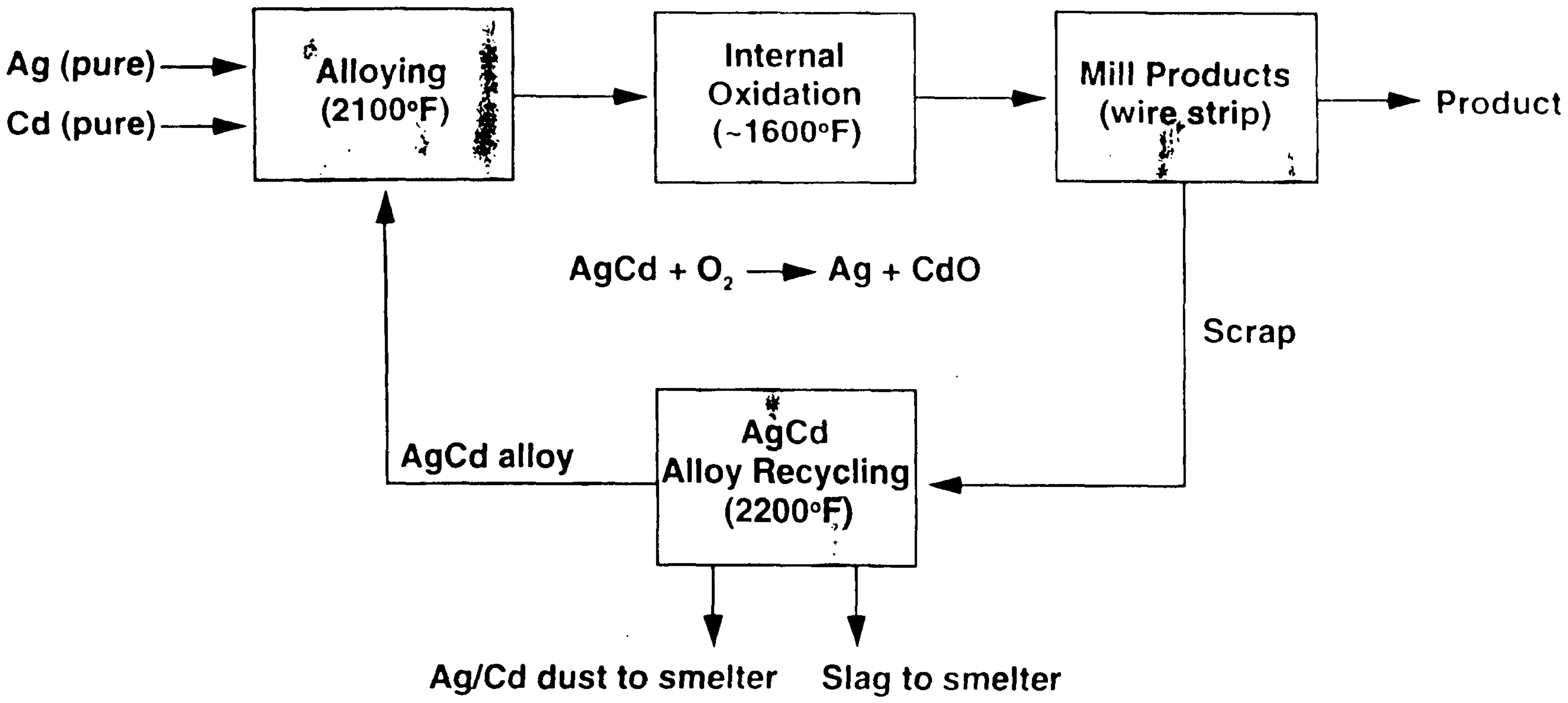
630
5,259
3,420
1,198
641
1991
1992
1993
1994
1995
Year



TNO/ESDEX/LETO

HANDY & HARMAN



Ag (pure)

Cd (pure)

Alloying (2100°F)

Internal Oxidation (~1600°F)

Mill Products (wire strip)

Product

$AgCd + O_2 \longrightarrow Ag + CdO$

Scrap

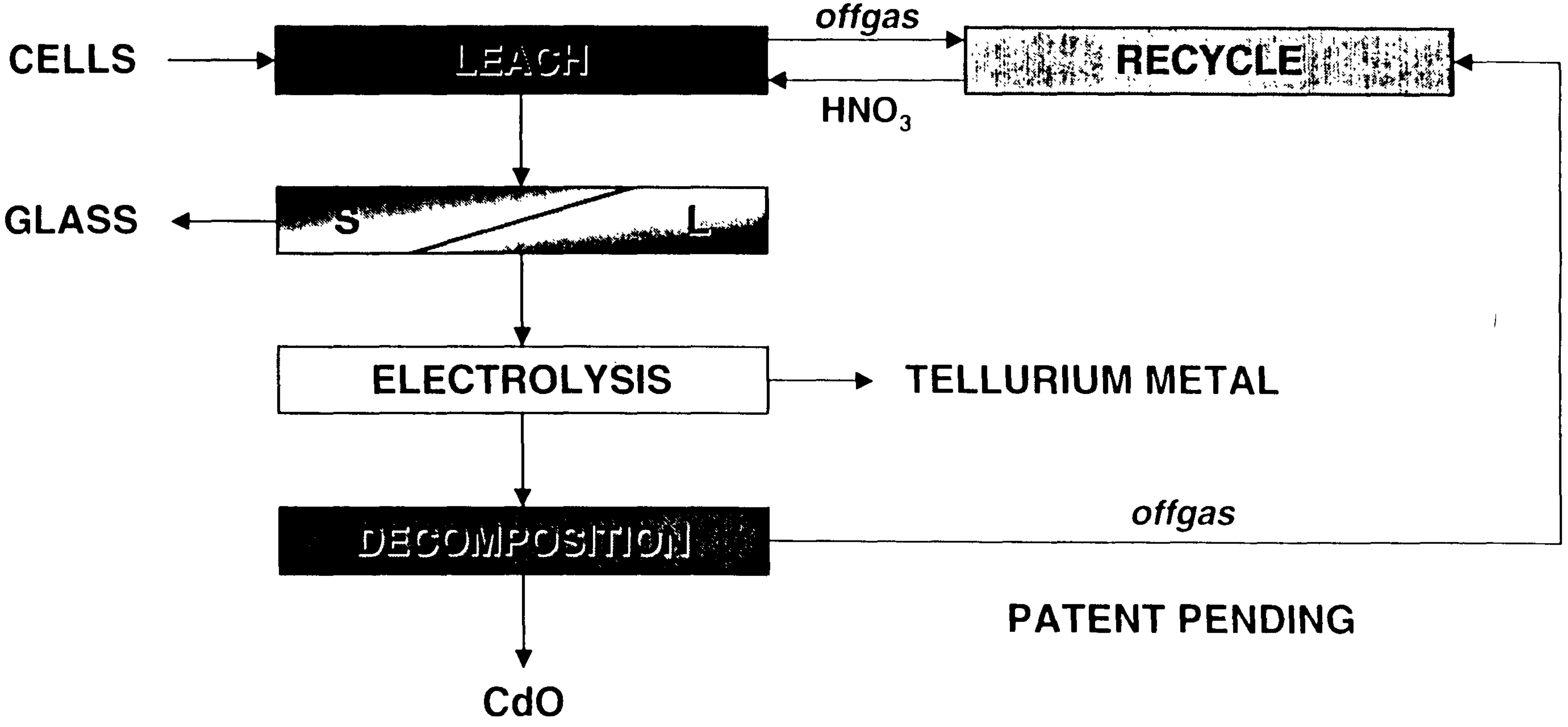
AgCd alloy

AgCd Alloy Recycling (2200°F)

Ag/Cd dust to smelter

Slag to smelter

DRINKARD METALOX



CELLS

LEACH

offgas

RECYCLE

HNO_3

GLASS

S

L

ELECTROLYSIS

TELLURIUM METAL

DECOMPOSITION

offgas

CdO

PATENT PENDING

ECONOMIC FACTORS

- Volume, Economies of Scale
- Scope of Collection Program
- Nature of Metal Recovery Process
- Current Metal Prices
- Collection Funding Mechanism
- Regulatory Restraints to NiCd Collection, Storage, & Transport

EASING REGULATORY RESTRAINTS

- 40 CFR, Part 273
  "Universal Waste Rule"
- Public Law 104-142
  "Rechargeable Battery Management Act"
- OSHA SECALs for Cadmium Recycling

COLLECTION OPPORTUNITIES

- Reverse Original Equipment Manufacturers (OEMs)
- Retail Outlets
- Institutional Generators
- Municipal Collection Programs
- Battery Manufacturers' Programs
- Government & Military Users

CADMIUM RECYCLING RATES

• **NiCd Batteries**			
	Type:	**Industrial**	**85%**
		Consumer	**15%**
	Area:	**USA**	**23%**
		Japan	**20%**
		Europe	**5 - 50%**
• **Coatings**			**35 - 70%**
• **Alloys**			**35%**

CONCLUSIONS

- Low Human Cadmium Exposure
- Cadmium Products Small Source
- Decreased Cadmium Emissions
- NiCds, Coatings, CdTe Solar Cells Cadmium Alloys Recycled
- Economics & Regulations Reform Needed to Encourage Recycling
- Recycling Rates – 5% to 85%

2.1 Eric Alsema

CO_2 and Energy Payback of PV

Energy Requirements and CO_2 Mitigation Potential of PV Systems[*]

E.A. Alsema
Dept. of Science, Technology and Society,
Utrecht University, The Netherlands

ABSTRACT: In this paper we investigate the energy requirements of PV modules and systems and calculate the Energy Pay-Back Time for two major PV applications. Based on a review of past energy analysis studies we explain the main sources of differences and establish a "best estimate" for key system components. For present-day c-Si modules the main source of uncertainty is the preparation of silicon feedstock from semiconductor industry scrap. The best estimates of 4200 respectively 6000 MJ (primary energy) per m^2 module area are probably representative for near-future, frameless mc-Si and sc-Si modules. For a-Si thin film modules we estimate energy requirements at 1200 MJ/m^2 for present technology. Present-day and future energy requirements have also been estimated for the BOS in grid-connected roof-top systems and for Solar Home Systems. The Energy Pay-Back Time of present-day grid-connected systems is estimated at 3-8 years (under 1700 kWh/m^2 irradiation) and 1-2 years for future systems. The specific CO_2 emission of these systems is 60-150 g/kWh now and 20-30 g/kWh in the future. In Solar Home Systems the battery is the cause for a relatively high EPBT of more than 7 years, with little prospects for future improvements. The CO_2 emision is now estimated at 250-400 g/kWh and around 200 g/kWh in the future. This leads to the conclusion that PV systems, especially grid-connected systems, can contribute significantly to the mitigation of CO_2 emissions.

1. INTRODUCTION

The energy pay-back time or the energy requirement of PV systems has always been an issue receiving a great deal of public attention. Rightly so, because the energy requirement is a very good indicator of the net potential for CO_2 mitigation. The latter constitutes on its turn an important political motivation for PV technology development.

My objective in this paper is to review existing knowledge on energy requirements for manufacturing PV systems and give some example calculations for the energy pay-back time and the CO_2 emissions.

Over the past decade a number of studies on energy requirements of PV modules or systems have been published, among others by the author of this paper [1-12]. I have reviewed and compared these studies and tried to establish on which data there is more or less consensus and how observed differences may be explained. Based on this review of available data I have established a 'best estimate' of the energy requirement of crystalline silicon modules, thin film modules and BOS components.

Also I will show calculations of the Energy Pay-Back Time and CO_2 emissions for two representative PV system applications, namely a grid-connected rooftop system and a Solar Home System.

Throughout this paper I will present energy data as Equivalent Primary Energy requirements, that is the amount of primary (or fuel) energy necessary to produce the component. So all electrical energy input is converted into primary energy requirements, with an assumed conversion efficiency of 35%. (So 1 MJ of primary energy can supply 0.097 kWh of electrical energy.)

I restrict my assessment to the *production* phase of components because energy demands in the utilization phase are generally negligible for PV systems, and because there is very little data on recycling or other treatments of decommissioned systems.

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[*] *Presented at the BNL/NREL Workshop "PV and the Environment 1998", Keystone, CO, USA, 23-24 July 1998.*

2. CRYSTALLINE SILICON MODULES

Present technology

Published estimates [1, 2, 4, 6, 9, 10, 12] for the energy requirement of present-day crystalline silicon modules vary considerably: between 2400 and 7600 MJ/m² for multicrystalline (mc-Si) technology and between 5300 and 16500 MJ/m² for single-crystalline (sc-Si) technology. Partly, these differences can be explained by different assumptions for process parameters like wafer thickness and wafering losses.

The most important source of differences, however, is the energy requirement estimation for the silicon feedstock used to produce PV wafers. Currently the majority of PV cells are made from off-spec silicon that is rejected by the micro-electronics industry. The first source of silicon for PV wafers is a fraction of the poly-silicon material that is produced by the silicon purification process but which has a slightly lower purity than the standard electronic grade material.

The second (and largest) source of PV feedstock are the tops and tails of Czochralsky ingots which are cut off before the ingots are being sawn into wafers. These Cz tops and tails are then remelted to produce ingots for PV wafers, with the result that the silicon in this PV ingot has in fact undergone *two* crystallization steps. We will call these the primary and the secondary crystallization steps.

In some past studies the energy consumption for the *primary* crystallization step was allocated equally to the PV wafers and the micro-electronics wafers. Because of the very high energy use in Czochralsky growing this can increase the estimate of the total energy requirement for the PV module dramatically. However, the Cz tops and tails are more or less a waste product with a much lower economic value than the wafers produced for the micro-electronics industry. For this reason I hold the opinion, and other analysts now agree on this [13], that full energy accounting of the primary (as well as the secondary) crystallization step gives much too pessimistic a result for silicon-based modules.

	mc-Si		sc-Si		
Process	low	high	low	high	unit
mg silicon production	450	500	500	500	MJ/m² module
silicon purification	1800	3800	1900	4100	MJ/m² module
crystallization & contouring #1	-	5350	-	5700	MJ/m² module
crystallization & contouring #2	750	750	2400	2400	MJ/m² module
Wafering	250	250	250	250	MJ/m² module
cell processing	600	600	600	600	MJ/m² module
module assembly	350	350	350	350	MJ/m² module
Total module (frameless)	4200	11600	6000	13900	MJ/m² module
Total module (frameless)	*35*	*96*	*47*	*109*	*MJ/Wp*

Table 1: Break-down of the energy requirements for c-Si module production with present-day technology (in MJ of primary energy). The *low* and *high* variants present different approaches with respect to silicon feedstock production.

On top of this "methodological uncertainty" there is considerable variation in the energy consumption estimates for both the silicon purification process (900-1700 MJ/kg) and for the Czochralsky process (500-2400 MJ/kg)[1], which may be real variations or due to assessment errors. Unfortunately I cannot clarify this further due to lack of reliable and detailed data.

To show the total effect of these two sources of uncertainty I will give here two estimates for silicon modules (table 1). The low estimate is based on the lower end value for silicon purification and does *not*

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[1] *Note that the table expresses all energy values in MJ per m² module area. Under our assumptions 2.0 -2.4 kg of poly-silicon feedstock is needed per m² module.*

consider the primary crystallization step, while the high estimate assumes the high end value for Si purification and includes 2400 MJ/kg for the primary crystallization step.
From the silicon scrap material which comes out of the primary crystallization process, the PV industry subsequently prepares a multi- or single-crystalline ingot, which can be sawn into wafers. Assumed were a 64% (mc-Si) resp. 60% (sc-Si) ingot yield, and for both technologies a 350 µm wafer thickness and a 60% wafering yield. Energy use in the secondary Cz step was assumed to be considerably lower (1100 MJ/kg) than in the primary Cz step, because of the smaller ingot size (6") and lower quality required for PV material.

Regarding the energy requirements for the remainder of the solar cell production process there is less controversy. Our best estimate is that about 600 MJ/m^2 is added in cell processing and some 350 MJ/m^2 during module assembly, assuming standard screen printing technology and glass/tedlar encapsulation. The main uncertainty in the energy data concerns the 400 MJ/m^2 estimate for overhead energy that is used for functions like lighting and climatization of the module production plant and for environmental control. Taking into consideration also the production yields of cell and module processing (95% resp. 97%) we obtain total energy requirements for c-Si modules in the 4200-13900 MJ/m2 range. Note that for the cell and module processing our assumptions are the same for all four variants of table 1. Finally, we can remark that only a few percent of this total energy requirement is used in a non-electrical form.

If we now assume encapsulated cell efficiencies of 14 resp. 15.5% and module packing factors of 0.87 resp. 0.82 for mc-Si and sc-Si modules (cf. table 2) we can evaluate the energy requirements on a Wp basis (last row of table 1). We see that despite their higher efficiency sc-Si modules are slightly in the disadvantage over mc-Si modules. This is mainly due to the higher energy consumption for the sc-Si crystallization process.

It is unsatisfactory to have such a large uncertainty in the energy estimates. However, as I have stated above, the high estimate gives in my view too pessimistic a result, because it *fully* includes the primary crystallization step. So the actual value in the present situation will be closer to the lower estimate than to the higher one.

Future technology
In the near future (1-2 years) the supply of off-spec silicon will quickly become insufficient to meet the demands from the PV industry so that other feedstock sources will have to be drawn on. Because standard electronic-grade silicon is to expensive for PV applications, dedicated silicon purification routes will be needed. For this reason too, the lower energy estimates of table 1 are probably most representative for near-future c-Si technology.

For a view on the longer-term potential (up to 2007) we have to look first at the major determinants for the energy requirement of c-Si modules.
Our analysis above shows that these determinants are: 1) the inclusion or not of the primary crystallization step, 2) the energy consumption for Si purification and 3) the silicon content of the cells. For sc-Si cells the Czochralsky process is also a large contributor.
So it will be clear that future improvements in wafer production technology may bring down the energy requirements of Si modules. Technologies like EFG or other methods which eliminate the losses from wafer sawing, could have significant advantages.
A major factor determining future energy requirements will be the way silicon feedstock is produced. The introduction of a solar-grade silicon process might reduce the energy content of silicon feedstock to 600-1100 MJ/kg [1, 6] and make the discussion about one or two crystallizations obsolete. Because of the latter fact the values for future Si technology may be less uncertain than those for present-day technology.

Based on a number of independently performed studies [2, 4, 6] I expect that future mc-Si production technology may achieve a reduction in energy requirements to around 2600 MJ/m², assuming innovations like a dedicated silicon feedstock production for PV applications (solar grade or advanced Siemens) delivering material with an energy requirement of about 1000 MJ/kg, and furthermore improved casting methods (e.g. electromagnetic casting) and reduced silicon requirements per m² wafer. This kind of technology will probably become available in the next ten years.
For single-crystalline silicon modules a total energy requirement around 3200 MJ/m² [4] may be achieved with similar technology improvements.
If we further make a conservative assumption for future cell efficiencies of 16% resp. 18% (cf. table 2) we obtain energy requirements per Wp of 18.8 resp. 21.6 MJ for future mc-Si and sc-Si technology.

	Present (1997)		Future (2007)	
	cell	module	cell	Module
mc-Si	14	12.1	16	13.8
sc-Si	15.5	12.7	18	14.8
thin film	n.a.	6	n.a.	9

Table 2: Assumptions for encapsulated cell and module efficiencies for different cell technologies

CO_2 emissions

Because more than 95% of the energy for Si module production is used as electricity the CO_2 emissions due to module production can be estimated rather quickly[2]. Assuming a CO_2-emission of 0.57 kg per kWh produced electricity[3] (0.055 kg/MJ_{prim}) we obtain specific CO_2-emissions of 1.9 kg/Wp for near-future mc-Si and 2.6 g/Wp for near-future sc-Si. For year 2007 technology our estimates are resp. 1.0 and 1.2 kg/Wp. In our system assessment below we will calculate the CO_2 emission per kWh of delivered energy.

3.THIN FILM MODULES

Present technology

Concerning thin film modules most published studies on energy requirements deal with amorphous silicon technology [1, 2, 6, 8, 10, 11] and two with electrodeposited CdTe modules [2, 7]. Although estimates for the total energy requirement of a frameless a-Si module range from 710 to 1980 MJ/m², many of the differences may be explained by the choice of substrates and/or encapsulation materials, and the consideration or not of the energy requirement for manufacturing the production equipment. A remaining factor of uncertainty, which cannot be explained so easily, is the overhead energy use for functions like lighting, climatization and environmental control (estimated range 80-800 MJ/m²).
On the basis of a careful comparison and analysis of published energy estimates [3] I come to the best estimate for energy requirements of an a-Si thin film module, as given in table 3.

From table 3 we can see that the semiconductor and contact materials constituting the actual solar cell contribute only very little to the module's energy requirement. Low deposition efficiencies (<10%) in combination with high purity requirements, however, may drive up this value.

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[2] *CO_2 emissions from the silica reduction process are also quite small, about 0.1 kg/Wp[14]*

[3] *This is an approximate value within the UCPTE region, i.e. continental W-Europe [15]. In this region about 50% of the electricity is produced by nucleair and hydro power plants.*

The materials used for the substrate and encapsulation constitute about 1/3 of the total energy input, assuming a glass/glass encapsulation. A polymer back cover will reduce the energy requirement with some 150 MJ/m². On the other hand, if not one of the glass sheets of the encapsulation is used as substrate, but an extra substrate layer is added, this will increase the energy requirement considerably (e.g. with 150 MJ/m² in case of stainless steel foil).

	Energy requirement (MJ/m² module)	Share (%)
cell material	50	4%
substrate + encapsulation material	350	29%
cell/module processing	400	33%
overhead operations	250	21%
equipment manufacturing	150	13%
Total module (frameless)	1200	100%
Total module (frameless)	*20 MJ/Wp*	

Table 3: Contributions to the energy requirement of an a-Si thin film module for present-day production technology (in MJ of primary energy).

The actual cell and module processing, comprising contact deposition, active layer deposition, laser scribing and lamination, contributes roughly another 1/3 to the module's energy requirement. Of course significant variations may be found here between different production plants depending on the deposition technology and the processing times.

For other thin film technologies most of the energy contributions will be about the same as for a-Si, except with regard to the processing energy. Electrodeposited CdTe, for example, is estimated to require some 200 MJ/m² less during processing. On the other hand a slightly higher overhead energy use is expected (for environmental control). Also, an polymer back cover would be less desirable for CdTe modules [2]. Although no energy studies for CIS were available we might expect the processing energy for co-deposited CIS modules to be in the same range or possibly higher than for a-Si.

Assuming a 6% module efficiency we obtain an estimated energy requirement of 20 MJ/Wp for an present-day thin film module, which is considerably lower than the values found for c-Si technology. However, as we will see below, high BOS energy requirements may completely cancel out this advantage.

Future technology

Because the encapsulation materials and the processing are the main contributors to the energy input, the prospects for future reduction of the energy requirement are less clearly identifiable as was the case with c-Si technology. A modest reduction, in the range of 10-20%, may be expected in the production of glass and other encapsulation materials. It is not clear whether displacement of the glass cover by a transparent polymer will lead to a lower energy requirement.

The trend towards thinner layers will probably reduce processing time which in turn can lead to a reduction in the processing energy and in the energy for equipment manufacturing. An increase of production scale can contribute to lower processing energy, lower equipment energy and lower overhead energy.

By these improvements I expect the energy requirement of thin film modules to decrease with some 30%, to 900 MJ/m², in the next ten years [cf. 2, 6]. If concurrently the module efficiency can be increased to 9%, the energy requirement on a Wp basis may reach the 10 MJ level.

CO_2 emissions

To estimate the specific CO_2 emission we can again apply the CO_2 emission factor of 0.055 kg/MJ[4], resulting in an emission of about 1.1 kg CO_2/Wp.

4. BALANCE-OF-SYSTEM COMPONENTS

Like in economic analyses of PV systems the Balance-of-System is cannot be neglected in energy analyses. Therefore we will shortly analyse the impacts of array supports, module frames[5] and batteries.
Recently, the results of a detailed analysis of the primary energy content of present applications of PV systems in buildings have been published [16]. This study has considered several applications on rooftops and building facades, as well as a large power plant.
Here I will restrict the BOS considerations to very simple assumptions for grid-connected roof-top systems. I will assume that per m² module area 3.5 kg of aluminium is used for the supports of present roof-top installations, requiring 500 MJ/m² of primary energy and causing an CO_2-equivalent emission of 26.5 kg/m². For future roof-top systems I assume a reduced aluminium use of 2.5 kg/m². The contribution from the inverter is small ([17], cf. table 4), and cabling is not considered here, but presumably it is small too.

It is worth noticing the significant contribution of module frames in present-day systems. Its wide range of energy content (300-770 MJ/m²) in past studies is due to large differences in the amount of aluminium used for the frames. Here I assumed 2.5 kg Al to be used per m² module, requiring 500 MJ of energy input. In any case, PV modules are expected to be frameless for all future applications.

	Unit	Present energy requirement	Future energy requirement
Module frame (Al)	MJ/m²	500	0
array support - roof integrated	MJ/m²	700	500
inverter (3 kW)	MJ/W	1	1
battery (lead-acid)	MJ/Wh	0.9	0.9

Table 4: Energy requirements for Balance-of-System components and module frames.

Batteries constitute a critical part of autonomous PV systems. Estimates for the energy requirement of lead-acid batteries found in the literature range between 25 and 50 MJ/kg [18-21]. The lower estimates, however, only include the energy requirements for the input materials but not the energy consumed during the battery manufacturing process. This process energy has been estimated at 9-16 MJ/kg [20, 21]. In most estimates the lead input is assumed to comprise a certain fraction of recycled lead (30-50%). Without this lead recycling energy requirements would be higher.
As the specific energy density of a lead-acid battery is about 40 Wh/kg we obtain an energy requirement per Wh of storage capacity in the range of 0.6-1.2 MJ (table 4). For my further analyses I will assume the mid-range value of 0.9 MJ/Wh. Furthermore I assume that within the next ten years no significant improvements in battery technology or battery energy requirements will occur. The CO_2 emission from the battery production I estimate at about 2.4 kg-CO_2 per kg battery which is equivalent to 0.06 kg per Wh capacity (adapted from [20]).

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[4] *Although thin film modules have lower share of electricity in the total energy requirement (70%), the remaining 30% is used in glass production, where by chance the CO_2 emission is the same 0.055 kg per MJ of used energy.*

[5] *For energy analysis it is convenient to consider the frames separate from the modules, as part of the BOS.*

5. ENERGY PAY-BACK TIME AND CO2 EMISSION OF PV SYSTEMS

Grid-connected systems

Figure 1 shows the energy pay-back time for two major PV system applications, namely grid-connected rooftop systems and stand-alone solar home systems. The assumptions taken into account for calculations are summarized in Table 5. Results are reported for multi-crystalline and amorphous silicon technologies. For the reasons explained earlier, the present values for mc-Si are further split into a low and a high case. The difference between the two cases is the most striking result as far as grid-connected systems are concerned.

	Unit	Grid connected	Solar Home System
Irradiation	kWh/m²/yr	1700	1900
Final yield	kWh/Wp/yr	1.28	1.3
system life	yr	20	30
battery size	Ah (@12V)	0	70
# of batt. sets required over system life	-	n.a.	5
Energy eff. of alternative supply option	%	35	25

Table 5: Assumptions for the calculations on Energy Pay Back Time and life-cycle CO_2 emissions

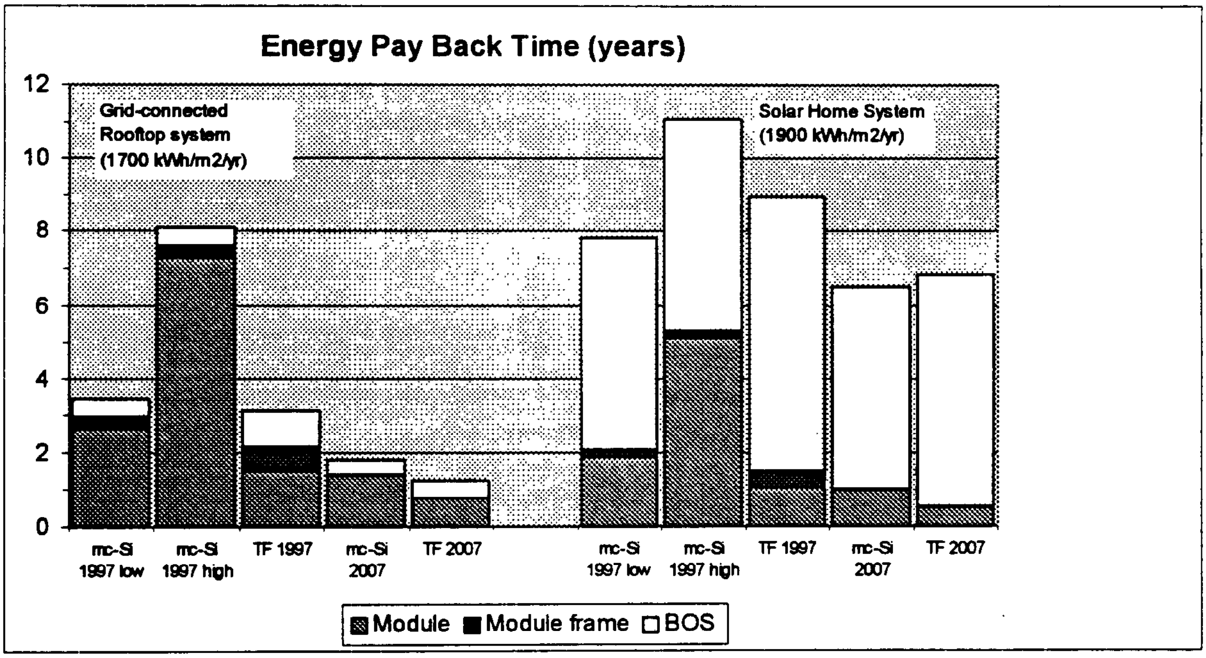

Figure 1: The Energy Pay Back Time (in years) for two major PV applications, both for present-day (1997) and future (2007) PV technology. For system-specific assumptions see table 5.

As a matter of fact, in the present mc-Si high case the energy pay-back time of a PV system is around eight years, even in the middle-good insolation conditions of 1700 kWh/m^2/yr. However, as already mentioned, I believe that this is a rather pessimistic view of present state-of-the art. Given the fact that PV industry will have to address the issue of feedstock anyway in the next few years, I think that the low case is more representative for the near-future situation.

Further we may note that the contribution from the BOS and frame is significant already today: each causing an increase in energy pay-back time in the order of 0.3-0.5 year in combination with mc-Si cells. Regarding thin film technology we can see that due to their lower efficiency, larger surface needed and consequently higher BOS requirements, the energetic advantages of present amorphous modules are cancelled by the higher BOS energy.
For future roof-top systems the expected energy pay-back time is 1-2 years both for mc-Si and a-Si technology.

These results show that grid-connected PV systems have considerable potential for saving on fossil-fuel energy production and thus reducing CO_2 emissions. This can also be seen in figure 2 where we have displayed the CO_2 emissions per kWh of supplied electricity for grid-connected PV systems and for a number of conventional power generation technologies. This shows that CO_2 emissions from PV are roughly a factor 10 lower than for fossil-fuel plants and that they will become even lower, around 20-30 g/kWh, in the future.

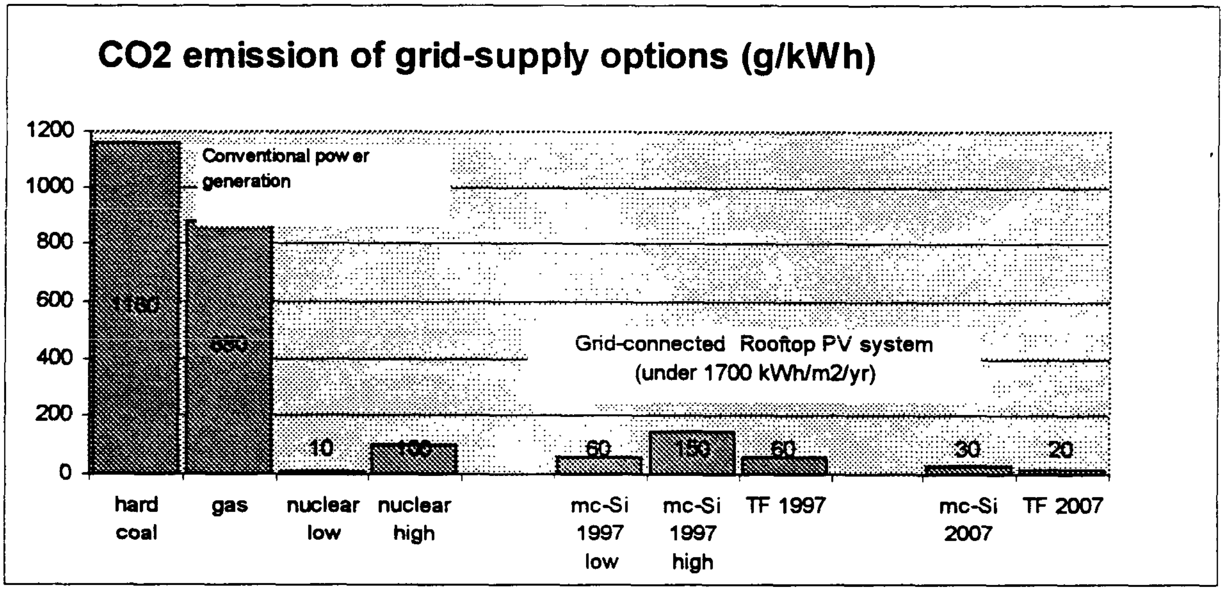

Figure 2: CO_2 emission for grid-connected roof-top PV systems and for conventional power systems (coal, gas, nuclear-low estimates from [15], nuclear-high from [22]).

Solar Home Systems
This potential for CO_2 mitigation by PV technology is less straightforward the case for our second application type, which concerns a Solar Home System, as has been introduced over the past years in many developing countries. A typical SHS as installed in for example Indonesia, comprises a 50 Wp module and a 70 Ah battery. Such a system may have a final yield of 1.30 kWh/Wp/yr under a 1900 kWh/m^2/yr irradiation. (Of course actual SHS performance data are heavily dependant on the user load profile, but we believe our assumption is fairly representative). We further assume a typical life time for the battery of 4 years, so that 5 battery sets are needed over a 20 year system life.
In order to evaluate an Energy Pay-Back Time we will compare the SHS with a diesel generator which converts primary energy (fuel) into electricity at an average efficiency of 25% . (Note that grid supply in a remote area may have a comparable conversion efficiency).

As the results in figure 1 show the EPBT of the assumed SHS configuration would be more than 7 years, even with the low module energy estimates for mc-Si modules. For future PV technology only a modest improvement is expected due to the large contribution of the battery (for which no improvement was assumed) to the system EPBT.

Figure 3 displays the CO_2 emissions per kWh of the SHS application in comparison with one alternative option, namely a diesel generator operating at 25% average conversion efficiency. Transportation energy to get the diesel fuel at the user location has not been accounted.

We see from figure 3 that the CO_2 emission from the PV installation is still considerably lower than for the diesel, although the difference is smaller than for the grid-connected systems.

One consequence of this result is that one should be careful when attributing a *large* CO_2 mitigation potential to SHS's. Some kind of break-through in electricity storage technology will be necessary if we want to improve the CO_2 mitigation potential of this application. In any case, the long-term worldwide contribution of SHS to CO_2 mitigation will always be small in comparison to grid-connected systems. Also one should remember that SHS are very valuable for a different reason, namely providing energy services at remote locations.

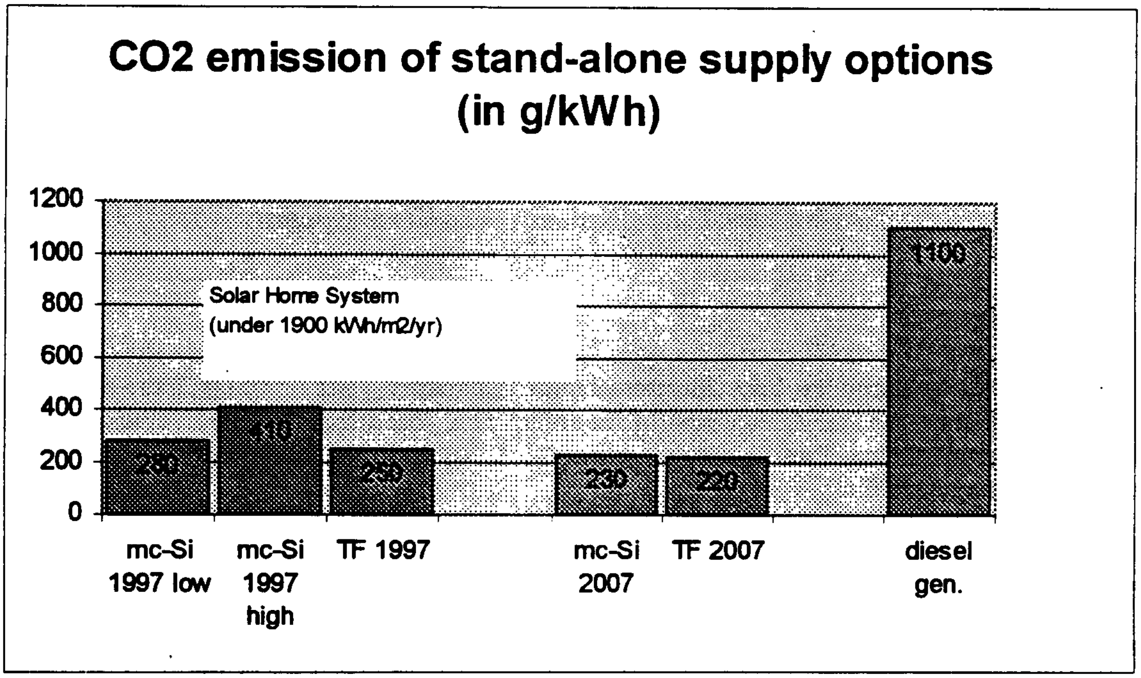

Figure 3: Life cycle CO_2 emissions from Solar Home Systems and from a diesel generator.

6. CONCLUSIONS

We have reviewed energy requirement data for PV modules and BOS components. It was found that there is considerable uncertainty with respect to the energy requirement of c-Si modules, due to accounting difficulties for off-spec silicon and due to lack of reliable data on silicon feedstock production. This is reflected in the large difference between calculated energy pay-back times, which range from around 8 years in the mc-Si high case to 3-4 years in the low case (under 1700 kWh/m²/yr irradiation).

I think that these two difficulties mostly explain the large difference of results which can be found in past literature. However, this will be no longer a major issue in the near future. In any case, dedicated processes for "PV-quality"' silicon feedstock, with a reduced energy requirement, are expected to bring significant improvements in the energy requirement of c-Si modules. The same can be expected from measures to reduce the amount of silicon required per m² wafer.

Thin film modules have a lower energy requirement per m² module area, but on a system level this is offset by their lower efficiency, leading to higher BOS energy requirements and lower energy production. With thin film technology the scope for a future reduction of energy requirements is more limited than for c-Si.

The energy pay-back times of PV rooftops are expected to decrease to less than 2 years both for mc-Si and a-Si module technology. Specific CO_2 emissions from these systems could go down from 60-150 g/kWh now to 20-30 g/kWh in the next ten years. These values indicate that such future systems will definitively have a high net fossil energy substitution and CO_2 mitigation potential.

This is less straightforward the case for Solar Home Systems, for which energy pay-back times of more than 7 years were found. Still, the CO_2 emissions from such systems (250-400 g/kWh) are relatively low in comparison with a diesel generator. In fact, the BOS is the crucial factor determining the energy and environmental profile of these systems and limiting its actual CO2 mitigation potential. Irrespectively of PV technology improvements, some kind of breakthrough in electricity storage means will be needed if we want to improve the over-all environmental effectiveness of Solar Home systems.

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2.2 Bjorn Andersson

Materials Availability and Waste Streams for Large Scale PV

MATERIALS AVAILABILITY AND WASTE STREAMS FOR LARGE SCALE PV

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1 INTRODUCTION

The aim of this paper is to address the issue whether thin-film solar cells based on rare metals could be part of the solution to the problem of *global climatic change.*

More specifically the objective is to discuss to what extent an expansion of PV production based on CdTe, CIGS and aSiGe could be constrained by limited materials availability. This is not the first time this issue is addressed. See for example Smith and Watts (1984), Zweibel et al. (1986) and Zweibel and Barnett (1993).

If the potential of a technology is limited then its role in the dynamic process of technology change ought to be assessed. Could it act as a *bridging technology* that will facilitate the introduction of technologies with greater potential or will it act as a *dead end technology* that deprive investments from or damage the reputation of the long term solutions and thereby prolong the transition to a more sustainable energy supply system.

From an environmental perspective the role of the technology in the *industrial metabolism* should be assessed. Could solar cells based on rare elements contribute to the creation of a sustainable industrial metabolism or will they introduce new environmental problems. At the end of the paper some environmental pros and cons associated with a large scale deployment of solar cells based on rare elements are discussed.

There is a general lack of data for the minor metals considered here. Most figures given in this text are rough estimates and ought to be treated with caution.

2 AVAILABILITY OF MINOR METALS

Cadmium (Cd), tellurium (Te) used in CdTe cells, indium (In), selenium (Se) and gallium (Ga) used in CIGS cells and germanium (Ge) used in some aSi cells are elements that all could be considered as rare or geochemically scarce elements. The average abundance in the continental crust varies among these from less than 0.01 ppm (Te) to about 15 ppm (Ga). In fact Ga is as abundant as lead and almost as abundant as copper (25 ppm). The primary refinery production of Ga is however a factor 10,000 smaller than the primary refinery production of copper and lead. Figure 1 illustrates that the refinery production of Te, Se, In, Ge and Ga is substantially smaller than for other metals of comparable abundance. This is due to the fact that the availability of metals is depends on the extent to which they are concentrated in certain minerals and ores. Te, Se, In, Ge and Ga do seldom form any minerals of their own and high levels of concentration in any mineral are exceptional. Therefore these metals are sometimes classified as "scattered metals" (Habashi 1997).

Cadmium is heavily concentrated in sphalerite (ZnS, the main source of zinc), where it, due to its similarity with zinc, substitutes for this metal in the crystal lattice. Therefore the output of Cd is comparatively large. The revenue from Cd refinery can however not affect mining rates, it only makes up a small fraction of the total revenue from zinc mine production (about 1%). It is therefore termed a *minor metal.* Of course, also Te, Se, In, Ge and Ga are minor metals recovered as byproducts from base metal mining. Te and Se are enriched in copper minerals and concentrated in the process of copper refining. In and Ge are mainly byproducts of zinc. Also Ga is somewhat concentrated in sphalerite but it is mainly recovered from bauxite. (See Figure 2.)

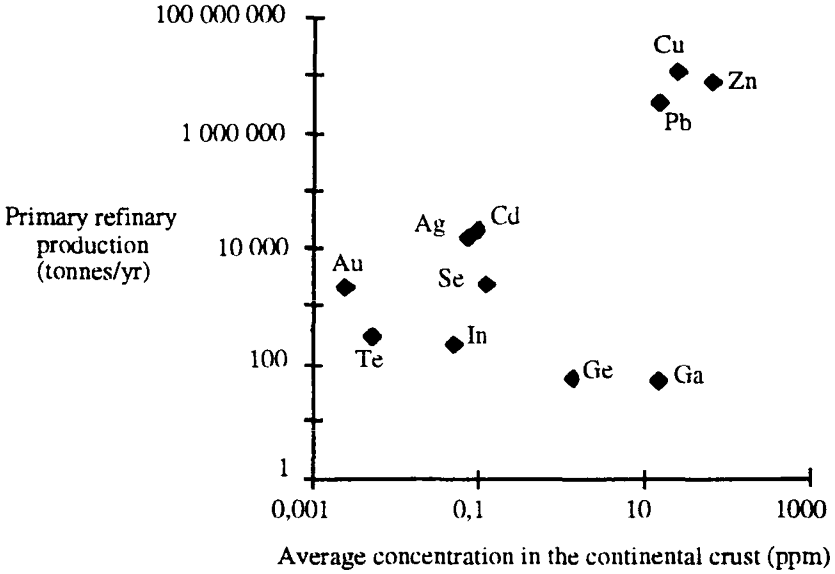

Figure 1 Two dimensions of scarcity. Production figures are taken from Crowson (1994) and crustal abundance from Wedepohl (1995).

Due to the low value and/or complex processes needed to recover the minor metals the recovered amounts are not only dependent on the amounts present in the ore but also depends heavily on the specific processes used to recover the base metal or more valuable byproducts such as precious metals. As an example the recovery of Te and Se can be attributed to recovery of gold and silver from copper anode slimes.

From Table 1 it is evident that only a fraction of the considered here minor metals contained in mined minerals are recovered (with the exception of Cd). This discrepancy is especially large for the more geochemically abundant elements Ga and Ge. The amounts contained in mined coal are about 500 times the amounts presently refined from metal ore.

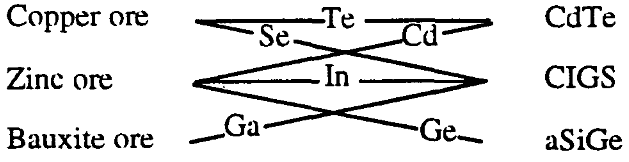

Figure 2 The minor metals are produced as byproducts from base metal recovery.

To avoid confusion when discussing annual availability of metals we need a clear terminology. In figure 3 the flows and stocks of a minor metal is outlined. *Extraction* here denotes the total amount of metal contained in mined minerals. The term *mine production* is here avoided since it in the literature sometimes include recovery factors. *Primary refinery production* is the part of the extracted amounts that is refined to metal. Total refinery production also comprise secondary refinery production, i.e. the recycling of scrap from manufacturing processes (new scrap) and post consumer scrap (old scrap). For minor metals, in most cases, only figures of total refinery production and refinery capacity are given. However, in most cases recycling rates are low. Due to variation in supply, demand and price the metal may be stockpiled in different parts of the system. Therefore, averages over five years are used in this paper.

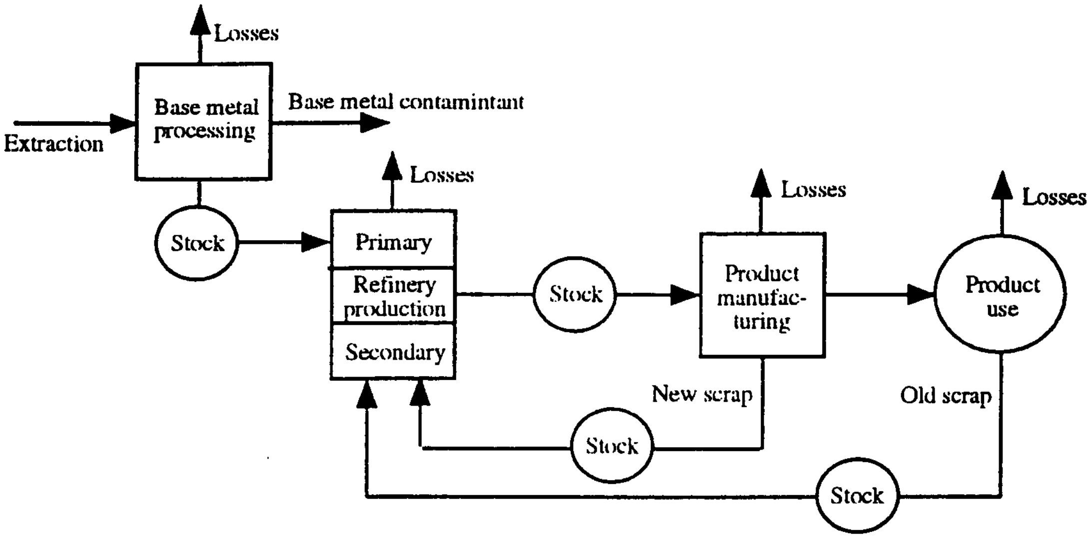

Figure 3 The principle flows of a minor metal.

Table 1 Annual availability of primary metal

	Refinery prod. average 1993-1997[a]	Refinery capacity 1992[b]	Extraction, annual average 1993-1997[c]				
			Total	Zn-ore[d]	Cu-ore[e]	Bauxite[f]	Coal[g]
			(tons/yr)				
Te	280	450	2,100		*2,000*		*100*
Cd	19,000	26,000	34,000	*32,000*			*2,000*
In	190	250	1,100	*430*	*610*		*100*
Se	2,200	2,300	15,000		*8,200*		*7,000*
Ga	45	145	28,000	*480*		*5500*	*22,000*
Ge	52	270	31,000	*3,200*	*610*		*27,000*

a Secondary refinery production is included in all figures except for Ga. This fraction is however believed to be modest. Data are taken from USGS Mineral Commodity Summaries. Data for Te and Se are completed with estimates from Crowson (1994).

b Data from Crowson (1994).

c Extraction refers to the total amount of the elements contained in mined minerals. Underlined figures denotes the prime source of present primary recovery. In addition, small amounts of Te and Se are extracted from lead ores and small amounts of In is extracted from tin ores.

d Based on zinc mine production (USGS Mineral Commodity Summaries) and estimates of concentrations in sphalerite (ZnS), Cd: 3000 ppm (Roskill 1988), In: 40 ppm, Ga: 45 ppm and Ge: 300 ppm (Weeks 1973).

e A Te:Cu ratio of 200 ppm in ore is assumed (Roskill 1982). By using estimates of Se recovery per ton of mined copper for Canada 650 ppm and the rest of the world 215 ppm (USBM 1985) the Canadian share of world mine production and a recovery efficiency of 31% (USBM 1985) a Se:Cu ratio of 800 ppm is derived. Figures of median In and Ge content in chalcopyrite of about 20 ppm (Weeks 1973) are used to estimate In:Cu and In:Ge ratios to 60 ppm. Copper mine production from USGS Mineral Commodity Summaries.

f The average Ga concentration in bauxite is assumed to be 50 ppm (USBM 1985). Bauxite mine production from USGS Mineral Commodity Summaries.

g Based on coal "production" figures from BP (1996) and typical contents of elements in coals. Cd: 0.5 ppm (Swaine 1990, Clarke and Sloss 1992), In: 0.02 ppm (Bowen 1979), Se: 1.5 ppm, Ga: 5 ppm, Ge: 6 ppm (Swaine 1990). Te content is estimated to be in the same order of magnitude as In. Davidson and Lakin (1973) assume a Se:Te ratio of 100 and Clarke and Sloss (1992) gives 0.1 ppm as an upper limit.

To avoid confusion when discussing annual availability of metals we need a clear terminology. In figure 3 the flows and stocks of a minor metal is outlined. *Extraction* here denotes the total amount of metal contained in mined minerals. The term *mine production* is here avoided since it in the literature sometimes include recovery factors. *Primary refinery production* is the part of the extracted amounts that is refined to metal. Total refinery production also comprise secondary refinery production, i.e. the recycling of scrap from manufacturing processes (new scrap) and post consumer scrap (old scrap). For minor metals, in most cases, only figures of total refinery production and refinery capacity are given. However, in most cases recycling rates are low. Due to variation in supply, demand and price the metal may be stockpiled in different parts of the system. Therefore, five years averages are used in this paper.

This paper will not deal with the availability of secondary metal explicitly. It will be assumed that the metal scarcity and the relatively low costs of recycling will foster a system with close to 100% closed loops for the rotation of both new and old scrap. This is an assumption and not a result. The issue of what technology and administration that are needed to reach high collection and recovery rates of secondary materials deserves several assessments of its own. One effect of the closed loop assumption is that materials utilization in solar cell manufacturing becomes less critical.

3 CONSTRAINED PV EXPANSION RATES

In Table 2 the figures on refinery production, refinery capacity and extraction are translated into potential annual increases of the solar cell stocks. It is evident from the limits set by present refinery production and refinery capacity as well as from the potential to use more of the extracted materials that the availability of Te and In are bottlenecks for the growth of CdTe and CIGS respectively. Ge is neither essential for aSi solar cells nor as limiting as Te and In. Higher Ge prices could probably increase primary refinery production substantially. The discussion will therefore in the following focus on Te and In.

Table 2 PV expansion rate constrained by annual availability of metals

	Metals requirements[a]	Metals intensities[b]	Potential expansion rate limited by:			
			Refinery production[c]	Refinery capacity[d]	Max. recovery from traditional source[e]	Max. recovery from total extraction[f]
	(g/m^2)	(g/Wp)	(GWp/yr)			
Te	4.7	0.038	7.4	12	37	39
Cd	4.9	0.039	480	660	570	610
In	2.9	0.023	8.2	11	13	34
Se	4.8	0.038	57	60	150	280
Ga	0.53	0.0042	11	34	910	4,600
Ge	0.22	0.0018	30	150	1,300	12,000

a Estimates from Andersson et al. (1998). Thickness of CdTe, CIGS and aSiGe layers are 1.5 µm, 2.0 µm and 0.1 µm respectively.

b An efficiency of 12.5 % is assumed.

c Derived from refinery production in Table 1 (used as a proxy for primary refinery production).

d Derived from refinery capacity in Table 1.

e 70% of the extracted material from the base metal ore that currently is a source of the minor metal, i.e. 70% of the underlined figures in Table 1. 70% is a typical value of the total efficiency of copper recovery from ore to refined metal (Chapman and Roberts 1983).

f 70% of total extracted metal as given in Table 1.

If we assume that all of the current primary refinery production of Te and In but no more will be available for solar cells then the expansion rates would be limited to about 7-8 GWp/yr for CdTe and CIGS. Consider a scenario where a production capacity of 50 MWp/yr is present in the year 2005 and that the production capacity thereafter grows by 30%/yr. Then the production volume would be constrained by Te and In availability in the year 2025 (Figure 4). If they after 2025 keep the pace of 7-8 GWp/yr of production from primary material not more than 230-250 GWp or 360-390 TWh/yr[1] would be installed in the year 2050. To reach the size of the present global electricity production of 10,000 TWh we would have to wait about 800 years.
Clearly the availability of Te and In has to be increased substantially to make an impression on the electricity market and even more to be of any major importance for CO_2-mitigation. We should also consider that the materials intensity of the cells can be increased, i.e. thinner films could be developed.

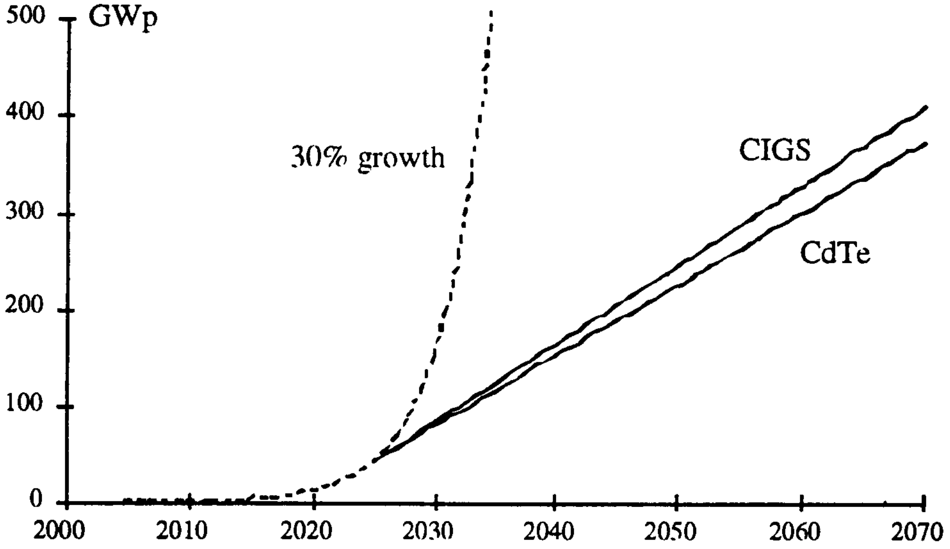

Figure 4 Expansion constrained by current levels of primary refinery production. In the scenario the exponential growth comes to a halt in 2025. Based on Table 2.

4 PROSPECTS FOR INCREASED AVAILABILITY

The availability of primary metal for one technology, e.g. CdTe solar cells, is determined by the supply, i.e. primary refinery production, and by the demand for the metal from other applications. In this section the supply side will be more thoroughly examined. The issue of *resource competing technologies* will be touched upon at the end of the section.

Changes in supply could be divided into changes independent of the increased demand from the solar cell industry and changes that occur due to increased demand and raised prices. Independently of demand for the minor metal in question, output could increase or decrease due to a change in demand for *resource complementary technologies*. For example, if the use of technologies using copper would increase, the availability of Te would increase. If the demand for gold would decrease the recovery of Te would also decrease. New ways of processing the base metal ore could also alter the output of the minor metals.

If demand for the metal increases the revenue from the recovery of the metal will increase. This will affect the price and the production volume. Recovery of the minor metal might spread to a larger fraction of the mining operations. Existing processes of recovery can be optimized. If the price would increase even more the processing of the base metal might be changed to increase

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[1] Assuming 2000 kWh/m^{2}yr and a total efficiency of BOS, power conditioning and temperature correction of 80%.

recovery rates. Recovery from sources, previously subeconomic, could emerge, such as Ge recovery from coal ash. If the price could be elevated by about two orders of magnitude and remain stable the minor metal may become a major metal. It then could become the main product or at least a high value co-product, that could influence mining rates.

The scenario introduced in the previous section may now be revisited. Due to economic growth and population growth the demand for base metals will most likely increase. The increases in mine production could be held back by elevated recycling rates and more efficient materials utilization (dematerialization). If we assume a growth rate of 2% for the mine production of base metals during the next 27 years, 1.7 times the present levels would be produced in the year 2025. If the raised demand could increase the overall recovery rates for In and Te to 70% (the efficiency of copper recovery) the output of In from zinc operations could increase by a factor 1.6 and of Te from copper ores by a factor 5 (see Table 2). Moreover, if the thickness of the CdTe layer could be decreased from 1.5 to 1 µm and the CIGS layer from 2 µm to 0.5 µm, these assumptions taken together could increase the amount of available Te and In in the year 2025 by 13 and 11 times respectively. The annual expansion potential for CdTe and CIGS would then be about 90 GWp/yr.

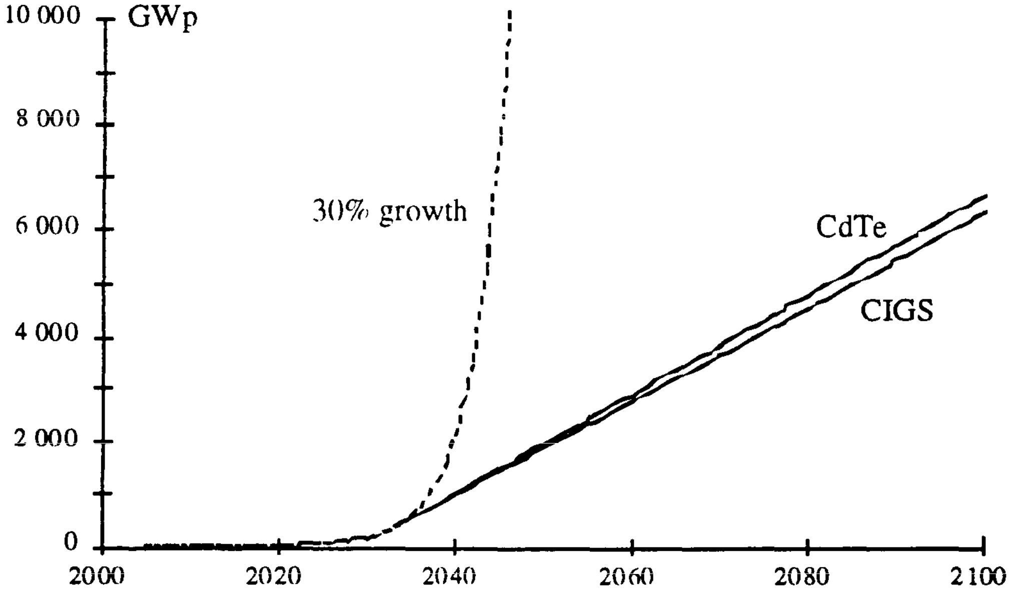

Figure 5 Thinner films, higher recovery rates and increased base metal mining could increase the expansion potential significantly. See text for assumptions.

The 30% growth scenario would then be halted in the year 2034 (see Figure 5). CdTe and CIGS could in this example reach 1900 GWp or about 3000 TWh/yr in 2050. 10 000 TWh/yr would be reached around year 2100.

The amounts of In and Te that will be available will to a large extent depend on the price that solar cell manufacturers are ready to pay for the metals, and ultimately on how much more electricity per cent these cells can produce compared to competitors. Let us make a thought experiment. Consider a reference cell with a module efficiency of 10%, an operating efficiency of 8% and a module cost of 50 USD/m^2. Let assume that area related BOS cost is 50 USD/m^2 and that this reference device is competitive on the mass markets for electricity (about 6 c/kWh). If a CdTe or CIGS cell having the same production cost but 12.5% module efficiency and 10% operating efficiency could be produced it would generate 25% more electricity at the same cost as the reference module. The implication of this is that such CdTe and CIGS cells could pay up to 25 USD extra for materials and still be profitable. The effects on metal prices of such a situation is indicated in Table 3. The effects on zinc and copper ore economy of drastically elevated prices of Te and In is indicated in Table 4.

Table 3 Low manufacturing cost and high efficiency can increase the willingness to pay for the metals by two orders of magnitude. See text for details.

	Average prices 1993-1997	Metals requirements high	low	Potential metal price (equivalent of 25 USD/m^2)		Potential price/ current price	
	(USD/kg)	(g/m^2)		(USD/kg)		(ratio)	
Te	53	4.7	3.1	5,300	8,000	100	150
In	280	2.9	0.73	8,600	34,000	31	123
Ge	1,400	0.22		110,000		81	

Table 4a Value of metals contained in a typical zinc ore.

		Ore conc[a].	Metal price	"Ore value"
		(ppm)	(USD/kg)	USD/ton
Zn		40,000	1.0	40
Cd		180	2.5	0.4
Ge		18	1,400	25
Ga		2.7	410	1.1
In	1990s	2.4	280	0.7
In	potential		8,600-34,000	21-82

Table 4b Value of metals contained in a a typical copper ore.

	Ore conc[a].	Metal price	"Ore value"
	(ppm)	(USD/kg)	USD/ton
Cu	5,000	2.3	23
Se	4.4	9.5	0.1
Au	0.13	13,000	3.3
Te 1990s	1.0	53	0.1
Te potential		5,300-8,000	11-16

a Au:Cu ratio from Lucas (1985), other ratios from Table 1

b Average prices 1993-1997 from USGS (1998), In and Te potential prices from Table 3.

At least two conclusions can be drawn from this example. First, it is not impossible that demand for Te, In and Ge could increase recovery rates and eventually become a force behind accelerated mining.[2] Second, the limited supply of Te and In and the large price increases needed to affect mining imply that any cost advantage of CdTe and CIGS would induce higher materials costs.

There are figures indicating that the In content in mined copper ore is substantial (see table 1). If this is so the copper ores might become an attractive source for In. Te is heavily concentrated in manganese nodules on the ocean floor. Estimated median values vary between 30 ppm (Weeks 1973) and 48 ppm (Bowen 1979). The high Te prices indicated above could give rise to new interest in ocean floor mining. Old waste dumps at mining sites could be another source of various metals in the decades to come.

The high potentially high value of Te and In in solar cells will make it difficult for other large scale applications to compete for the metal. The fastest growing market for In is thin film ITO (indium tin oxide) used for displays and energy efficient windows. If CIGS production take off, CIGS and ITO will be resource competing technologies at least in the short run.

5 STOCKS

So far only annual availability and constraints on the expansion rate has been considered. Estimates of the In and Te contents in zinc, copper and ocean floor resources are given in Table 5. Using the totality of land based and ocean floor resources of In and Te would limit CIGS cells to about 26 TWp or about 40 000 TWh (insolation 2000 kWh/m^2yr) and CdTe to about 40 TWp or 60 000 TWh/yr.

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[2] If mines were to be operated mainly to recover In or Te energy payback times would be increased substatially.

Table 5 Potential In and Te resources

	Ore contents[a]		Potential solar cell stock (70% recovery)[b]	
	In	Te	In	Te
	(ktons)		(GWp)	
Zinc reserve	11		1,400	
Zinc reserve base	26		3,100	
Zinc resources	110		14,000	
Copper reserve	19	64	2,300	1,800
Copper reserve base	38	130	4,600	3,500
Copper resources (land based)	96	320	12,000	8,900
Manganese nodules (ocean floor)		>1,000		>30,000

a Based on zinc and copper resources as given by USGS (1998) and In and Te concentrations as cited in Table 1. Resources in manganese nodules from Weeks (1973)

b A module efficiency of 12.5% is assumed. A recovery rate of 70% is substantially higher than prevailing recovery rates.

6 THE CADMIUM PARADOX: HOOVER AND PANDORA TECHNOLOGIES

It is not the use of metals that cause environmental problems but the emissions and leakage from society to the environment. Different types of metal use are more or less dissipative. If the price of a metal is high it is less likely that it will be discarded as waste or used in short lived products. It is more likely that it will be contained in long lived products and recycled in closed loops. Therefore it has been suggested that technologies where the hazardous metal can be contained in a controlled fashion could be used to "soak up" metals that otherwise would have been lost to the environment. The argument has been used by Ayres and Ayres (1996) for arsenic and electronics, by Andersson and Råde (1998) for cadmium, lead and vanadium and electric vehicle batteries and by Andersson and Jacobsson (1998) for the here discussed metals and solar cells. Andersson and Råde introduce the term *hoover technologies*. CdTe solar cells could be a hoover technology that soak up cadmium that otherwise would have been lost to environment.

Raising the value of a metal could however also lead to accelerated mining causing an increased environmental pressure for example in the form of sulfur dioxide emissions, metal leakage from waste dumps and large scale land transformations. It becomes a *pandora technology* that releases deleterious elements into the environment.

This could lead to an interesting paradox. A large scale use of CdTe solar cells could decrease the overall cadmium emissions and leakage. A large scale expansion of CIGS and aSiGe cells could lead to increased mining of indium and germanium rich zinc minerals containing large amounts of cadmium, and thereby cause an overall increase in cadmium emissions and cadmium leakage.

We should also consider the *riddance problem*. Even if the metals can be safely stored in solar cell systems, one day these technologies might be superseded by better performing alternatives. Then the scrap price will fall drastically. We then face the riddance problem. Who will pay for getting rid of tons of hazardous waste. At present, in Sweden the use of mercury is supposed to be phased out and mercury is to be put in final storage. However, no money has been collected to pay for this.

Conclusively there are environmental problems associated with high metal values and as well as with low metal values.

7 CONCLUSIONS AND QUESTIONS

If major efforts to increase refinery output of Te and In are made CdTe and CIGS could reach TWp levels of installed capacity during the next century. If the development of CdTe and CIGS would at all succeed it is not unlikely that they could pay for such efforts. Long term contracts between metal producers and solar cell manufacturers might be necessery avoid that swinging prices will substantially increase the risk associated to investments in CdTe and CIGS production.

It is however doubtful if CdTe and CIGS could become of any major importance to CO_2-mitigation. The implication of such an unlikely development would be that solar energy would become the "coal industry" of the 20th century extracting about as much material from the crust for every kWh of electricity produced.

The possible role for CdTe and CIGS in the process of decarbonizing the energy system is as bridging technologies. What important knowledge is gained by doing research on CdTe and CIGS? Can the development of CdTe and CIGS production processes generate experience at a critical point in time? Can they tear down market barriers, create distribution channels, shape up legislation and increase the consumers interest in PV? Such questions ought to be addressed.

Direct solar energy is one of the major options for a sustainable energy supply system. In the worst case the investment of time and money in the development of CdTe and CIGS could delay a development of a global solar energy system.

Even if these solar cells can not be of major importance to global climatic change they can form an impressive industry that can deliver demanded products. For such an industry it is important to develop a careful materials management. The resource scarcity and the environmental problems associated with the used rare metals call for strategies to obtain closed loop recycling, including recycling of old scrap. One possibility to facilitate post consumer recycling is to sell CdTe and CIGS cells only to certain market segments, e.g. professionally operated large scale installations.

2.3 Robert Williams

PV and the Competition in 21st Century

THE COMPETITION FACING PV IN A GHG EMISSIONS-CONSTRAINED WORLD

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Presented at the Workshop "PV and the Environment 1998"
Sponsored by Brookhaven National Laboratory (BNL)
and National Renewable Energy Laboratory (NREL) Thin-Film Partnership

23-24 July 1998
Keystone, Colorado

OUTLINE OF PRESENTATION

Some Major Competitors For PV in A Greenhouse Gas Emissions Constrained World

Small-scale biomass power generation

Baseload wind power from large remote wind farms

Decarbonized Fossil Fuel Power Cycles

<u>Present Technology</u>: Combined Cycles Operated on Hydrogen Derived From Natural Gas

<u>2010 Technology</u>: Solid Oxide Fuel Cell/Gas Turbine Hybrid Cycles Fueled with Hydrogen Derived from Coal Using Advanced Ceramic Membrane for H_2/CO_2 Separation

Suggestions for PV Community Responses to These Competitive Challenges

BIOMASS ENERGY POTENTIAL

Estimated Biomass Residue Resources for 2025 (IPCC, 1996):

	Recoverable Fraction	*Recoverable Supplies (EJ/year)*
Mill residues (forest product industries)	*3/4*	*10.5*
Forest residues	*½*	*3.2*
Sugar cane	*bagasse + 2/3 T,L*	*10.3*
Cereals	*¼*	*10.9*
Dung	*1/8*	*8.5*
Urban refuse (ICs only)	*¾*	*3.1*
Total		*46.5*

GHG emissions reduction potential by displacing coal with biomass residues~ 1.2 GtC/y

Dedicated Biomass Energy Crop Potential ~ 30 EJ/y (0.75 GtC/y coal emissions displacement potential) for each 100 Mha dedicated to biomass energy production (assuming average yield = 15 dry tonnes/ha/y):

- *Surplus Agricultural Lands, Industrialized Countries: 20-24 Mha of U.S. cropland (12-14% of total) held out of production to keep food prices high (deficiency payments to farmers ~ $5.5 billion/y, 1990-95) or control erosion (13 Mha in CRP, costing taxpayer $1.4 billion/y)*
- *Degraded Lands Potentially Available Worldwide for Biomass Energy Crops ~ 760 Mha of moderately degraded land (out of 2100 Mha total)*

SMALL-SCALE BIOMASS POWER GENERATION FOR RURAL AREAS IN DEVELOPING COUNTRIES

(*all based on atmospheric pressure, down-draft, air-blown gasifiers and cold gas clean-up, generating "producer gas," which is typically made up of* ~ 20% CO, 20% H_2, 10% CO_2, 50% N_2)

<u>Commercial technology</u>:

5 – 500 kW biomass gasifier/producer gas engine generator sets
Typically compression-ignition engines are used, for which the use of biomass enables 70% reduction in diesel oil requirements
Diesel pilot oil/lubricating oil requirements are significant costs
Relatively high maintenance/replacement capital costs
Low energy efficiency

<u>Advanced technology (2000)</u>:

25 – 500 kW biomass gasifier/recuperated microturbines
Can eliminate pilot oil/lubricating oil requirements
Low maintenance requirements
Modest improvement in energy efficiency

<u>More advanced technology (2010)</u>:

200 kWe – 2 MWe biomass gasifier/solid oxide fuel cell/microturbine hybrids
No pilot oil/lubricating oil requirements
Low maintenance requirements
High efficiency at small scales → makes it feasible to use dedicated energy crops

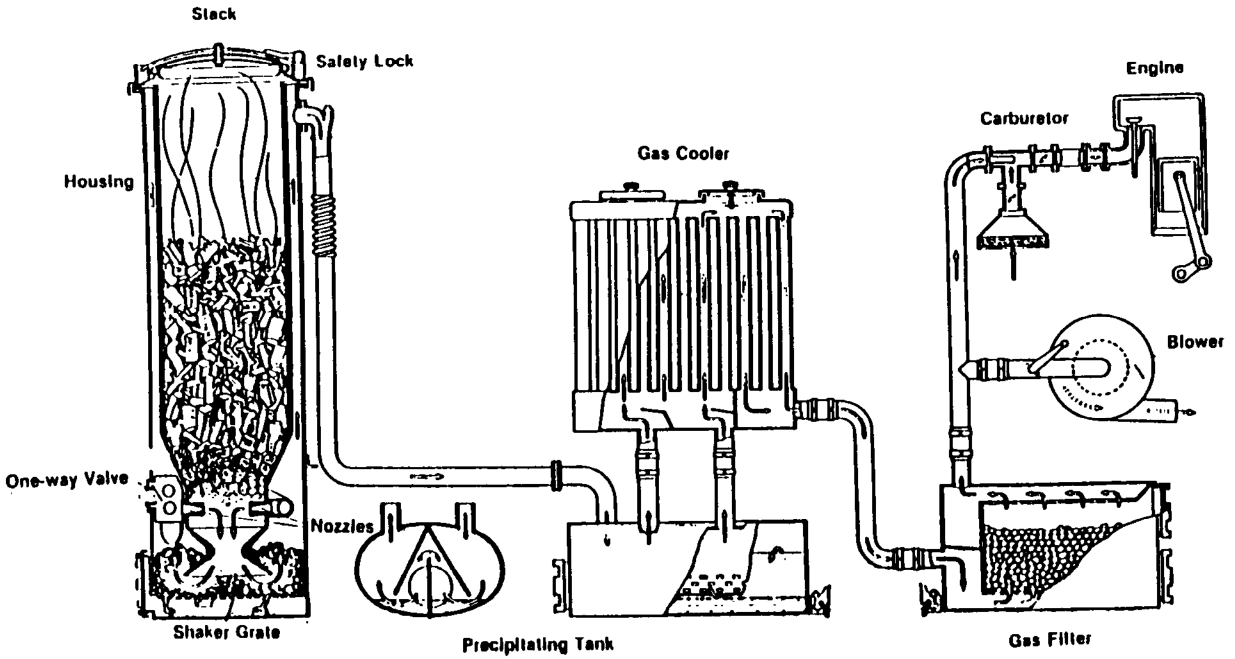
BIOMASS GASIFIER/PRODUCER GAS ENGINE GENERATOR SET

(*present technology, biomass residues, poor peasant plant operators*)

<u>Example</u>: 100 kW$_e$ unit in India [*\$480/kW$_e$ initial capital cost; \$350/kW$_e$ present value future capital replacements; η = 16%; 17% of fuel from diesel @ \$0.26/liter or \$6.65/GJ, 83% from biomass @ \$1/GJ; 1 skilled + 1 semi-skilled operator @ \$0.60/hour total; 12% discount rate; 65% system capacity factor; 25-year system life*]

Electric generation cost (1997 cents/kWh)	
Capital, initial unit	1.12
Capital, future replacements	0.81
Operating labor	0.23
Maintenance	0.46
Lubricating oil	0.48
Diesel pilot oil	2.50
Biomass feedstock	1.90
Total generation cost	7.50

To compete, installed PV system cost (incl. storage) must be \$1/W$_{AC}$ where the insolation is 1800 kWh/m^2/year.



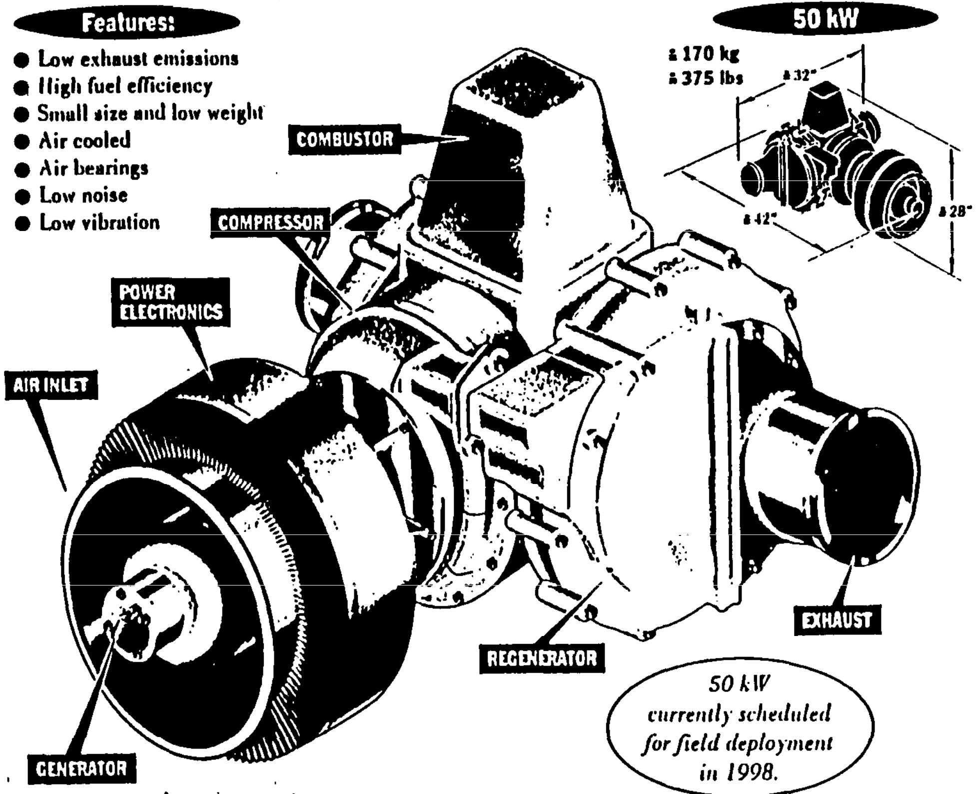
SMALL-SCALE REGENERATIVE GAS TURBINES

Micro-Turbine™ PowerPlants

50 kW and 250 kW *Micro-Turbine PowerPlants* designed and furnished to IP&L by Allison Mobile Power Systems, Allison Engine Company. Electrical system components are currently designed and furnished by General Electric Company.

Features:

- Low exhaust emissions
- High fuel efficiency
- Small size and low weight
- Air cooled
- Air bearings
- Low noise
- Low vibration



50 kW currently scheduled for field deployment in 1998.

Low initial cost expected to be ~ $250/kW$_e$.

High speed turbine (~ 80,000 rpm) mounted on air bearing (one-moving part).

No lubrication needed.

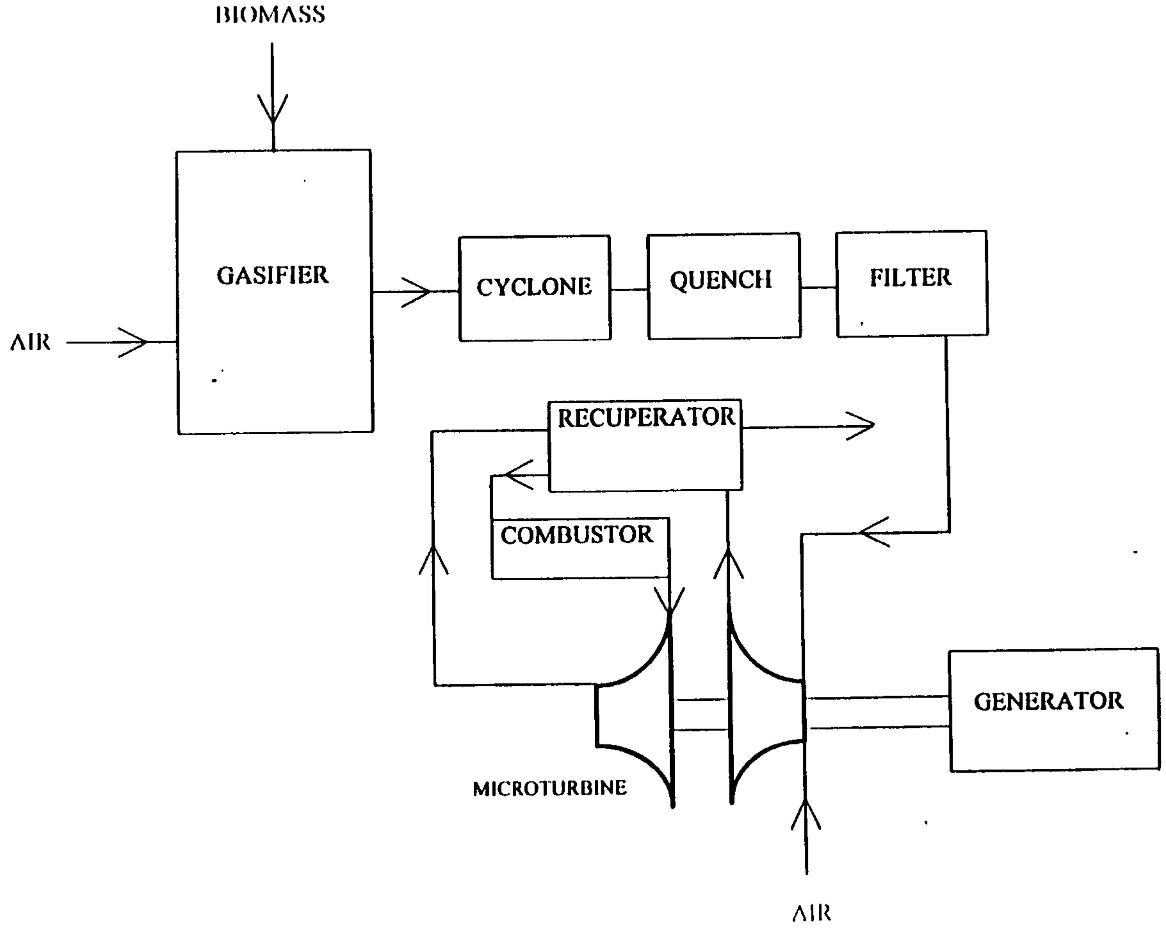
Major maintenance required only once every 3 or 4 years (vendors claim).

BIOMASS GASIFIER/MICROTURBINE GENERATOR SET
(*2000 technology, biomass residues, poor peasant plant operators*)

<u>Example</u>: 50 kW$_e$ unit in India [*\$600/kW$_e$ initial capital cost; \$150/kW$_e$ present value future capital replacements; η = 22%; \$1/GJ biomass residue fuel; 1 skilled + 1 semi-skilled operator @ \$0.60/hour total; 12% discount rate; 65% system capacity factor; 25-year system life*]

Electric generation cost (1997 cents/kWh)	
Capital, initial unit	1.40
Capital, future replacements	0.35
Operating labor	0.23
Maintenance	0.39
Biomass feedstock	<u>1.64</u>
Total generation cost	4.01

To compete, installed PV system cost (incl. storage) must be \$0.54/W$_{AC}$ where the insolation is 1800 kWh/m^2/year.



WIND POWER: PROGRESS AND PROSPECTS

Wind Power Price Trends and U.S. DOE Price Projections (*cents/kWh*)

Early 1980s	**25-50**
Present	**3 – 7**
2000	**2.2 – 4.4** (*2.7 - 4.4 for Class 4 winds:* $5.6\ m/s < V_{ave} < 6.0\ m/s$ *at 10 m*)
2005	**1.7 – 3.4** (*2.1 - 3.4 for Class 4 winds*)
2010	**1.6 – 3.1** (*1.9 – 3.1 for Class 4 winds*)

When wind power cost = 2.5 cents/kWh, "baseload wind power" can be provided for < 3.5 cents/kWh by coupling coupling wind farms to compressed air energy storage (CAES) ➔ it becomes feasible to transmit wind power long distance from good remote resources to major electricity markets via long-distance transmission lines

Estimates of global practical wind-electric potential (subtracting out potential in cities, forests, unreachable mountain areas and taking into account social, environmental, and land-use constraints)

Grubb and Meyer (1993) ~ 53,000 TWh/y (12 GtC/y emissions reduction potential if coal electricity displaced)

World Energy Council (1994) ~ 20,000 TWh/y (4.5 GtC/y emissions reduction potential if coal electricity displaced)

For comparison, global electricity generation ~ 12,800 TWh/y in 1995

CAPITAL COSTS FOR ELECTRICITY STORAGE

(1997 Dollars)

Technology	$/kW	$/kWh	Total Capital Cost ($/kW)	
			2 hours	20 hours
Compressed Air				
Large (350 MW)	350	1	352	370
Small (50 MW)	450	2	454	490
Above Ground (16 MW)	500	20	540	900
Conventional Pumped Hydro	900	10	920	1,100
Battery (Target, 10 MW)				
Lead Acid	120	170	460	3,520
Advanced	120	100	320	2,120
Flywheel (Target, 100 MW)	150	300	750	6,150
Superconducting Magnetic Storage (Target, 100 MW)	120	300	720	6,120
Supercapacitors (Target)	120	3,600	7,320	72,120

Source: Robert B. Schainker
Electric Power Research Institute
Presented to the PCAST Energy R&D Panel
14 July 1997

ECONOMICS OF "BASELOAD WIND POWER"

(A. Cavallo, "High Capacity Factor Wind Energy Systems," *Journal of Solar Engineering*, **117**, 1995:137-143)

Consider a 6 GW_e wind farm coupled to a CAES unit with 20 hours of storage

System delivers "baseload wind power" (*CF = 90%*) to 2000-km, 2 GW_e DC transmission line

Assume wind power cost = 2.5 cents/kWh

22% of power comes from CAES @ 6.5 cents/kWh
Cost of 2000-km DC transmission = 1.4 cents/kWh
Line losses in transmission = 8.3%

Delivered cost of electricity = 1.083*[0.78*2.5 + 0.22*6.5 + 1.4] = 5.2 cents/kWh

<u>CO_2 emission rate for baseload wind power system</u>

Distillate oil is used for firing CAES combustor (*heat rate = 4.22 MJ/kWh*)

Emission rate = 0.22*(73 gr CO_2/MJ)*(4.22 MJ/kWh) = 68 gr CO_2/kWh

For comparison, the emission rate for a 35%-efficient coal plant is 940 gr CO_2/kWh.

OPTIONS FOR CO_2 STORAGE

Deep Ocean Disposal (> *3 km*)

--Most discussed option
--Eliminates rapid transient CO_2 buildup in atmosphere
--Significantly reduces long-term (> *2000 yr*) atmospheric CO_2 concentration (> 50%)
--But there are many environmental concerns (e.g., ocean life impacts of pH changes,
impacts of hydrate particles on benthic organisms, ecosystems)

Depleted Oil and Gas Fields

--Large capacity
--Most secure option if original reservoir pressure not exceeded
--Geographically limited option

Aquifers

--Aquifers deeper than 750 m (*saline aquifers*)
--Wide geographic availability
--Uncertainties about storage security,
but time scales for reaching near-surface fresh water aquifers ~ 2000 years
--Enormous potential if structural trap is not needed to ensure secure storage

Deep Coal Beds

--Injection of CO_2 can be used to recovery methane from unminable coal beds
--CO_2 will remain in place (*adsorptivity of CO_2 on coals is much higher than for CH_4*)

PRINCIPAL FINDINGS OF JOULE II PROJECT ON

"The Underground Storage of CO_2"[3]

"Underground disposal is a perfectly feasible method of disposing of very large quantities of carbon dioxide."

"We estimate that there is space available in the European Union and Norway to store approximately 800 Gt CO_2." (*Note: This would be adequate to store up to 250 years of total CO_2 emissions from OECD Europe, at the 1990 emission rate of 3.2 Gt CO_2 per year.)*

"All the necessary technological steps are commercially proven and thus could be implemented today."

"...the study of large naturally occurring CO_2 accumulations indicates that CO_2 can be retained in underground reservoirs for millions of years."

"The main obstacle to the implementation of the underground disposal of carbon dioxide from fossil-fueled power stations is its high cost. Most of the cost is incurred by the necessity to separate the CO_2 from the flue gas before disposing of it." (*Note: This is not true for CO_2 recovered when hydrogen-rich fuels are produced from carbon rich fuels–in which case the byproduct CO_2 can be recovered at low incremental cost.*

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[3] Sam Holloway, "An Overview of the Joule II Project `The Underground Disposal of Carbon Dioxide," *Energy Conversion and Management,* vol. 37, nos. 6–8, pp. 1149-1154, 1996.

COMPETITIVE NEAR-ZERO CO_2 EMITTING NATURAL GAS POWER PLANTS

In April 1998, Norsk Hydro Announced It Will Build 1600 MW_e of Combined Cycle Power-Generating Capacity Operated on Hydrogen Derived from Natural Gas and Claimed That the Electricity Produced Would Be No More Costly Than Electricity from a Conventional Natural Gas Combined Cycle Plant.

Is This Credible? Recently Foster-Wheeler Designed Such a Power Plant (*Precombustion Decarbonization, Report Prepared for the IEA Greenhouse R&D Program, June 1998*). It involves:

Step # 1: catalytic air-blown partial oxidation of natural gas to produce CO, H_2
$CH_4 + H_2O \rightarrow CO + 3H_2$, $\Delta H = +206.2$ MJ/kmol; and $CH_4 + \frac{1}{2} O2 \rightarrow CO + 2H_2$, $\Delta H = -35.7$ MJ/kmol
Step #2: water gas shift reaction $CO + H_2O_{(g)} \rightarrow CO_2 + H2$
Step #3: Separate CO_2 from Other Gases Using a Solvent Extraction Technique
Step # 4: Burn H_2-Rich Gas in a Combined Cycle Plant to Produce Electricity
Step # 5: Compress Separated CO_2 to 90 Bar for Delivery to Pipeline
Step # 6: Transport CO_2 to Enhanced Oil Recovery Site
Step # 7: Sell CO_2 to Oil Producer for Enhanced Oil Recovery

Without Credit for CO_2 Sales, Power Plant Performance and Cost Are As Follows:
(*485 MW power plant, 10% discount rate, 90% Capacity Factor, 25-Year Plant Life, \$1.8/GJ Natural Gas*)

	Natural Gas Combined Cycle	H_2 Combined Cycle	
Unit Capital Cost	\$400/kW_e	\$710/kW_e	
Overall Efficiency (*HHV Basis*)	53%	45%	
CO_2 Emission Rate (*gr/kWh*)	350	57	[*Emission rate ~ 940 gr/kWh for coal*]
Cost of Generation (*cents/kWh*)			
Capital	0.69	1.23	
O&M	0.13	0.24	
Natural Gas	1.21	1.43	
Total	2.03	2.90	

USING CO_2 RECOVERED AT HYDROGEN COMBINED CYCLE PLANT FOR TERTIARY OIL RECOVERY

Cost of Separating and Compressing to 90 Bar 174 t/h of CO_2	**$24.4/tonne**
Cost of Transporting 174 t/h of CO_2 100 km (*in D = 0.3m pipe, costing $450/m*)	**$4.7/tonne**
Total Cost of Delivering CO_2 to Oil Field for Enhanced Oil Recovery	**$29/tonne**

MAXIMUM PERMISSIBLE COST OF CO_2 FOR ENHANCED OIL RECOVERY[a,b] (*$ per tonne of CO_2*)			
Oil Price (*$ per barrel*)	**10**	**20**	**30**
Displacement Efficiency[c] (*tonnes CO_2 / barrel of oil*)			
0.16	30.6	66.5	102.6
0.32	12.7	30.7	51.6
0.53	5.5	16.3	27.0

[a] Source: M. Blunt, F.J. Fayers, and F.M. Orr, Jr., "Carbon Dioxide in Enhanced Oil Recovery," *Energy Conversion and Management*, **34** (9-11), pp. 1197-1204, 1993.

[b] For a 10% discount rate.

[c] 1 tonne of CO_2 = 18.9 Mscf.

MAKING HYDROGEN FROM CARBON-RICH FUELS

1. For simplicity, assume carbon is the feedstock.

2. Begin with partial oxidation of carbon:

$$C + \tfrac{1}{2}\, O_2 \rightarrow CO.$$

3. Then use the "water-gas shift reaction" to "shift" the energy content of CO to H_2 via reaction with "water gas" ($H_2O_{(g)}$):

$$CO + H_2O_{(g)} \rightarrow H_2 + CO_2.$$

[The combination of the water-gas shift reaction plus the phase change to produce the needed steam from water:

$$H_2O_{(l)} \rightarrow H_2O_{(g)}$$

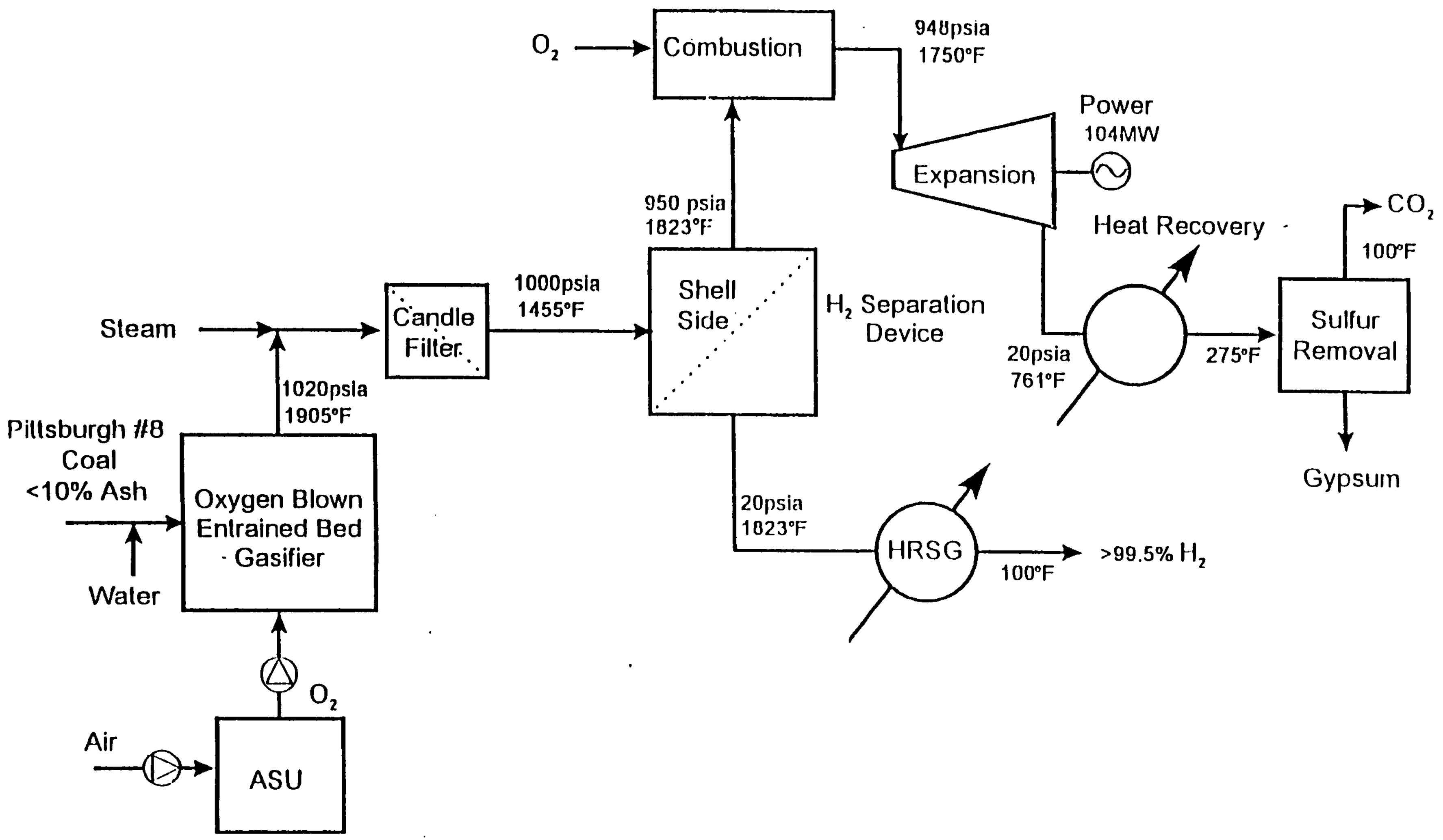
is approximately "autothermic."]

4. The H_2 can be separated from the CO_2 via "pressure swing adsorption" to product H_2 with 99.999% purity.

5. A stream of nearly pure CO_2 is produced "free" as a byproduct. If required because of "greenhouse concerns," the separated CO_2 can be stored underground at low incremental cost.

PRODUCING H_2 FROM COAL WITH THE “H_2 SEPARATION DEVICE”

(*Involving Ceramic Membranes*)



HYDROGEN SEPARATION DEVICE (HSD)

HSD is based on inorganic ceramic (Al_2O_3 or other) membrane

Membrane manufacturing technology established at large scale at ORNL for production of membranes for gaseous diffusion-based uranium enrichment technology. Manufacturing technology is classified.

Inorganic membranes are far more expensive than polymer membranes

Proposed membrane for H_2 separation costs ~ \$1,000/m^2
Installed HSD cost ~ \$6,000/m^2

For comparison, current grid-connected rooftop PV systems cost \$6/Wp
Insolation ~ 1000 W/m^2, $\eta = 10\%$ → PV system cost = \$600/m^2

But rated H_2 separation rate is very high.

Membrane coefficient = 1lb H_2 /hour/ft^2 = 192,200 W/m^2 → \$0.03/W

CENTRALIZED SOLID OXIDE FUEL CELL/GAS TURBINE HYBRID CYCLE FUELED BY HYDROGEN DERIVED FROM COAL USING A HSD PLUS AQUIFER DISPOSAL OF THE SEPARATED CO_2

Overall efficiency of providing electricity from coal ~ 50% or more
Near zero lifecycle CO_2 emissions
"Guesstimated" electricity generation cost, including cost of CO_2 sequestration ~ 4 cents/kWh

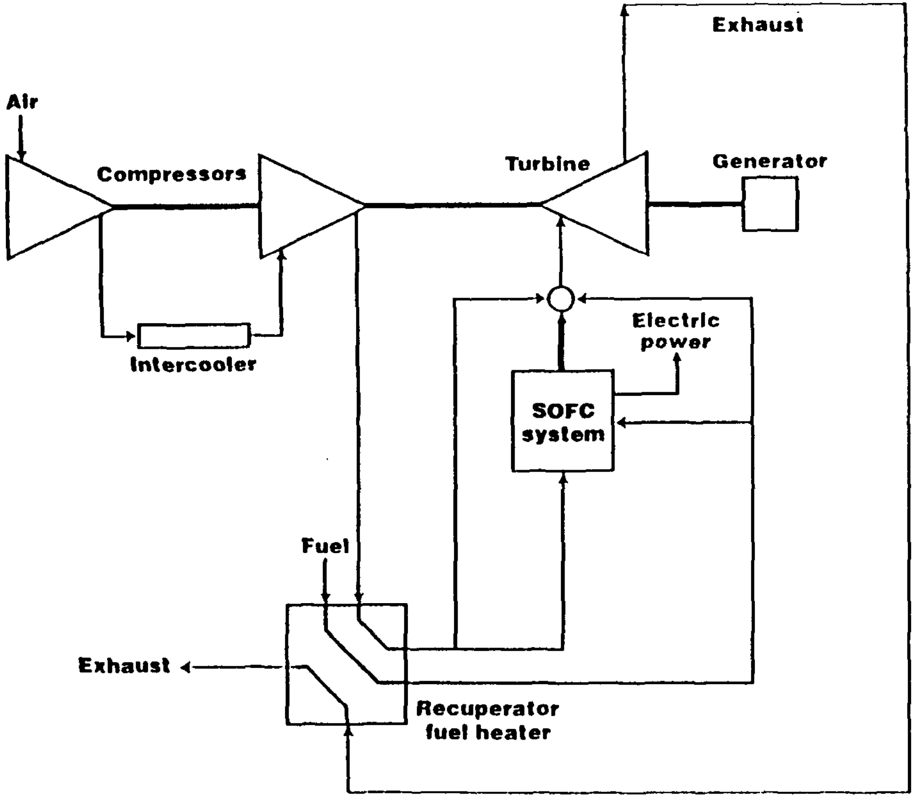


Figure 3 SOFCs may be advantageously combined with a gas turbine by using vitiated air and unconsumed fuel from a pressurized fuel cell to power the turbine. EPRI studies indicate that unprecedented combined electrical efficiency—75% or more—is likely for SOFC–gas turbine combined-cycle units, at costs projected to be competitive with conventional generation options.

EXPERIENCE WITH CO_2 STORAGE IN AQUIFERS

Ongoing: Sleipner CO_2 Injection Project, North Sea (*Statoil*)

- 1 million tonnes/year of CO_2 is being recovered from natural gas (9.5% CO_2) withdrawn from the Sleipner West gas field using an amine solution of MDEA.
- Recovered CO_2 is being be transported to and stored in a 250 m-thick deep aquifer (Utsira formation) located 800 m under the seabed beneath the nearby Sleipner East field.
- Project investment: \$50-\$80 million.
- Project came onstream in 1996 and will last ~ 20 years.

Prospective: Natuna CO_2 Capture & Storage, So. China Sea (*Pertamina/Esso E&P Natuna*)

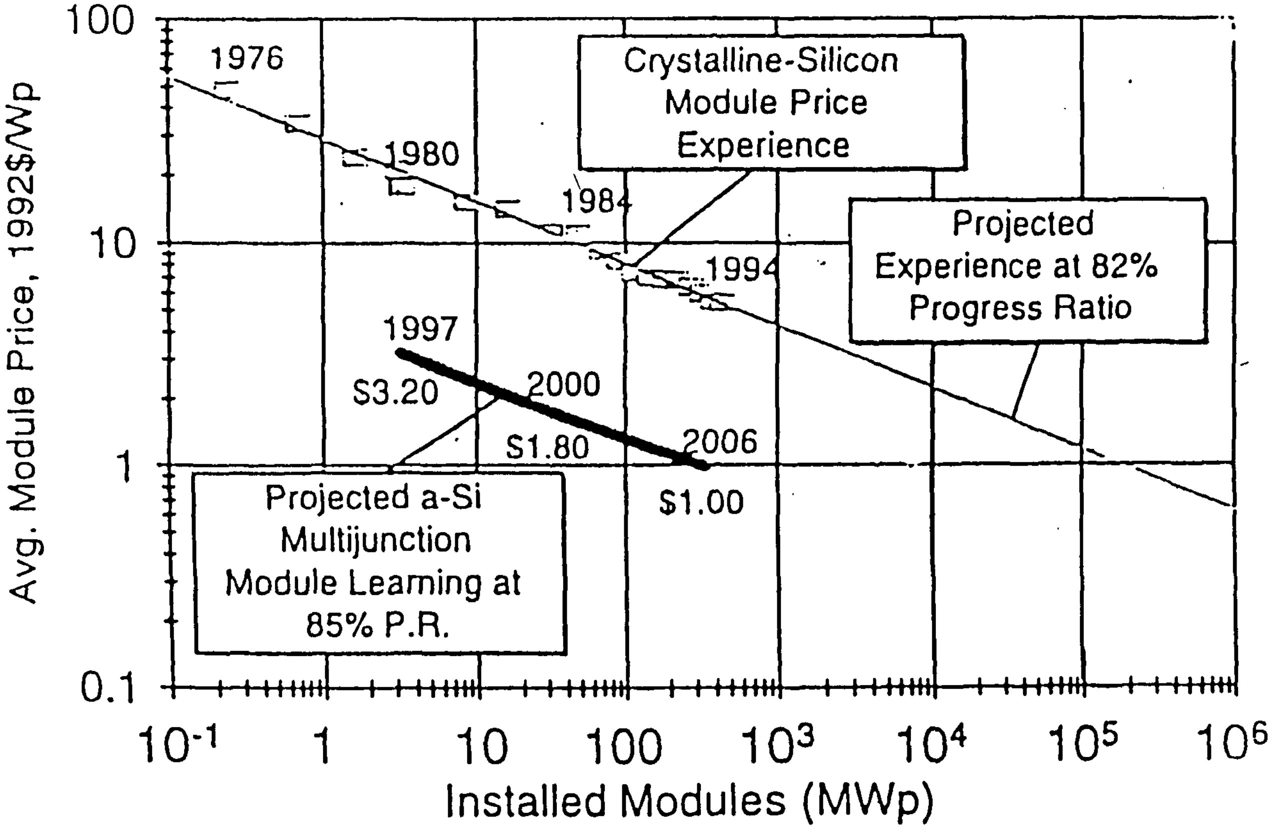
- Natuna gas field (1.27 x 10^{12} Nm^3 recoverable NG reserves) is 225 km from Natuna Island.
- Field gas is 71% CO_2. Offshore the field gas will be cryogenically separated into product gas (mainly CH_4) and waste gases (mainly CO_2). Product gas will be piped to Natuna Island for further purification and processing to LNG. The separated CO_2 will be stored in two underground aquifers north of the Natuna field.
- Sequestration rate will be > 100 million tonnes of CO_2/year; equivalent to 0.5% of total CO_2 emissions from fossil fuel burning.
- Project is currently in the planning stage. Once construction begins it will be 8 years before first LNG deliveries to customers takes place.

HOW SHOULD PV COMMUNITY RESPOND TO THESE COMPETITIVE CHALLENGES?

1. **Find ways to "jump to" a faster experience/learning curve.**
   ...will thin films make it possible to do this?

2. **Use competitive instruments such as a RPS to force PV prices down quickly.**

3. **Emphasize grid-connected distributed PV markets in developing as well as industrialized countries.**



CUMULATIVE PRODUCTION AND COST FOR GLOBAL EFFORT TO "BUY DOWN" PV MODULE PRICE TO $1 PER PEAK WATT

FOR AVERAGE TECHNOLOGY *(would be encouraged by administrative approach)*

CUMULATIVE PRODUCTION REQUIRED = 135,000 MWp
BUY-DOWN COST = $50 BILLION

FOR LEAST-COST TECHNOLOGY *(would be encouraged by market approach: e.g., Renewable Portfolio Standard, Renewables NFFO)*

CUMULATIVE PRODUCTION REQUIRED = 430 MWp
BUY-DOWN COST = $120 MILLION

IMPORTANCE OF COMPLEMENTING REMOTE STAND-ALONE PV APPLICATIONS WITH DISTRIBUTED GRID-CONNECTED APPLICATIONS

1. **Rural domestic lighting market is relatively limited:**
   - ◆ **63% of LDC population is in rural areas**
   - ◆ **67% of these have no access to electricity**
   - ◆ **10% of households can afford to pay for PV if financing available**
   - ◆ **Assuming 50 W_{AC} per HH, total market = output of one 600 MW coal plant**

   For other rural stand-alone markets (*e.g., water pumping*) PV will face stiff competition from other renewables (*e.g., biomass*)

2. **Grid-connected, distributed markets are large and relatively easy to access and probably very competitive @ \$3/$_{WAC}$ PV system cost ➔ good potential for moving quickly along experience/learning curves**

3. **System costs of \$3/$_{WAC}$ might be realized in less than 5 years**

4. **Supply curves for PV markets as a function of installed system price for grid-connected applications for developing as well as industrialized countries, taking into account various distributed benefits**

2.4 Vasilis Fthenakis

MARKAL-MACRO: A Computer Tool for Integrated Energy-Environmental-Economic Analysis

MARKAL-MACRO: A Computer Tool for Integrated Energy-Environmental-Economic Analysis

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SUMMARY

MARKAL-MACRO, is a well-established model for energy-environment-economic systems analysis, which is currently in use by many industrialized and developing countries and regions. The model describes all possible flows of energy from resource extraction through energy transformation and end-use devices to demand for useful energy services and conservation. It finds the "best" energy scenario for a given period by selecting the set of options that minimizes the total system's cost over the period. More than 200 technologies including PV, wind, solar thermal, biomass fuels, wave, and ocean-thermal gradients are modeled. The potential role of Photovoltaic (PV) technologies to reduce carbon dioxide (CO_2) emissions in the United States in a competitive market environment was evaluated using MARKAL-MACRO. Under specific assumptions on projected cost and efficiency improvements, PV may compete favorably as a general source of electricity supply to the grid by about 2010 in the southwestern United States. This analysis indicates that PV has the potential to reach a total installed capacity of 140 GW by the year 2030, and to displace a cumulative 450 million metric tons of carbon emissions from 1995 to 2030. Under constraints on carbon emission, PV becomes more cost effective and would further reduce carbon emissions from the US energy system.

INTRODUCTION

The cost of photovoltaic power has decreased over seven-fold in the past two decades and is projected to decrease a further four-fold in the next two decades [1]. PV already competes favorably in the United States for certain niche markets, (e.g., accent lighting, security lighting, sensing devices, water pumps, and communications). Many of these uses compete directly with grid-connected service, but non-grid-connected PV is chosen for convenience or to avoid the cost of electric connections. Current installed capacity in these applications in the United States amounts to about 60 MW, it is expected to grow about 10% per year through 2000 [2], and then its growth will accelerate, as our model predicts. PV is also cost-effective in remote applications where connection to the grid is not feasible, and the competition is diesel generators.

Near-term utility applications of PV in the US are likely to focus on peaking power and power-conditioning applications. Many utilities, especially in the Southwest, experience a peak load coinciding with peak solar insulation; this maximizes the value of PV for peaking power. The modular capability of PV allows utilities to install appropriate capacity levels in needed locations. Grid-connected demand-side systems are now being installed on roofs of buildings. Thirty-nine US utilities are testing grid-connected PV systems [3]. Several new demonstration installations are expected over the next five years.

Over the longer term (2000 to 2030), if the projected improvements in efficiency and cost materialize, PV may become competitive with fossil fuel plants. If drastic reductions in carbon emissions are required in the future, both energy demands and energy prices are likely to be affected. Carbon-free technologies, such as PV, then will have an additional advantage. A long-term potential application of PV is the production of hydrogen to provide a carbon-free fuel for heating and motive power. We did not consider this in the current analysis, but it was explored and found cost-effective under severe carbon emission constraints (over 20% below the current level) in Europe [4]. We used the NREL projections on the efficiency and cost of PV module in this analysis to characterize the capital and operating costs and the system's efficiency by vintage year (Table 1). We also used capacity factors ranging form 0.17 to 0.23, corresponding to the range of solar insolation of 1800-2480 kWhr/yr/m^2.

THE MODEL

The MARKAL-MACRO model (5) is an integration of MARKAL, a dynamic linear programming model that optimizes a technology rich network representation of an energy system, and MACRO, a single sector macroeconomic growth model. MARKAL was developed at the Brookhaven National Laboratory (BNL) in a collaborative effort under the auspices of the International Energy Agency (6,7). MARKAL-MACRO was also pioneered at BNL in close collaboration with Alan Manne, Stanford University. Most countries in OECD, over half-a-dozen economies in transition, and more than 20 developing countries and regions currently use MARKAL and MARKAL-MACRO.

In MARKAL, the entire energy system is represented as a Reference Energy System (RES), depicting all possible flows of energy from resource extraction through energy transformation and end-use devices to demand for useful energy services. Each link in the RES is characterized by a set of technical coefficients (e.g., capacity, efficiency), environmental emission coefficients (e.g., CO_2, SO_x, and NO_x), and economic coefficients (e.g., capital costs, date of commercialization). MARKAL finds the "best" RES for each period by selecting the set of options that minimizes the total system's cost over the entire planning horizon. By combining MARKAL (a "bottom-up" technological model) and MACRO (a "top-down" neoclassic macroeconomic model) in a single modeling framework (Figure 1), MARKAL-MACRO captures the interplay between the energy system, the economy and the environment, which is crucial in analyzing energy and environmental policies under sustainable development.

In optimizing the energy-economic system, the model explores a wide range of options, including reducing demands for energy services, investing in energy conservation measures, investing in higher efficiency supply and end-use devices, switching from coal or oil to natural gas, and switching from fossil fuels to renewable technologies. In addition to PV, renewable technologies explored by the model are wind, solar thermal, biomass fuels, wave, and ocean-thermal gradients. The model thus can evaluate the potential of PV in a competitive market environment. The cost characteristics of some of the competitive technologies are shown in Table 2.

SCENARIOS OF PV PENETRATION IN THE US

Three PV scenarios were studied in the analysis. To evaluate the full benefit of future PV market potential, we chose a Base scenario with PV cost and efficiency levels fixed at 1995 levels; this is labeled as "BASE". In the second scenario, we assume the NREL expectations of improvements in PV technology and cost (Table 1) and average US solar insolation of 1800 kWh/m^2-yr. Since large PV electricity generation plants are expected to be built in locations of better than average solar intensity, this case is labeled "Low-PV". In the third scenario we assume that all PV power plants would be built in the areas of the maximum US solar insolation (e.g., Arizona) where the solar insolation is 2480 kWh/m^2-yr; it is labeled "High-PV". Cases with solar insolation in the range of 1900-2400 kWh/m^2-yr were also examined. To complete the input data-base for model runs, each of these three basic PV scenarios was combined with the US MARKAL-MACRO data base used in the least-cost energy strategy study conducted by the U.S. Department of Energy (8).

Two model runs were made under each scenario, one with no limit on CO_2 emissions, and one with CO_2 emissions in 2010 through 2030 constrained at 20% below the 1990 level, which is one of the proposed reduction targets currently under discussion in the Framework Convention on Climate Change (9). Thus, six cases were generated; they are listed below.

Case Name	Description
BASE	Base Scenario, no CO_2 constraint.
BASE-20% CO_2	Base Scenario, 20% CO_2 reduction beginning in 2010.
Low-PV	Low solar insolation, no CO_2 constraint.
Low-PV-20% CO_2	Low solar insolation (1800 KWhr/m^2/yr), 20% CO_2 reduction beginning in 2010.
High-PV	High solar insolation (2480 KWhr/m^2/yr), no CO_2 constraint.
High-PV-20% CO_2	Southwest Scenario, 20% CO_2 reduction beginning in 2010.

RESULTS

The analysis examines three kinds of results. The first is the projected PV market penetration in the different cases. To what extent does the model find the technology cost-effective and how rapidly does it enter into the energy system? How is PV technology valued relative to its competitors? The second is the effect of investing in PV on U.S. CO_2 emissions.

How do these emissions change in the unconstrained cases? How is the marginal cost of CO_2 control affected in the carbon constraint cases? The third is the implication for the broader economy. What is the impact on gross domestic product (GDP) in the different cases?

Projected Market Penetration

Figure 2 shows the projected capacity of PV for the four basic cases cases. As expected, there is no new capacity of PV technologies installed neither in the "BASE" case nor in the "BASE-20% CO_2" case. Also, there is no significant market penetration of new PV technologies in the "Low-PV" case. In the "High-PV" case, PV becomes competitive and enters the market on a large scale (from 9 GW in 2010 to 140 GW in 2030). The projected difference in market penetration between the two cases indicates that site conditions are crucial in determining the economic competitiveness of the PV technologies as technically characterized by NREL. Under the constraints of the 20% CO_2 emission reduction, PV becomes competitive in the "Low-PV-20% CO_2" case and is projected to penetrate the market on a large scale after 2015. (Figure 3). In the High-PV-20% CO_2" case, PV energy is projected to reach its full market potentials specified in MARKAL-MACRO after 2005. As shown in Figures 4 and 5 the corresponding penetration of wind and biomass in the electricity market is projected to be much smaller. PV starts replacing mainly gas turbines in 2010 and later in 2020, also replaces coal steam plants (Figure 6). Table 3 shows the reduced costs (shadow prices) of PV technologies by vintage. Negative reduced costs indicate how much the economy would lose (in millions of 1990 \$) if one unit (in GW) of PV is forced into the energy system, in a given year. These values represent the non-competitiveness of PV in the centralized market for electricity supply, given today's environmental constraints; they assume zero credit to PV due to environmental benefits. Furthermore, these reduced costs do not reflect PV's value in the limited niche market (e.g., remote location) in which PV already has proven competitive against the grid, nor they reflect PV's value in non-grid application (e.g., electronics). Positive reduced costs represent the economic benefit gained on further increases in the capacity of PV above the bounds set in MARKAL-MACRO. In the "Low-PV" case, the absence of positive marginal costs (from -124 million \$ in 1995 to \$0 in 2030) explains the lack of PV market penetration in that case. Under relatively low insolation conditions, MARKAL-MACRO projects that PV will not compete favorably against other improving technologies such as advanced gas turbines, wind generators, and cogenerators. In regions, however, where the solar insolation is higher than 1900 $kWhr/m^2/yr$, PV does compete favorable with other electricity generating technologies, in time frames varying with the insolation. Under CO_2 emission constraints, the values of marginal cost in turn positive even in the "Low-PV-20% CO_2" -20% CO_2" case, showing cost-effectiveness of Central-PV systems even in relatively low solar intensity conditions.

Carbon Emissions and Control Costs

Figure 7 shows the projected carbon emissions for the four cases (CO_2 is represented by equivalent carbon). Assuming there are no constraints on carbon emissions, the "High-PV " case resulted in a reduction of over 64 million metric tons of carbon emission in 2030 from the "BASE" case carbon emission of over 2 billion metric tons. The total cumulative reduction over the entire 1995-2030 time frame in the "High-PV" case amounts to over 450 million metric tons. We note that most of the reductions occurred in the later periods, as shown in Figure 3; these reductions would be the beginning of a longer term trend as the market share of PV technologies is expected to keep increasing after 2030.

Table 4 shows the marginal costs of CO_2 reduction in the CO_2 constrained cases. These values represent the increase in total cost of the energy system to further reduce one ton of carbon emissions. They fluctuate from period to period, depending on the availability of efficient CO_2 mitigating technologies in a period. In the "BASE-20% CO_2" case, these values range from US$ 238 per ton in 2010 to 283 per ton in 2020. In the "High-PV-20% CO_2" case, the marginal CO_2 reduction costs are consistently lower than the "BASE" case, implying that the energy system becomes more cost-effective in controlling its future CO_2 emissions with the introduction of low-cost PV technologies. Although the marginal cost of CO_2 reduction in the "Low-PV-20% CO_2" case (with less favorable site conditions for PV technologies) are higher than those for "High-PV-20% CO_2", the availability of these technologies will still provide lower marginal costs for CO_2 reduction compared to the "BASE-20% CO_2" case. The marginal costs of CO_2 reduction derived in MARKAL-MACRO are direct measurements of a country's economic and technological flexibility to respond to a more stringent CO_2 emission standard in its energy system. Across different countries, they represent the basic information needed in analyzing strategies for mitigating CO_2 emissions at the global level.

Impact on Gross Domestic product (GDP)

Table 5 depicts the growth trends in GDP projected in MARKAL-MACRO for the six cases. Under the three CO_2 emission-reduction cases, the impact of higher energy cost is reflected in the economy through their lower GDP values relative to the projected GDP in the unconstrained cases. With or without CO_2 emission constraints, the introduction of low-cost PV technologies has a positive impact on GDP growth. The GDP is projected to grow at 1.82% per year in the "Low-PV" case. The growth projection increases slightly more in the "High-PV" case; the impact is about 0.1% per year accumulating to about \$3 billion out of \$11 trillion by 2030. When the carbon constraint is imposed, GDP growth slows to 1.77%/year in the "BASE-20% CO_2" case due to higher overall energy costs. However, the impact of PV technologies on GDP growth is larger in the "High-PV-20% CO_2" case under constraints, amounting to an increase of 24 billion dollars in 2030. The GDP growth does not account for job creation or manufacturing energy requirements for PV, competing technologies or a CO_2 mitigation industry. It only describes the impact of electricity costs to US customers.

CONCLUSION

This study shows the capabilities of MARKAL-MACRO in integrated energy-environmental-economic analysis. As an example, the penetration of Central-PV in the US was studied using this model. It was shown that, under our assumptions regarding cost and efficiency improvement, PV could be competitive as a general source of electricity supply to the grid in the southwestern U.S. by 2010. This PV penetration in the energy market would replace fossil-fuel combustion technologies and will, therefore, reduce the emissions of carbon by 450 million tons from 1995 through 2030 on a strictly economic basis. Such penetration may also help to lower the marginal cost of reducing carbon emissions generated from the US energy system. This study is limited to describing the impact of central PV stations in the highly competitive US energy market; it does not examine the PV prospects in the promising markets of the developing countries.

ACKNOWLEDGMENT

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Table 1. CHARACTERISTICS OF CENTRAL PV SYSTEMS [1].

	1995	2000	2005	2010	2020	2030
Capital Cost ($/W) [1]	6.250	3.125	1.785	0.893	0.714	0.571
O&M (Cents/kWh) [1]	2.7	0.6	0.3	0.2	0.1	0.1
Module efficiency, %	7	10	12	14	15	16

[1] Data supplied from NREL for flat panel stationary systems with lifetime of 30 years; Costs in 1990 US$;

Table 2. ESTIMATED COSTS OF SOME ELECRICITY GENERATION TECHNOLOGIES[1]

Technology	1995	2000	2005	2010	2020	2030
Central Wind[2]						
Capital ($/W)	0.816	0.792	0.779	0.799	0.779	0.779
Fixed O&M ($/W)	0.023	0.020	0.017	0.017	0.017	0.017
Natural Gas Combined Cycle[3]						
Capital ($/W)	0.691	0.691	0.691	0.691	0.691	0.691
Fixed O&M ($/W)	0.032	0.032	0.032	0.032	0.032	0.032
Var. O&M ($/GJ)	0.255	0.255	0.255	0.255	0.255	0.255
Biomass ATS Turbine Cycle[4]						
Capital ($/W)				1.060	1.060	1.060
Fixed O&M ($/W)				0.035	0.035	0.035
Var. O&M ($/GJ)				0.60	0.60	0.60
Biomass Combine Cycle[4]						
Capital ($/W)	1.242	1.242	1.242	1.242	1.242	1.242
Fixed O&M ($/W)	0.045	0.045	0.045	0.045	0.045	0.045
Var. O&M ($/GJ)	0.77	0.77	0.77	0.77	0.77	0.77
Coal Atmosph. Fluidized Bed[5]						
Capital ($/W)	1.440	1.440	1.440	1.440	1.440	1.440
Fixed O&M ($/W)	0.033	0.033	0.033	0.033	0.033	0.033
Var. O&M ($/GJ)	2.1	2.1	2.1	2.1	2.1	2.1
Coal Steam[6]						
Capital ($/W)	1.533	1.533	1.533	1.533	1.533	1.533
Fixed O&M ($/W)	0.020	0.020	0.020	0.020	0.020	0.020
Var. O&M ($/GJ)	1.35	1.35	1.35	1.35	1.35	1.35

[1] All costs are in 1990 US $

[2] Central Wind; Capacity Factor = 0.33

[3]. Natural Gas Combined Cycle; Capacity factor = 0.80

[4] Biomass ATS Turbine & Combine Cycle; Capacity factor = 0.80

[5] Hard Coal Atmospheric Fluidized Bed; Capacity Factor = 0.6

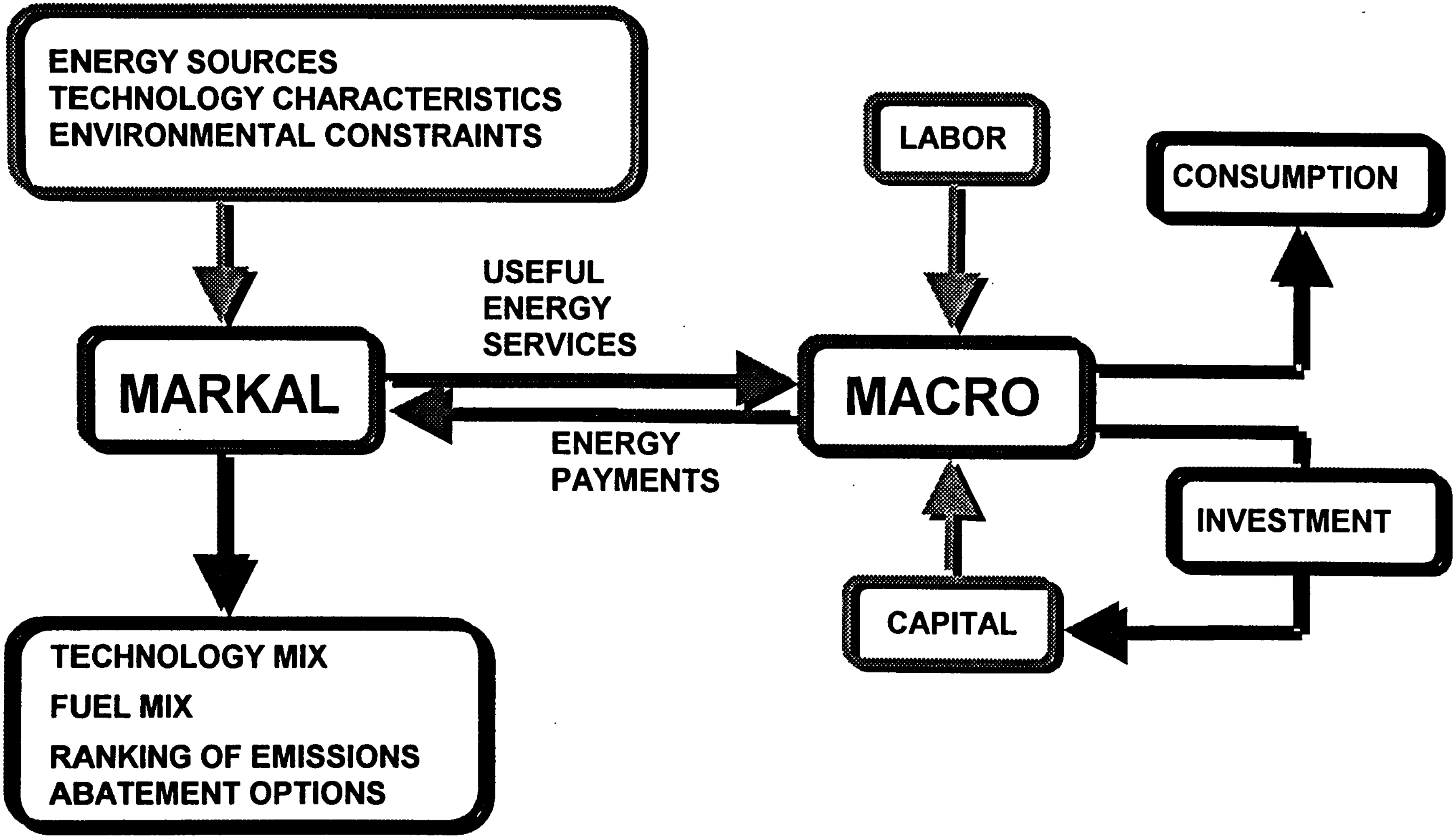
[6] Bituminus Coal Stem Electric; Capacity factor= 0.7

TABLE 3. MARGINAL COST OF PV (Million $/GW)					
	1995	2000	2010	2020	2030
Low-PV	-124	-100	-123	-63	0
High-PV	-78	-22	+5	+12	+25
Low-PV-20% CO_2	-119	-78	-52	0	+23
High-PV-20% CO_2	-50	0	+26	+34	+25

TABLE 4. MARGINAL COST OF CARBON REDUCTION ($/Ton)					
	2010	2015	2020	2025	2030
BASE-20%CO_2	238	272	283	275	267
Low-PV-20% CO_2	238	267	281	272	256
High-PV-20% CO_2	238	267	280	272	251

TABLE 5 GROSS DOMESTIC PRODUCT (In billion 1990 $)					
Case/Year	1995	2000	2010	2020	2030
BASE	6224	7045	8648	10094	11479
Low-PV	6224	7045	8648	10094	11479
High-PV	6224	7045	8649	10094	11482
BASE-20% CO_2	6224	7037	8537	9907	11249
Low-PV-20% CO_2	6224	7037	8538	9908	11262
High-PV-20% CO_2	6224	7037	8538	9910	11273

MARKAL-MACRO



ENERGY SOURCES
TECHNOLOGY CHARACTERISTICS
ENVIRONMENTAL CONSTRAINTS

MARKAL

USEFUL
ENERGY
SERVICES

ENERGY
PAYMENTS

MACRO

LABOR

CONSUMPTION

INVESTMENT

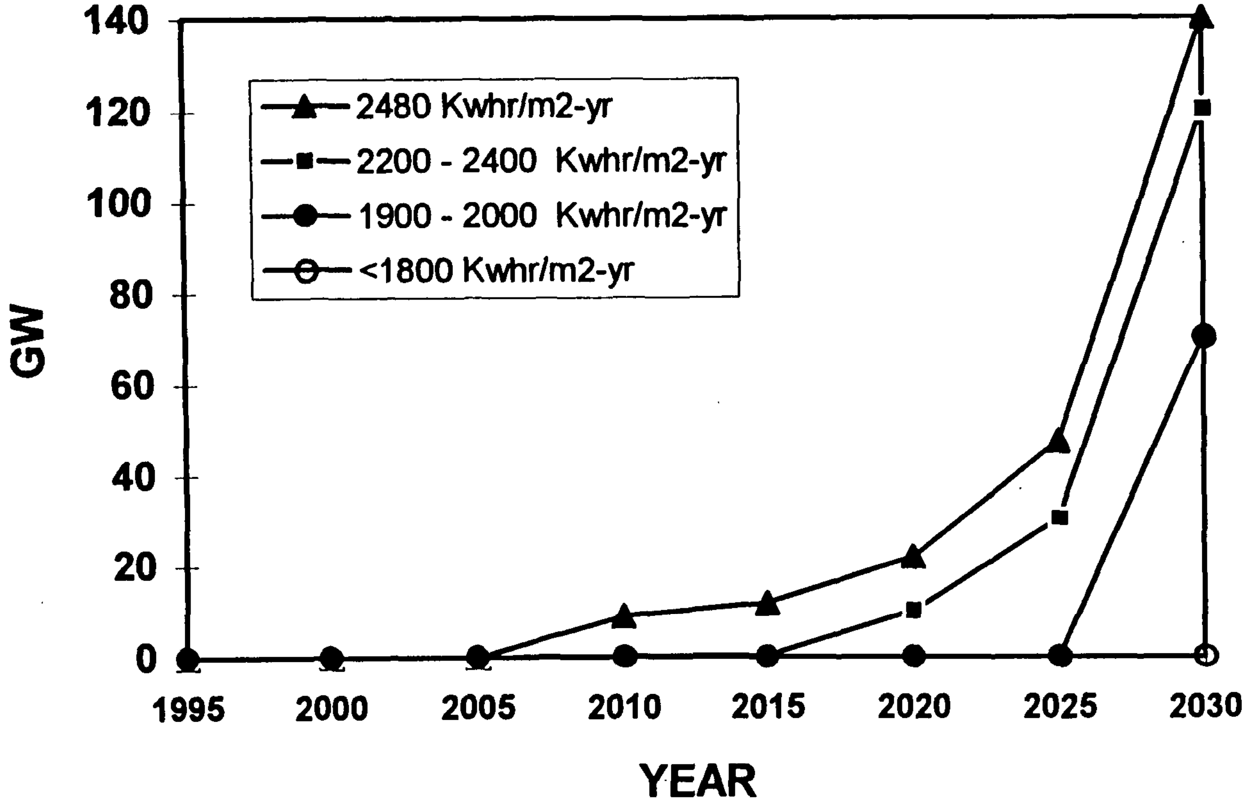
CAPITAL

TECHNOLOGY MIX

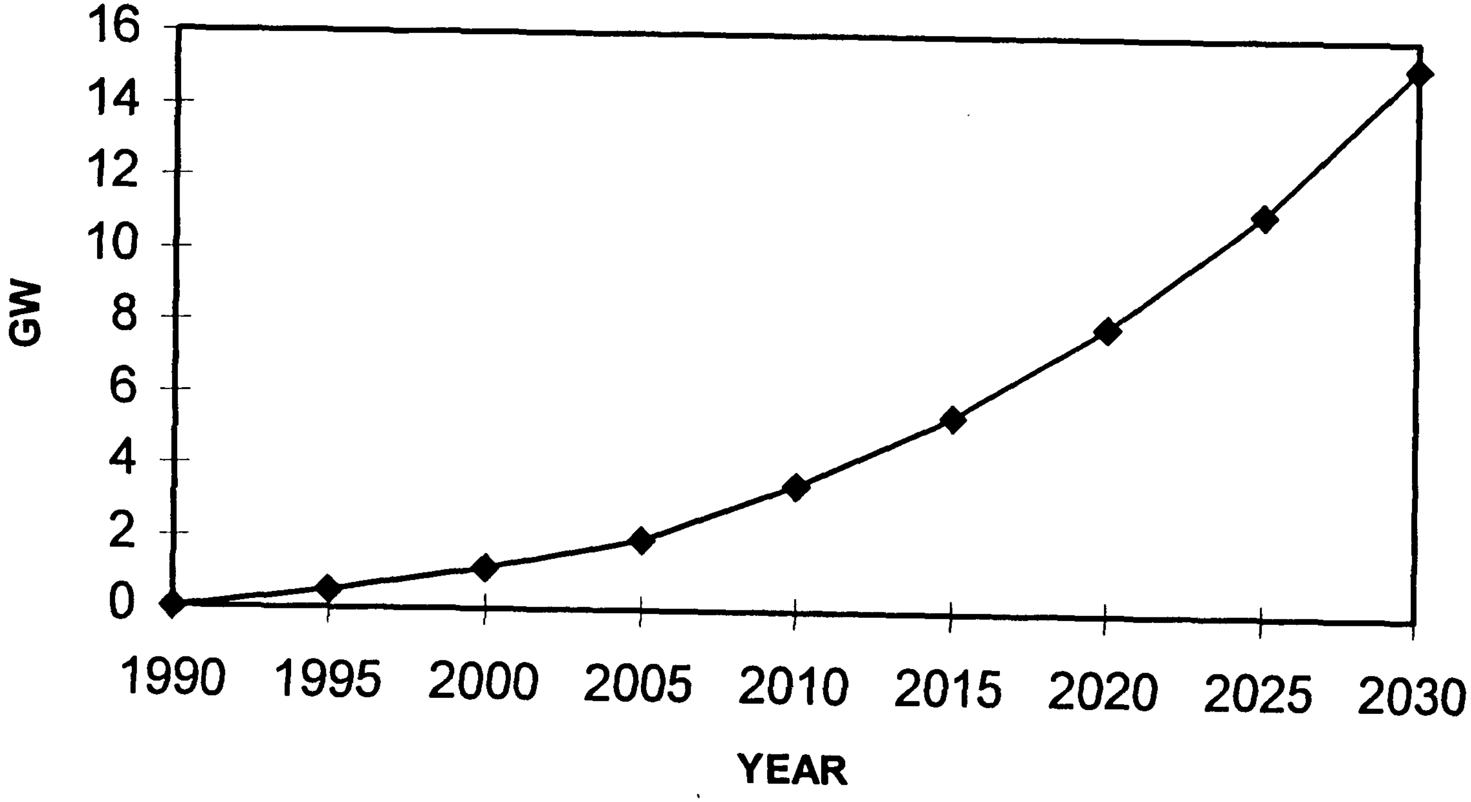
FUEL MIX

RANKING OF EMISSIONS
ABATEMENT OPTIONS

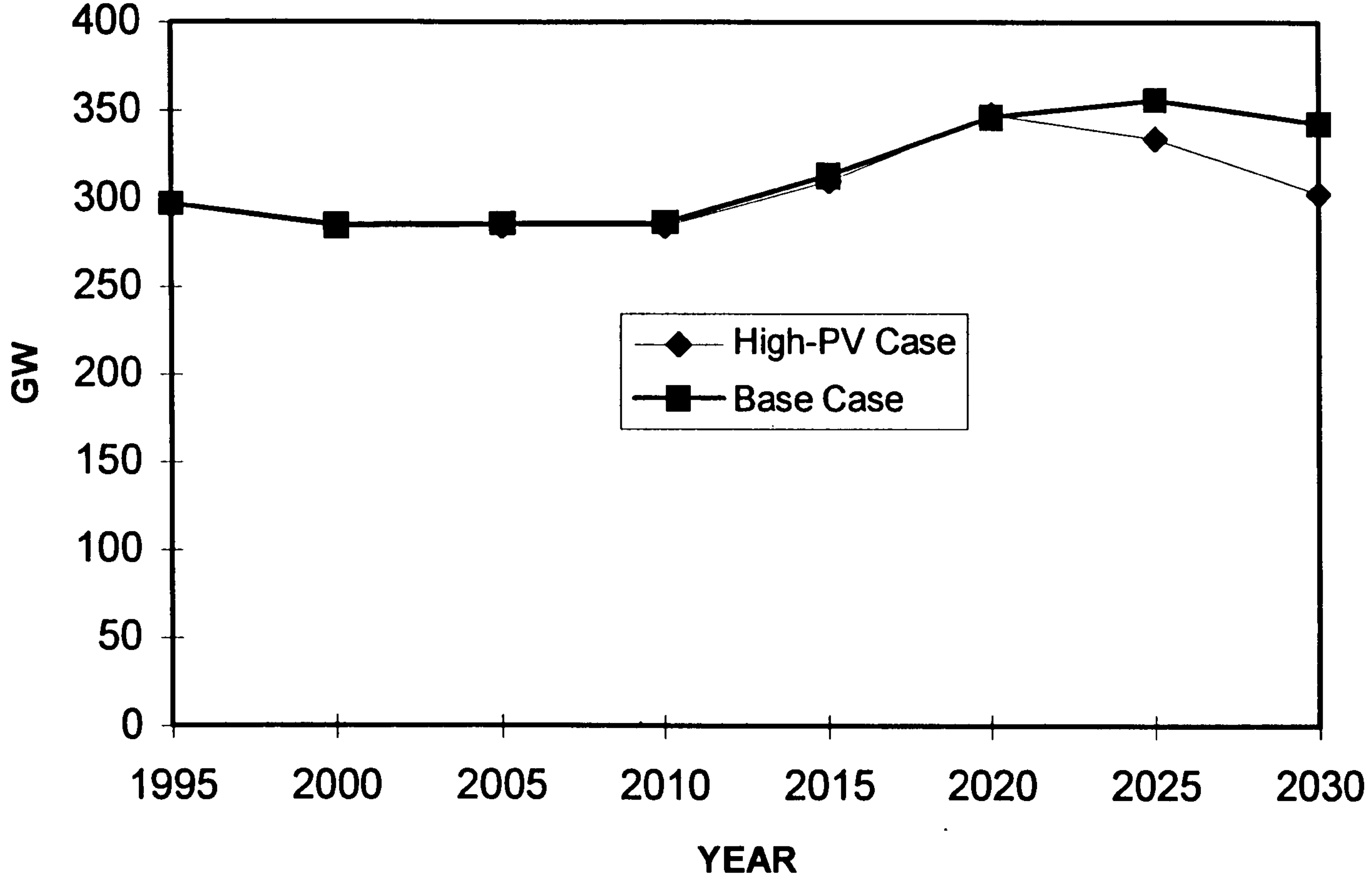
Projections of PV Penetration in the US



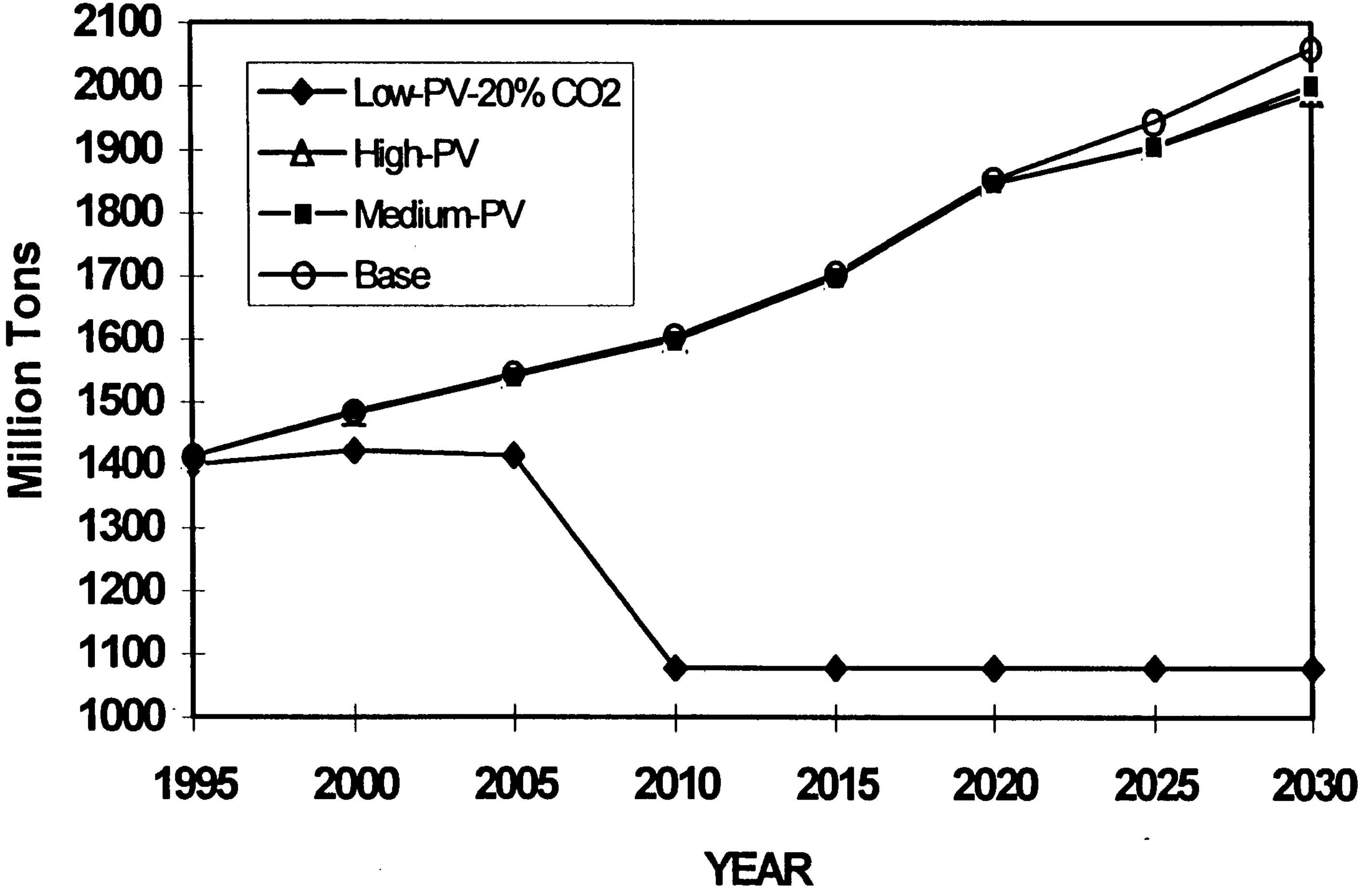
Projections of Biomass Generation Capacity in the US

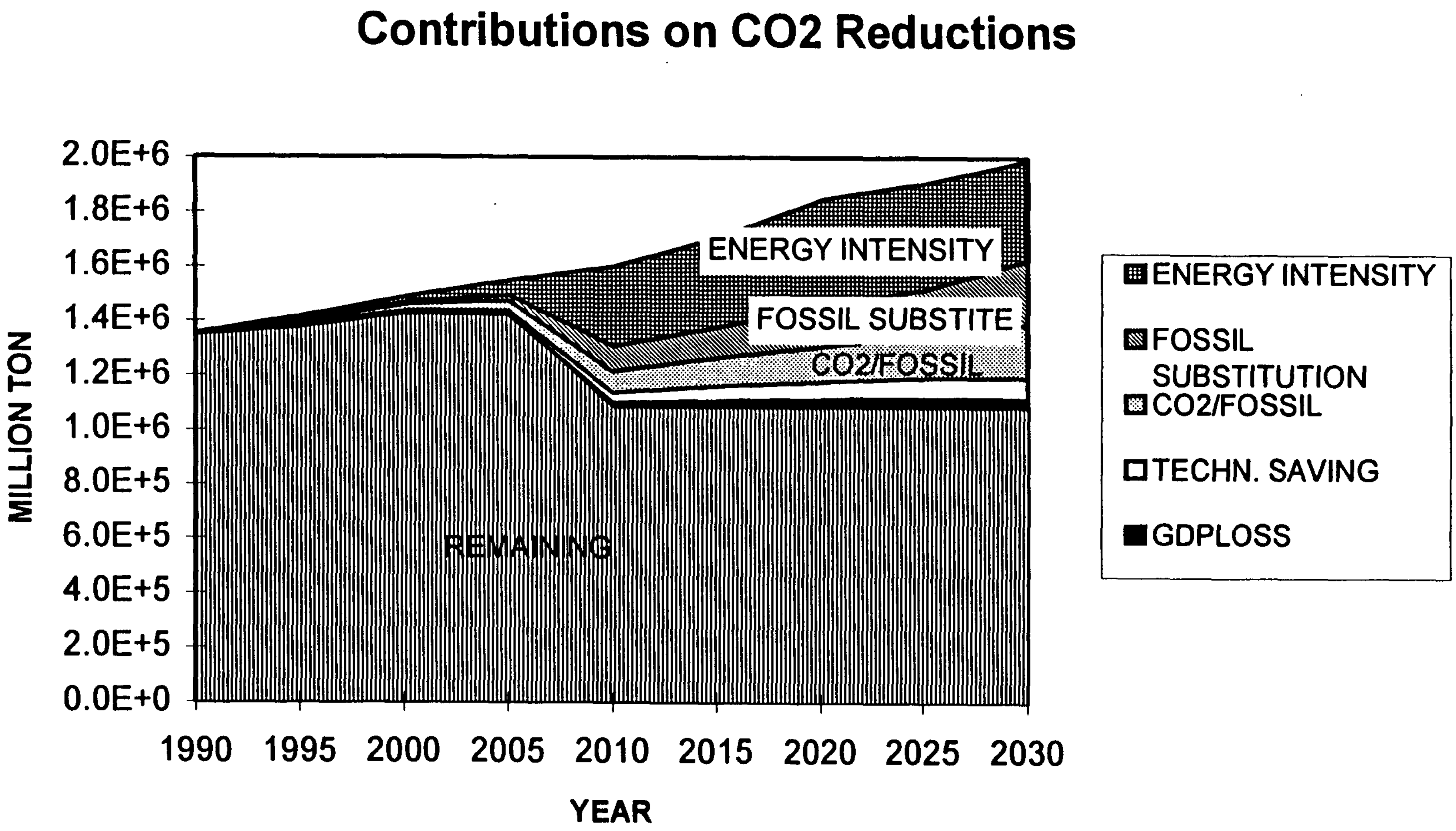


Projections of Coal Steam Power Plants
(under two PV scenarios)



Annual US Carbon Emissions




Contributions on CO2 Reductions
2.0E+6
1.8E+6
1.6E+6
1.4E+6
1.2E+6
1.0E+6
8.0E+5
6.0E+5
4.0E+5
2.0E+5
0.0E+0
MILLION TON
1990
1995
2000
2005
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2030
YEAR
ENERGY INTENSITY
FOSSIL SUBSTITE
CO2/FOSSIL
REMAINING
ENERGY INTENSITY
FOSSIL SUBSTITUTION
CO2/FOSSIL
TECHN. SAVING
GDPLOSS

2.5 Steve Johnson

Meeting Very Low Cost Goals for Cost-Effective PV

High-Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules

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Abstract. The main obstacle to the wide spread use of photovoltaics as a major source of renewable energy has been cost. The key to lowering the cost of photovoltaic generated energy to the levels of conventional sources of energy is to have a technology that is adaptable to manufacturing processes. It is necessary to have a technology that is scalable in order to reach the production throughputs needed to make the use of photovoltaic power economically viable. It is also necessary to have a stable end product in order to gain wide acceptance. Solar Cells, Inc. (SCI) has been working at producing large-area CdS/CdTe photovoltaic (PV) modules and the processes developed at SCI can be scaled to achieve high production levels at cost effective rates.

INTRODUCTION

Harold McMaster founded SCI in 1987. The focus at SCI from the very beginning was to develop and manufacture low cost PV modules on a large scale capable of producing energy at prices competitive with conventional energy sources. The concept would involve developing a continuous inline PV manufacturing process that would be coupled to a glass float line. Currently, the industry average manufacturing costs of a PV module is greater than \$3.00/watt. The SCI process would ultimately produce PV modules at less than \$.50/watt. The primary focus of this paper will be to review the advances in the development of semiconductor deposition equipment.

PROCESS

Initially, SCI began by working with amorphous silicon semi-conductor for the PV modules. Early on it became apparent that this technology did not fit SCI's goals of high throughput and low cost and therefore was abandoned. SCI's scientists began a search for a material system that would be compatible with the company goals. CdTe was selected for several reasons including the following: possesses an ideal bandgap, has a simple structure and requires no doping, films are well bonded, devices are inherently stable, materials are readily available, tolerant to impurities. Most importantly the process is adaptable to large scale manufacturing processes. For example, this process is performed in the low vacuum regime. Construction and maintenance cost are lower compared with a high vacuum system. The natural drive towards the stiochiometric formation of CdTe crystals allows greater latitude in operating parameters and therefore greater ease of manufacturing.

The process steps used to manufacture thin-film CdTe PV modules are listed in Figure 1. The key step in the process is the semiconductor deposition. SCI's scientist have developed a proprietary deposition process named Vapor Transport Deposition (VTD). This process has increased deposition rates by an order of magnitude over close space sublimation. The line speed for a glass float line is typically greater than 6 cm/sec. SCI has already demonstrated deposition line speeds of up to 4.6 cm/sec, which would coat a 60 cm X 120 cm substrate in less than 30 seconds. There are no technical obstacles in reaching line speeds equal to a glass float line.

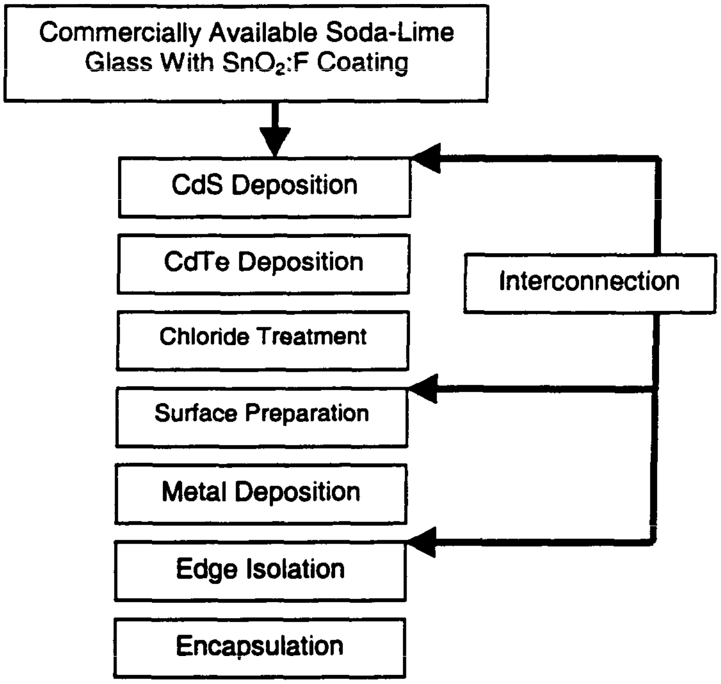

FIGURE 1. Process sequence in making CdTe PV modules.

EQUIPMENT

The semiconductor deposition process has been routinely demonstrated on the 100 kW pilot production coating equipment. This is a batch system with a load lock equipped vacuum chamber. SCI engineers are currently designing a production 50 MW semiconductor coating machine (Figure 2) for SCI's first manufacturing facility. The actual mechanism used in VTD is simple in design and operation. Presently cross webs of up to 120 cm are being coated with good uniformity and material utilization. The ability to increase the cross web coating capability presents no technical obstacles. The new 50 MW coating equipment will be capable of producing plates with a width of 120 mm and a length up to 240 mm.

The 50 MW coater is a scaled up version of the pilot production coating machine and will function similarly. An advanced 20 MW module finishing line will be built in conjunction with the 50 MW coater. This line will incorporate new technologies encompassing laser scribing, metalization and encapsulation processes. This line will be installed and operating by the year 2000. With this technology SCI will be able to reduce the cost of photovoltaics to approximately $1.00/watt.

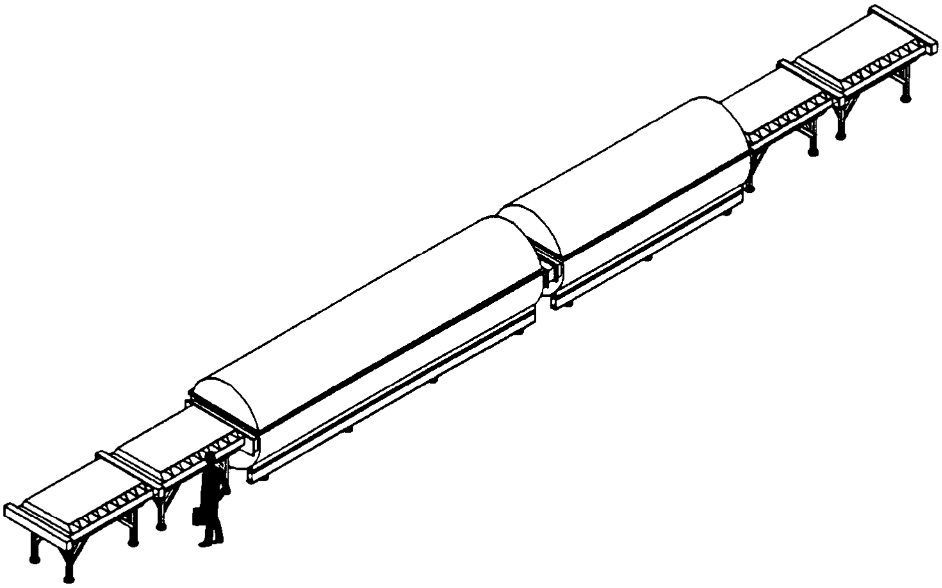

FIGURE 2. 50MW Production Coating Machine

As stated earlier, it will be necessary to incorporate a glass float line into a continuous inline semiconductor process in order to achieve the $.50/watt goal. This necessitates changing from a batch type operation using load locks to a continuos inline system.

Development has begun on the next generation coating equipment (Figure 3). By the use of a slit seal design, the load locks can be eliminated thus allowing the transport of a continuous glass ribbon substrate through the vacuum chamber. The coating would be done using the same VTD technology as in the load lock systems. The continuous coating system has been built, installed and is currently being tested. Initial testing involves the cycling of glass substrates through the system under simulated coating conditions. This will be followed by actual semiconductor coating trials. There are several advantages in using a continuous coating machine verses the load lock type. Throughputs can be higher due to the mechanical simplicity of the continuous machine. The vacuum portion of the system can be greatly reduced. Since all of the heating can be done at atmospheric pressure only the semiconductor coating portion needs to be under vacuum. The 50 MW coater has a vacuum system over 2100 cm long verses less than 100 cm long for the continuous coating machine. Not only does this reduce the capital costs involved but also the operating costs. The smaller vacuum chamber shortens the required startup and shut down cycle, therefore increasing up-time. The inline process eliminates many intermediate handling steps. Initially the glass will be reheated using a standard roller hearth furnace. This can be either electric radiant heaters or gas fired convection heaters that are particularly efficient at heating low-E glass very uniformly. When the process is integrated into a glass float line much of the energy used in making the glass will also be used during the process steps downstream, thereby requiring limited make up heat. The TCO would be made online using standard atmospheric coating processes. This will supply a pristine surface for semiconductor deposition. The scribing would be done online using multiple head lasers. Eventually metalization could be accomplished using VTD technology. The temperature profile of the process steps is favorable, in that temperatures are continuously decreasing. This eliminates the need for any re-heating.

FIGURE 3. Experimental Continuous Coating Machine

PERFORMANCE

Another important ingredient to the success of the process is the demonstrated stability of SCI's CdTe films. SCI Currently has eight module field installations actively producing solar energy and being used for demonstration and testing purposes. Product installed at the National Renewable Energy Labs in Golden, Colorado is completely stable after 2 ½ years of continuous outdoor exposure (Figure 4). This stability has also been confirmed by 40,000 hours of indoor testing performed at SCI.

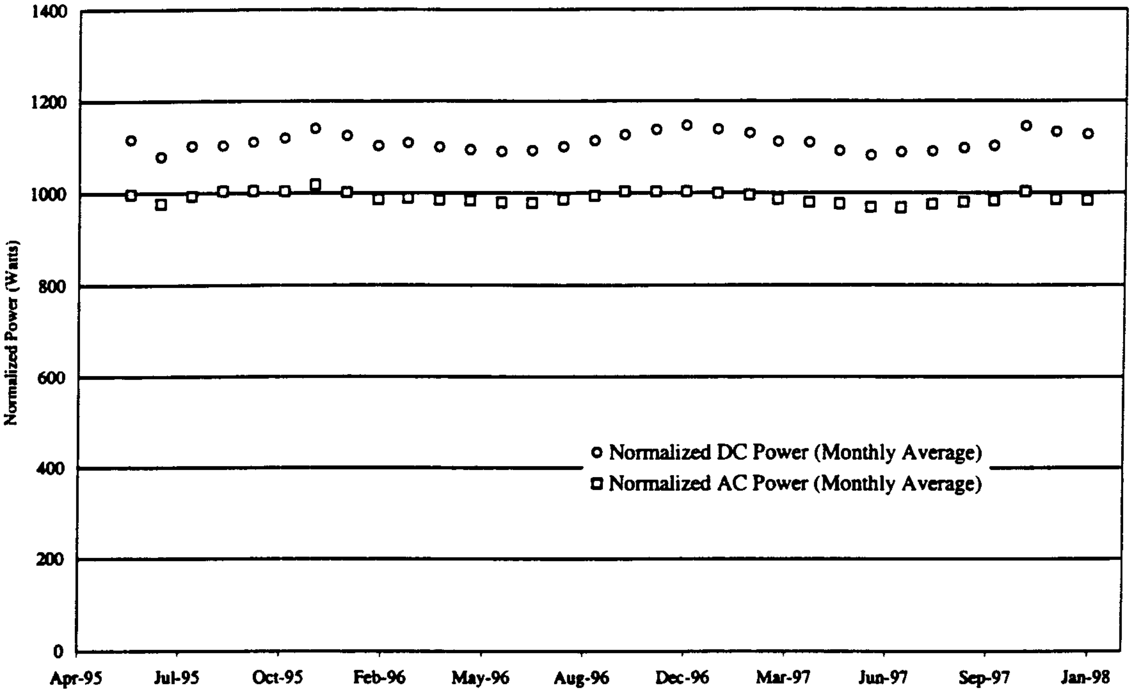

FIGURE 4. Stability Chart for Array Installed at NREL, Golden, Colorado.

SUMMARY

The focus at SCI has been the development of a high throughput low cost PV process. Significant progress has been made especially in the full scale demonstrations of high speed semiconductor deposition rates. This has allowed SCI to proceed with a design of a 50 MW coating machine that will be capable of producing product at a profitable rate. The next generation of coating equipment, using the in-line continuous process can ultimately achieve the PV cost goal of $.50/watt.

3.1 Ward Bower

PV Installations: Electrical Issues and Codes

Codes and Interconnect Safety Issues for Rooftop and Building-Integrated Photovoltaic System Installations

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ABSTRACT:

The United States does not have one single guideline, code or standard by which photovoltaic (PV) systems may be connected to the utility grids, or for installations of stand-alone or PV hybrid systems. Many utilities that are active in PV programs have written their own guideline for PV and other dispersed generation system interconnections. Where no such document exists, a number of standards, guidelines, codes and local rules are used. Utilities have documents to include grid performance issues such as harmonics or voltage operating ranges. The National Electrical Code (NEC) focuses primarily on fire and personnel safety.[1] The issues of waveform distortion, electromagnetic interference, power factor, voltage ranges, PV-system islanding, and performance are covered in a wide variety of other standards. The documents come from the Institute of Electrical and Electronic Engineers (IEEE), the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), and the International Electrotechnical Commission (IEC). Underwriter's Laboratories, Inc. writes standards for recognizing and listing of components. This paper will describe efforts to ensure that the National Electrical Code, Article 690 -Solar Photovoltaic Systems- includes the PV-unique requirements for safe installations of roof mounted and building-integrated systems and will overview the changes that will appear in the 1999 edition of the NEC. Efforts of the other standards making groups will also be reviewed and described.

INTRODUCTION:

There is not one single guideline, code or standard by which PV systems may be safely installed or connected to the utility grids, and it is equally true for installations of stand-alone or PV-hybrid systems. Many utilities that are active in PV programs have written their own guideline for PV and other dispersed generation system interconnections. Where no such utility-generated document exists, a selection of a number of standards, guidelines, codes and local rules are used. The most universal requirement however, is that PV system installations must meet requirements of the NEC as mandated by law in at least 40 states and by most major cities.[1] Where the NEC has not been adopted as law, it is often used with additional requirements that have been added to better fit the local environment.[2]

In addition to fire protection and safety as covered in the NEC, the issues such as waveform distortion, electromagnetic interference (EMI), power factor, voltage ranges, PV-system islanding, and performance are covered in a wide variety of publications. The documents come from the Institute of Electrical and Electronic Engineers (IEEE), the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), and the International Electrotechnical Commission (IEC). Underwriter's Laboratories, Inc. writes standards for recognizing and listing of components.

THE NEC:

The NEC, also (ANSI/NFPA 70), published by the American National Standards Institute/National Fire Protection Agency is the most used document for inspecting and accepting PV installations. The NEC does not address the issues of performance, power quality, islanding, operating windows for voltage or current (except for a 600-Volt limitation in one- and two-family dwellings), or power ratings. It does require components that are listed or certified by a recognized certification laboratory when those components are available. Also, the NEC is primarily a fire protection document, but it does now also address the issue of human safety with requirements for ground-fault interrupters and minimizing electrical shock hazards.

The NEC was established and has been continually revised and expanded since 1897. It deals with the safe installation and use of nearly all electric power components and systems that are outside of the utility owned and operated generation or distribution system. Control circuits, computer and data processing circuits, antenna cables and CATV systems, fire-alarm circuits, and nearly all other low- and high-powered electrical and electronic circuits are included. Automobiles, railroad cars, ships and self-contained, PV-powered devices like wristwatches, calculators, and small toys are not covered by the NEC.

Nearly all devices that have external electrical terminals, that must be wired or connected to other powered or power supplying devices, come under the auspices of the requirements established by the NEC. Motor-driven generators are also covered, as are systems with voltages less than 50 volts, emergency systems, and legally required standby power systems.

Article 690 -Solar Photovoltaic Systems-, covers PV systems and was added to the NEC in 1984. It has been revised and expanded in 1987, 1990, 1993, 1996 and now the1999 editions. Although 1984 was the first time PV systems were explicitly mentioned, there is a general understanding among electrical inspectors, who enforce code compliance, and some electrical contractors, that PV power systems have always come under the NEC.

Residential-size PV systems are limited to single-phase installations. Intermediate- and Central Station-size systems range into the megawatt size, are generally three-phase, and are covered by this same NEC Article 690. There is no categorization except for class of equipment that must be used to meet the voltage and power requirements. The NEC does limit the dc voltage for PV systems to 600 volts for residential applications, and this limitation was specified for one-and two-family dwellings for the 1999 NEC.

The 1999 NEC code revision cycle has been completed. There were fifty-nine proposals submitted for changes in Article 690 of the NEC this cycle by an ad hoc Task Group appointed by the National Fire Protection Association as requested by the chairman of Code Making Panel 3 (CMP#3). The Task Group was asked to provide expertise to determine if the scope of Article 690 was sufficient or if the Article needed to be rewritten. The Task group was also required to provide substantiation for each proposal it submitted and to study the issues that needed clarification or expansion in Article 690.

THE ARTICLE 690- SOLAR PHOTOVOLTAIC SYSTEMS- TASK GROUP:

Collaborative work was completed by the PV industry-supported Task Group to write proposals for changes to bring Article 690 of the 1999 NEC up to the state-of-the-art in PV device and system technology. The Task Group consisted of nine members was appointed by the National Fire Protection Association as an "ad hoc Task Group" for Article 690 - Solar Photovoltaic Systems. The Department of Energy's National Photovoltaic Program, the Solar Energy Industry Association (SEIA), and most importantly by all sectors of the PV module and balance-of-system industries supported the Task Group.

Seven meetings served to unify the PV industry participants on code issues. The meetings were held as joint events between the NEC Article 690 Task Group and the SEIA, Standards and Codes Technical Review Committee. Discussions, information exchange, and industry consensus also served to greatly clarify the needs and justifications for the proposed code changes. A number of the changes were needed because of recent advances in technology. They included AC PV modules, modular inverters with multiple modes of operation (utility-interactive, stand-alone, and hybrid), triple-junction PV modules, building-integrated PV such as roofing shingles, PV-laminated roofing, window walls, and facades. Many changes were also written to provide clarifications of the current language or to change requirements currently included in the NEC.

The Task Group wrote and submitted 59 proposals for PV system-related changes to the National Fire Protection Association (NFPA). The work concentrated on PV industry-prioritized issues related to safety and installation. Changes were proposed for fire and personnel safety, system servicing, AC PV modules, integration of PV into building electrical systems, point-of-connection for building-integrated systems, clarifications for hybrid systems, batteries, and charge controllers. All proposed changes made by the Task Group were based first on safety. Other considerations were PV system installation impacts, good engineering practice, interconnection with the utility grid, availability of hardware, and system cost and performance. Close coordination with Underwriters Laboratories, Inc. (UL) and the Institute of Electrical and Electronic Engineers (IEEE) standards committees have also been an important part of this work.[3][4][5]

SUMMARY OF ARTICLE 690 CHANGES FOR 1999:

Definitions

Changes addressed all sections of Article 690. A significant number of changes and additions were proposed in the definition section. They defined new devices, tied the Sections of Article 690 to the remainder of the code, and improved consistency in language throughout Article 690. Table 1 lists the new and changed definitions.

Definition	**Type of Change**	**Impact, Consequence or Description**
AC Module (AC PV Module):	New Definition.	Allows AC module applications. Defines AC modules as a complete listed package for Section 690-6 (AC Modules).
Array:	Minor Change to clarify and correct.	Removed the old reference to thermal controller.
Charge Controller:	New Definition.	Defined the role of charge controller in PV systems.
Electric Production and Distribution System:	New Definition.	Defined a utility grid as one that is not controlled by the PV system. Needed to better differentiate hybrid systems.
Hybrid System:	New Definition.	Defined hybrid systems and energy sources in hybrid systems.
Interactive System:	Change Definition.	Defined an interactive system as tied to the utility grid.
Inverter:	Change Definition.	Better defined charging functions associated with some inverters.
Inverter Input Circuit:	Minor Change to Clarify Application Definitions.	Defined inverter input circuit for both stand-alone and interactive inverters.
Inverter Output Circuit:	Minor Change to Clarify with New Figure 1.	Clarified definition to be consistent with new Figure 1.
Module:	Minor Change to Clarify New Definition.	Clarified definition and differentiated AC modules.
Photovoltaic Output Circuit:	Minor Language Change.	Changed to make language consistent.
Photovoltaic Source Circuit:	Minor Language Change.	Changed to make language consistent.
Stand-alone System:	Change to Clarify.	Clarified and removed tie to utility interactive systems.
System Voltage:	New Definition.	Added to provide consistency throughout Article 690.

Table 1. List of definition changes for 1999 Article 690, NEC

New Part I Added for Systems Greater than 600 V

One new part was written for Article 690 to provide requirements for PV systems operating at greater than 600 Vdc. It was designated Part I. The addition of Part I, dealing with PV systems with dc voltages greater than 600 volts, and clarification that installations in single- and two-family dwellings be limited to 600 volts, gives valuable safety requirements for PV installations. The addition also clarifies the intent of PV-system voltage calculations and requirements, and makes it perfectly clear that systems with maximum system voltages over 600 volts must use a different set of requirements consistent with Article 710.

New Sections for Article 690

Several new sections for Article 690 were also proposed for the 1999 NEC. One completely new section (Section 690-6 - AC Modules) was added to address requirements for the new AC PV module products and their connection to the utility lines. Other new sections included 690-10: Stand-alone Inverter, 690-11: Sizing and Protection, 690-52: AC Photovoltaic Modules, 690-54: Interactive System Point-of-Connection, 690-60: Identified Interactive Equipment, and 690-72: Charge Control. Some of the new sections consisted of language modified and/or moved from other parts of Article 690. Other changes were added for clarification and to address new applications, other new language and/or definitions.

PV-Unique Features Highlighted with Revised Figure

Revisions of the existing Figure 1 of Article 690 were needed to clarify the intent of the figure. Numerous installations have been plagued with uncertainty because designers have tried to use the existing figure for system design, or because electrical inspectors have insisted that the installed system should look like the figure. The new figure specifies that it is for component identification only and is purposely designed to identify PV-unique components, connections and system options. The new figure includes connection and configuration nomenclature and options for grid-tied, stand-alone, and hybrid PV system applications.

Removal of Cross References

Deletion of a requirement (690-3) to install a PV system in accordance with the provisions of Article 705 "Interconnected Electric Power Production Sources" clarifies PV-system installation requirements. PV systems and equipment have characteristics that are justifiably different from other interactive equipment such as uninterruptible power supplies and emergency generators addressed in Article 705. This deletion eliminated the cross-reference in the NEC and allows Article 690 to stand on its own for PV installations.

Ground Fault Protection

A revised Section 690-5 provides much needed clarification for ground-fault protection of residential roof-mounted PV installations for fire protection. The revisions provide rules for the detection, interruption and indication of ground faults. Indication is a very important addition here, since ground-fault interruption of grounded PV sources may involve disconnecting (or lifting) the grounded conductor or placing a high resistance in the ground path. The 1996 NEC gave no direction. The 1996 NEC Handbook tried to address the issue, but used the term "disable the array" that was a topic of more confusion, since the only way to truly disable an array is to block the sunlight. The revisions give requirements for disconnecting the faulted PV source, interrupting the fault current, and indicating the status or condition of the system.

AC PV Modules

A very significant proposal for building-integrated PV was the addition of Section 690-6 to provide the hardware, circuit and labeling requirements for installation of the new and evolving AC module technologies. Although just emerging as a new product, these devices will very likely find their way to hardware and department stores, architect's manuals, and builder's product lines by the time the 1999 NEC is issued. There have been more than 100 AC PV modules installed in the USA already, and new orders exist for more than 1000.

This new section provides the necessary functional requirements for safe installation and connection of listed AC modules to the utility lines and provides the requirements for labeling AC PV modules. The new section 690-6-AC Modules is reproduced below.

> ***(a) Photovoltaic Source Circuits.*** *The requirements of Article 690 pertaining to photovoltaic source circuits shall not apply to ac modules because the photovoltaic source circuit conductors and inverters are all one integral unit.*
> ***(b) Inverter Output Circuit.*** *The output of an ac module shall be considered an inverter output circuit.*
> ***(c) Disconnecting Means.*** *A single disconnecting means, in accordance with 690-17, shall be permitted for the combined ac output of one or more ac modules. Additionally, each ac module in a multiple ac-module system shall be provided with a connector, bolted, or terminal-type disconnecting means.*
> ***(d) Ground Fault Detection.*** *AC module systems shall be permitted to use a single detection device to detect only ac ground faults and to disable the array by removing ac power to the ac module(s).*
> ***(e) Overcurrent Protection.*** *The output circuits of ac modules shall be permitted to have overcurrent protection and conductor sizing in accordance with Article 240-4, Exception No. 2.*

Section (a) above acknowledges that AC PV modules have no user-accessible dc circuits and that other dc requirements of PV source circuits in Article 690 are not applicable. Section (c) allows the combined output of multiple AC PV modules to feed a single dedicated branch circuit provided that each AC PV module is provided with an accessible disconnect.

System Voltage versus Temperature Compensation

Section 690-7 begins with new language for determining maximum system voltage and other circuit requirements. The new Table 690-7, "Voltage Correction Factors for Crystalline and Multi-crystalline PV Modules," and the rules for applying the temperature correction for crystalline and multi-crystalline PV applications more accurately use local temperature corrections to open-circuit voltage in those systems. This table addresses the PV module technology (crystalline) that has the greatest temperature coefficient for open-circuit voltage. The temperature break points for the temperature ranges in the table are carefully selected to match PV modules that are commercially available. Section 690-7(a) also gives instructions to refer to manufacturer specifications when other than crystalline PV technologies are installed. The new table is reproduced below as Table 2.[3]

Ambient Temp. °C	For ambient temperatures below 25°C (77°F), multiply the rated open-circuit voltage by the appropriate factor shown below	Approximate Ambient Temp. °F
25 to 10	1.06	77 to 50
9 to 0	1.10	49 to 32
-1 to -10	1.13	31 to 14
-11 to -20	1.17	13 to -4
-21 to -40	1.25	-5 to -40

Table 2. Proposed Table 690-7 Voltage Correction Factors for Crystalline & Multi-crystalline Silicon Modules.

A comparison of the 1996 and the new 1999 NEC is provided here to illustrate the positive impact of the new Table 690-7. This example shows how the change will allow for continued safe installation of PV systems in all climatic regions of the country, while making allowances for regional climatic differences that were previously ignored and unnecessarily restricted the PV systems' designers and installers. The example is for a PV installation in Phoenix, AZ where the coldest temperature is -9°C (16°F). The example system uses crystalline silicon PV modules that are listed to UL Standard 1703.[3] The design requires strings of 24 series-connected modules, each with a rated open-circuit voltage of 22 V, to optimize performance and utilization of the inverter. The system designer or integrator must multiply the rated open-circuit voltage of the modules by 125% to allow for the worst-case cold-temperature of -40°C under the requirements of the 1996 NEC and using the current UL-1703 listing criteria. No allowance was provided for the fact that the coldest recorded temperature in Phoenix is -9°C. Using the 125% factor allows only 21 modules to be connected in series (21 X 22 X 1.25 = 577.5 Volts) to keep the string voltage less than 600V. Engineers using only UL label information on the PV module to design the example system have discovered that the inverter operating window no longer matched the PV array output, sometimes requiring expensive inverter modifications.

Using the new Section 690-7 and new Table 690-7 allows the designer or system integrator to calculate the system voltage using a temperature-dependent factor more in line with the Phoenix environment. The new calculation allows a multiplication factor of 1.13 from the new Table 690-7 that corresponds to a minimum temperature range of -1 to -10°C (31 to 14°F). With the new 1999 NEC, the system can now use 24 modules in series (24 X 22 X 1.13 = 597 Volts) and remains under the 600-volt limit for a residential application.

Solar Irradiance and Conductor Deratings

Solar irradiance of 1250 W/m^2 is common in many parts of the country. The integration of the PV module current factor of 125%, which is currently written as a UL requirement, and the NEC-required 80% derating factor for continuous current for all conductors and overcurrent devices has been needed. Many opened fuses and loose connections in early PV systems can be attributed to overheating due to undersized wiring or improper temperature ratings for terminal blocks and fuses. There has been much confusion in applying these factors because they appear in different documents, but the change (690-8) for 1999 puts all requirements in the NEC and simplifies the calculation. Coordination with UL will remove the 125% requirement from the UL-1703 Standard used for listing PV modules [3]. The new language is reproduced below [3].

> ***690-8. Circuit Sizing and Current.***
> ***(a) Computation of Maximum Circuit Current.*** *The maximum current for the specific circuit shall be computed as follows:*
>
> > (1) ***Photovoltaic Source Circuits.*** *The maximum current shall be the sum of parallel module rated short-circuit currents multiplied by 125 percent.*
> > (2) ***Photovoltaic Output Circuit.*** *The maximum current shall be the sum of parallel source circuit rated short-circuit currents as calculated in (1).*
> > (3) ***Inverter Output Circuit.*** *The maximum current shall be the inverter output current rating.*
> > (4) ***Stand-Alone Inverter Input Circuit.*** *The maximum current shall be the stand-alone inverter input current rating when the inverter is producing rated power at the lowest input voltage.*
>
> ***(b) Ampacity and Overcurrent Devices.*** *Additionally, circuit conductors and overcurrent devices in solar photovoltaic systems shall be sized at not less than 125% of the maximum currents as computed in (a) above. The rating or setting of overcurrent devices shall be permitted in accordance with Sections 240-3(b) and (c).*
>
> > *Exception: Circuits containing an assembly together with its overcurrent device(s) that is listed for continuous operation at 100 percent of its rating shall be permitted to be utilized at 100% of its rating.*
>
> ***(c) Systems with Multiple DC Voltages.*** *For a photovoltaic power source having multiple output circuit voltages and employing a common-return conductor, the ampacity of the common-return conductor shall not be less than the sum of the ampere ratings of the overcurrent devices of the individual output circuits.*

Interconnection Requirements

Two related new sections address connecting inverters to service entrance panels. They were written to clarify the requirements for supplying power (690-10) to service entrance hardware at lower than service panel rated currents and sizing conductors (690-11). Proposals using a "maximum system voltage" terminology were also written to provide code language consistency.

A proposal was also submitted to provide the necessary language in Section 690-64(b) to allow the ac connection of PV systems at the load side of the service disconnecting means or at any distribution equipment on the premises. This serves the practical side of PV systems since PV arrays may be located on the roof of buildings and the service disconnecting means is usually at a lower level in an equipment room. These changes will better facilitate building-integrated PV installations.

An example for a commercial PV interconnection is a PV-powered, electric vehicle charging station on a commercial building that has a main circuit breaker rated at 300 amps at the ac load center. Six 60-amp load circuits and breakers are connected to the load center to supply power to six battery chargers.

A 60-amp circuit breaker is added to the load center to allow the output from a PV utility-interactive inverter to supply PV power to the main panel, hence the charging stations. This new connection could allow the bus bars in the load center to be over loaded. If all six charging stations are drawing 60 amps and the PV system is supplying 60 amps, then the grid is supplying 300 amps. Circuit breakers would not trip, but the internal 300-amp bus bars in the load center could be over loaded and carrying up to 360 amps. Section 690-64(b)(2) requires that the sum of the ratings of all overcurrent devices connected to a cable, conductor, or bus bar be less than the ampacity of that conductor.

Solutions for adding PV to this system are to reduce the total ratings of the input breakers to be equal to or less than the load center rating.

1. The 300-amp load center could be replaced with a load center having a rating of 360 amps or higher while retaining the 300-amp main breaker.
2. If the actual power drawn by the charging stations were less than 240 amps, the rating of the main circuit breaker could be reduced to 240 amps while retaining the 300-amp load center.

The restrictions for residential installations (690-64(b)(2) (Exception)) are not as stringent as for commercial applications. The sum of the overcurrent devices in residential applications can be up to 120% of the rating of the load center.

A residential load center rated at 100 amps may accept a 20-amp feeder from a PV system (2400 watts of PV at 120 volts or 4800 watts at 240 volts). A load center rated at 200 amps may accept a 40 amp feeder from a PV system (4800 watts of PV at 120 volts or 9600 watts at 240 volts). These power levels are consistent with the maximum expected sizes of residential PV systems.

Inverters and Multi-wire Branch Circuits

A proposal to permit a single-phase, 120V inverter to supply power to a single-phase 120/240V service entrance panel provided there are no multi-wire branch circuits was made to clarify PV system connections to service entrance panels. There are estimated to be more than 50,000 such inverter installations already, but no allowance for them is given in the existing code. The multi-wire branch circuits contain a common neutral conductor that may be overloaded when used with single 120V-inverters. The task group will provide additional input to the NFPA to insure concerns are addressed in the 1999 NEC.

For example, many newer houses are wired with multi-wire branch circuits to reduce the cost of wiring. These multi-wire branch circuits are connected so that the 120/240V load center supplies a three-wire with ground cable from two circuit breakers connected to each (opposite) side of the 120/240V service. A common neutral is run with the ungrounded conductors to a remote location in the dwelling. The three-wire 120/240V cable is then split into two separate 120V branch circuits, and the common neutral conductor is spliced to two separate neutral conductors. The common neutral conductor (between the load center and the point where the circuit branches) carries the difference in currents from the two 120V branch-circuits when connected to 120/240V because the currents are 180° out of phase.

In a stand-alone PV system, a single, 120V inverter may be connected to the dwelling load center by connecting the output of the inverter to the two ungrounded conductors leading to the main load center disconnects. The currents in the two 120/240 conductors, which are out of phase when connected to a utility, are in phase when connected to a single inverter, and currents in the common neutral in the multi-wire branch circuit that subtracted (difference) are now in phase and add. When both of the 120V branch circuits are fully loaded, the neutral conductor in the multi-wire branch circuit now carries twice its rated current and is not protected by an overcurrent device.

Suggested solutions for connecting 120V inverters to service entrance panels include:

1. Removing the multi-wire branch circuits by rewiring into separate 120-volt branch circuits,
2. Connecting both hot conductors of the multi-wire branch circuit to a single circuit breaker,
3. Adding a second inverter to provide 120/240-volt power that is phased like the utility.

All solutions involve reconfiguration of the electrical system and should be made only if other code requirements, such as exceeding the maximum allowable number of receptacles on a branch circuit, are not violated. Additionally, the output current of a single inverter must be limited by a single overcurrent device rated no higher than the rating of the load center to prevent possible overloading of the neutral buss in the load center.

IEEE STANDARDS, RECOMMENDED PRACTICES AND GUIDELINES:

The IEEE has published seven standards and guidelines related to PV system components out of Standards Coordinating Committee 21 (SCC21) on Photovoltaics. IEEE Standard 1262, "Recommended Practice for Qualification of Photovoltaic Modules was the latest publication.[6] Other important SCC21 documents include terrestrial PV system criteria, recommended practices for installation of batteries for PV systems, and recommended practices for sizing of batteries for PV systems.[6][7][9] The recommended practices for batteries are now in the process of being recertified.[9]

PV System Safety Guideline

The fire safety and personnel safety of installed PV systems is a top priority for designers, installers, inspectors and users. The NEC spells out the installation requirements for installation of all electrical systems, but the 1069 pages are often unfamiliar to those involved with PV systems. A Project Authorization Request (PAR) 1374 to write a guideline titled "IEEE Guide for Terrestrial Photovoltaic Power Systems Safety" has now been completed. The guideline has been successfully balloted and will become IEEE Standard 1374 during the fall 1998. It is written to provide an easily read safety document targeted specifically for PV systems. It is closely correlated with the NEC and other ANSI/IEEE recommended practices and standards.

The purpose of the guide is to describe PV-specific topics or components related to the design and installation of PV power systems that affect safety, and to suggest good engineering safety practices for PV electrical balance-of-system design, equipment selection and hardware installations. PV-unique electrical power requirements are emphasized in the guide. The guide describes system types and addresses wiring for PV modules, balance-of-system, and batteries. Particular attention is given to the critical temperature considerations required for PV systems at the module and array level, voltage ratings, cable and insulation types, wiring ampacity, and sizing calculations needed for safe and reliable design. Other important topics such as overcurrent protection, disconnects, grounding, surge and transient protection, and instrumentation are also described with examples and recommendations for selection of the hardware. The guide is carefully cross-referenced to the applicable articles and sections in the NEC.

Utility Interconnect and Interface Guidelines

A very critical standard for utility interface and interconnects, now designated PAR929, "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems," is currently being revised and rewritten with a targeted publication date also late 1997. This document is being revised by utility and PV industry experts to integrate the utility and PV system issues into a document that can be used by utilities, designers and installers for utility-interactive PV systems.

Important issues that are the focus of the PAR929 revision include defining the requirements for inverter shutdown under abnormal utility condition, anti-islanding protection, reconnect after a utility disturbance, the need for manual disconnects, power quality requirements, and direct current isolation.

Field Test Methods for Grid-Connected PV Systems

Field test methods are being formulated for PV systems through an approved project authorization request designated PAR1373, "Recommended Practice for Field Test Methods and Procedures for Grid-Connected Photovoltaic Systems," The PAR was issued in 1993, and the document has now been reviewed by the committee. The test methods specified in this document could be used for confirming performance of newly installed PV systems or used to obtain data to determine if systems were subject to degradation over time. Tests for inverters, modules, and arrays will be included in the guideline.

PV Module Energy Rating

A project authorization request was submitted for module energy rating in July 96 and was approved in September 1996. The working group includes industry applications groups and was designated PAR1479. Work is progressing and the draft has been submitted to the SCC21 committee for review.

Concentrator PV Receivers and Modules

A project authorization request was submitted for concentrator PV technologies including the receiver sections and PV modules has also been submitted. It is awaiting IEEE standards board PAR approval. The approval is expected during the summer of 1998 and work is progressing toward a standard for testing and certifying concentrator PV hardware.

LISTING STANDARDS:

Underwriters Laboratories, Inc. is currently in the process of reviewing the proposed first edition of the "Standard for Inverters, Charge Controllers and AC Modules for Use in Residential Photovoltaic Power Systems, UL1741". UL conducted an UL Industry Advisory Group (IAG) meeting in January 1997 to review the latest version of their Subject 1741, the draft standard intended for listing inverters and charge controllers and AC modules for use in PV power systems. The meeting was held to allow IAG members to provide PV industry input during preparation of the draft standard and before public review. The IAG consisted of participants associated with PV module manufacturing, inverter manufacturing, charge controller manufacturing, ac module development, systems integration and the US DOE Photovoltaic Program. The UL goal for publishing the completed standard projected for December 1998 but correlation with the IEEE P929 may delay the publish date. The draft UL1741 now includes new language for testing and listing of AC modules, charge controllers and inverters. [4] Dates were established to coincide with the 1999 NEC in order that code changes may also be reflected in the UL standard. The timing also allows UL to incorporate requirements spelled out in the revised IEEE 929 "Guideline for Interconnection of Photovoltaic Power Systems to the Utility Grid" in the UL1741. UL has also begun review of their UL1703 "Standard for Flat-Plate Photovoltaic Modules and Panels."[3]

ASTM:

There are more than 20 ASTM standards related to PV systems, performance, testing, reference cells, insulation integrity, mechanical integrity and corrosion testing for PV components.[10][11] Additional six documents are being worked on with expected publication dates in the 1999 time frame. Documents being written or revised, as of April 1997, include a test method for electrical performance and spectral response of multi-junction PV cells and modules, a test method for PV array wet insulation resistance, a specification for solar simulation for terrestrial PV testing, test methods for measuring spectral response of PV cells, and a test method for PV modules in cyclic temperature and humidity environments.

IEC TECHNICAL COMMITTEE 82 (IEC 82) STANDARDS:

The IEC TC 82 has published more than 19 PV-related standards. PV-related standards already published include procedures for measuring I-V characteristics and using temperature and irradiance correction to the measured I-V characteristics for PV cells and modules, spectral response and mismatch measurements, solar simulator performance requirements, overvoltage protection for PV systems, characteristics of stand-alone PV systems, module design qualification for crystalline and thin-film PV, corrosion testing, impact damage, utility interface characteristics, and on-site measurements of I-V characteristics of PV arrays.[8] Work underway includes a new safety standard for PV modules, a PV module environmental test standard for marine environments, a new method for determining the linearity of PV devices, a new method for defining solar simulator requirements, and new standards for rating PV modules for power and energy delivery. IEC standards are considered to be the most likely base-line criteria for the emerging PVGAP (global accreditation program).

IEA PV POWER SYSTEMS COLLABORATION:

The IEA Photovoltaic Power Systems (IEA PVPS) Implementing Agreement was established in 1993 as an effort by 20 countries to focus on the planning, design, construction, operation, performance, and promotion of photovoltaic power systems. The mission of the program is to enhance international collaboration efforts through which photovoltaic energy becomes a more significant energy option in the near future. The United States is currently active in five of the seven annexes of the implementing agreement as listed below.

Task I is responsible for the exchange and dissemination of information on photovoltaic power systems (PVPS). Task IV is focused on modeling of dispersed PVPS in support of the utility grid, but currently is limited to an *ad hoc task group* between the USA and Italy. Task V concentrates on the technical issues for grid interconnection of building-integrated and other dispersed PVPS. Task VI focuses on the design and operation of modular photovoltaic plants for large-scale power generation. Task VII has just begun and will focus on PVPS in the building environment. Task VII held the second official meeting at Soltech98 in May 1998. Task VII concentrates on building-integrated PV systems and issues. A new Task IX is currently being proposed to address issues associated with PV applications and infrastructure in developing countries.

US participation concentrates primarily on Task I, Task V and, recently, Task VII. Task I has identified three subtasks. They are to publish a PVPS status survey report to be updated every two years, to provide quarterly newsletters, and to hold an executive conference on strategic photovoltaic business opportunities for utilities. The second bi-annual survey report was published in March 1997 and has been distributed to the US photovoltaics industry through the Edison Electric Institute and Sandia National Laboratories. The Edison Electric Institute participates in Task I by supporting their US expert while Sandia provides the alternate expert member and technical support for the task. The "Executive Conference on Strategic Photovoltaic Business Opportunities" was held in the US in September 1995 as part of Task I activities.

The US DOE participates directly in Task V and a new Task VII through Sandia and the National Renewable Energy Laboratory. Task V has an overall objective to develop and verify technical requirements that will serve as technical guidelines for grid interconnections for building-integrated and other dispersed power systems. These guidelines focus on safety and reliable interties to the grid at the lowest cost. The work focuses on three categories: review, definition of guidelines, and collaborative testing to demonstrate technical issues such as islanding or control algorithms with solutions to identified problem areas. Task V has already published reports on existing interconnect guidelines for PVPS interconnections and on utility distribution systems. A report on interconnection equipment is also available for distribution to industry. Nine technical topics are under investigation in Task V for addressing utility-interconnect guidelines. A summary of the findings and proposed guidelines for each will be published as part of the final report for Task V and distributed through Sandia and the IEA. The final report will be presented at the next Task V meeting in Albuquerque in September 1998.

Another important milestone for Task V work was an international workshop that was held in Zurich, Switzerland on September 15 and 16, 1997. The workshop was designed to involve utilities, inverter manufacturers, photovoltaic system suppliers, and engineers in international discussions to discuss guidelines that may be used and an international level. Topics included islanding, reclosing, external-disconnect requirements, overvoltage protection, grounding, and dc injection.

SUMMARY:

Publication of the 1999 NEC, with a strong and well-developed Article 690 on PV power systems, represents a safety code that enables PV systems to be installed with well understood requirements, to be easier to inspect, and, above all, to be safer for the user and for maintenance. Good installation practices required by the NEC will also improve long-term system performance and reliability. Publication of new IEEE standards and guidelines will serve the PV industry and the utilities by providing clearly defined qualification procedures, interface requirements and design criteria. ASTM standards already in place and scheduled for publication in the near future will provide the means for test methods for components and materials. The IEC international standards will provide the international perspectives and requirements for the manufacturers and designers of PV systems. Convergence of the publication of these codes, standards and guidelines in the 1999 time frame will strengthen the PV industry's ability to design, install and apply the technology in a wide range of applications.

ACKNOWLEDGMENTS:

The author acknowledges the important and critical contributions of many dedicated engineers working in the collaborative efforts to bring codes and standards for PV systems applications up to the state-of-the-art of the technology. A few of the leaders are listed here. Richard DeBlasio of the National Renewable Energy Laboratory (NREL) chairs the IEEE Standards Coordinating Committee 21 (SCC21) on Photovoltaics. Jodi Smyth of UL's Engineering Services Department is the project engineer designated to prepare and review PV-related standards at UL for publishing. Carl Osterwald of NREL is the chairman of E44.09 for photovoltaic electric power conversion test methods through ASTM. Jerry Anderson represents SEIA and holds the secretariat position in the International Electrotechnical Commission (IEC) Technical Committee 82, and Steve Chalmers is the Secretary of Working Group #3 (systems) under the IEC TC82 work. Additionally, Mr. Chalmers represents US for the Technical Advisory Group for WG#3.

Subcommittee chairs working on PARs under the SCC21 include John Stevens of Sandia for PAR929, Chuck Whitaker of Endecon for PAR1373, John Wiles of the Southwest Technology Development Institute for PAR 1374, Ben Kroposki of NREL for PAR 1479, and Jay Chamberlin of Sandia National Laboratories for IEEE1013, IEEE1144, IEEE 1145, and PAR1361.

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[11] *Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules,* ASTM: E1462-94, American Society for Testing and Materials, Philadelphia, PA, April 1994.

IEEE Standards/Guidelines for PV Components and Systems

Document #	Title
519	IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters
928	IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems.
929	IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic Systems. (Being Rewritten)
937	IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems
1001	IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems
1013	IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems
1035	IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters. (Out of Print)
1144	Sizing of Industrial Nickel-Cadmium Batteries for Photovoltaic Systems
1145	IEEE Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic Systems
1146	IEEE Recommended Practice for Grounding of Battery Subsystems in Photovoltaic Systems
1262	Recommended Practice for Qualification of Photovoltaic Modules
1374	Guide for Terrestrial Photovoltaic Power System Safety
WG C5	Special Publication on Static Power Converters Serving as the Utility Interface Package (IEEE PES Power System Relay Committee, WG C5)
C62.41	IEEE Recommended Practice on Surge Voltages in Low-Voltage AC power Circuits

IEEE Standards/Guidelines In Process for PV Components and Systems

Document #	Title
P 1361	Recommended Practice for Determining Performance Characteristics and Suitability of Batteries in Photovoltaic Systems
P 1373	Recommended Practice for Field Test Methods and Procedures for Grid-Connected Photovoltaic Systems
P-1479	Recommended Practice for the Evaluation of Photovoltaic Module Energy Production
P-1513	Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules.
P 926	PV Energy Performance Ratings.
P 927	PV Energy Calculations.

ASTM E44.09 Standards/Guidelines for PV Components and Systems

Document #	Title
E 927-91	Specification for Solar Simulation for Terrestrial Photovoltaic Testing
E 948-83	Test Methods for Electrical Performance of Non-Concentrating Terrestrial Photovoltaic Cells Using Reference Cells
E 973-91	Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
E 1021-91	Methods for Measuring the Spectral Response of Photovoltaic Cells
E 1036-85	Methods of Testing Electrical Performance of Non-Concentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E 1038-93	Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls
E 1039-85	Method for Calibration and Characterization of Non-Concentrator Terrestrial Photovoltaic Reference Cells Under Global Irradiation
E 1040-93	Specification for Physical Characteristics of Non-Concentrator Terrestrial Photovoltaic Reference Cells
E 1125-86	Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum
E 1143-87	Test Method for Determining the Linearity of a Photovoltaic Device with Respect to a Test Parameter
E 1171-93	Test Method for Photovoltaic Modules in Cyclic Temperature and Humidity Environments
E 1328-90	Terminology Relating to Photovoltaic Solar Energy Conversion
E 1362-90	Test Method for the Calibration of Non-Concentrator Terrestrial Photovoltaic Secondary Reference Cells
E 1462-92	Test Method for Insulation Integrity and round Path Continuity of PV Modules
E 1524-93	Test Method for Saltwater Immersion and Corrosion Testing of Photovoltaic Modules for Marine Environment

ASTM E44.09 Standards/Guidelines in Progress for PV Components and Systems

Document #	Title
131	Test Method for Concentrator Devices
192	Test Method for Solar Radiation Weathering of Photovoltaic Modules
198	Test Method for Saltwater Pressure, Immersion and Temperature Testing of Photovoltaic Modules for Marine Environments
199	Test Method for Wet Insulation Integrity Testing of Photovoltaic Modules
200	Test Method for Electrical Performance and Spectral Response of Multi-junction Photovoltaic Cells and Modules
201	Test Method for Mechanical Integrity of Photovoltaic Modules

IEC TC-82 Standards/Guidelines for PV Components and Systems

Document #	Title
IEC-891	Procedures for Temperature and Irradiance Corrections to Measured I/V Characteristics of Crystalline Silicon PV Devices
IEC-904-1	Measurement of PV I/V Characteristics
IEC-904-2	Requirements for Reference Solar Cells
IEC-904-3	Measurement Principals for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data
IEC-1173	Over voltage Protection for PV Power Generating Systems
IEC-1215	Design and Type Approval of Crystalline Silicon Terrestrial PV Modules

Underwriters Laboratories Inc., Certification for PV Components

Document #	Title
UL-1703	Flat-Plate Photovoltaic Modules and Panels*

*Note: Various Certification Laboratories use a combination of their standards and UL Standards for testing. Other Non-PV Standards are used where needed.

Proposed Underwriters Laboratories Inc., Certification for PV Components

Document #	Title
UL-1741	Proposed Draft of the Standard for Static Inverters and Charge Controllers For Use in Photovoltaic Power Systems

Current National Electrical Code for PV Systems

Document #	Title
ANSI/NFPA 70-1996	National Electrical Code, Article 690 and Other Pertinent Articles Related to Solar Photovoltaic Systems

Current FCC Documents Used for PV Components and Systems

Document #	Title
FCC Rules & Regulations	Part 15, Radio Frequency Devices, Subpart B

1. Note: Some of the documents associated with batteries are typically not used with grid-interactive systems but may be used with some of the new bi-mode or four-quadrant inverters and also PV arrays.

3.2 Paolo Frankl

Analysis of Energy/CO_2 Aspects of Building Integration

ANALYSIS OF ENERGY AND CO_2 ASPECTS OF BUILDING INTEGRATION OF PHOTOVOLTAIC SYSTEMS

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SUMMARY

In the past, most of net energy or environmental analysis studies of photovoltaic (PV) systems have been focused on the module manufacturing issues. On the contrary, this paper focuses more on the Balance-of-System (BOS), particularly as far as building integration is concerned. It is argued that as PV module technologies and manufacturing processes improve, the contribution of BOS will proportionally became more significant. The first objective of the study is to quantify the materials and energy flow related to BOS during the installation of PV systems. The second objective is the quantitative evaluation of the benefits of building-integrated PV systems over their entire life-cycle and the identification of best solutions to maximize their energy efficiency and CO_2 mitigation potential. The results of a simplified Life-Cycle Analysis (LCA) are reported. Firstly, a number of existing applications have been studied. Secondly, a parametric analysis of possible improvements in the Balance-of-System (BOS) has been developed. Finally, the two steps have been combined with the analysis of both crystalline and amorphous silicon technologies. Results are reported in terms of several indicators: energy pay-back time, energy yield, and net CO_2 balance. The indicators show that the integration of PV systems in buildings clearly increases the environmental benefits of present PV technology.

1. INTRODUCTION

The integration of PV systems in buildings shows several advantages with respect to conventional PV power plants in open fields. Major benefits are the occupation of ground and surfaces that are already used for other purposes, the saving of construction material needed for PV module supporting structures, the substitution of building envelope materials, and the possibility of recovering a significant fraction of the thermal energy dissipated by the PV panels. The objective of the present study is twofold: the first goal is to quantify the relevance of Balance-of-System (BOS) in terms of energy consumption and emissions during manufacturing and installation of PV systems. The second objective is to quantify the benefits of the integration of PV systems in buildings over their entire life-cycle, in terms of energy consumption and related emissions.

2. METHODOLOGY: THE SIMPLIFIED LIFE CYCLE ANALYSIS

Given the complexity of the systems studied and the wide range of materials involved in the analysis, a *simplified* LCA has been applied to PV systems. The results are reported in terms of energy consumption, energy pay-back time and CO_2 emissions. Firstly, a number of existing applications have been studied, namely the Serre power plant and several examples of integration in buildings. Secondly, a parametric analysis of possible improvements in the BOS has been developed and included in the model. Finally, the two steps of the analysis have been combined with the analysis of both present and future crystalline and silicon technologies.

Some assumptions and simplifications have been adopted, with respect to several issues.

With respect to the *system boundaries*: all PV systems considered in the analysis are connected to the electric grid; the combination of PV module manufacturing, materials for BOS and PV energy production (both electric and thermal) has been considered as the "system" to be analyzed; mining of raw materials, all transportation steps and recycling are not included in the analysis.

With respect to the *time framework*: results are presented both for present (1997) PV crystalline and amorphous silicon technology and for future technologies. The optimizations considered here are certainly technically feasible and do not rely on any significant technological break-through. The actual time of adoption for large-scale production of future PV technologies will depend on the evolution of R&D programs, investments and PV market.

With respect to *data sources*: in the case of PV, data on both manufacturing and energy production vary from place to place. Italian average data have been adopted for all the parameters that are site-dependent, such as: average annual insolation (the adopted value is 1700 kWh/m^2 on a 30° tilted surface), energy consumption and CO_2 emissions related to PV module manufacturing, efficiency and CO_2 emissions of the electricity production mix. The latter figures have been calculated by adapting a specific software (TEMIS) to the Italian boundary conditions [1]. All the above assumptions may be considered as reasonable estimates.

As far as the production of BOS materials is concerned, energy consumption and CO_2 emission values can vary extremely from Country to Country and even from a manufacturing plant to another. Several data-bases have been reviewed and best estimate average values have been used for calculations.

3. ANALYSIS OF THE BALANCE OF SYSTEM (BOS)

Types of Installations

For the comparison of PV systems two major categories are identified, namely "conventional" installations (array field PV power plants), and PV systems in buildings. The latter can be further classified into sub-categories, corresponding to the part of the building on which the PV system is applied (terrace or flat rooftop, tilted roof, facade etc.). Furthermore, the classification depends on whether the PV system is mounted on existing structures (retro-fit systems) or designed together with a new building (integrated installations). Finally, integrated hybrid systems with heat recovery are considered. The different types of installations included in the analysis are synthesized in Tab. 1. Specific primary energy contents and emission factors of various materials used for calculations are shown in Tab. 2. Of course, large differences may occur depending on the type of material, the manufacturing process, and on the production site. For each single material, the table indicates *average* values taken and adapted from various sources. These values represent our best estimate and are representative for a mean European situation.

Array field PV power plants.

The 3.3 MW array field power plant of Serre, Italy, has been studied in detail [2, 3]. Power plants in the open field require large quantities of reinforced concrete and steel needed for the structures necessary to support PV modules. This leads to a relatively high primary energy content of the BOS (slightly more than 1800 MJ_{th}/m^2). As shown in the next paragraphs, this value is much higher than the corresponding figure for the majority of PV systems in buildings. It should also be observed that, in the case of Serre, data on BOS energy consumption are a rather conservative estimate as the plant represents the real state-of-the art of such type of systems[1].

For the above mentioned reasons, the BOS primary energy content of future array field power plants is not expected to decrease significantly, at least in a near future.

Existing installations PV in buildings : learning by doing.

Several existing installations have been analyzed recently [2, 4, 5]. These include the retrofit system at the German School of Rome, Italy, (20 kW_p - both flat and tilted roof), the retrofit facade in a building property of ENEL in Rome (1,3 kW_p), the retrofit PV cladding facade at the University of Northumbria, United Kingdom, and several installations in Switzerland. PV tiles produced by the German company BMC have been studied as well [2].

Most of these systems have been pilot projects and/or first installation examples in each country. As a consequence, the use of materials has not always been optimized. This is clearly the case of the PV cladding facade at the University of Northumbria, for which a large use of very energy-intensive primary aluminum has caused a BOS primary energy requirement almost as high as for the PV power plant of Serre (see Fig. 1). Although to a less extent, primary aluminum is also responsible for the relatively high BOS energy content of integrated tilted roofs in Switzerland [4]. The flat roof at the German School in Rome shows a high primary energy content (around 1300 MJ/m^2) as well, because of an excessive use of steel for the supporting structures. The PV tile shows a relatively high energy content, attributable to the large quantity of clay needed (almost 1,7 m^2 per m^2 of PV modules). In contrast, most of the other systems in buildings have a significantly lower total primary energy content of around 600 MJ_{th}/m^2. Fig. 1 summarizes the primary energy content of the BOS of present PV systems.

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[1] As a matter of fact, the BOS material requirements of this plant are much lower than those of similar European

Future installations : possible optimizations:

In the future, PV installations in buildings will likely be designed taking into account the full life-cycle of materials. This is necessary for an energy-conscious, energy efficient and environmentally sound design of the systems. Two approaches can be followed, *namely*: to minimize absolute quantities of materials and to use a large fraction of recycled, secondary materials. Fig. 2 shows the possible primary energy content of future optimized PV systems. The scenario depicted is characterized by the following assumptions: *i)* future installations will contain 80% of secondary aluminum. This strongly decreases energy consumption for most PV systems in buildings; *ii)* light concrete supporting structures will likely be used for PV systems on flat roofs, both for economic reasons and for the simplicity of installation and maintenance; *iii)* an advanced type of clay will be used for PV tiles, which allows energy consumption to be reduced by about 30% [6].

If all the above mentioned factors are taken into account, the comparison between the BOS energy content of PV plants and PV systems in buildings becomes radically favorable to the latter, as clearly illustrated in Fig. 2.

4. CRYSTALLINE AND AMORPHOUS SILICON MODULE MANUFACTURING

Crystalline silicon

Very recently, a critical review of a number of studies on energy requirement of PV modules or systems has been performed [7]. The study points out that the published estimates for the energy requirement of present-day crystalline silicon vary considerably : between: 4200 - 11600 MJ/m^2 for multi-crystalline silicon (mc-Si); and between 6000 - 13900 MJ/m^2 for single-crystalline silicon (sc-Si). Partly, these differences can be explained by different assumptions for process parameters like wafer thickness and wafering losses. However, the most important source of differences is the energy requirement estimation for the silicon feedstock used to produce PV wafers. Currently the majority of PV cells are made from off-spec silicon that is rejected by the micro-electronics industry. As a matter of fact, the major source

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installations, e.g. Phalk 500 in Switzerland [3]. For this reason, the figures for Serre have been used also for the future of uncertainty is the preparation of silicon feedstock from electronic industry scraps, involving two crystallization steps. The present manufacturing energy requirement very strongly depends on i) allocation criteria for the primary crystallization step ; ii) the silicon content of the cell ; iii) the specific energy consumption rates for silicon purification.

This situation is depicted in Fig. 3, which shows the primary energy requirement for present PV systems for three technology cases (mc-Si "high", mc-Si "low" and amorphous silicon (a-Si) and three main applications (array field power plant, roofs and facades).

In the future the introduction of solar-grade silicon preparation processes might significantly reduce energy requirements down to 2600 MJ/m2 and make the discussion about one or two crystallization steps obsolete [7]. The significantly lower expected energy consumption values will mainly be caused by three factors, namely: i) a much higher silicon mass efficiency (that is a much better use of silicon feedstock input per kWp output, ii) internal recycling and iii) less specific energy consuming processes (i.e. faster Czochralsky and/or directional solidification processes).

Amorphous silicon

The differences in published estimates for the manufacturing of amorphous silicon modules (710 - 1980 MJ/m^2) can be explained by the choice of substrate and/or encapsulation materials, and by whether the overhead auxiliary energy use and energy consumption for equipment manufacturing are taken into account or not. The cell material itself accounts for only a few percent of the total energy requirements. The best estimate for present primary energy requirement for amorphous silicon manufacturing is around 1200 MJ/m^2 [7]. Assuming a 6% module stabilized efficiency, this corresponds to a specific energy requirement of 20 MJ/W$_p$, which is significantly lower than the one of present crystalline silicon modules (35-96 MJ/W$_p$ for mc-Si). However, lower efficiencies and thus higher BOS requirements can cancel out this advantage, at present and in the future. The potential for improvement is lower than for crystalline silicon modules (max. 30% energy requirement reduction) with current encapsulation materials.

Table 3 summarized the technological parameters used for the calculations.

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installations.

5. ENERGY PROFILES OF SILICON PV SYSTEMS

Present (1997) situation

Fig. 3 shows the primary energy requirements for present PV systems. As a consequence of the high energy requirement for crystalline silicon module manufacturing, the contribution of BOS is of minor importance, at least in the case mc-Si "high". As a matter of fact, in this case the Energy Pay-Back Time (EPBT)[2] slightly higher than eight years, even if the system is installed in a place with a relatively high sun radiation, such as Central Italy[3]. Because of the large contribution of PV modules, the installation of PV systems in buildings reduces the EPBT only to a limited extent (max. 18% for roofs). Facades show even worse results because of the bad exposure to the sun at these latitudes. The most effective PV system seems to be the simple installation on flat roofs [2].

However, in the case of mc-Si "low" and a-Si, the contribution of the BOS is proportionally higher. Therefore, the benefits of the integration in buildings are more significant. Even the contribution of the aluminium module frames will be not negligible. This will be even more true with future PV modules and is described in more detail in the next paragraph.

Future prospects

In future, the manufacturing of crystalline silicon cells will require significantly less energy. Whatever the specific technology (single- and/or multi-crystalline silicon derived from electronic industry, or solar-grade silicon), the production chain will be optimized for solar energy cell manufacturing. A smaller amount of silicon feedstock will be required to produce a cell. The cell and module efficiencies will also increase. Also the technology of amorphous silicon is expected to improve significantly.

Table 3 summarizes the expected technological evolution of silicon modules [adapted from 2 and 7].

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[2] The EPBT is the time needed for the PV system to supply the amount of energy consumed for its production. It is defined as: *EPBT (years) = Consumed energy for system production / Annual energy produced by the system*

[3] Other parameters used for calculations are: *i*) PV plant electric BOS efficiency: 85%; *ii)* efficiency of Italian electricity production mix: 39,1%; grid distribution losses: 7%; *iii)* for integrated systems, the primary energy content of the building materials substituted by the PV components have been subtracted from the BOS primary energy content of Figg. 1 & 2.

Fig. 4 shows the EPBT of future multi-crystalline silicon PV systems. Results are subdivided according to the various manufacturing steps of crystalline silicon PV systems, namely the preparation of high-purity silicon feedstock, the cutting of silicon ingots into wafers, the manufacturing of cells, the assembling of modules, and the BOS. Moreover, the contribution of process electricity and primary energy content of materials are distinguished.

As a consequence of manufacturing and efficiency improvements, the expected EPBT of such "optimized" power plant is reduced by more than a factor three (from 8 down to 2,3 years) with respect to present power plants.

Moreover, as already mentioned, the BOS plays a more important role in the total energy balance. This means that the integration in buildings gives proportionally more benefits than today. The EPBT of a fully integrated future mc-Si PV roof system is expected to be about 40% smaller than that of a future PV plant.

Moreover, the EPBT is further strongly reduced if heat recovery is taken into account. In integrated systems, at least part of the heat dissipated by the PV panels can be recovered by means of an air channel between the back-plates of the modules and the roof (or facade) itself. This air flow has a double effect: first, it allows the warm air to be used in the building for air conditioning and/or pre-heating of water; second, it cools down the cells, thus increasing their efficiency. In this study an annual mean value of 2 kWh_{th} recovered heat per kWh_{el} produced by the PV system is assumed. The value was taken according to simple installations in Switzerland, which use only small air fans as auxiliary systems to provide air circulation [8]. In this case, the thermal energy recovery in tilted roof can reduce the EPBT by almost a factor 3 with respect to a PV power plant. As a matter of fact the expected EPBT of an integrated tilted roof with heat recovery is lower than 10 months[4]. It is also worth noticing that the PV facades become interesting when equipped with a heat recovery system (Fig. 4). However, given the difficulties to effectively recover and use the thermal energy throughout the whole year, these results have to be interpreted with care.

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[4] To calculate the corresponding primary energy, the substituted heat has been supposed to be produced by methane boilers.

Finally, the negative BOS contribution for PV integrated facades and roofs should be remarked. This (theoretical) result reflects the possible use of PV modules to replace conventional building cladding materials. The result is particularly significant for the case of Alukobond panels[5]. The energy needed to manufacture a 1 mm thick aluminum foil is very high, larger than the BOS energy content of a PV facade-integrated systems. As a consequence, the BOS contribution is negative. The planning and design of a PV facade instead of an Alukobond facade can be therefore considered as a conceptual energy saving measure. Although purely theoretical, this result highlights the need for energy-conscious architects and engineers to be aware of the hidden energy contents of building materials.

All these results are even more significant in the case of future amorphous silicon modules. As shown in Fig. 5, in this case the EPBT of PV roof systems is always lower than one year. With heat recovery it further drops down to less than six months. If the substitution of Alukobond panels occurs, the total (theoretical) EPBT is zero !

Figure 6 shows the net energy yield of future PV systems[6]. The expected energy yield value for crystalline silicon power plants is around 12-14 times. Amorphous silicon systems show a lower value because of lower efficiency and consequent higher BOS requirements. Retrofit PV roof systems increase the energy yield values up to 20 times. This value further increases in the case of full integration in buildings. In this case, the disadvantage of amorphous silicon is canceled by much lower BOS requirements due to the substitution of conventional building cladding materials. As a matter of fact, amorphous silicon systems show the highest energy yield values. In the case of heat recovery, they are expected to produce more than 50 times the amount of energy needed for their integration in buildings. These values indicate that future PV systems will definitively have a high net fossil energy substitution and CO_2 mitigation potential. If compared with the energy yield of present crystalline silicon array field power plants (between 2,5 and 3 times), they also show the impressive improvement potential of PV technologies *and* applications.

5. ENVIRONMENTAL PROFILE OF FUTURE PV SYSTEMS

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[5] An Alukobond panel is made by a sandwich of two thin aluminum foils (total thickness 1 to 3.5 mm) with a hard rubber

The CO_2 mitigation potential constitutes an important political motivation for PV technology development. The mitigation potential can be shown with several indicators. Here, results are presented in terms of CO_2 balance and CO_2 specific emissions. Fig. 7 shows the CO_2 balance of $1m^2$ of multi-crystalline and amorphous silicon systems during their lifetimes. The indirect air emissions caused during manufacturing and installation of modules have been calculated according to the Italian electricity production mix (0,531 kg CO_2 / kWh_{el}). The avoided emissions have been calculated considering the Italian distribution mix (0,567 kg CO_2 / kWh_{el}) [1][7]. A specific emission factor of 0,198 kg CO_2 / kWh_{th} has been taken into account for thermal energy production (natural gas boilers).

As expected, and in contrast with the present situation, the balance is radically positive, that is the avoided CO_2 emissions are much higher than the emission caused during the manufacturing phase. Amorphous silicon systems cause very low emissions during manufacturing. However, due to lower efficiencies, and, most important, to much shorter life-times, they avoid much less emissions than multi-crystalline silicon systems during their life-cycle (recycling is not taken into account here). As a matter of fact, mc-Si systems are expected to save a net amount of more than 3000 kg CO_2 /m^2, while a-Si show a value of around 1000 kg CO_2 /m^2.

The figure further shows the importance of the recovery of heat recovery. A future hybrid PV/Th mc-Si integrated PV roof system is expected to avoid more than 5000 kg CO_2 /m^2. It is interesting to notice that despite worse insolation conditions, facades with heat recovery show a very interesting CO_2 mitigation potential. However, it is worth recalling that results concerning hybrid systems should be interpreted with some care, since they still require more detailed investigations and further tests. More detailed LCAs of hybrid systems are needed in the future, in order to take into account the downstream use of the recovered heat.

In any case, the figure demonstrates that future PV systems will have significant environmental performances.

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layer in between. These panels are often used in modern office buildings

[6] *Energy yield = gross energy produced during lifetime of PV system / energy consumed during production of PV system*

[7] PV systems in buildings substitute low-voltage electricity and have no distribution losses, therefore their environmental benefits are higher.

The significant improvement achievable by PV systems can also be expressed in terms of specific emissions during lifetime. Today, a single-crystalline silicon PV power plant has a specific emission value of around 0,2 kg CO_2 / kWh_{el}. This is mainly caused by indirect emissions deriving from high electricity consumption during the manufacturing of modules. In future, this value is expected to drop as low as 0,06 kg CO_2 /kWh_{el} for PV power plants and 0,04 kg CO_2 /kWh_{el} for integrated PV roofs [3].

6. CONCLUSIONS

The results of a detailed analysis of the primary energy content of the BOS of several PV systems is reported. With few exceptions, the BOS energy content of most PV systems in buildings is around three times lower than that of a PV power plant. In future, this energy content will be further reduced by minimizing absolute quantities of materials and using large fractions of recycled materials.

Today, the BOS relevance in the total energy balance of PV systems is limited, because of the very high energy content of crystalline silicon cells. However, this energy content will be drastically reduced in the future. As a consequence, the BOS will increasingly become the crucial factor determining the total energy and environmental profile of PV systems. This holds even more strongly for amorphous silicon modules. Thin film modules have lower energy requirement per m^2 module area, but on a system level this is offset by their lower efficiency, leading to higher BOS energy requirements and lower energy production. As a matter of fact, the analysis shows that in the future the integration in buildings will give proportionally much larger benefits than today.

The study argues that the integration of PV systems in buildings presents favorable effects when compared to conventional PV power plants, both in terms of energy production and CO_2 avoided emissions. These benefits increase significantly if the installation allows the recovery of part of the heat dissipated by PV panels.

For example, EPBT values are expected to drop from the 8 years of present crystalline silicon power plants down to 1,4 years and 0,8 years for mc-Si and a-Si PV roof systems respectively. The EPBT are further halved in integrated systems if heat recovery is allowed. Similarly, CO_2 specific emissions are expected to drop from present 0,2 kg CO_2 / kWh_{el} of array field power plants down to 0,04 kg CO_2 /kWh_{el} for integrated PV roofs.

These values definitively indicate that future building-integrated PV systems will have a high net fossil energy substitution and CO_2 mitigation potential. In order this potential to be fully exploited however, it will be necessary to focus the attention not only on module technology improvements but also on the right choice and optimization of BOS. This implies that at the very early design stage, both engineers and architects have to carefully consider the most appropriate choice of materials for PV building installations.

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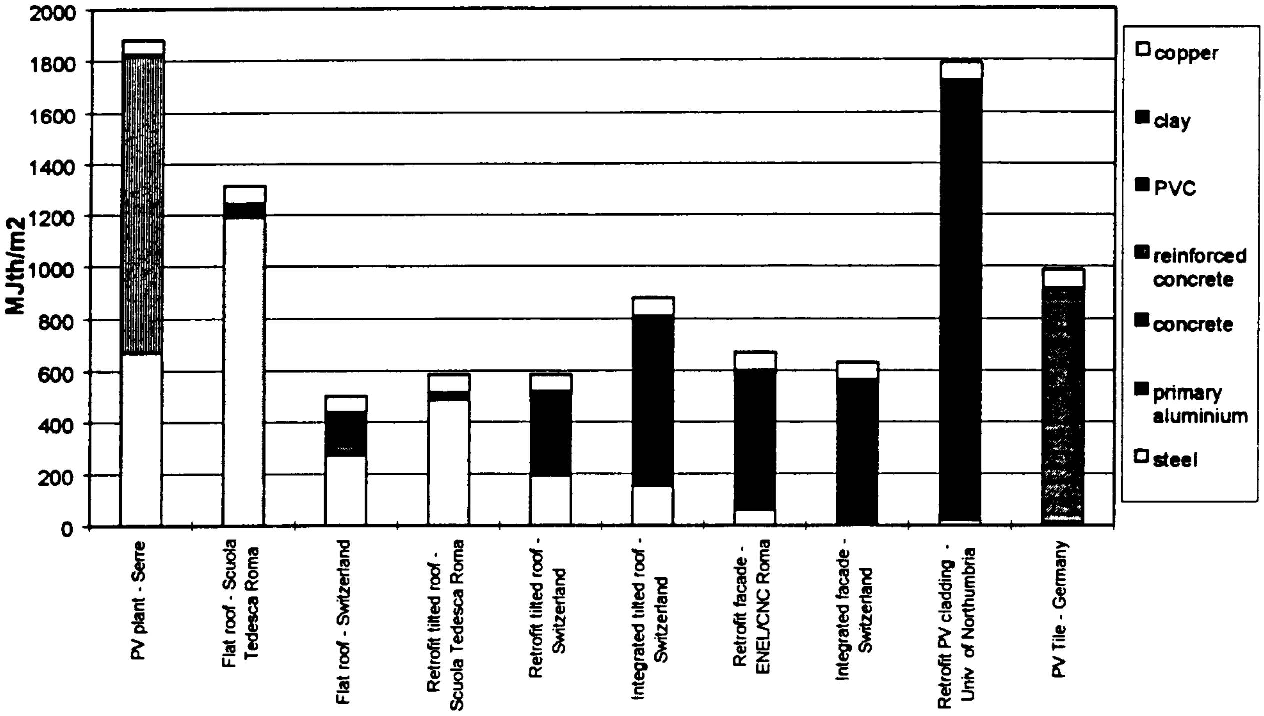

Fig. 1 - Primary energy content of the BOS of present PV systems

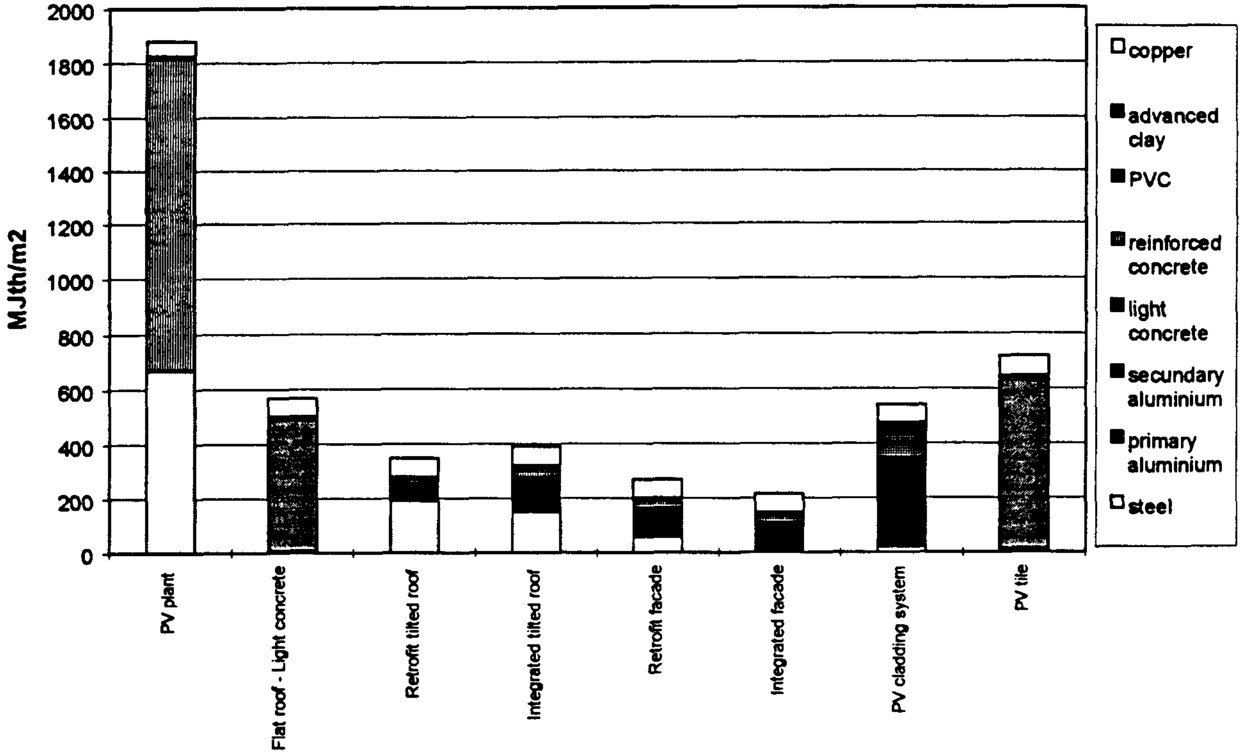

Fig. 2 - Possible future BOS primary energy content of optimized PV systems

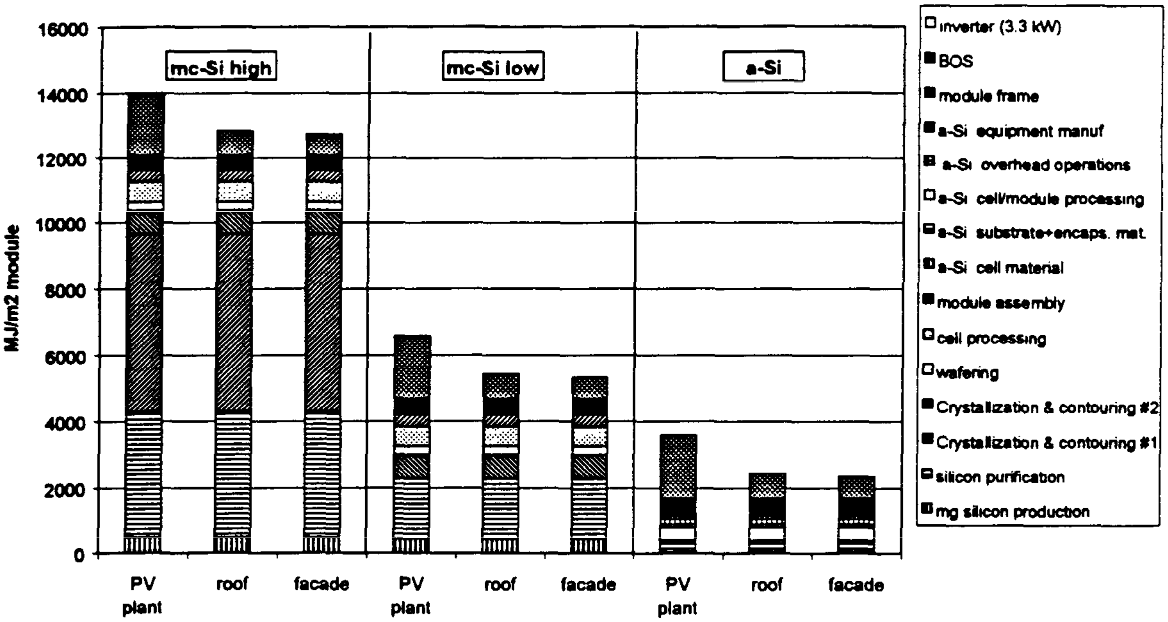

Fig. 3 - Primary Energy requirements for present silicon PV systems

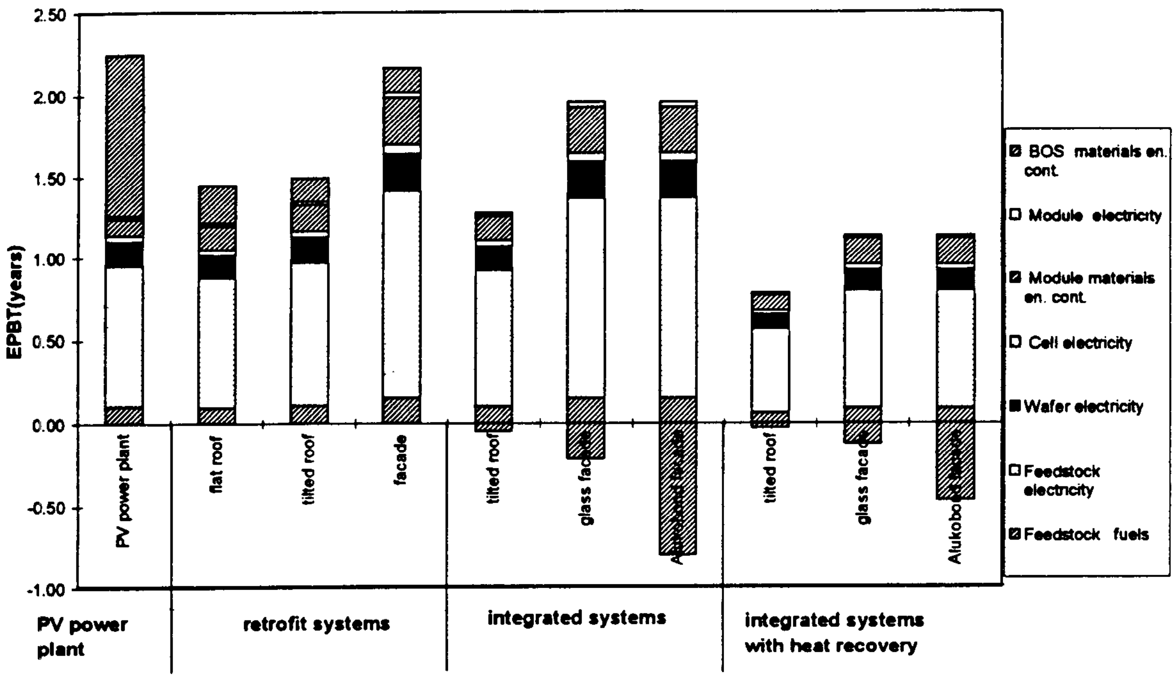

Fig. 4 - Expected Energy Pay-Back Times for future optimized multi-crystalline silicon PV systems

(mean annual insolation: 1700 kWh/ m^2 year on a 30° tilted, south-oriented surface; cell efficiency: 16.0% ; module efficiency : 14.5%)

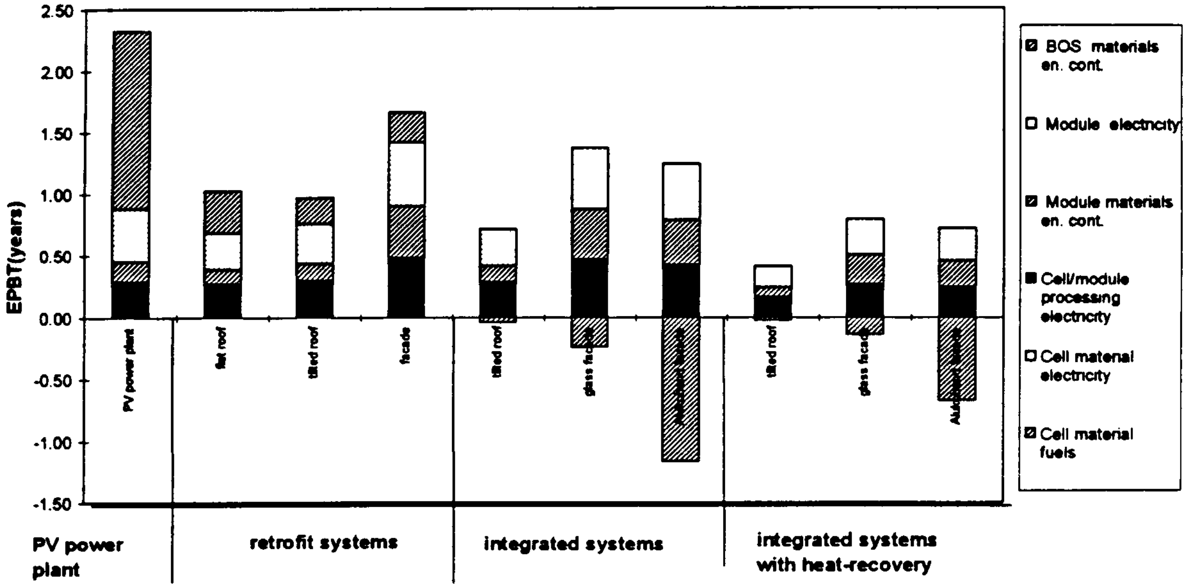

Fig. 5 - Expected Energy Pay-Back Times for future amorphous silicon PV systems

(mean annual insolation: 1700 kWh/ m^2 year on a 30° tilted, south-oriented surface; module efficiency: 10%)

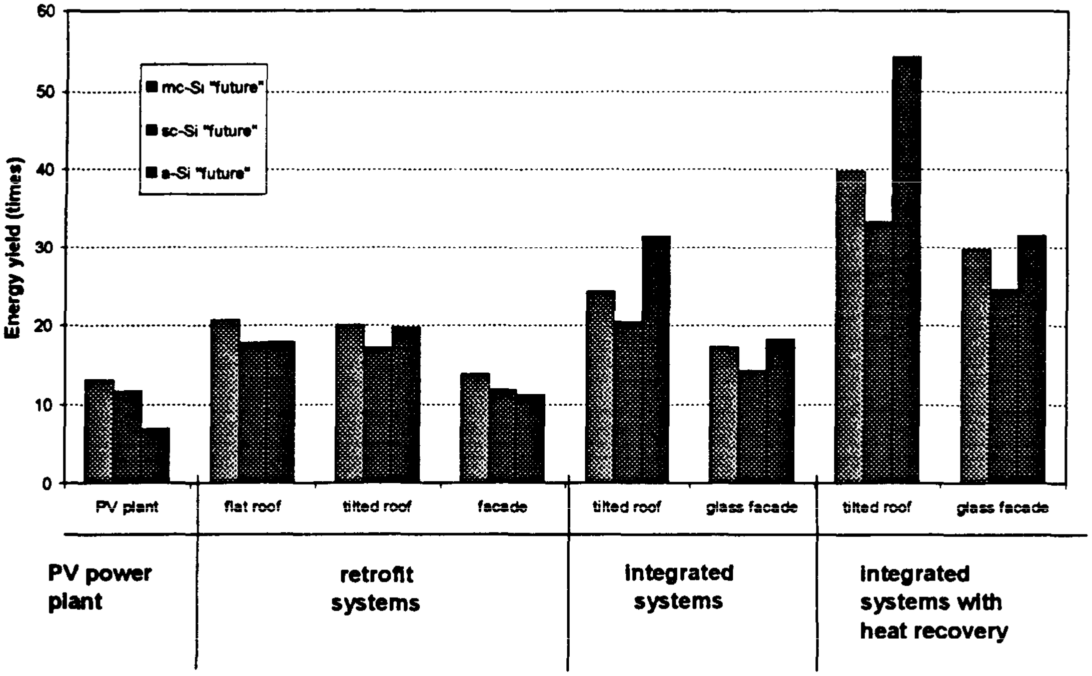

Fig. 6 - Energy yield of future silicon PV systems

(mean annual insolation: 1700 kWh/ m^2 year on a 30° tilted, south-oriented surface;

module efficiency: mc-Si: 14.5%, : sc-Si: 14.2%,: a-Si: 10%,

module life-times: mc-Si and sc-Si: 30 years; a-Si: 15 years)

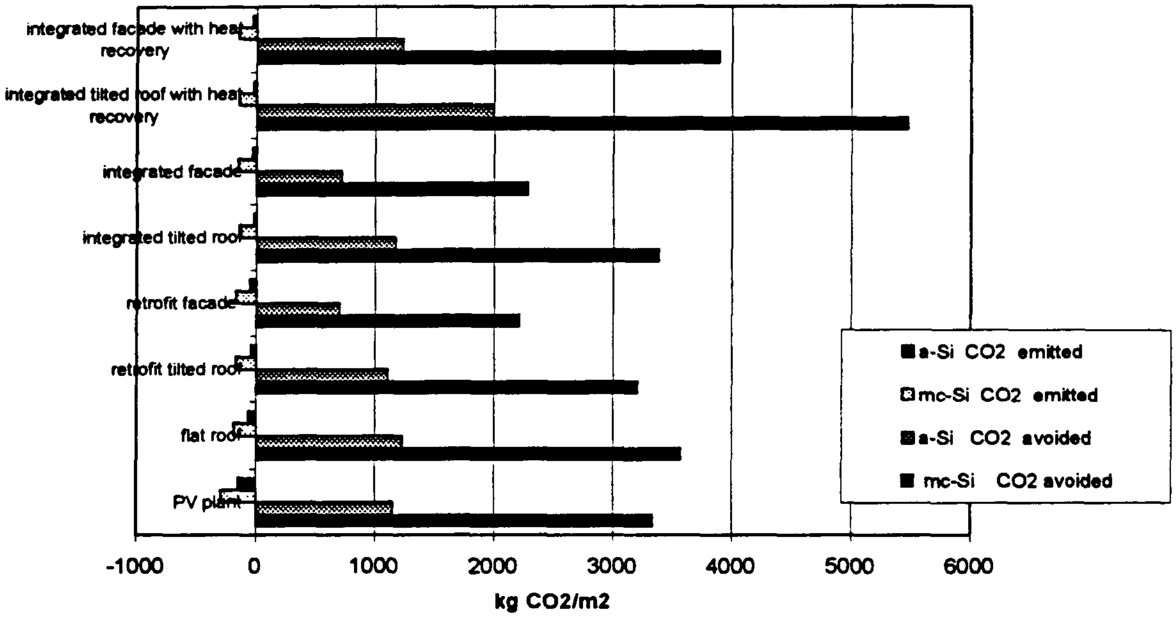

Fig. 7 - CO_2 - balance of future multi-crystalline and amorphous silicon PV systems

(mean annual insolation: 1700 kWh/ m^2 year on a 30° tilted, south-oriented surface;

module efficiency: mc-Si: 14.5%, a-Si: 10%,

module life-times: mc-Si: 30 years; a-Si: 15 years)

PV plant	Conventional PV plant in outdoors fields; this installation requires a careful preparation of land, and special structures to support the PV panels. Exposure of panels to the solar radiation is optimized by means of fixed south-oriented structures or tracking systems. An electric efficiency of 85% has been assumed for these systems.
Flat roof	In this type of installation, PV modules are fixed on the flat surface of the rooftop by means of suitable light structures. Exposure is optimized (fixed panels, south-oriented).
Tilted roof (retro-fit)	PV modules are directly applied on the existing surface of the roof. The sun exposure cannot be always optimal, since it is a "retro-fit" operation. Electric system losses can be higher. Mean losses of 10%with respect to the optimal reference case (PV plant or flat roof) have been therefore considered.
Tilted roof (integrated)	The PV system and the building are designed together. The possibility of planning a better exposure of the panels and of using cell cooling systems leads to slightly lower losses (5%) with respect to the reference case[8]. PV panels substitute parts of the roof from the beginning of the project. Thus there is an additional energy saving due to the construction materials which are not used in the roof part covered by the PV panels.
Facade (retro-fit)	PV modules are used as cladding materials for covering an existing facade. A loss of 38% compared to the optimal case is caused by the reduced incident radiation on a vertical surface at the latitude of Central Italy.
Facade (integrated)	PV system and the building are planned and designed together. Losses are 2% lower than the retro-fit facade. As usual, there is also an energy saving due to the substitution of the conventional construction materials with PV modules.
PV cladding (retro-fit)	PV modules function as facade cladding. However, they are tilted with respect to the facade, thus forming a "PV sawtooth curtain wall". Losses are the same as for retro-fit tilted roofs.
Systems with heat recovery	BOS efficiency is the same as for integrated systems. Additionally, a mean heat recovery of 2 kWh$_{th}$ per kWh$_{el}$ produced is taken into account.

Tab. 1 - Classification of different PV installation types - source : [2]

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[8] Silicon cells efficiency decreases when temperature increases.

	Energy content of materials			**CO_2 specific emissions**
	total primary energy	**of which electricity**		**total (process + energy)**
Materials	**MJ_{th}/kg**	**KWh_{el}/kg**	**MJ_{th}/kg**[9]	**kg CO_2/kg**
steel	32.00	2.20	20.25	1.91
primary aluminum	198.00	17.00	156.51	10.59
secundary aluminum	12.60	0.00	0.00	0.51
light concrete	4.40	0.10	0.92	0.28
concrete	1.63	0.04	0.37	0.16
armored concrete	6.06	0.15	1.38	0.40
copper	70.00	4.72	43.45	3.09
glass	14.40	0.12	1.10	0.77
PVC	66.80	4.26	39.22	4.20
clay	10.70	0.05	0.46	0.66

Tab. 2 - Primary energy content and CO_2 specific emissions of BOS materials.

Average values adapted from [9, 10, 11, 12, 13, 14, 15]

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[9] A mean efficiency of 39,1% of the Italian electricity production mix has been considered to convert electricity into primary energy consumption.

	Silicon PV technologies					
	multi-crystalline		single-crystalline		amorphous	
	present	Future	present	future	present	future
Cell efficiency	14%	16%	15,5%	18%	-	-
Module efficiency	12,1%	14,5%	12,7%	14,8%	6%	10%
Primary energy content for module manufacturing (MJ / m2)[9]	4200 - 11600	2600	6000 - 13900	3100	1200	840
Module lifetime (years)	25	30	25	30	10	15

Tab. 3 - Technological parameters of present and future silicon PV modules

adapted from [2 and 7]

3.3 Christi Herig

The Million Roof Initiative: Current Status

Million Solar Roofs

http://www.millionsolarroofs.com

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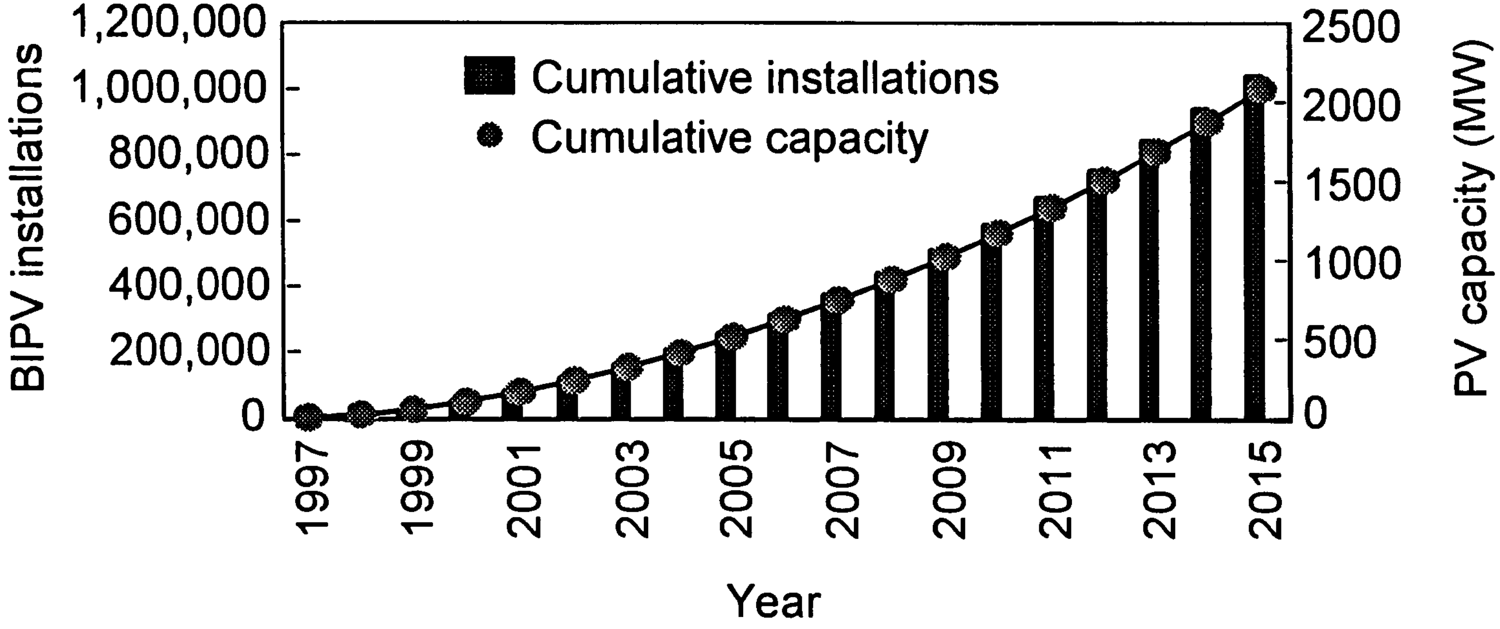
Million Solar Roofs



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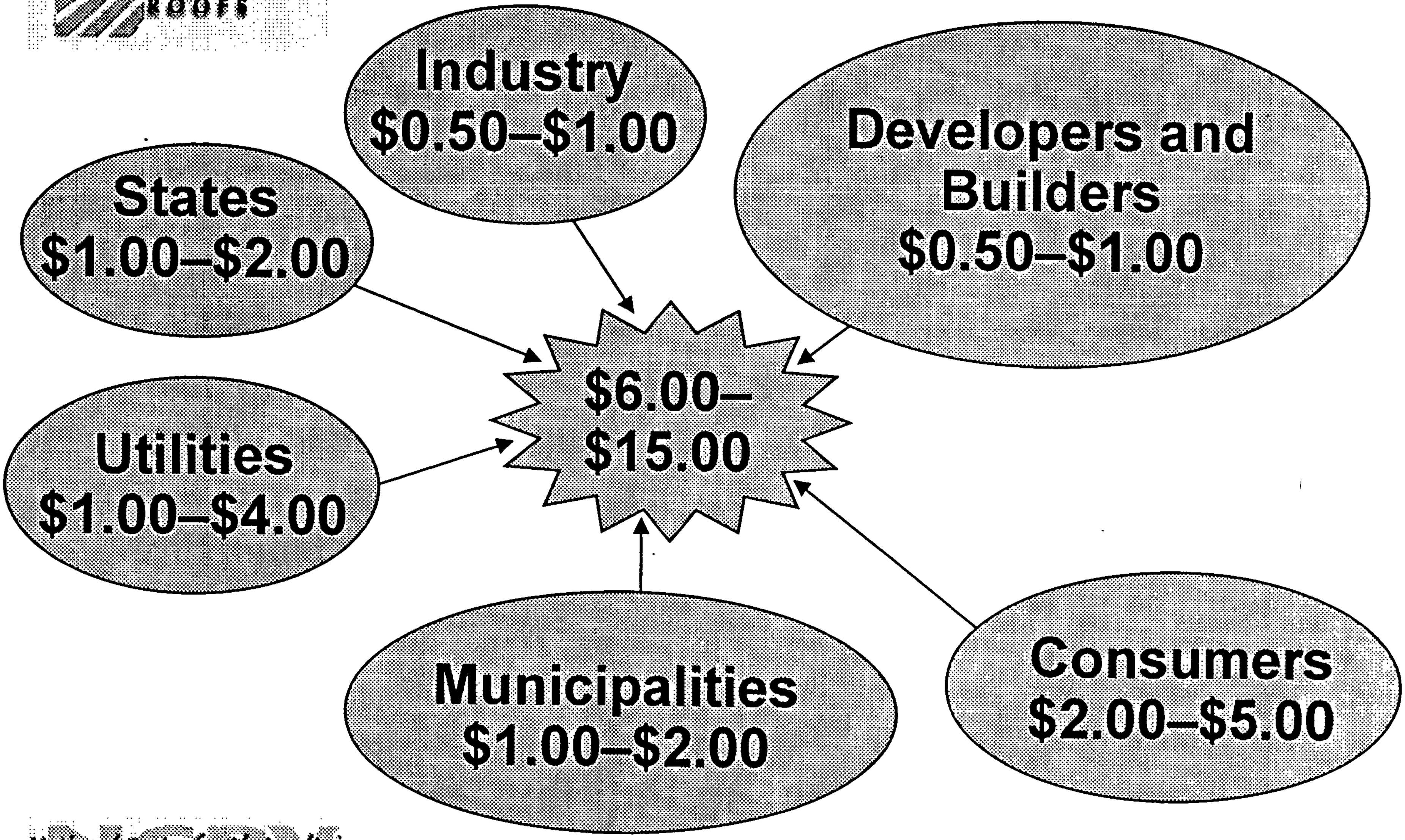
Team Partnerships



Industry
$0.50–$1.00

Developers and Builders
$0.50–$1.00

States
$1.00–$2.00

$6.00–
$15.00

Utilities
$1.00–$4.00

Municipalities
$1.00–$2.00

Consumers
$2.00–$5.00

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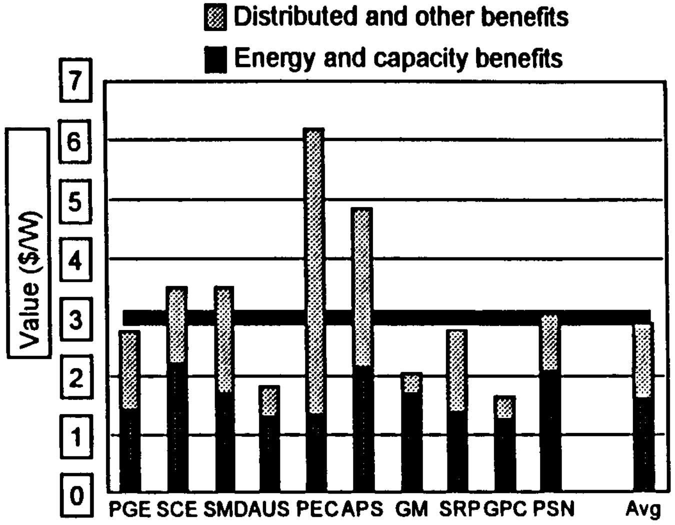
MILLION Solar ROOFS

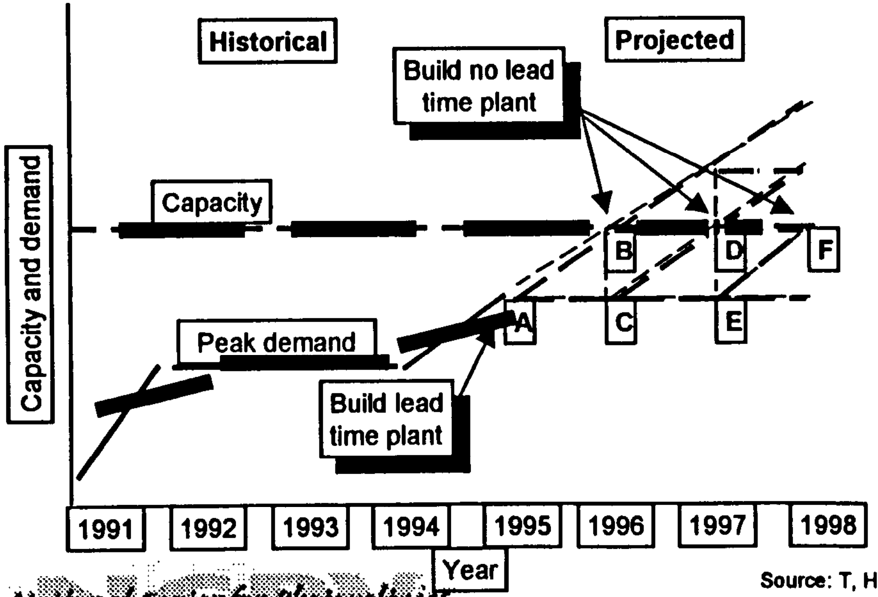
Partnership Development

Utilities

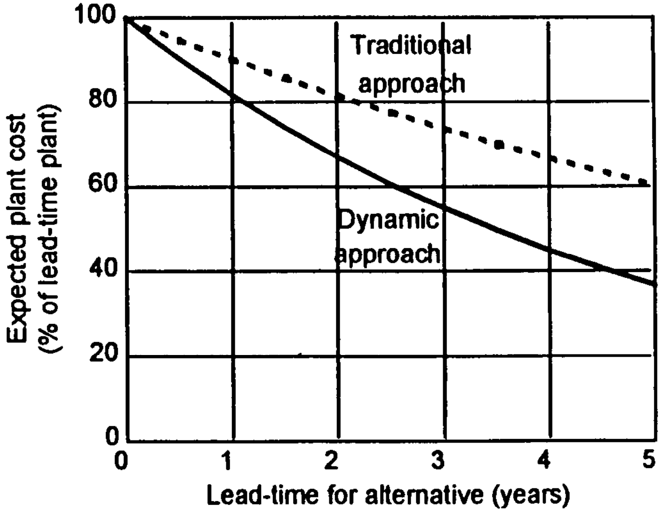
- Distributed resource
- Customer retention
- Financial risk mitigation
- Business and marketing plan development



Source: H. Wenger, Pacific Energy Group



Source: T, Hoff, Pacific Energy Group



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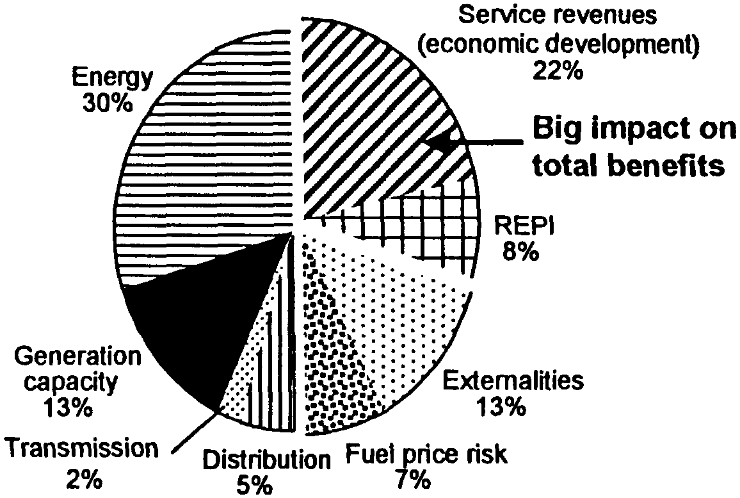
MILLION Solar ROOFS

Partnership Development

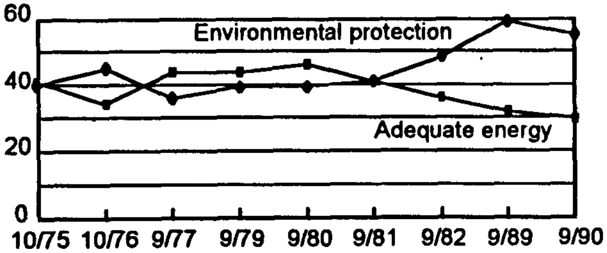
Municipalities

- **Planning integration**
- **Constituency preference**
- **Economic development**
- **Disaster mitigation**

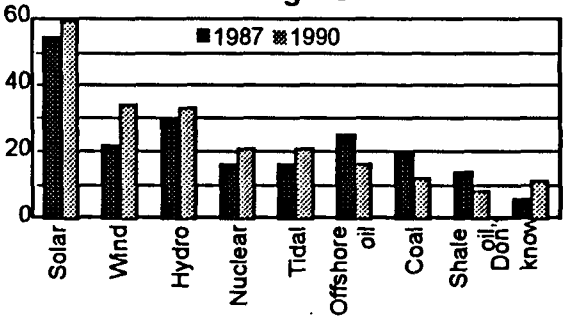


Source: H. Wenger, Pacific Energy Group

Preference for Adequate Energy or Environmental Protection



Development Preference for Replacing Foreign Oil



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Energy Efficiency and Renewable Energy Network | U.S. Department of Energy

MILLION Solar ROOFS

Background

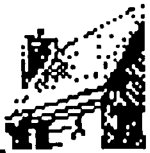
Program Plan

Program Goals

How do YOU Fit In?

Additional Resources

Learn More about
Solar Energy Technologies



> *Capturing the sun's warmth can help us to turn down the Earth's temperature.*
>
> – President Clinton

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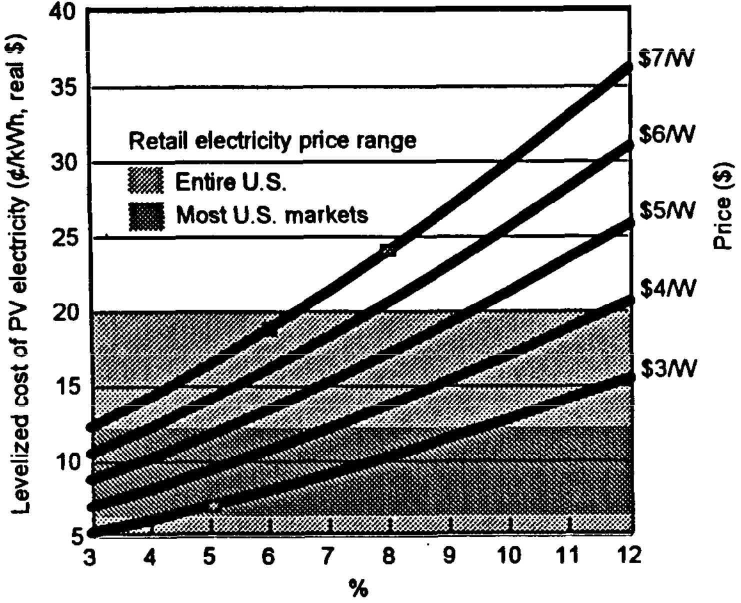
Partnership Development

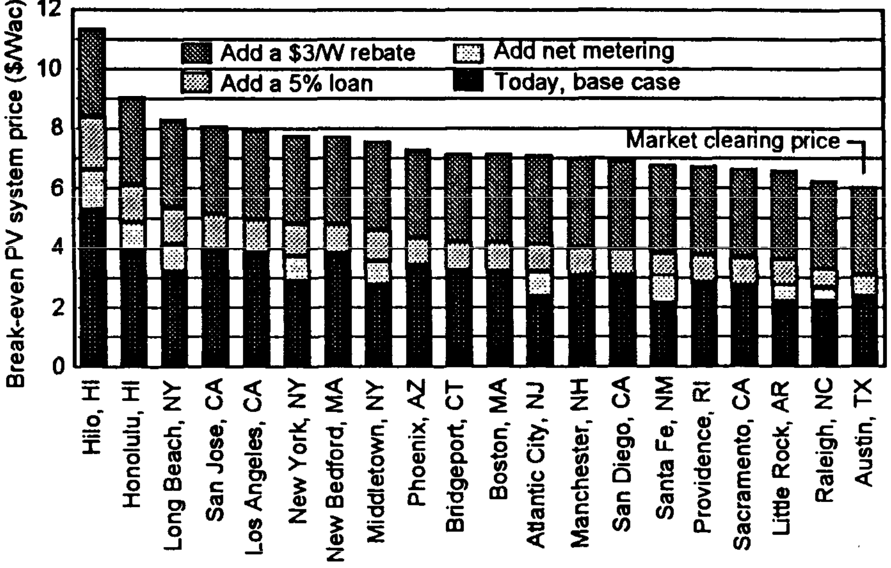
Sample Planning and Policy Analysis

Low Interest Financing

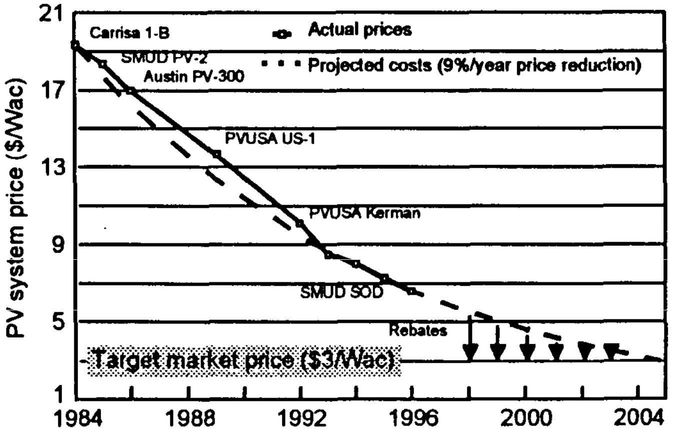


Source: H. Wenger, Pacific Energy Group

Scenario for 20 Cities



Rebates Used to Bridge the Gap



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Partnership Development

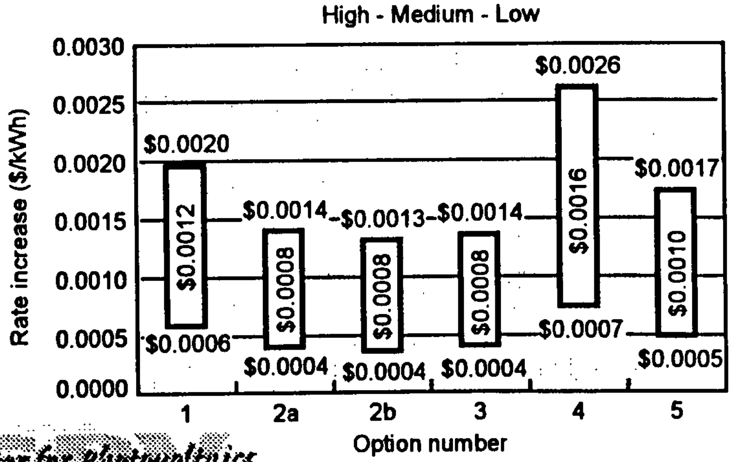
States

- Economic development
  - Segmented gross product
  - Income index
  - Spending index
  - Indigenous resources
  - Employment index
  - Environmental
- Revenue impacts
- Implementation resolution

Cumulative Investments and Savings: 1997–2010
Billions of 1993 $

End Use Sector	Investment	Savings	Consumer Payback Period Years	Scenario Benefit/Cost Ratio
Residential	$1.58	$1.50	7.4	0.95
Commercial	$0.77	$1.56	3.5	2.04
Industrial	$0.63	$1.14	3.9	1.82
Transportation	$1.09	$3.67	2.1	3.37
Total	$4.06	$7.88	n/a	1.94

Source: Skip Laitner, Economic Research Associates



Source: H. Wenger, Pacific Energy Group

Analysis for AZ Portfolio Standard

Parameter	Result
Jobs created by 2010	600 jobs
Wage, salary, and state income tax revenue (1998–2020)	$200 million
Global warming CO_2 emissions avoided by 2020	12 million tons, $120 million
Acid rain SO_x emissions avoided by 2020	32 thousand tons, $85 million
SMOG NO_x emissions avoided by 2020	38 thousand tons, $40 million

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Partnership Development
Builders and Developers

- Valuation of product or image differential
- Building product displacement
- Off-grid, micro-grid and remote land development valuation

Material credit ($\$/\text{ft}^2$)	Material avoided by BIPV installation
1	Asphalt shingle roof, monolithic glazing
5	Laminated glass w/coatings metal roofing/cladding
10	Roofing slates, clay tile, high performance coatings
20	Stainless steel, photochromic glass

Source: A. D. Little

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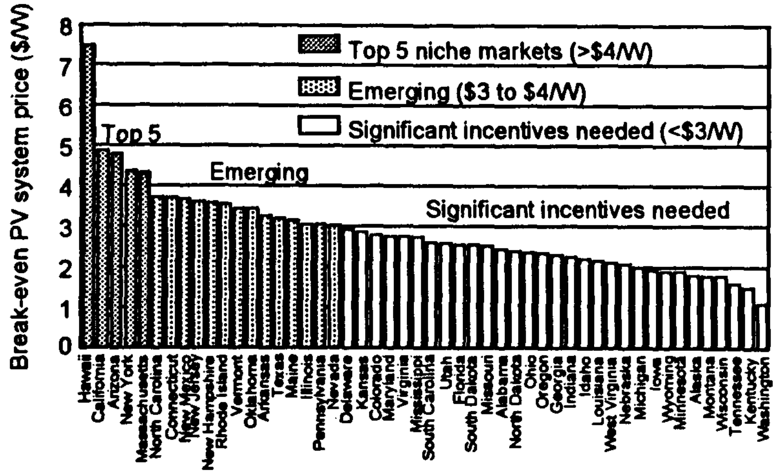
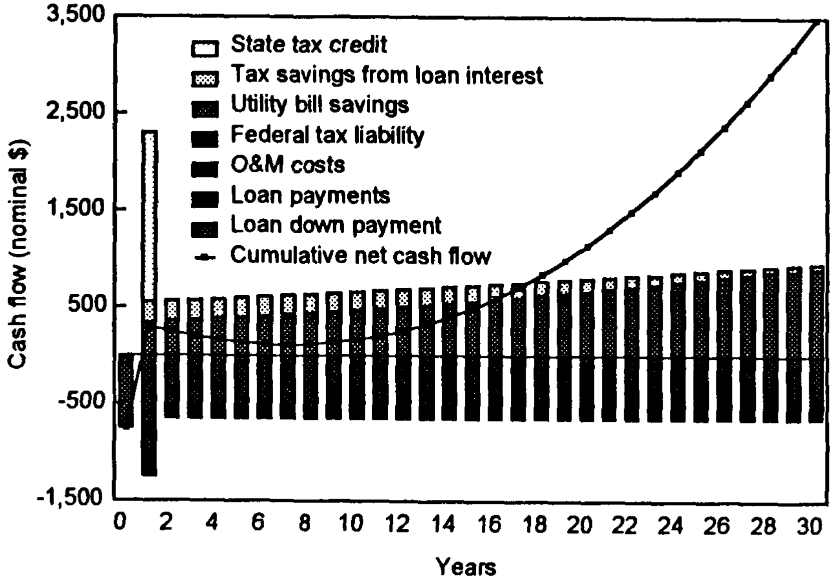
Partnership Development

Consumers

Large Customers and Aggregated Customers

- Cash-flow analysis on investments
- life-cycle operational benefits and costs





Source: H. Wenger, Pacific Energy Group

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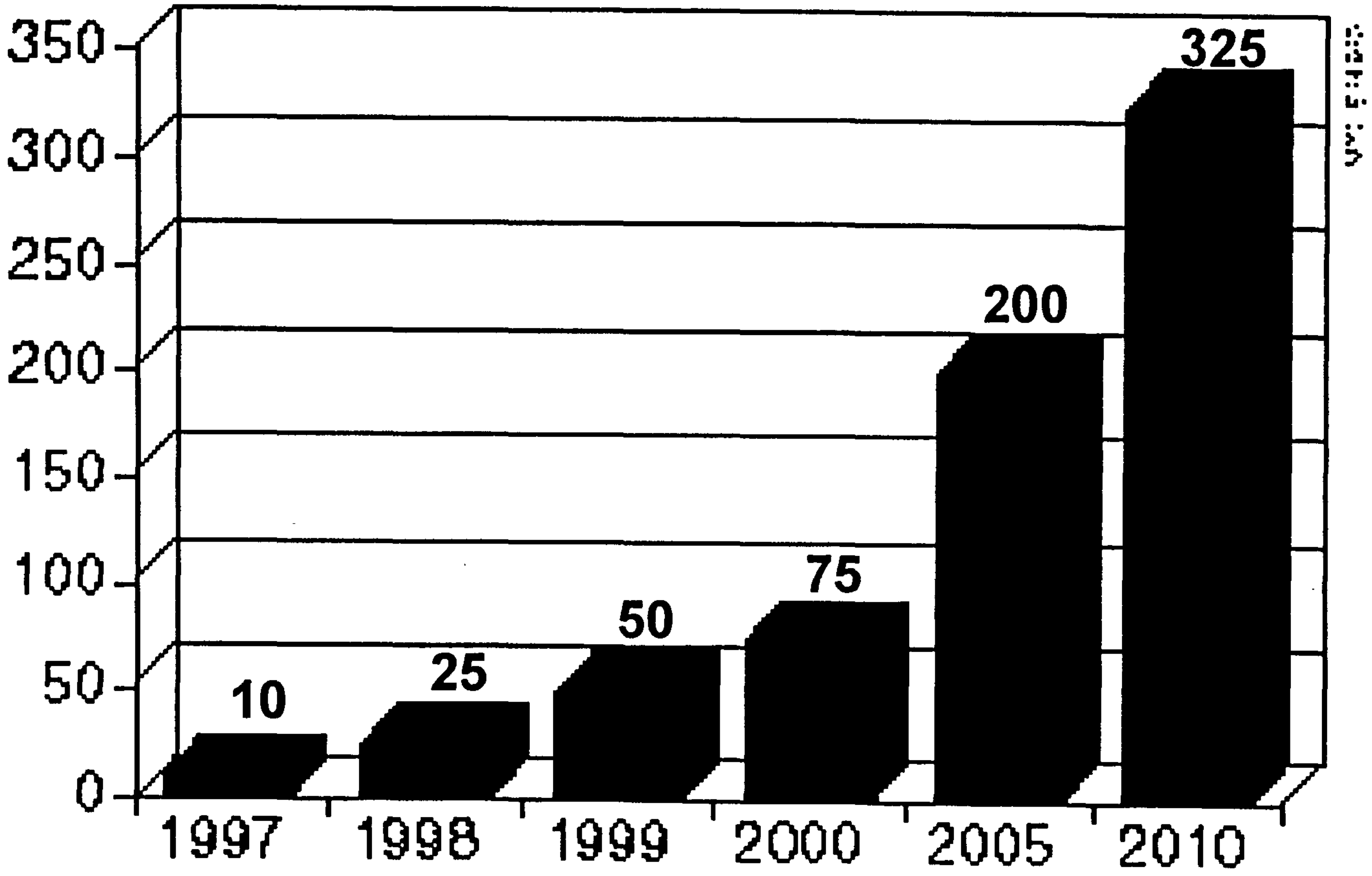
MILLION Solar ROOFS

Participating Partners



Projections show a growing number of "solar cities" spread across the United States.

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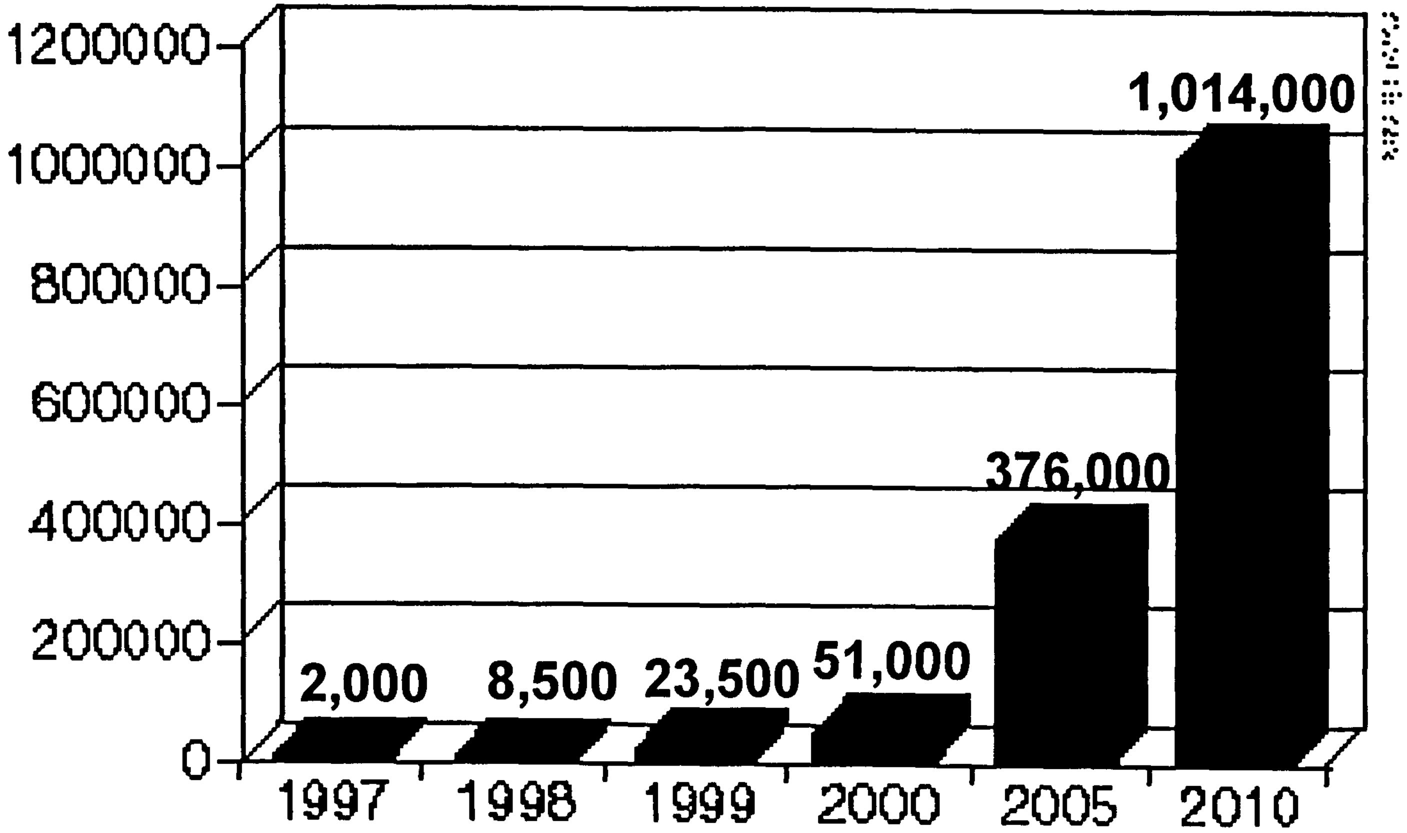
MILLION Solar ROOFS

Solar Buildings



The numbers speak for themselves: from 2000 solar-equipped buildings in 1997 to over one million in 2010.

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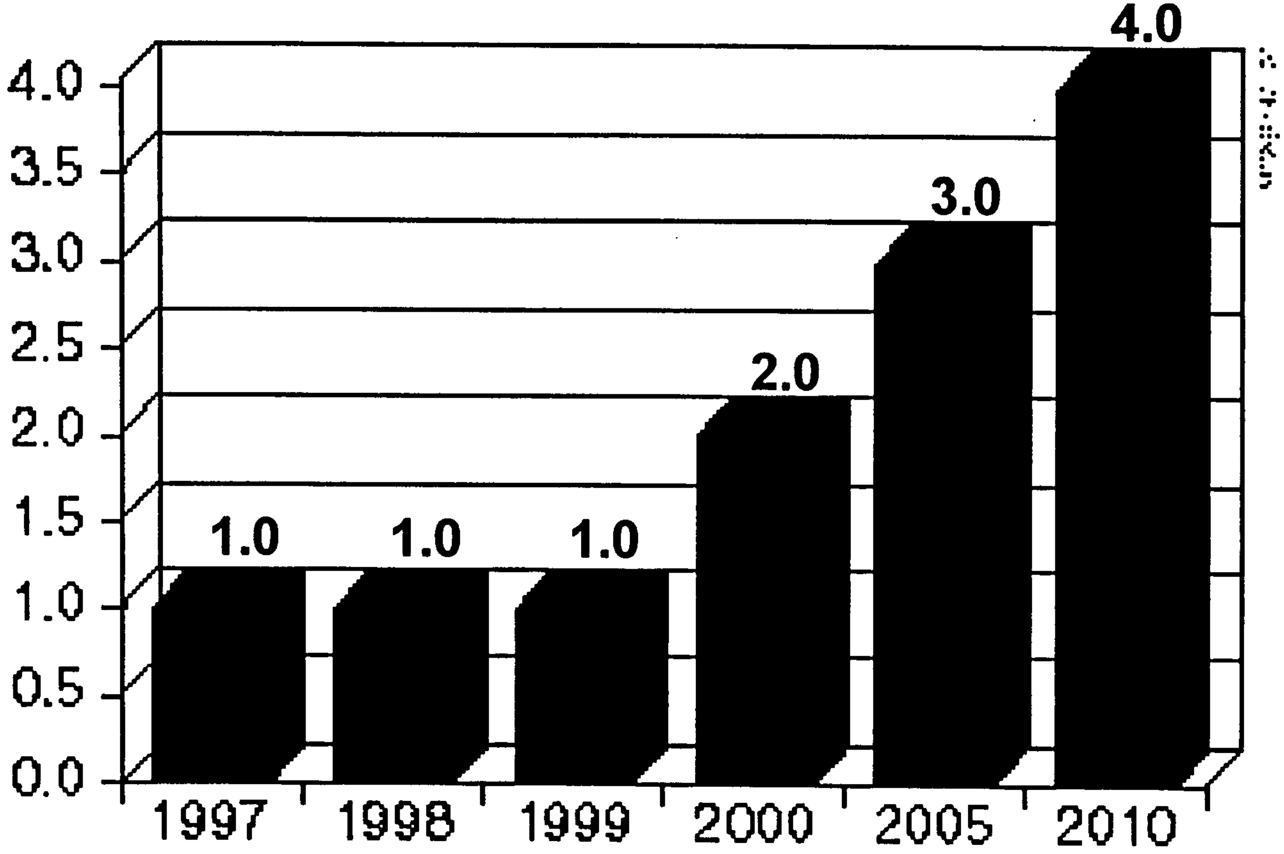
MILLION Solar ROOFS

System Size (kW)



The average photovoltaic system size will double by the year 2000 and quadruple by 2010.

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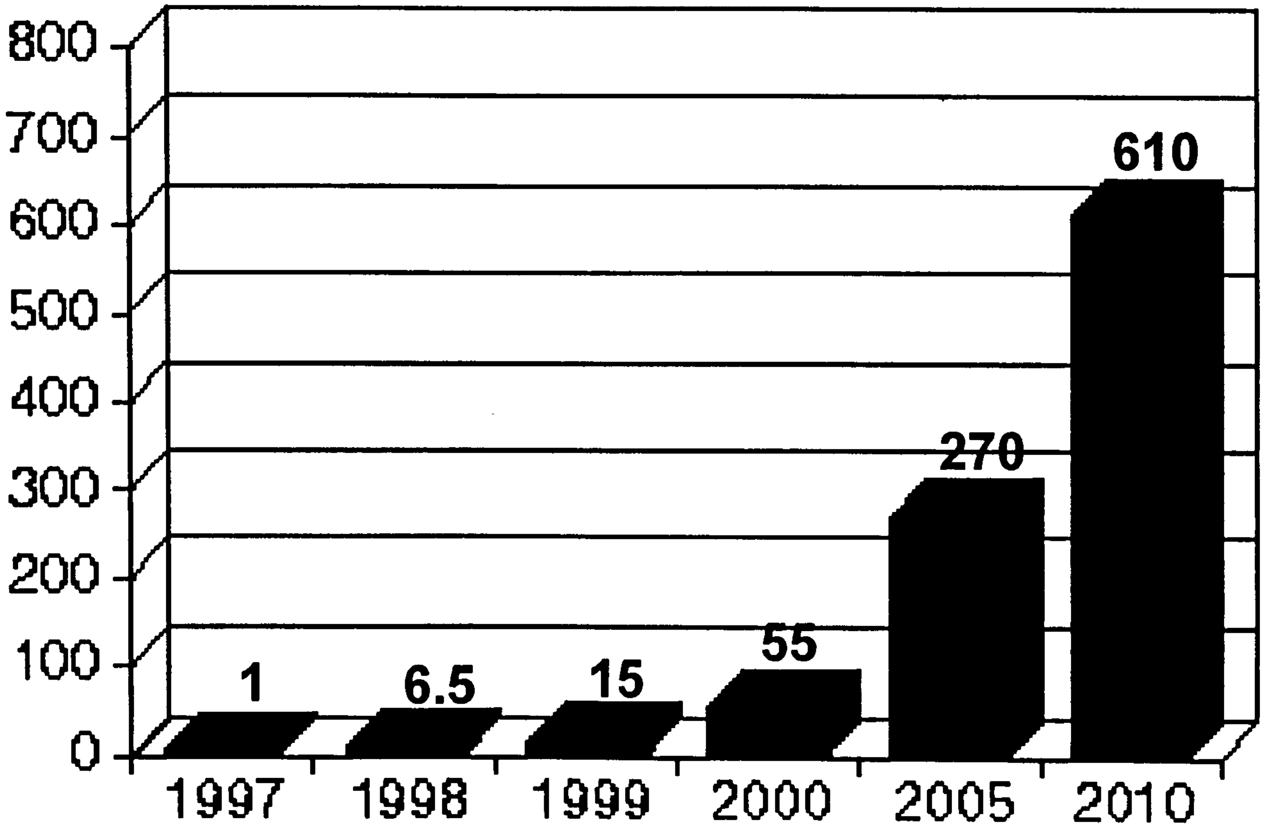
MILLION Solar ROOFS

Annual Capacity (MW)



Each additional solar megawatt enriches our nation's domestic economy.

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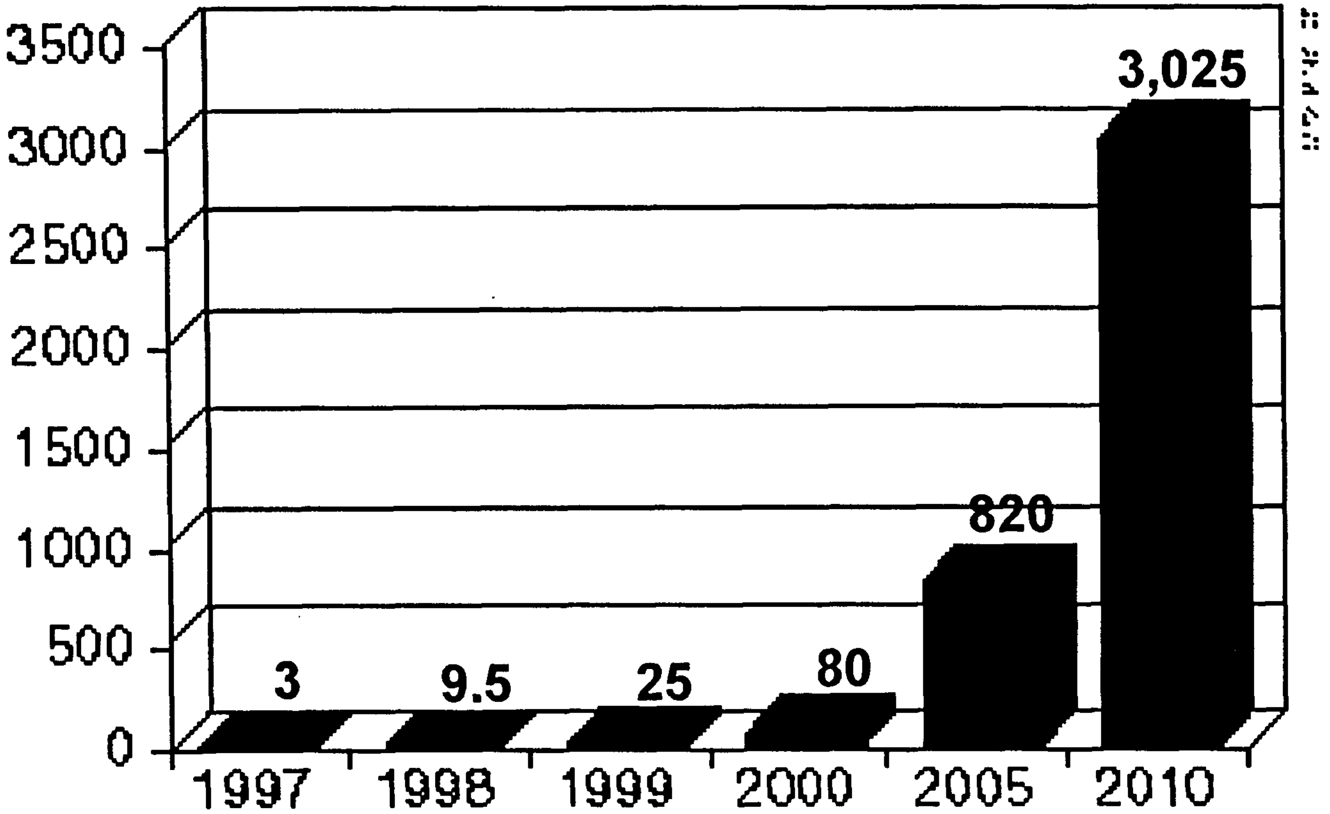
Million Solar Roofs

Total Installed Capacity (MW)



By establishing local suppliers and service companies, the initiative will keep community resources invested locally rather than having to export dollars to import fuel or electricity.

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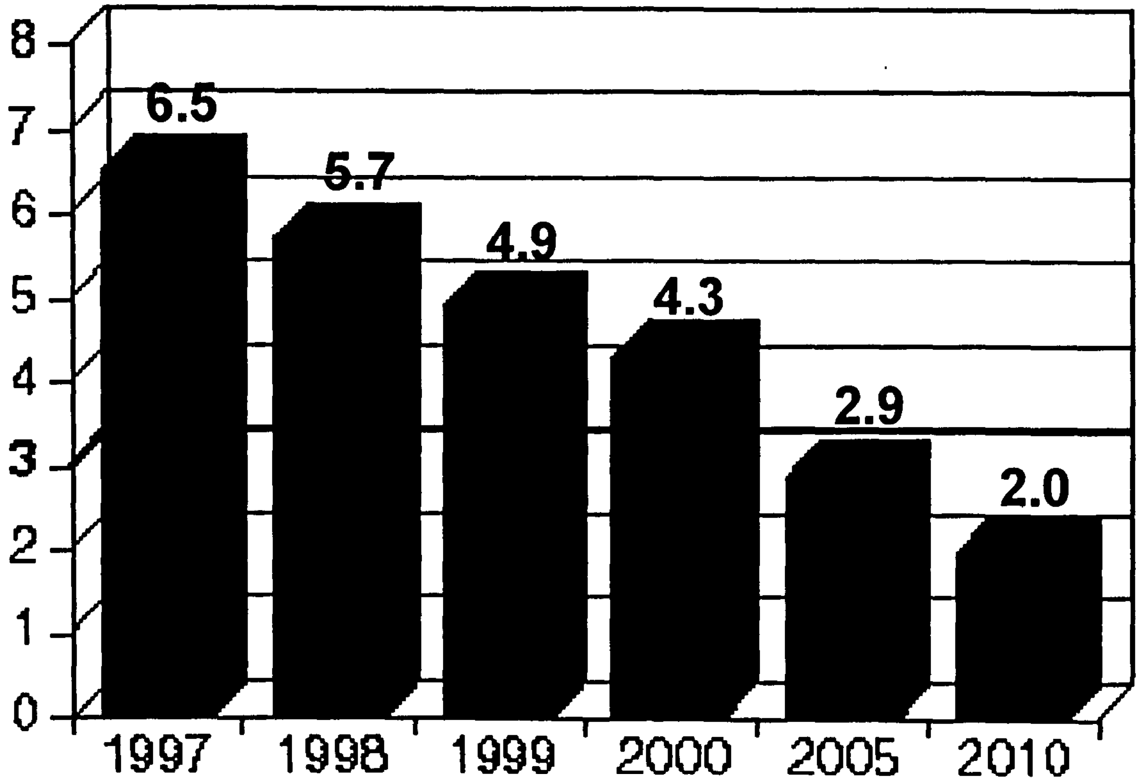
Installed Cost ($W)



It's certain that as volume goes up, the cost of solar systems will decline dramatically. Actual prices in the marketplace may vary from these benchmark goals due to numerous market factors. The installed cost of $3.00 per watt is a key threshold for broader commercial use of photovoltaics.

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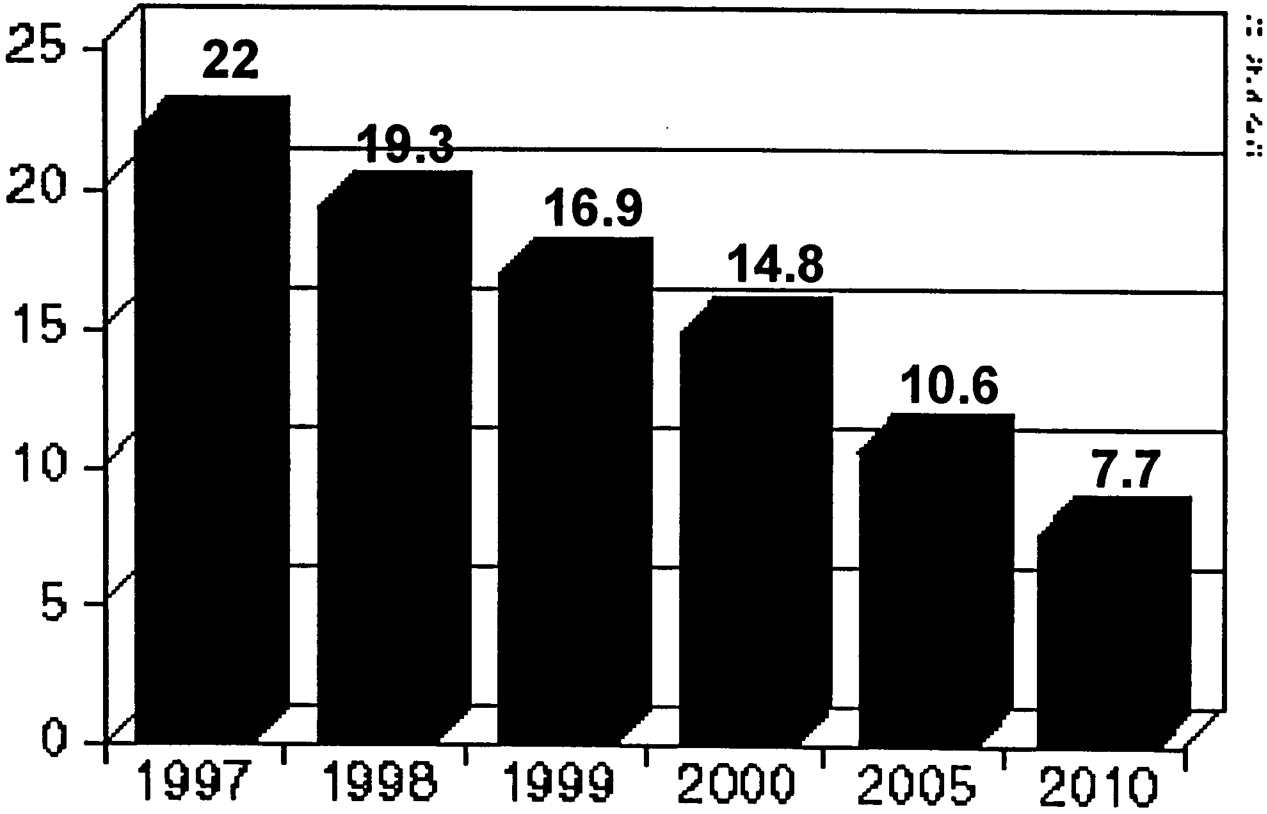
MILLION Solar ROOFS

Energy Cost (¢/kWh)



The per-kilowatt cost of solar energy is projected to decline by nearly 300% over the 13-year span of the Initiative. The optimistic benchmark goals shown here do not reflect the many variables that affect true energy costs.

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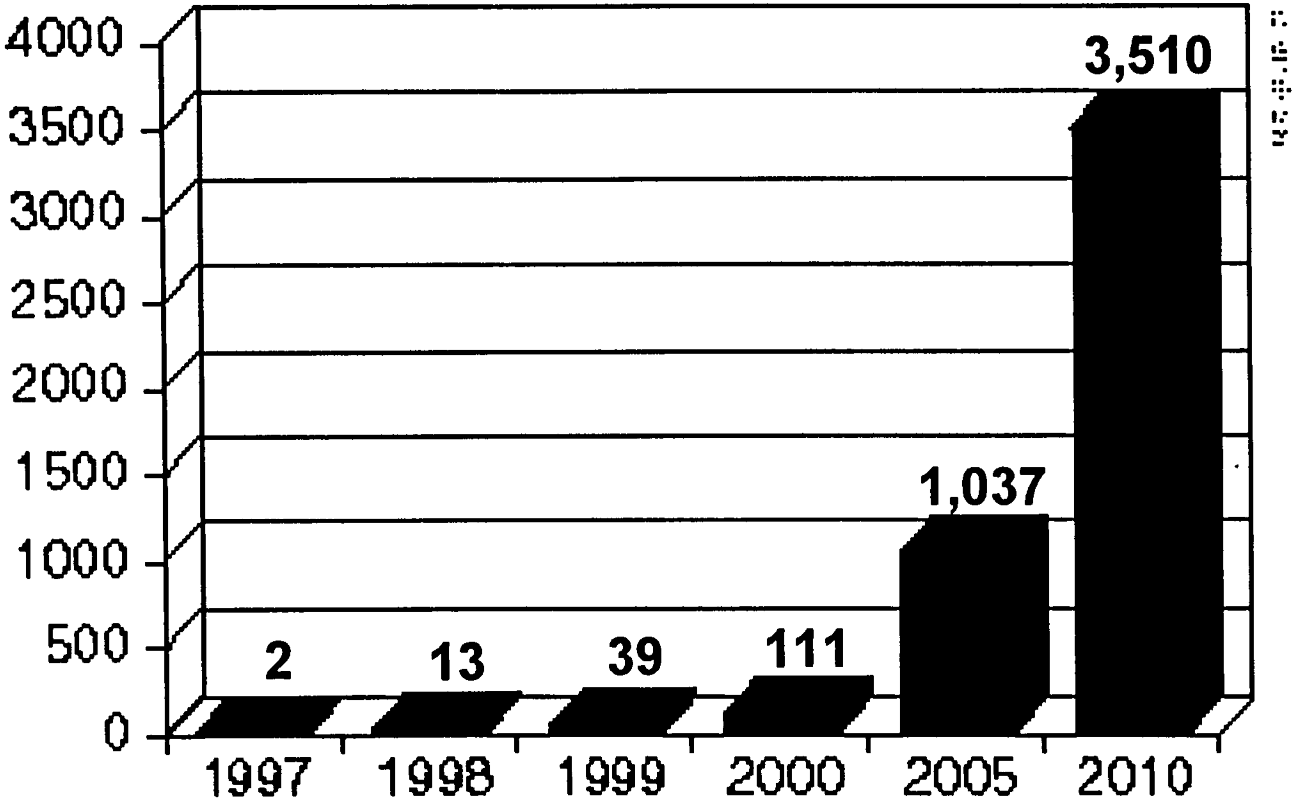
Total Annual CO_2 Savings

(Thousands of Tons)



By 2010, emissions of carbon dioxide, the most "prolific" Greenhouse gas, will be reduced by an amount equal to what is now produced by 850,000 automobiles.

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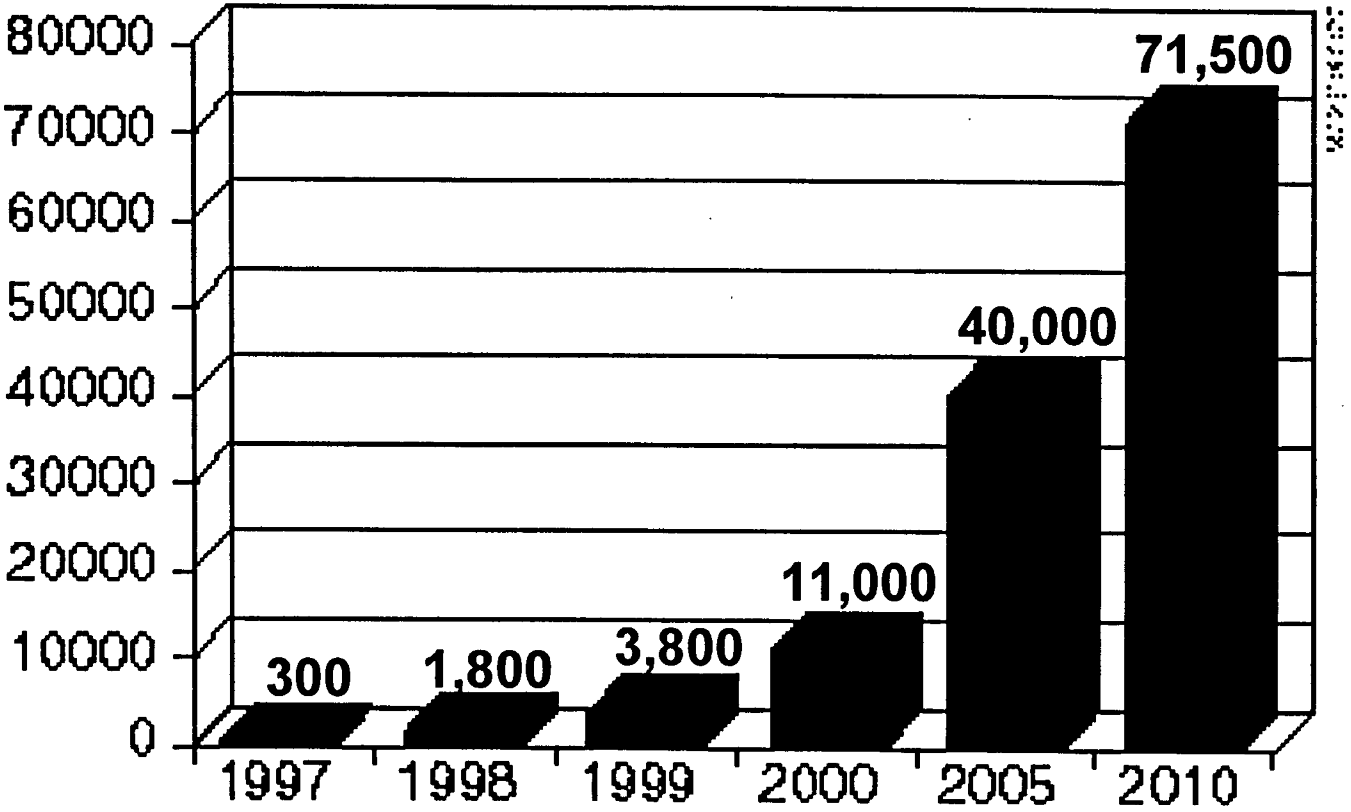
MILLION Solar ROOFS

Jobs Created



For every $100 million invested in the Initiative, 3,850 direct and indirect jobs will be created, resulting in more than 70,000 new high-tech jobs by 2010.

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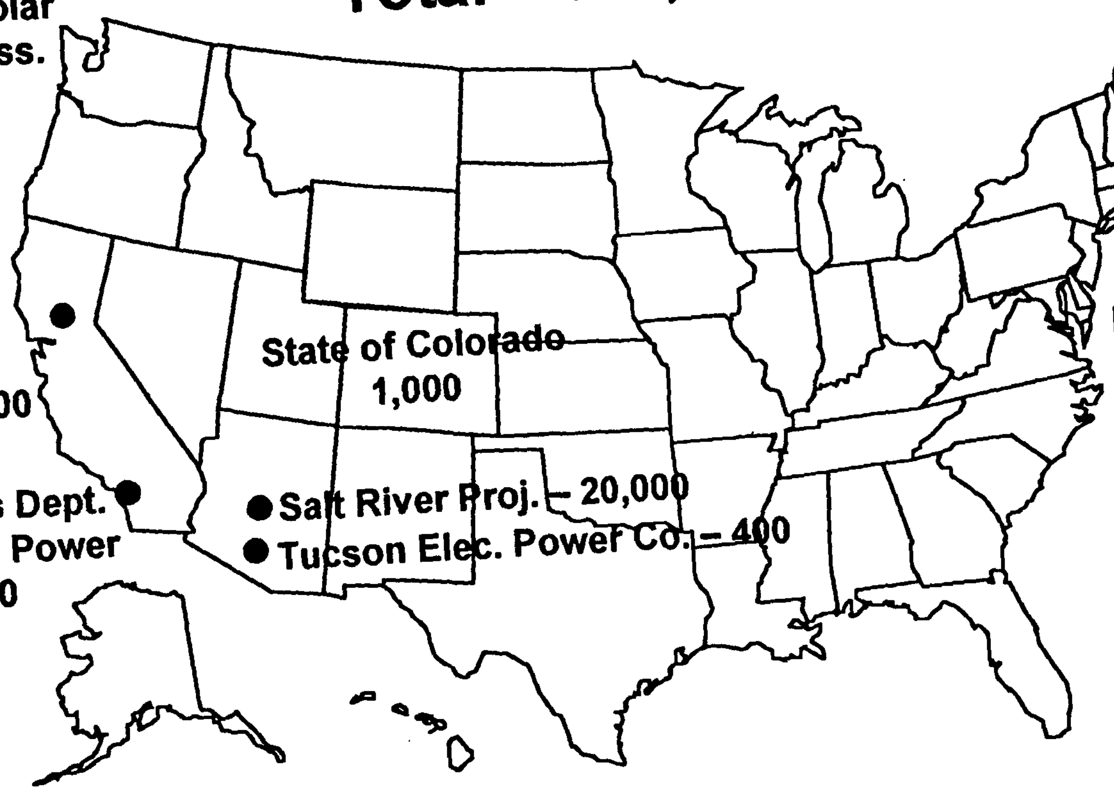
Million Solar Roofs Partnership Commitments

Total = 526,400



Wash. State Solar Energy Ind. Ass.
20,000

Sacramento Munc. Util. Dist.
- **Within SMUD terr. 25,000**
- **Within CA – 200,000**

Los Angeles Dept. of Water and Power
100,000

State of Colorado
1,000

- **Salt River Proj. – 20,000**
- **Tucson Elec. Power Co. – 400**

New England Elec. Service
100,000

Maryland Energy Adm.
20,000

Hawaii Elec. Light Co.
20,000

Federal Commitment
20,000

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Goals

- Reduce greenhouse gas and other emissions
- Create high-tech jobs
- Keep the U.S. solar energy industry competitive

10 Point Action Plan

1. Establish 25 major partnerships to install solar energy systems by Sept. 30, 1999
2. Improve access to financing for solar energy systems
3. Build a network of state renewable energy funds
4. Establish *Million Solar Roofs* tax credit
5. Obtain commitments from other federal agencies

10 Point Action Plan

6. Support adoption of the administration’s utility restructuring plan
7. Establish uniform interconnection standards for photovoltaics and promote net metering
8. Support major partnerships through the DOE Regional Support Offices and training and technical assistance
9. Support research, development, and demonstration
10. Hold quarterly progress meetings

Department of Energy
Washington, DC 20585

Million Solar Roofs Initiative

Top Ten Questions

1. What is the Million Solar Roofs Initiative?

Million Solar Roofs is an initiative to install solar energy systems on one million U.S. buildings by 2010. It was announced by President Clinton on June 26, 1997 in his speech before the United Nations Session on Environment and Development. This effort includes two types of solar technology -- photovoltaics that produce electricity from sunlight and solar thermal panels that produce heat for domestic hot water, for space heating or for heating swimming pools.

The U.S. Department of Energy will work with partners in the building industry, other federal agencies, local and state governments, utilities, the solar energy industry, financial institutions and non-governmental organizations to remove market barriers to solar energy use and develop and strengthen local demand for solar energy products and applications. The Million Solar Roofs Initiative will bring together the resources of the Federal government with key national businesses and organizations and focus them on building a strong market for solar energy applications on buildings.

The three principal goals of the Initiative are:

- Reduce greenhouse gas and other emissions using clean energy from the sun. In 2010, with one million solar energy roofs in place, the Initiative would reduce carbon emissions in an amount equivalent to the annual emissions from 850,000 cars.
- Create high-tech jobs in the solar energy industry. By 2010, approximately 70,000 new jobs could be created as a result of the increased demand for photovoltaic, solar water heating and related solar energy systems.
- Keep the U.S. solar energy industry competitive. By increasing the domestic market for solar energy, increasing domestic production and reducing the unit cost for solar energy systems, the Initiative will enable U.S. companies to retain their competitive edge in the worldwide market. By 2005, the photovoltaic market alone is expected to exceed $1.5 billion worldwide.

Printed with soy ink on recycled paper

2. Why are we undertaking this Initiative and at this time?

Greenhouse gas emissions are caused mostly by the inefficient burning of fossil fuels. By increasing the efficiency of how we use fossil fuels, reducing our use of these fuels and switching to alternative, non-polluting fuels, we can significantly reduce the amount of greenhouse gases we put into the atmosphere and reduce the threat of global climate change. One of the most promising non-fossil sources is solar energy. As President Bill Clinton said in a June, 1997 speech to the United Nations, "Capturing the sun's warmth can help turn down the Earth's temperature."

Photovoltaics were invented approximately 40 years ago at AT&T's Bell Laboratories and later developed as a means to power satellites and space vehicles. As the U.S. investment in the technology improved their performance and reduced their costs, other countries saw their potential and started their own development efforts. In the past two decades, research and development have improved the efficiency and reliability of photovoltaics reduced the costs of photovoltaic electricity by a factor of 5.

The Million Solar Roofs Initiative will help increase the market for solar energy and encourage increased development and production of solar energy systems. At the same time, the Initiative will give consumers an affordable, clean-energy option, create new U.S. high technology jobs and play an important role in reducing greenhouse gas emissions.

3. What are the qualifications for a building to be a part of this Initiative?

To be included in the Million Solar Roofs Initiative, a building's solar energy system must comply with all relevant parts of the National Electrical Code (NEC), Underwriters Laboratories (UL) standards and the Solar Rating and Certification Corporation (SRCC) standards, be located on or immediately adjacent to the building and meet the following minimum standards:

Photovoltaic Systems:
- Residential systems must be a minimum of 0.5 kW
- Commercial systems must be a minimum of 2.0 kW

Solar Thermal Water Heating Systems:
- Residential domestic must be a minimum of 1.0 kW equivalent or 20 square feet of collectors
- Residential swimming pool heating must be a minimum of 100 square feet of collectors
- Commercial domestic must be a minimum of 2.0 kW or 40 square feet of collectors
- Commercial swimming pool heating must be a minimum of 400 square feet of collectors

Solar Thermal Space Heating Systems:
- Collector must be a minimum of 100 square feet or 4.0 kW

4. Who is a Million Solar Roofs Partner?

The Million Solar Roofs Initiative will encourage participation of all interested individuals, businesses, industries, governments, federal agencies, utilities and non-governmental organizations. The Initiative will attract partners building by building, community by community, state by state and business by business. It will work "top-down" and "bottom-up" through three types of partnerships:

Individual Partnerships: Any person or organization who installs the minimum size solar electric or solar thermal energy system on a residential, commercial, institutional or government building will be able to register with the Million Solar Roofs Registry. There is no requirement for participation in any other activities for these parties to be a partner in the Initiative.

State and Community Partnerships: Million Solar Roofs State and Community Partnerships bring together business, government and community organizations at the regional level with a commitment to install solar energy systems. Examples of State and Community Partners include:

- Builders
- Energy Service Providers
- Utilities
- Non-Governmental Organizations
- Environmental Groups
- Local Governments
- State Governments
- Federal Government Agencies

National Partnerships: At the national level, partners will make a commitment to install a significant number of solar energy systems and provide national support for the Initiative. Examples of potential National Partners include:

- Any Entity that commits to installing over 5,000 solar roofs by 2010
- Solar Energy Equipment Manufacturers and Distributors
- National Utility Companies and Energy Service Providers
- National Financial Institutions
- National Government Associations such as the National Association of Counties, the National League of Cities, the National Association of State Energy Officials, the U.S. Conference of Mayors and the International City/County Management Association
- National Business Associations such as the Solar Energy Industries Association and Utility Photovoltaic Group
- National Environmental Organizations

5. What activities will partnerships undertake?

Examples of activities that Million Solar Roofs partners may undertake include:

- Developing a plan for solar energy installations under the Million Solar Roofs Initiative.
- Committing to a specific number of solar energy systems to be installed on buildings in the period between 1998 and 2010.
- Committing government efforts to overcome barriers to solar energy and energy efficiency applications in buildings.
- Identifying financial incentives for solar energy installations.
- Establishing net metering for photovoltaics.
- Developing and/or modifying codes and standards that affect solar energy installations.
- Implementing training programs for building officials, the construction industry, solar energy installers and utility personnel.
- Providing outreach support for solar energy and energy efficiency.
- Taking part in national information sharing, peer-to-peer exchanges and cooperative research and training efforts.
- Connecting the Million Solar Roofs Initiative with other sustainable community initiatives.

6. What assistance is available?

The Million Solar Roofs Initiative, coordinated by the U.S. Department of Energy and supported by its partners, provide the following:

- Assistance in accessing low-cost loans, buy-down grants and other financial assistance.
- Training and information about the experience implementing the Initiative in communities around the United States.
- Recognition and support on a national, regional and local basis.
- Marketing and technical assistance from DOE's Regional Support Offices and the program staffs of DOE's Offices of Utility Technologies and Building Technology, State and Community Programs and the DOE Federal Energy Management Program.
- Technical assistance and training support from DOE's national laboratories.
- Linkage with and access to customers and solar energy businesses, associations and related industries that can provide assistance to local teams and others interested in solar energy applications.

7. What is the Federal commitment with its own buildings?

The federal sector represents approximately 1/2% of the U.S. building inventory with its 500,000 buildings. These half-million buildings require the Federal government to spend over $3 billion each year for heating, cooling, lighting and powering the operations. During the past twenty years, actions have been taken to reduce that energy bill through energy efficiency investments and the application of renewable, including solar, energy systems on new and existing federal buildings.

President Clinton has committed the Federal government to install solar electric and solar thermal energy systems on 20,000 federal buildings by 2010. The U.S. Department of Energy's Federal Energy Management Program will assist Federal agencies to meet that commitment.

The Federal Energy Management Program recently established umbrella contracts with energy service companies to purchase energy efficiency services for Federal buildings. These "Super Energy Savings Performance Contracts" enable all Federal agencies to improve the efficiency of their buildings through cost effective partnerships with the private sector. The next round of procurements will put in place almost $200 million in contracts which will use private financing to install solar energy systems at Federal facilities and enable Federal agencies to support the Million Solar Roofs Initiative. In addition, the General Services Administration has developed and implemented streamlined procurement procedures for Federal agencies to obtain solar energy systems. The Department of Defense has already installed many solar energy systems on its buildings including, for example, solar hot water systems on Navy housing and a solar space heating system on an Army aviation maintenance facility.

8. What are Photovoltaics?

Photovoltaic devices, or solar cells, convert sunlight directly to electricity. It is an attractive alternative to conventional sources of electricity for many reasons: it is silent, non-polluting, and renewable; it requires no special training to operate; it is modular and versatile; it is extremely reliable and virtually maintenance free (with no moving parts); and, it can be installed almost anywhere. The customer pays only for the system; the fuel is free.

Photovoltaic cells are made of a semiconductor material, usually silicon, and produce an electric current in the presence of light. Individual cells are combined to create modules that produce a specific amount of peak power. The modules, in turn, can be combined to create arrays that produce larger amounts of power. These arrays can be sized to meet the power requirements of the particular application.

9. What is Solar Thermal heating?

Solar energy can be used to heat both water and air. Solar water heaters use the sun to heat either water or a heat-transfer fluid, such as an antifreeze mixture, in collectors usually mounted on the roof. The hot water, produced directly in the collector or via heat from the transfer fluid, is then stored in standard insulated water tank. Some systems use an electric pump to circulate the fluid through the collectors. These environmentally friendly systems are increasingly cost competitive for providing domestic hot water and for swimming pool heating.

Solar space heating offsets building heating loads by either heating recirculated building air or preheating outside or ventilation air. For heating recirculated air, solar energy panels are normally required to receive direct sunlight and provide air temperatures higher than the interior temperature to be effective. The transpired collector, which uses a dark collection surface with perforated metal plates to heat the air just behind the plate surface, is very effective in preheating outside or ventilation air. One additional benefit of the transpired collector is that it can also serve as a component of the building shell.

10. How much will solar energy systems cost?

A residential solar hot water system may cost anywhere from $1,800 to $3,500 and compete effectively with water heated by electricity that costs 8 cents per kWh or more. Solar thermal space heating is very effective in most areas of the country. For example, the cost of a 100 square foot transpired collector installation can range from $1,000 for retrofits on existing buildings and $500 -$700 for new systems, but can produce energy savings to offset the entire cost of the system in five years or less.

Photovoltaic costs are more complicated because system size, features and net cost to the users depend on the financing terms and interest rates, available incentives and access to low cost hardware and installation through bulk purchasing programs. For example, residential photovoltaic systems recently installed in Sacramento, California cost just under $7,000 per kilowatt, and provide energy at approximately 24 cents per kilowatt-hour.

Solar technologies are cost-effective in many niche applications today, for example, the use of photovoltaics at remote installations not on the power grid. A solar energy system's cost can also be reduced by Federal and State tax incentives and other financial support. Additional cost reductions are possible through the use of state-implemented net metering options. Financing assistance can, in many cases, reduce the cost of solar energy systems to the point where monthly payments for the system are less than the monthly energy bill savings.

For More Information:
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Solar Energy Industries Association
www.seia.org