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Experience Scaling-Up Manufacturing of Emerging Photovoltaic Technologies

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Subcontract Report
NREL/SR-640-39165
January 2007

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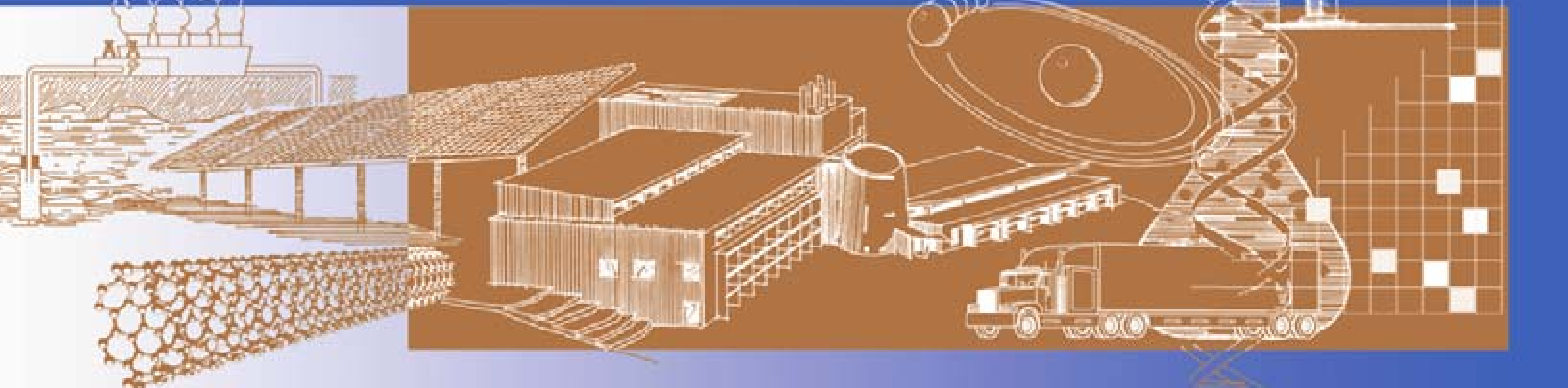

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Table of Contents

Authors' Preface

We had close visibility to two important generic photovoltaic technologies at particularly revealing stages of development, i.e., the stages between R&D and stable commercial production and profitable sales.

After considering and incorporating comments on our original draft, we feel the need to be very clear about what this report attempts and what it does not attempt. Based on two historical cases, it attempts to shed light on the difference between: 1) costs and schedules validated by actual manufacturing and market experience, and 2) estimated costs and schedules that rely on technology forecasts and engineering estimates. The amorphous Silicon case also identifies some of the costs that are incurred in meeting specific market requirements, while the Cadmium Telluride case identifies many of the operational challenges involved in transferring R&D results to production.

We do not claim that the experience reported is typical of what may be expected in other cases of thin-film PV commercialization. Nevertheless, it may be illuminating in general terms, i.e. costs and timescales involved in replicating favorable R&D results in the much more demanding context of commercial production. The problems we encountered may not be unique to the cases we discuss; they may be relevant to parallel and future efforts. Some in fact are generic concerns, e.g. the problems of scaling from R&D results to larger area products in high volume production. Likewise, managing the interplay between markets, technology and manufacturing is a challenge every new PV enterprise must face, and the challenge is compounded by inherent differences between incumbent products and new offerings. Other problems probably were unique, e.g. some specific product finishing costs dictated by emerging and innovative market applications.

We were not tasked to present a management case study. It is impossible to illuminate all of the considerations that enter into investment and operational decisions in a competitive environment. We caution against inferring that easy choices were missed. We know of none.

The transition between R&D and commercial success takes a great deal of time and money for emerging energy conversion technologies in general. The experience we report can be instructive to those managing comparable efforts, and to their investors. It can also be instructive to R&D managers responsible for positioning such new technologies for commercial success via the U.S. Department of Energy Solar Technology program. We commend Dr. Robert Margolis' recognition of the latter opportunity, and we appreciate reviewer comments that led to clarifications and improvements in our report.

Gerry Braun and Doug Skinner

Executive Summary

At the end of 2002, a first-tier PV module manufacturer, BP Solar, announced its decision to abandon two leading thin-film PV manufacturing scale-up and commercialization efforts. These intensive efforts spanned a decade and were the culmination of private-sector R&D investments totaling a few hundred million dollars during the prior decade. Combined capital expenditures approached 100 million (2005) dollars and were supported by significant U.S. Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) R&D expenditures. In both cases, hard challenges were met – and a wealth of experience was gained.

In late 2004, a study was commissioned to review what was learned specifically about cost, i.e. to:

- Identify real-world cost models that can be used to evaluate comparable emerging technologies
- Identify decisions and cost drivers that may be influential in other cases
- Understand the reasons actual product costs may have exceeded original estimates
- Apply related insights to evaluate the potential for future cost reductions using comparable technology

Two cases were considered:

1) Introduction of large-area tandem amorphous silicon (a-Si) thin-film modules into the global PV market, and
2) Transfer of cadmium telluride (CdTe) thin-film research results to a production environment.

Recognizing that “time is money” in matters of this sort, it is instructive to place cost experience in the context of R&D and commercialization phases and their duration. Figure EC-1 below provides a program chronology for the two cases.

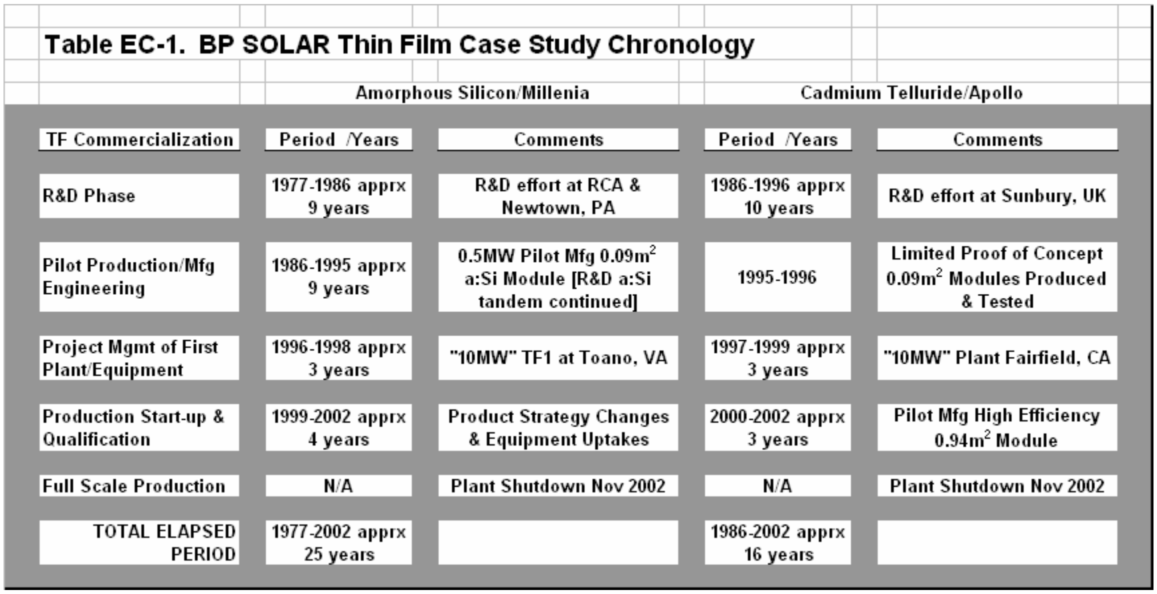


Table EC-1. BP SOLAR Thin Film Case Study Chronology

	Amorphous Silicon/Millenia		Cadmium Telluride/Apollo	
TF Commercialization	Period /Years	Comments	Period /Years	Comments
R&D Phase	1977-1986 apprx 9 years	R&D effort at RCA & Newtown, PA	1986-1996 apprx 10 years	R&D effort at Sunbury, UK
Pilot Production/Mfg Engineering	1986-1995 apprx 9 years	0.5MW Pilot Mfg 0.09m^2 a:Si Module [R&D a:Si tandem continued]	1995-1996	Limited Proof of Concept 0.09m^2 Modules Produced & Tested
Project Mgmt of First Plant/Equipment	1996-1998 apprx 3 years	"10MW" TF1 at Toano, VA	1997-1999 apprx 3 years	"10MW" Plant Fairfield, CA
Production Start-up & Qualification	1999-2002 apprx 4 years	Product Strategy Changes & Equipment Uptakes	2000-2002 apprx 3 years	Pilot Mfg High Efficiency 0.94m^2 Module
Full Scale Production	N/A	Plant Shutdown Nov 2002	N/A	Plant Shutdown Nov 2002
TOTAL ELAPSED PERIOD	1977-2002 apprx 25 years		1986-2002 apprx 16 years	

The chronology suggests that the average time elapsed between the start of the R&D phase and program termination was roughly 20 years for two cases that stopped short of full commercial success. While this result may not be representative of an entire class of technology, or other on-going cases, it does provide potentially useful benchmarks.

Tandem amorphous silicon summary

The tandem amorphous silicon commercialization efforts began with funding and construction of a manufacturing plant intended to produce 10MW per year. Product efficiency, plant throughput, and yield shortfalls limited actual realized capacity to around 6MW per year.

The commercialization effort was driven by three dramatically different market strategies at different stages:

1) The original strategy (internal sales of frameless and otherwise unfinished glass to glass laminates for large privately financed power projects) proved infeasible.[1]
2) The second strategy (competition with crystalline products for market share in all major market segments) proved feasible, though financially unattractive, under the circumstances. It required significant product development and inline process work.[2]
3) The third strategy (internal sales of a specialized building integrated PV (BIPV) product) was temporarily successful and also required significant product development and manufacturing process enhancements.

Factory and support organizations struggled to support the strategy changes. Related customer and internal company coordination posed significant challenges.

Cost models evolved toward greater detail but did not change in basic structure. Cost forecasts did change significantly. Some of the significant individual changes were independent of product specification; including those driven by the inability to achieve originally forecast conversion efficiencies, line yields, staffing levels, depreciation, and other fixed costs. Original material cost estimates held up fairly well.

Other significant changes were driven by the above market strategy changes, as reflected in product specifications. The first strategy change resulted in a requirement for a product line with nominal voltages and other product features compatible with typical PV end uses at the time. These features included:

- Framing and strengthened glass for robustness,
- Factory-installed industry standard cables and connectors, and
- Improved encapsulation and edge insulation as necessary to meet various safety and product life qualification and certification processes and standards.[3]

The second strategy change introduced the requirement for "vision glass," i.e. semi-transparent laminates with special edge connectors suitable for use in canopies and, ultimately, windows.

Both market strategy changes involved trade-offs among marketing, technology, engineering, and manufacturing. Some trade-offs would have been better and more economically manageable prior to production rather than during an extended production ramp. For example, the transition to processing strengthened glass was especially slow and costly – and never fully executed. In the meantime, both factory and customers dealt with the problems of material more susceptible to breakage and crack propagation in handling, shipping, and long-term operation than competing products already in the market.

The owners of the commercialization effort and its assets probably considered the cost experience analyzed here in deciding to abandon the effort. The original plan called for the prototype factory to be replicated extensively while being upgraded with new deposition technology. The vision was to achieve hundreds of MW/year of cumulative manufacturing capacity over in the decade following successful prototype factory operation. Prototype factory performance could not have been regarded as successful relative to the original targets; accordingly, the original strategic vision had been abandoned well before the prototype factory itself was abandoned. A break-even factory operation might still have survived based on yet a third market strategy change, i.e. to focus on markets involving single modules vs. larger arrays.

A recommitment to this original vision for the technology, as some have recently proposed, might reasonably target manufacturing costs in the same range as originally forecast, i.e. $0.75/W *in 1995 dollars* for unframed annealed glass laminates lacking cables and connectors. Success would require achievement of the originally targeted efficiencies as well as the ability to spread fixed costs over multiple, identical new factories once the cost target could be validated in a prototype plant. Success in achieving these costs would not guarantee market success. One thing experience makes clear is that the existing and foreseeable markets want products more robust and completely featured – and, therefore, significantly more costly – than the product targeted more than10 years ago.

A different original vision, involving a more appropriate choice of entry markets, might have yielded different results. The appropriate entry market for tandem amorphous might, for example, have been the remote power market, ironically a market segment in which its sponsor had excellent access. Instead, applications in the targeted entry market, large-scale power plants, would have not only required near-perfect execution in the scale-up phase but also significant subsequent technology and engineering upgrades.[4]

Cadmium telluride summary

The cadmium telluride commercialization effort was launched at a plant originally intended to produce 10MW of single-junction amorphous silicon product annually.[5] The project replaced front-end amorphous silicon deposition equipment with cadmium telluride deposition equipment. Unlike the above tandem amorphous silicon effort, the effort was not preceded by pilot manufacturing and sale of small area modules using the same basic film deposition technology. The market vision was relatively under-developed at the time scale-up was committed, although the product and manufacturing vision were well informed by previous single junction amorphous silicon production experience at the same site. The experience, however, did not overcome the cost, schedule, and performance challenges associated with unique chemical deposition processes and equipment.

In support of investment decisions, detailed manufacturing cost models were developed. In contrast to the tandem amorphous silicon case above, forecasted costs changed in a favorable direction during the preproduction phase as significant efficiency improvements – higher watts per unit – were achieved during process development before full-scale production was attempted. Subsequently, because the endeavor was abandoned before routine shipments of commercial product could be achieved, the cost model and forecasted costs did not evolve further except to accommodate various module engineering changes related to encapsulation, cabling, and connectors; and strengthened glass and framing options. Product stewardship costs were a major consideration, based on market information suggesting that arrangements would be needed to support "cradle-to-grave" or even "cradle-to-cradle" product recovery, disposal, and/or recycling. Again, forecasts were made but were not validated by commercial experience.

The cadmium telluride effort was instructive regarding the time and cost required to transfer limited R&D processes into full-scale manufacturing. Examples include accommodating the realities of local labor markets, and the losses of continuity and technology support when originating R&D staff is not co-located with nor accountable to the commercialization project manager. The effort took place under conditions not likely to be repeated. The unique circumstances of a corporate merger and related downsizing activity had an impact. There was a need to convert an incomplete R&D result to complete engineering reality on a compressed schedule that had no margin to accommodate technical setbacks or accomplish inevitable process and engineering changes. There was also no time to investigate and design around phenomena that had not been exposed in the R&D process (e.g., anomalous differences between outdoor and indoor performance) nor was there time to adjust product design and process engineering in order to pass qualification tests and achieve necessary product certifications.

Perspective

The reviews summarized here focused on cost experience. Some cost-related observations common to both cases include:

- First-order thin-film PV cost drivers are module electrical efficiency and process throughput[6]; second order is production yield; third order is economies in materials and labor; there may be no single dominant driver[7].
- Both efforts validated the intrinsic ($/Wp) cost advantage of thin-film PV, i.e. unlike crystalline, thin-film's intrinsic material costs are largely (around 80%) associated with materials other than the active PV materials. However, this advantage can be overwhelmed by other fixed and variable manufacturing costs (capital and labor) when thin-film efficiencies fall well short of crystalline efficiencies.[8]

- Large-scale thin-film manufacturing requires major financial investment over several years. Initial capital investment in a factory scaling up from R&D results can be as high as \$2-3 per watt for a 10MW/year thin-film factory; capitalized operating losses on the way to mature full capacity operation can be in the same range, in which case the financial breakeven horizon may be pushed out a decade or more beyond its original target.
- The *manufacturing* cost targets of the two efforts reviewed were quite aggressive yet well above \$1/Wp (2005 \$) for glass-glass laminate modules. The review did not suggest ways these goals could have been achieved with the technologies at their stage of development when the factories were abandoned. Targeting *installed* costs in the same range for generically similar products from new factories[9] lacks grounding either in experience reported here or foreseeable technology improvements.

Low cost per Watt is a necessary, but not sufficient, condition in order for thin-film modules to take power array sales away from crystalline modules; the generically lower power density of thin-film modules imposes greater balance of system costs which scale with the efficiency deficit. The effect varies with application. In some applications thin-film modules having significantly lower efficiency than crystalline counterparts cannot be priced low enough to off-set the balance of system cost penalty without jeopardizing the financial viability of the manufacturer. Regardless of efficiency, thin-film products lacking a track record in the market may not command the same unit price (\$/W) the market is willing to pay for familiar and proven products having equivalent specifications. Thus, there are significant barriers to market entry facing new PV module offerings that are not addressed by the current study.

Cost experience cannot completely be separated from other observations, which include:

- Good R&D and pilot production using R&D equipment does not guarantee commercial success – both tandem a-Si technology and CdTe technology achieved impressive efficiency targets over short time periods, but the knowledge base needed for high volume manufacturing at competitive costs was still in development at the time of production start-up and even when each effort was concluded.
- The stage-gate management of a developing technology does serve to emphasize critical performance measurements and to focus the management of the project; significant resources in time, equipment and staff may still need to be expended before a clear path to commercial success or a shutdown decision can be reached; in both thin-film cases covered here, the parent enterprise was already producing technically competitive products, thus reducing the incentive to persevere in dealing with set-backs and limitations. The bar was high for both challenger technologies.
- Initial product specifications in both cases were consistent with minimizing factory value-added features and therefore manufacturing cost, envisioning that mounting system and interconnection designs suitable for glass-glass laminate modules would be prepared by others. More recent module industry trends are actually maximizing factory value-added features in pursuit of plug-and-play functionality to minimize installation costs and complexity.[10]

- Emerging PV technology should aim to meet the requirements of existing markets, unless it offers an extremely inviting competitive advantage in an emerging market. *Managing both market risk and technology risk is much more difficult than managing one or the other independently.*
- PV markets demand results that research per se cannot deliver. This is especially true if, as above, the plan is to meet the requirements of existing markets. In this case, product development and engineering to meet industry standards (for reliability, safety and product life) must precede, not catch up with, factory operations.
- Manufacturing start-up requires a skilled and dedicated work force; technicians and operators generally need to be trained by the enterprise. Depending on local and national conditions, recruiting of technical staff can be problematic when local applicants with necessary specialized knowledge cannot be identified; location in strong industrial economies makes it easier to find second- and third-tier employees.
- It is encouraging to note that some other glass-metal, thin-film product commercialization efforts appear to be progressing well. Partnership with outside agencies can make substantive contributions in bringing a new technology on line; in terms of the cadmium telluride effort, there were demonstrable gains in technology and time as the result of working agreements with NREL and the Institute for Energy Conversion.

Introduction

As part of reviewing the U.S. DOE Solar Program's technical and economic targets for PV technology, it is important to place future projections in the context of real-world experience. While current PV production is dominated by crystalline silicon technology, there are a number of emerging PV technologies that could gain significant market share in the future, if they can successfully compete with crystalline technology on price, performance, and overall functionality and aesthetics. Estimating the potential for these emerging technologies to realize projected cost reductions is more of an art than a science. Thus, examining the available experience with scaling-up PV module manufacturing for a number of emerging PV technologies can help to build a sound foundation for evaluating the potential for these emerging PV technologies to meet the Solar Program's technical and economic targets.

In late 2002, two leading thin-film PV manufacturing scale-up and commercialization efforts were abandoned by a first-tier PV module manufacturer (BP Solar). This report will refer to them variously by location, technology, and brand as follows:

1. A tandem amorphous silicon (a-Si) PV module factory, dubbed by its owner as TF1, was built at Toano, Virginia, (near Williamsburg) based on several years of pilot manufacturing of smaller single-junction aSi modules at a combined research and production facility in Newtown, Pennsylvania. The tandem a-Si modules shipped from Toano were branded generally as Millennia.

2. A factory was assembled at Fairfield, California, by converting a factory originally designed to produce single-junction amorphous silicon modules to instead produce cadmium telluride (CdTe) PV modules using a technology known internally at BP Solar as Apollo.

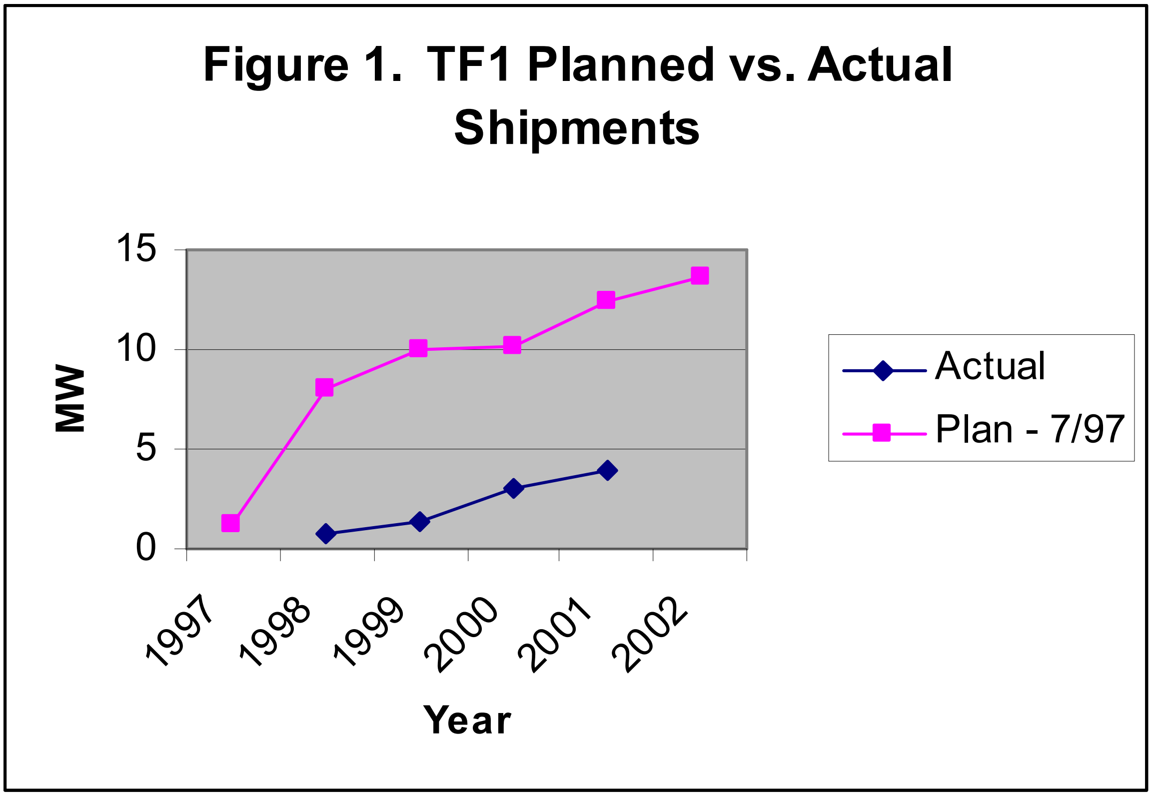
These two efforts afford a unique opportunity to examine such scale-up and commercialization experience without hazard to ongoing private-sector initiatives. Efforts over a 5- to 10-year scale-up period were reviewed in order to:

- Trace the evolution of production cost models;
- Develop a chronology of decisions made that influenced manufacturing cost;
- Examine the factors that drove changes in projected cost estimates;
- Evaluate the differences between realized cost and expected cost in order to gain insights into the reasons for divergence between these costs.
- Identify key factors that influenced realized cost and expected cost (such as changing market requirements, warranties, qualification processes, the degree of factory vertical integration, etc.); and
- Draw experience-based insights in order to estimate the potential for future cost reductions in these technologies over the next 10-15 years.

The available experience must be understood as incomplete. The Apollo CdTe factory operated in an extended start-up mode only; the Millennia tandem a-Si factory was ramped up over a period of years to operate at full staffing and a capacity of several MW per year – though not at its design capacity of 10MW per year. Nevertheless, valuable and still relevant cost experience and practical lessons were learned at both locations and are presented separately in subsequent sections.[11]

Case Study: Tandem Amorphous Silicon

A factory (to be referred to hereafter as TF1) was funded, constructed, staffed, and operated for a few years; and its initial commercial products (to be referred to hereafter by their brand name, Millennia) were shipped to customers worldwide. However, (see **Figure 1**) TF1 never operated close to its intended capacity, nor were product specifications and product mix consistent from year to year. As a result, available cost data reflects the status of a work in progress, not by any means the statistics of a mature manufacturing operation. Trends are discernible – some cost elements stabilized nicely – and some favorable cost trends emerged. Some specific quantitative results are generically representative, but all reflect a variety of interactive circumstances and design and operational choices, the composite of which is unlikely to be precisely replicated.



Some words of perspective are necessary before turning to the analysis.

First, deposition of amorphous silicon can be accomplished my multiple methods on multiple substrates using deposition recipe and device structure designs that are nearly unlimited. The basic design used for Millennia involved deposition on a tin oxide coated glass surface using an in-line process, with encapsulation of the film accomplished by laminating the film between two glass sheets bonded together with a layer of ethyl vinyl acetate encapsulant. The relative advantages and disadvantages of this approach vs. others under development at the time are significant and beyond the scope of the work reported here. The advantages were demonstrated in commercial practice. The disadvantages may be inferred from sections of the report describing market strategy, process and module engineering changes required during the commercialization process.

Second, the TF1 experience brought together unique and powerful capabilities and resources under qualified management. In the areas where the organizations involved fell short, the lack was not in the organization, its experience or its leadership. The attempt was as well-positioned for success as possible at the time, drawing on extremely strong and patient corporate ownership, a foundational 15-year $200 million R&D investment resulting in world-leading organizational experience and competency, and the technical and business infrastructure support of the largest U.S.-owned PV manufacturer. However, the challenge was much greater than anticipated by investing and supporting organizations.[12]

Third, U.S. PV R&D programs have usefully turned their attention to cost, especially "system-driven" cost. In parallel, there has been an equally useful exploration of economic value by leading PV analysts. The TF1 story features the interplay of cost and value and is particularly instructive in that regard. In setting initial targets, nearly every parameter related to customer value was adjusted to minimize manufacturing cost, at considerable sacrifice to product attributes of standard crystalline modules. As a result of cost minimization on the module side and extremely aggressive assumptions on the system side, extremely aggressive installed costs were forecast by the project's sponsors. When it became necessary to adjust the factory's products to compete for a share of less ideal, but already established – or at least emerging – markets, manufacturing costs increased incrementally for a number of market- and system-driven reasons. Unframed laminate costs were already higher than targeted because of substantially lower than targeted efficiencies. When later it became necessary to exploit unique features of the technology to capture large special orders, further significant costs were added. The "system driven" added costs in both cases are sometimes overlooked in analyses that focus on process- and efficiency-driven core product unit ($/W) costs. The result can be "apples and oranges" comparisons between functionally non-equivalent products.

Visions and Models

Business visions and models changed as experience accumulated.

First Business Vision – Solar Farm Deployment and "Super-Large-Scale" Manufacturing: The initial view of TF1 was that it was to be the sole source of module supply to a new business unit chartered to develop, design, and finance central solar power plants and other grid-tied PV applications. At the time, the initial vision was revolutionary and hinged on unprecedented manufacturing scale-up in support of large projects that were to create the necessary demand. The related business model anticipated forward integration from module production through the sale of electricity. It hinged on a pre-negotiated transfer price (set at $0.75/Wp), according to the terms of the joint venture that funded the factory and the specification for the product to be delivered (to the project development business unit) at this transfer price.

Validation of this business model failed. No solar farm projects achieved financial closing, and thin-film modules meeting the intended specification would not have been available to them if they had.[13]

Second Business Vision – Supplant Crystalline in Emerging High Growth Markets: Accordingly, TF1 was re-cast in the role of supplying and enhancing an ongoing crystalline PV module manufacturing business (Solarex[1]) by introducing a new product that promised lower production costs and, therefore, enhanced the profitability and growth potential of the original business. It was accepted that this would lead to capping Solarex crystalline capacity, while thin-film capacity expanded to meet market growth. The vision was founded on internal Solarex manufacturing scale-up forecasts completed in 1994 showing that thin-film manufacturing costs would level out well below costs of polycrystalline modules, thus providing a new technology platform for the already established module manufacturing business. The related business model anticipated forward integration from module production to the sale of systems, with internal module sales supplemented by sales through distribution. The model evolved pragmatically – product variations were added opportunistically with a goal to fill the factory, as well as profitably satisfy the requirements of existing distribution customers and emerging on-grid markets.

Third Business Vision – "The Future is BIPV": The third and final business vision tacitly conceded that the path to decisive cost advantage vs. crystalline would, at best, be longer and less certain than expected. Exploiting the ability to alter the visual and optical specification of Millennia modules, it incorporated aspects of both preceding visions, i.e. sales of a single special-design product to a sister business unit, i.e. BP Retail, along with sales of this new product (and the existing product line) to external customers in emerging BIPV market segment. The related business model was a hybrid between the two prior models, differing from the original in emphasizing a revolutionary premium product for captive customers vs. a cost-engineered economy product unsuited to the existing external market.

These models influenced key related corporate functions – including sales and marketing and R&D. They did not directly affect intrinsic costs of the basic product platform, but they did significantly affect finished product costs in each case.

Cost Models

The core cost model supporting all three business visions and models was simple and traditional. Consistent with the PV market at the time, its primary metric was the cost of a finished module divided by product nameplate rating in peak direct current Watts. Starting with a single product intended for a single customer, product variations expanded to the point that the TF1 product line essentially mirrored the Solarex crystalline product line in meeting a range of segment-specific market requirements.

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[1] Solarex was founded independently in 1973, purchased by Amoco in 1983, and became a business unit of Amoco/Enron Solar, a joint venture between Amoco and Enron formed at the end of 1994.

This created the need for a more detailed (but not fundamentally different) cost model able to account for differences among products having different electrical characteristics, mechanical specifications, and framing and electrical termination designs (see **Table 1**). Subsequent expansion of the product line to include and emphasize “vision glass” modules (to be referred to hereafter by their brand name, PowerView) required only incremental changes to the cost model initially, because the initial PowerView products were sized and rated in the same range as existing products. Had such premium products succeeded in the broader building products market, a manufacturing cost model facilitating trade-offs between power output and optical specifications eventually would have been needed.

Table 1. Cost Model

	$/Wp (1)	**$/module**	**$/Wp (1)**	
Varible Costs				
Direct Labor (2)				
Materials (3)				
Labor Overhead (4)				
Total Variable				
Fixed Costs (3)				
Utilities/Rent/Interest				
Indirect Labor				
Depreciation (6)				
Total Fixed				
Total Cost (FOB factory)				

Notes:
1. Wp = nameplate power, i.e. instantaneous module power under standard test conditions
2. Yielded hours per unit times DL rate per hour divided by Wp
3. Yielded unit cost divided by Wp
4. Yielded hours per unit times O/H rate per hour divided by Wp
5. Allocation in $/Wp reflecting corporate accounting model, actual costs and cost allocation
6. Depreciation life of manufacturing equipment taken as 15 years.

Cost Evolution Detailed Analysis

Major Product and Cost Model Changes

The cost model in Table 1 can be used to analyze the nature and impact of specific manufacturing and product-line changes that were implemented over the course of commercialization efforts. The model did not change structurally, but its imbedded assumptions did evolve. **Table 2** expands the model to evaluate the impact of manufacturing process changes and experience, as well as product-line changes. Representative costs are included – they are experience-based estimates, not actual recorded costs. Unit costs are presented in $/Wp, and total costs are also presented in $\$/\text{m}^2$. The following narrative briefly outlines each evolutionary change and its rationale.

Table 2. Estimated TF1 Manufacturing Costs

			$/W internalized and fully built up (5)													$\$/\text{m}^2$
Year	Reason for Change	Watts	Variable Base				Variable Delta					Fixed Delta (4)		Total	Chg.	Total
			Direct Labor	Matl	Labor O/H	Fixed Base	Plug and Play	Frame	Semi-transparent	Strong Glass	Power	Yield	Power			
Factory Development																
Solar Farm Vision																
1994	Base annealed HV lam	62	0.04	0.37	0.17	0.25								0.83		64.2
1995	Project re-design/re-est. (1)	56	0.04	0.49	0.19	0.35								1.07	0.24	74.8
1995	Depreciation correct.	56	0.04	0.49	0.19	0.65								1.37	0.30	95.7
1995	Staffing re-est.	56	0.15	0.49	0.19	0.65								1.48	0.11	103.4
1999	Material re-est.	56	0.15	0.51	0.19	0.65								1.50	0.02	104.8
Commercial Production (2)																0.0
Supplant Crystalline Vision																0.0
1996	Switch to MV	56	0.15	0.54	0.19	0.65								1.53	0.03	106.9
Plug and Play																0.0
1999	P&P lam product	56	0.15	0.54	0.19	0.65	0.06							1.59	0.06	111.1
2001	HS lam product	56	0.15	0.54	0.19	0.65	0.06			0.15				1.74	0.15	121.6
2001	Actual module power (3)	43	0.15	0.54	0.19	0.65	0.10			0.15	0.34		0.20	2.32	0.58	124.5
2002	Actual total yield	43	0.15	0.54	0.19	0.65	0.10			0.15	0.34	0.15	0.20	2.47	0.15	132.4
Framing				0.54												0.0
1998	P&P framed product	56	0.15	0.54	0.19	0.65	0.06	0.21						1.80	0.27	125.8
2001	HS P&P framed product	56	0.15	0.54	0.19	0.65	0.06	0.21		0.15				1.95	0.15	136.3
2001	Actual module power (3)	43	0.15	0.54	0.19	0.65	0.10	0.21		0.15	0.34		0.20	2.53	0.58	135.8
2002	Actual total yield	43	0.15	0.54	0.19	0.65	0.10	0.21		0.15	0.34	0.15	0.20	2.68	0.15	143.7
Future is BIPV Vision				0.54												0.0
Vision Glass																0.0
2000	BIPV lam product	53	0.15	0.54	0.19	0.65	0.06		0.32		0.05		0.04	2.00	0.47	132.6
2001	Cosmetic BIPV lam	53	0.15	0.54	0.19	0.65	0.10		0.32		0.05		0.04	2.05	0.04	135.3
2001	HS BIPV lam	53	0.15	0.54	0.19	0.65	0.10		0.32	0.15	0.06		0.04	2.20	0.16	145.6
2001	Actual module power	40	0.15	0.54	0.19	0.65	0.10	0.21	0.32	0.15	0.44		0.20	2.95	0.74	147.1
2002	Actual total yield	40	0.15	0.54	0.19	0.65	0.10	0.21	0.32	0.15	0.44	0.15	0.20	3.09	0.15	154.5

Notes:

1. Module power reflects efficiency loss due to CTO outsourcing (-10%).
2. LV and "cut" products were introduced in 98, having higher manufacturing costs and also higher customer value - cost estimates are not included.
3. Actual avg module power was 43W, not 56W, reflecting soda lime vs. low iron glass (-10%), MV vs. HV (-2%), and process transfer loss (-18%).
4. Throughput and line availability (key fixed cost drivers) limited annual factory financial performance, but are assumed, for estimation purposes to have been on target at 25 starts per hour and 7000 hours per year.
5. All costs are consultant estimates based on interpretation of actual experience - no comparable tabulation exists in company files.

Initial Product Functional Specification

The initial product specification called for a module having a total area of 0.8 square meters, stabilized efficiency under standard test conditions of 8% (based on aperture area), resulting in a nameplate rating of 61.7 Watts, and a cell width resulting in nominal operating voltages above 100V, consistent with the product's intended use in large "solar farm" arrays.

Target Costs

In the early stage of joint venture negotiations (May 1994), the first manufacturing plant was envisioned as a full-scale prototype of future plants to be rated at 120MW/year. Later target production costs for TF1 were remarkably consistent with the initial scenarios, even to the extent of assuming identical direct-labor costs. Target fixed and variable costs for TF1 were $0.25/W and $0.58/W respectively, consistent with a negotiated transfer price between the joint venture's manufacturing unit and power project development unit of $0.75/W (1995$)

Project Redesign and Re-estimation

Emphasis in the second half of 1994 was on validating the 8% efficiency target, and also on establishing a capital budget. It was not until the joint venture closed at the end of 1994 that efforts were initiated to develop a project plan, select a site, or select engineering and construction contractors. By August 1995, having accomplished these tasks, it was possible to re-estimate the project cost based on site-specific information, results of process validation, preliminary equipment specification/design/selection, further process development, and initial plant layouts. The resulting project capital cost estimate exceeded the target budget by about 50%, primarily because the number of silicon deposition chambers had apparently been underestimated by 36%.[14]

Design efforts also failed to validate the readiness of the process and equipment used to deposit conductive tin oxide in pilot production, and it was determined that an additional tin oxide-deposition furnace would be required. As a result, a decision was made to out-source tin oxide-coated glass and eliminate the coating equipment from the front of the line. This decision had major implications for product efficiency and therefore cost (i.e. 10% reduction and 11% increase respectively), and also major implications for variable material cost (i.e. 22% increase), though the eventual effect was thought to be less at the time.[15]

In addition, revised estimates of Germane[2] costs and use resulted in another 11% variable materials cost increase. Finally, labor overhead costs were revised upward by 12%.

The project capital re-estimate would have increased the depreciation component of fixed costs by about 40% from $0.15/W to $0.25/W; however, around the same time, the original allocation for depreciation – was increased to around $0.55/W, for an overall 267% increase.[16] The latter allocation for depreciation appears consistent with a 15 year depreciation period, depreciation schedules consistent with generally accepted accounting standards, and plant capital costs in the $30-35 million range, combined with capitalized pre-commercial operating costs in the $5-10 million range.

The target direct-labor estimate, $0.04/W, would have been consistent with plant staffing in the 25-30 range, whereas later staffing estimates based on start-up operations and initial production put the requirement in the 80-100 range, consistent with a philosophy of relying on manual intervention in critical line transitions before moving to full automation. Direct-labor estimates ranged somewhat higher but eventually stabilized in the range of $0.15/W, a 275% increase from the original target, suggesting that the original target may have carried forward without examination from early estimates for conceptual plants rated at >100MW/year.

Re-estimated variable material costs (for full area laminates, i.e. the original target product) proved more reliable and were only adjusted upward by a small percentage over subsequent years.

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[2] Germane is a gas containing Germanium

Overall, correction of errors ($0.41/W), experience-based re-estimates of various cost elements ($0.15/W), and targeting 9% lower product efficiency initially ($0.11/W) resulted in a $0.67/W (or roughly 81% increase) in the base cost of the original target product, without accounting for the effects of actual vs. targeted line yield and actual vs. targeted product efficiency.[17] These latter effects, to be considered below, resulted in combined incremental additional increases in base cost of $0.70 to $0.80/W, depending on the specification of the finished product. Thus, in 1995, the base cost of the product, assuming originally targeted line yield and efficiency, increased by nearly $0.70/W. Factoring in the effect of actual vs. targeted yield and efficiency results in an additional $0.70/W to $0.80/W increase.

In summary, the reasons for higher than forecast base product cost were:

1. Underestimates, including direct labor, plant equipment, depreciation and material costs
2. Inability to achieve target product efficiencies and line yields[18]

Product Specification Changes

"Medium" Voltage (MV)

While TF1 was being built, a separate business unit was working to develop large grid-tied projects to absorb its output. Meanwhile, efforts were underway among U.S. utilities and government allies to promote other PV applications in the United States, including smaller grid-tied applications. Though the TF1 product, as specified, was a questionable fit with these applications (due to its efficiency disadvantage), emerging grid rooftop markets offered an opportunity to deploy relatively large numbers of modules from the new factory without "cannibalizing" the existing crystalline module sales. Accordingly, proposals were developed that would tap government programs to allow the new thin-film modules to be offered at a discount and packaged conveniently for use in grid rooftop projects. Projects resulting from these proposals ultimately facilitated nearly 2MW of thin-film module sales[19].

The "high-voltage" thin-film module targeted by the new thin-film joint venture, though conceptually optimum for large arrays, was poorly suited to grid rooftop and other near-term, grid-tied markets. Suppliers of inverters for grid-tied applications in the United States were few, and their products were designed to accommodate the electrical specifications of typical commercial PV modules.[3] Accordingly, a decision was reached to introduce a module with cell interconnects running parallel to the long side of the module instead of parallel to the short side, as in the high-voltage module. This allowed

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[3] Most crystalline PV modules at the time had nominal voltages that were multiples of 12V (i.e. 12V for battery charging applications and 24V larger area modules for both battery charging and grid-tied arrays). One crystalline manufacturer had introduced a 48V module that was popular in the US for grid-tied arrays, and Solarex had a similar design not yet in production.

for a nominal voltage of 48 volts (vs. the original 110V) without unduly compromising module efficiency. Some compromise was necessary due to the change in cell width and additional length of current collection paths, which also increased the use of "frit," the silver-based paste used to create low-resistance internal current paths within the module. The effect of the additional frit use is estimated at $0.03/W, increasing overall materials cost by about 6%.

Plug and Play

The target module specification for solar farms was ideal from a manufacturing perspective, i.e. not only, as discussed, in calling for a single product for a single customer, but also in calling for a product with no value-added features at all. Such a product is a convenient basis for comparison with other "ideal," i.e. "no value-added," products[4]. However, such comparisons need to be undertaken with care for the following reasons:

- Some value-added features are demanded by the market,
- These features account for significant percentages of overall product cost, that vary with module footprint and efficiency
- The percentages vary significantly depending on the product platform,

For example, products sold at the time into the general market had factory-installed "junction boxes," which typically added a few cents per watt to crystalline module manufacturing cost. At the time, plug-type connectors were an emerging, not fully proven, solution – though leading system integrators quickly began to demand factory installation of specific plug-type connectors. For on-grid applications – the now-dominant market segment – factory-installed connector cables terminated in plug-type connectors are now standard, adding, in the case of Millennia, $4 to $9 to product unit cost. The estimated cost impact of plug-and-play finishing is $0.22/W and $0.15/W for laminate and framed products respectively. BIPV products involving light transmission have a cosmetic requirement to move the electrical termination to the module's edge, at an additional cost estimated in the $0.05/W to $0.10/W range. A variety of "edge connector" designs were evaluated. Initial generic vision glass and service station canopy products did not include them, but later versions did.[20]

Strengthened (toughened) Glass

Early visions for large thin-film factories recognized the fact that, in markets where modules would substitute for other glass-based products, they would have to include the same type of glass. Glass that is "framed," as in smaller residential windows, does not need to be particularly strong, because the frame protects it from bending stresses and crack initiators such as edge chips and handling impacts. Other glass applications, i.e.

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[4] The target TF1 product was essentially stripped down for low cost. The real products that were actually sold included many value added aspects and were more costly.

any in which glass is both an optical and structural element (or any where impacts could result in breakage and flying shards) require toughening the glass both to prevent breakage and to minimize the related hazards by minimizing the size of broken fragments.

Toughening is basically accomplished by heat treatment that results in compressive stresses in the surface layers of the glass, which tend to cancel the tensile stresses that are induced in one surface layer when the glass is twisted or bent (glass is weak in tension.) The toughening process adds significantly to the cost of the glass. Further, because toughened glass tends to shatter rather than crack, it does not lend itself to products that require final sizing after other value-added steps. There are no commercially useful processes for cutting toughened glass.

Crystalline modules use a single layer of tempered (high-strength) glass to provide structural stability and environmental protection for thin, fragile PV cells. Framed crystalline modules are remarkably resistant to impact and the rigors of shipping and normal handling. If the targeted initial use of TF1 product had been the general market, it is almost certain that at least one of the two glass elements would have had to be strong, preferably both. If pilot manufacturing had been attempted on strong glass, the factory and deposition equipment design would have accommodated the requirement to preserve the dimensional stability of the front glass during the deposition process. Unfortunately, the factory was built in anticipation of depositing the films on “annealed,” i.e. standard, non-strengthened glass. Being free of pre-stressed areas, such glass does not tend to warp significantly when its surface layers are subjected to convective or radiant heating, as in some steps in the piloted TF1 film-deposition process.

There was cursory consideration of using strengthened glass in the early stages of project planning and implementation. The decision against strengthened glass might have been compelled by the likely cost impact and related technical jeopardy to implementing the factory project; but it also might have been rationalized on the (then baseline) assumption that the product would primarily be used in large arrays where annealed glass solutions had already proven suitable.[5]

As it turned out, the decision had major implications for product cost and other important market considerations. Glass breakage and cracking was a thread that ran through the commercialization effort like a painful nerve. Its symptoms, chronologically, can be briefly traced as follows:

1996 – Customer Samples. Modules from half-area (4ft2) pilot production were offered to the initial customer base and used in demonstration arrays. Many broke or cracked in transit or in use, resulting in a requirement for more careful handling and more robust packaging.

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[5] The 400kW single junction aSi array at PVUSA incorporated frameless double annealed glass laminates.

1997 – Prototype Multi-module Panels. Demonstration arrays and installations involved mounting of glass laminates to metal racks or in preassembled, multi-module panels using two-sided tape as the attachment vehicle. Accidental twisting of the multi-module panels resulted in cracks and breakage that compromised array performance, though methods were developed to make module removal and replacement more convenient.

1998 – The "Pillow Effect." The initial lamination process used in production resulted in squeezing encapsulant preferentially out of module edge areas, resulting in what was referred to as a "pillow effect" with the glass layers ending up closer together at the edges than in the middle surface layers and the glass edge areas pre-stressed in tension after the glass cooled and the encapsulant cured. This made the modules more vulnerable to cracks initiating and propagating from their edges due to thermal stresses and thermal shocks in normal operation. The two initial customers most enthusiastic about Millennia's performance and cost advantages in their applications, i.e. PowerLight Corporation (a U.S. system integrator) and Polyene (a company developing the solar water pumping market in India), were the first to raise concerns about excessive module cracking and the premature module failures that could be expected as a result. Both companies invoked the product warranty and were partially compensated for their losses.[6] The lamination process defect that caused the vulnerability to cracking was corrected as soon as it was identified. However, by then some product made with the defective process had been shipped and installed.

1999 – Market-Driven Business Plan. At year-end, a cross-functional[7] planning team was chartered to:

- Provide a new vision for the TF business unit, and
- Identify key actions leading to profitability by year-end 2000, shipments of 100% of production by year-end 2001, and sustainable business growth thereafter.

The team concluded that acceptance of the then-current product (43W, annealed glass, glass-to-glass encapsulation) would be limited to a few sub-segments of the overall PV market; and that this would result in insufficient demand to support profitability or business growth. Their plan called for converting the factory to flexible production of a range of products generally accepted in current markets and significantly advantaged in emerging on-grid markets. They recommended shifting production to deposit films in multiple electrical configurations, resulting in lighter-framed 12V modules with ratings of 5, 10, 20 and 43W for remote markets, to deposit films on heat strengthened or tempered glass, resulting in lighter and more robust framed and unframed, full-size modules for on-grid markets (site assembled and packaged system solutions), and finally

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[6] Polyene's business success hinged on the success of its initial installations using Solarex thin-film products; the company eventually failed after lengthy negotiations to resolve its claim that the modules found to be cracked were defective as shipped and that consequential costs should be covered .

[7] Manufacturing, marketing, technology, business development, sales, finance, and product development

to add the capability to laser ablate the film, resulting in light-transmitting "vision glass" and special feature (logo patterned) modules for BIPV.

2000 – Deposition on Strengthened Glass. By year-end 1999, the implications of the planned switch to heat-strengthened products were better understood, and plans were in place to introduce such products starting in the first quarter of 2000. Heat-strengthened glass/Tedlar laminate costs were expected to be $0.2/W higher than comparable double-annealed glass laminate costs. Attempts during 2000 to process heat-strengthened glass using existing equipment and processes were unsuccessful – and also costly to factory operations – because of the need to use the manufacturing line for numerous engineering test runs over many months.[21] Eventually, process and equipment modifications were identified and implemented that enabled limited numbers of heat-strengthened laminates (about 25kW) to be made for vision glass and other products in the first half of 2001. It is assumed that heat-strengthened product production increased over the following year until BP Solar announced termination of TF1 operations.

2001 – "Arc Risk." Because of delays in switching to at least partial production of heat-strengthened product during 2000, PowerView modules shipped for initial BP service station canopy applications were double-annealed glass laminates. By the end of 2000, several hundred kW of this product had been shipped. In early 2001, eight modules in five installations in Indianapolis were damaged by electrical arcing. All eight modules exhibited cracks of the front glass and resulting corrosion of film material. Subsequent investigation determined that Millennia modules in grounded arrays operating at >100V relative to ground and experiencing glass breakage during or after installation were, or would be, at risk of arcing along the silver frit bus bars, and that heat generated by the arc could soften or melt the adjacent glass and/or pose hazards due to fire or falling objects under certain conditions. Primary risk factors related to breakage risk and operating voltage. Breakage risk, in turn, was determined by whether the glass was annealed or heat-strengthened; whether the glass was supported at its edges by a frame; and, if unframed, whether the glass laminate was properly mounted.[8]

Cost Impact of Heat Strengthened Glass

The cost impact of using stronger glass depends on the encapsulation approach. For double-glass laminates, the total cost impact of two heat-strengthened glass layers is

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[8] The consequences of this determination were serious. First, heat strengthened modules were not yet in production, and most existing Millennia installations, including those involving greatest safety risk (service station canopies) used power conversion equipment requiring array operation well over 100V. Affected service station installations were tagged out pending inverter replacement, extensive testing was done in support of failure analysis and preparation of installation guidelines and risk assessment, and a communications plan was prepared. In the end, such information remained closely held, and a comprehensive effort was made to evaluate risks, and where necessary, inspect and identify the condition of every existing Millennia installation, to the extent possible. Considering the volume of product shipped by 2001, and assuming an average system size of 15kW, the numbers of installations covered by the investigation would have run into the hundreds. System reconfigurations were required in some cases. Detailed statistics are not available.

estimated at $0.20/W, though lack of production experience suggests putting the cost impact in a range between $0.15/W and $0.30/W. The total cost impact of switching framed modules from a double-annealed glass laminate to a heat-strengthened glass/EVA/tedlar laminate is estimated, again without benefit of production experience, at $0.15/W. This estimate may be optimistic; production validation may or may not have occurred.[22]

Frames

Recognizing the below-target efficiency of the initial thin-film products and the problematic experience with preassembled multi-laminate panels, an effort was undertaken in support of the PV-VALUE[9] program, targeting mounting solutions for double-glass laminate modules that would minimize area-related balance of system and installation costs, particularly for applications on residential roofs. The innovation that resulted, the Integra framing and mounting system, was greeted with enthusiasm by some initial grid market customers, whose focus was retrofit applications on residential roofs, the application for which the solution was intended.

Innovative solutions for installation on commercial roofs, i.e. PowerLight Corporation's system using insulated roof pavers, were compatible with the original medium voltage (MV) laminate product. However, grid-tied customers in non-U.S. markets, where the Integra product was not safety-certified, were demanding modules having standard frames. Breakage experience (noted above) with annealed glass laminates also encouraged introduction of a broader range of framed modules.[10]

The total cost impact of framing of a nominal 43W Millennia modules is estimated at $0.21/W.

"PowerView"

Until 1999, the emerging market for building-integrated PV (BIPV), i.e. the substitution of PV modules for other building-envelope materials, had been a low priority, because of inherent conflicts with the company's role as a leading high-volume, low-cost manufacturer of standard products. (BIPV applications typically involved special products specified for use in "one-off" projects.) However, during 1999, new company

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[9] A program established to develop and deploy packaged residential rooftop systems incorporating Millennia, with the assistance of a $2/Wac buy-down made possible by DOE cost sharing.

[10] Module frames, while adding significantly to module manufacturing cost, off-set some balance of system costs (the module frame becomes part of the overall mounting structure) and require no re-engineering of mounting solutions used with crystalline modules, nor any special new mounting hardware. More importantly, frames provide the structural support necessary to package and ship individual modules rather than crates of modules, a strong consideration for distribution customers selling modules in smaller quantities. It is of course essential that the active area of the laminate be properly insulated electrically and properly protected from water ingress; otherwise the frame provides a current path to ground accelerating module failure and resulting in ground faults.

leaders,[11] most of whom had plate-glass manufacturing industry experience, established a direction for the thin-film business unit that envisioned high-volume production of standard BIPV products. Their imagination had been captured by the technical ability to create architecturally and aesthetically unique modules using a laser-ablation process that created microscopic holes in the film. The demonstrated potential to make a light-transmitting, thin-film laminate was quickly married to an initiative of the company's new owner, BP, aiming to include PV arrays in the canopies of all new BP service stations in selected markets, including the United States. The cost impact of "PowerView" processing is estimated at about $0.41/W, including the impact of power loss slightly greater than the level of film removal, i.e. 5% for initial products.

Module Power

Module power shortfalls had a major effect on cost, adding about $0.20/W to nominal fixed costs and more than $0.40/W to variable cost. A factory sized to produce a certain number of units at the target rating will have an actual output proportional to module efficiency and costs inversely proportional to module efficiency.

Specifically, a technology envisioned to rapidly achieve stablized 8% module efficiencies in production and improve significantly from there (see **Figure 2**), struggled at first to achieve 5.5%; and then stubbornly refused over a period of a few years to reach a point where significant numbers of higher-rated modules could be made, in spite of ongoing forecasts by company technologists that promised results consistent with the original vision.

How could this happen? No published explanation exists; a few observations can be offered to provide perspective:

- There was significant efficiency variation in various process "recipes" evaluated during 1995 after the demonstration of 7.8% stabilized efficiency on half-size plates in 1994. There were also differences among the various recipes in terms of deposition time, process readiness, and equipment and material cost. It would have been natural to sacrifice efficiency in order to make conservative choices in other aspects (e.g., the decision to outsource tin oxide-coated glass at a penalty of about half a point in stabilized efficiency), hoping to recover lost efficiency via future process optimization and improvement.
- Whether, in fact, any recipe demonstrated in experimental chambers operated by research staff could be effectively replicated in full-size, inline deposition chambers operated by factory floor staff is questionable. Variations even among experimental chambers were significant.
- Other decisions along the way – e.g., the switch from "high" to "medium" voltage discussed earlier.

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[11] In 1998, a new CEO and new technology and manufacturing executives were hired.

The catch-all explanation is simply "process transfer loss." A process that ostensibly delivered close to 8% efficiency using experimental chambers in pilot production of half-area plates somehow lost 18% of projected module power when transferred to production, and this loss was never recovered.

Yield

Cost is likewise inversely related to overall process yield. Relative to the original 92% target, actual total line yields for core products leveled off in the 70% to 80% range.[23] The estimated effect is to increase fixed costs by $0.15/W. The assumptions behind the original yield assumption are unknown.

Efficiency Penalty

The numbers of relatively large systems using Millennia modules provided an opportunity to assess the effect on overall system cost of low efficiency and other inherent electrical and mechanical features. Relative to the highest-performing modules available at the time, it was estimated that the impact on system cost of using Millennia instead of a higher-efficiency product was in the range of $0.16/efficiency point/W, or roughly $1/W vs. crystalline modules in commercial production at the time. This impact was confirmed by an NREL-funded analysis by a major U.S. system integrator[24] and was a major deterrent to the use of Millennia modules (even by BP Solar's system sales teams) in large projects where high-volume crystalline pricing typically did not exceed high-volume Millennia pricing by enough to offset the penalty. Obviously, the penalty would likely be greater now, based on crystalline module efficiency improvements over the intervening years.

"Off-budget" or "Below the Line" Costs

Transfer of a PV module technology from R&D to commercial production can incur major costs that are not counted in models like the one applied here. Specifically, a factory has operating and fixed costs whether it is operating productively or not. Likewise, before, during, and after commissioning, there can be value in pilot production of prototype or precursor products. Pilot lines and experimental equipment can allow for validation of processes and designs without tying up part or all of the main manufacturing line. Continuing R&D aiming at future improvements in manufacturing processes or equipment may also be required if the factory is itself a prototype, and some technologies that may enhance future plants are not ready for commercial use at the time it is built and commissioned.

Pre-commercial Operations

In the case of TF1, the plan called for essentially full production within two years of project initiation. **Figure 1** shows the gap between planned and actual production. Some cost savings can be captured by regulating staffing according to the ramp rate that technical progress permits while avoiding extremely low-yield operation; but fixed costs remain, as do R&D costs and variable costs that exceed product revenues. For the TF1 start-up and production ramp, these costs ran to several millions of dollars annually. Some financial relief was available by "capitalizing" operating costs in the years prior to round-the-clock commercial production. This resulted in an apparent capital cost much higher than the original plant budget and much higher than would have been justified by the plant's originally projected economics.

Pilot Lines

Pilot operation continued only a year and some months beyond factory project initiation and so had minimal cost impact. A question arises as to whether continued pilot operations would have supported process experimentation that ultimately was done in the main production line. If so, economies of terminating off-line pilot operations prior to factory start-up may have been false.

R&D

TF1 was founded on the strength of a significant ongoing combined R&D and manufacturing operation in Newtown, Pennsylvania, employing approximately 70 to 80 people. Manufacturing operations in Pennsylvania produced a few hundred kW annually of 5W single-junction modules for customers who manufactured specialty products like livestock fence and recreational vehicle battery chargers. Arguably, resulting revenue covered the manufacturing unit's share of facility and labor costs, but the need to co-locate R&D staff with the new factory and the assumption that OEM customers could be "converted" to purchase comparable polycrystalline product led to a decision to close the Pennsylvania plant and terminate all employees not needed to staff the new factory or the scaled-down R&D group at the new factory. R&D costs in the range of $2M to $3M per year continued, along with the one-time cost of relocating relevant personnel and equipment. These costs were not counted against factory revenues but were partially off-set in early years through cost-sharing participation in DOE/NREL programs.

Downstream Costs

PV modules account for a major share of installed PV system costs. Their efficiency and value-added features have a major effect on remaining "downstream" costs. Along with module price per watt, two such costs were influential in market acceptance of the product line, i.e. the cost of shipping modules to the point of use and the cost of incorporating them in a properly functioning system.

Shipping and Packaging

Shipping costs are typically paid by the PV customer and would be considered in evaluating product and supplier offerings. For Millennia, they varied from an estimated $0.02/W for container shipments of laminate products destined for warehousing in Rotterdam to an estimated $0.13/W for container shipments of framed products destined for India. Additional shipping costs from distribution warehouse to end use would have been incurred in all cases. It is fair to say that Millennia shipping costs, simply due to low power density and low numbers of watts per container, significantly disadvantaged Millennia relative to competing higher efficiency products. It is also noteworthy that modules shipped to end customers are often shipped in small quantities, necessitating individual packaging at some point. For Millennia, the incremental cost of single-module packaging was several cents per watt more than crate packaging.

Interpretation

Decision Chronology Summary

To summarize, the decisions that influenced manufacturing cost were fundamentally market vision and business model choices, not independent manufacturing decisions.

The first decision that influenced manufacturing cost was the decision to target central station power applications. It meant that product features demanded by the existing market such as frames, strong glass, and convenient electrical terminations could be avoided.

The second decision that influenced manufacturing cost was the decision to offer the product in markets where standard crystalline modules were also an option for potential customers. This led to the need to engineer a product having competitive warranties and even superior plug-and-play functionality (to offset a portion of the base technology's inherent efficiency penalty). It also led to the need to offer product options not discussed above, including products having a nominal voltage of 12V rather than 48V, products having lower ratings typical of competing thin-film and crystalline modules used in village solar home systems and other off-grid applications. It led to the need to engineer a product certified for operation in European on-grid applications that had wider strips of film removed at the edges to provide proper electrical isolation for modules tested and certified for operation in systems designed for up to 1000V (vs. the U.S. National Electric Code limit of 600V). The cost of these products varied – the essential decision in each case was to accept the incremental manufacturing (and, in some cases, front- and back-end process and product development, qualification, and certification) costs in order to offer a product having the same or greater value than crystalline and competing thin-film offerings.

The third decision that influenced manufacturing cost was, like the second, a decision to increase cost as necessary to offer unique value, i.e. the combination of power generation and light transmission.

BP Solar's decision to shut down the factory in late 2002 and its related decision to abandon further effort on the technology are also of interest. These decisions did not hinge exclusively on manufacturing costs; rather cost experience was undoubtedly a significant factor.

First, there was a decision to abandon the factory, TF1. For cost reasons, it could not be profitably "filled", i.e. operated at full capacity in response to customer orders, without implementing yet another new market vision. Such a vision probably existed, but it probably also would have involved a niche market where small thin-film modules rated at 5W to 50W could be sold at high enough prices to generate good margins, a market already validated by previous Solarex thin-film manufacturing efforts and by others; and a market to which crystalline technology is poorly adapted to compete on cost. Relative to the company's need at the time to focus on the profitability of its crystalline business in the face of strong global competition, this option was probably not considered.

Second, there was a decision to abandon the technology. This was no doubt also influenced by cost, i.e. failure to validate production costs and product efficiencies that would support profitable sales in major market segments. This failure, which flowed from technical limitations of first generation manufacturing equipment and related deposition processes, left in its wake *no high confidence path to sufficient manufacturing scale where attendant off-budget and scale-up costs would be recovered and attractive returns on investment could be anticipated*. Clearly, the original strategy of proving and then replicating, many times over, a manufacturing line capable of reasonable efficiency could no longer be plausibly advocated, even if the owners had not been facing hard capital allocation and investment choices.

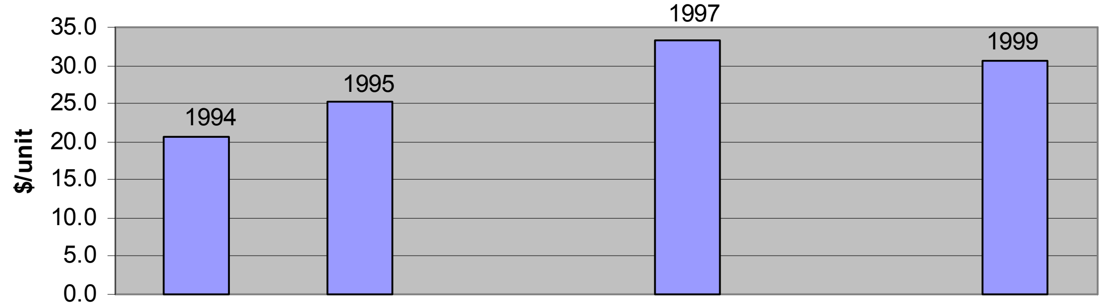
Cost Change Drivers

How did cost projections change, and what drove the changes?

Material Cost Drivers

Figure 2 summarizes unit material cost projections.

Figure 2. Unit Material Cost (laminate w/pigtails)



Differences in the two preproduction material cost projections (1994 and 1995) were discussed earlier. Increases from 1994 to 1995 were driven by costs of tin oxide-coated glass and increases in Germane gas cost and use. Differences between pre- and post-production projections were also driven primarily by more realistic assumptions regarding yield, and costs of back layer (glass or tedlar), frit, and encapsulant (EVA). Germane cost increases were offset by Silane cost decreases. Further reductions in overall specialty gas cost drove the differences between projections made in 1997 and 1999 for production years 1998 and 2000.

Labor and Other Unit Cost Drivers

Table 3 summarizes the increases in various unit cost projections from mid-1995 to late 1999. Labor and fixed cost increases, like material cost increases, apparently were driven by more realistic yield assumptions as well as lesser influences more difficult to identify than material cost drivers. The factory was not in full stable production during the period, so comparison of detailed labor hour and process step yield statistics would not be conclusive.

Table 3. Original vs. Experience-Based Cost Estimates

Unframed laminate w/pigtails ($/unit)

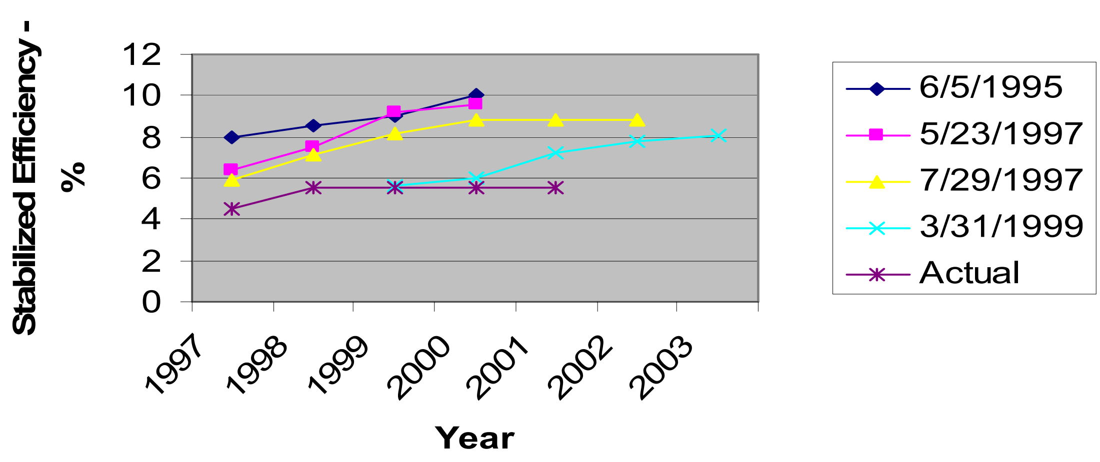
	1995	**1999**	**Change**
Labor Total (1)	12.88	15.39	19%
Direct Material	25.2	30.62	22%
Fixed Cost	36.26	47.30	30%
Total	74.34	93.31	26%

Notes:
1. Includes direct labor and labor overhead

Efficiency

The most persistent, and apparently unalterable, difference between realized cost and expected cost was actual efficiency vs. projected efficiency. From 1994 onward (see **Figure 3**) efficiency improvement forecasts were updated multiple times, and the scenarios for improvement were consistent from forecast to forecast; yet actually realized average efficiency did not change significantly during the roughly 5 years of commercial product shipments.

Figure 3. Efficiency Forecasts



Cost Experience Summary

Unit laminate costs (driven by materials and labor) were substantially underestimated initially; efficiency shortfalls drove laminate $/Wp costs up further; in parallel, the need to meet market requirements by shipping thin-film products technically equivalent to accepted and proven crystalline products drove $/Wp costs even higher; finally, value-added features were incorporated at significant incremental cost.

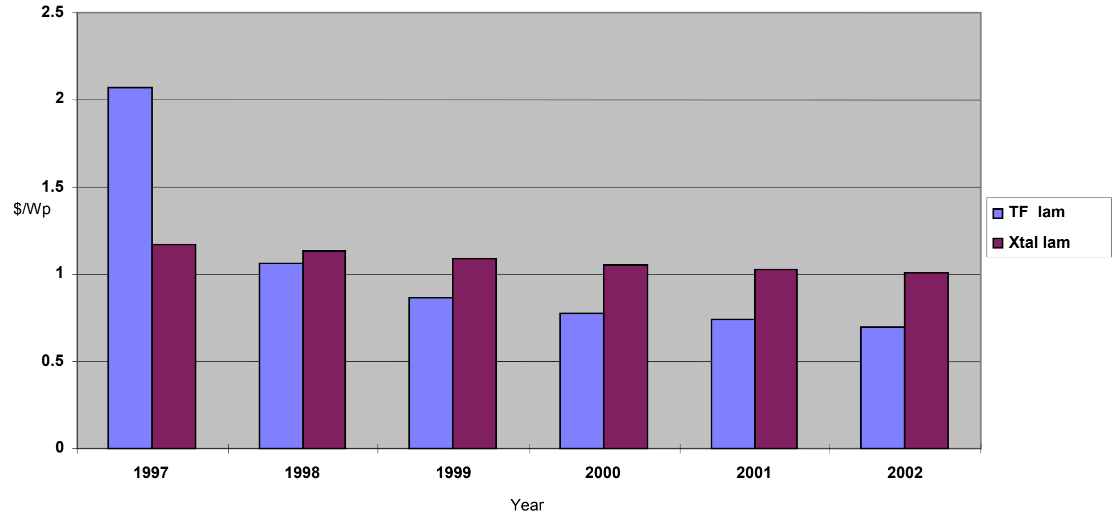
Cost/Value Trade-off

The above discussion of cost drivers risks reinforcement of a common but overly simplistic understanding that all module sales go to the low bidder, based on $/Wp price comparison. It suffices to say that, with PV modules (as with virtually every other manufactured product); manufacturing costs can be reduced by sacrificing functionality, convenience, quality, durability, operating life, etc. For example, it is technically very challenging to engineer and produce a thin-film module whose actual demonstrated lifetime under simulated long-term environmental assault is actually 20 years. Such a product is almost certain to cost more to manufacture than a module that achieves a lesser level of qualification. As is obvious from the above discussion, the evolution of TF1 product costs was equally and inextricably an evolution in TF1 product value.

Future Cost Reduction

A good place to start in assessing the potential for future cost reduction is cost comparisons that were drawn between the two major Solarex module manufacturing technologies, i.e. a-Si and polycrystalline. **Figure 4** reflects what would have to be regarded as the best-informed view of this comparison at the time (in mid-1997). It was based on world-leading manufacturing experience and hundreds of millions of dollars and decades of investment in both technologies; and it was essentially the bottom-line rationale for strategic plans, which forecast the eventual eclipse of the company’s crystalline manufacturing capacity by its thin-film capacity.

Figure 4. TF and Poly Laminate Costs



The favorable scenario hinged on thin-film production scale-up to levels comparable or even exceeding polycrystalline. As presented, the preference appeared decisive, but its absolute magnitude was in the range of $0.3/Wp in 2002. The preceding analysis suggests that several factors, or a combination thereof, could negate or reverse this advantage.

Could such a comparison like the above still come true? Perhaps, but much has changed on both sides of the comparison. In particular, crystalline technology and production scale have continued to progress in the intervening years while the Solarex a-Si technology suffered a devastating setback at the end of 2002, losing both physical assets with which to move the technology forward but also losing the organizational capability to use them.

Putting aside comparisons, can a-Si manufacturing costs be reduced from the levels achieved by Solarex and BP Solar over the next 10-15 years? Technically yes – it is evident from the preceding analysis that original targets were not achieved. Laminate costs exceeded original long-term targets by almost a factor of 2 at the end, but only part of the explanation was unrealistic cost targets imbedded in early cost models. The other part of the explanation – failure to achieve more realistic cost targets – can in principle be overcome with the expenditure of significant resources.

Recent proposals to undertake such expenditures are by no means revolutionary, but they actually mirror the visions and strategies underlying the decade-long effort analyzed above. In early strategic plans, TF1 was viewed as a prototype and precursor of a "factory of factories" that would assemble, tune, and qualify "cookie-cutter" lines from an ever-improving template, switching to more efficient films as they came out of the R&D pipeline, driving capital costs down, and adding automation and a complete process to deliver and staff turn-key factories anywhere in the world. The deployment scale envisioned at the time was comparable to the deployment scale envisioned in more recent proposals. See **Figure 5** for the results of this aggressive scenario.

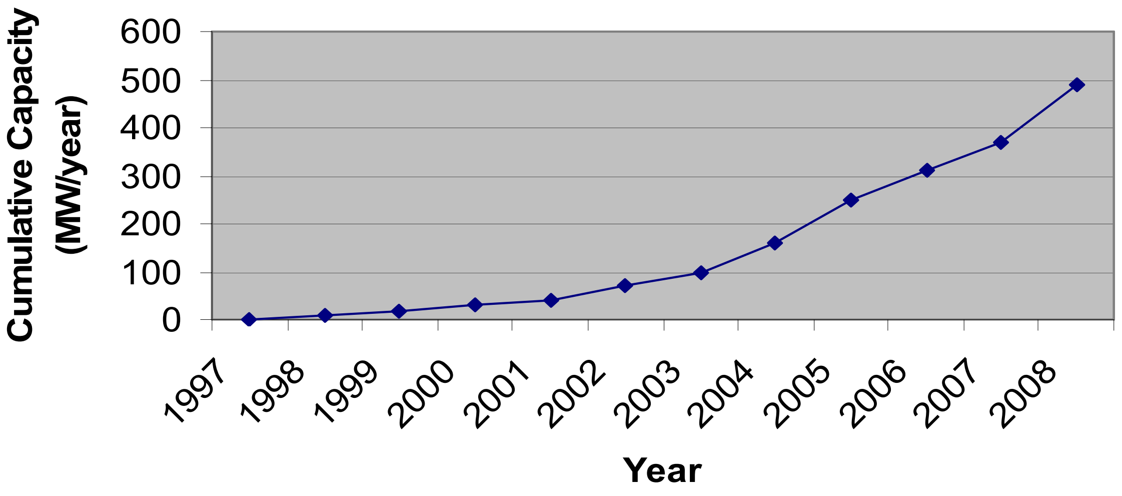


Figure 5. Factory of Factories Scenario

If current proposals are basically reincarnations of old proposals that were partially implemented, what guidance can be gleaned from the implementation experience?

First, target market validation is essential. The initial market hypothesis will drive both product and factory design; and, if wrong, it will have a crippling effect on subsequent efforts. It will result in a requirement to integrate and coordinate moving targets in too many fundamental aspects, i.e. emerging markets, product line reengineering, and factory process changes. Changes in one aspect alone are daunting enough and can be addressed relatively quickly, as long as complications and delays in one aspect do not cascade and aggravate complications in other aspects. As noted, TF1 and supporting product engineering had to adapt to not just one but two major changes in fundamental market requirements (i.e. from a requirement for a single high-voltage, essentially unfinished, and relatively fragile laminate product for a single customer) to a requirement for a broad line of products functionally equivalent to established product offerings in several diverse market segments, back to a single product for a single customer – but one with significant value-added features as yet undemonstrated in production or use. These basic redirections set in motion other changes that proliferated and were beyond the capacity of even an experienced parent organization to support or smoothly coordinate.

Second, early product introduction and sales can be valuable in smoking out problems, but it can also result in damaging and distracting customer and market reactions. Technology validation using experimental equipment and pilot lines can only be partial – it eliminates a negative theoretical possibility but does not prove a positive operational forecast. Operating a full-scale line without benefit of related revenues involves net costs well beyond the cost of the factory itself. These costs can only be justified by hypothetical revenues from multiple future plants, but they must be accounted for in realistic budgets.

Third, because thin-film PV technology challenges are so serious, it is tempting to assume that related product engineering, qualification, and certification challenges are not of the same importance and can be addressed once a factory is being built. For example, photovoltaic films are especially vulnerable to destruction by moisture ingress; and encapsulation strategies consistent with competitive warranties should be developed and validated in parallel with film-deposition processes. The cost of dealing with unresolved engineering issues can be significant, i.e. several hundreds of thousands of dollars per year, or a few percent of full capacity revenues of a 10MW/year factory. More important, lack of timely resolution can delay production and compromise pricing, with far greater negative financial consequences.

Fourth, there are no top-down management fixes when thin-film PV net income forecasts turn out to be optimistic. In the case of TF1, the challenges of unforeseen and unavoidable technology, product engineering, factory operations, and marketing changes outlined above were compounded by exhaustive consultant and management reviews and reorganizations.

Finally, patient capital and significant corporate parental support are truly necessary if thin-film commercialization initiatives are to proceed on an aggressive schedule. Amoco, BP, and their crystalline PV business units provided these indispensable ingredients, e.g., in the product engineering and legal disciplines, finance, marketing, sales, customer service, procurement, logistics, and health and safety. Capital and corporate infrastructure support are necessary but, of course, not sufficient. Execution of the plan is the sufficient condition. Even so, the importance of the diverse and essential organizational and financial resources Amoco and BP made available to TF1 and its planning and operations cannot be overstated.[25]

Case Study: Cadmium Telluride

Apollo Technology – R&D to Production Engineering Phase: 1986 – 1998

1986 to 1996: Acquisition of Apollo Technology and R&D Effort

The Apollo photovoltaic technology project started in 1986 when BP Solar acquired patents for CdTe photovoltaic devices from Monosolar Inc. (Santa Monica, California). The Monosolar patents described the electrochemical deposition of two semiconductor films – cadmium sulfide (CdS) and cadmium telluride (CdTe) – onto a conducting tin oxide-coated glass substrate.

BP Solar organized an R&D project at Sunbury (U.K.) named Apollo. The R&D team objective was to increase semiconductor efficiency and the size of the photovoltaic device using the Monosolar electrochemical process as a starting point. Monosolar inventors produced CdTe photovoltaic devices on substrates of a few square inches. During the 1987-1996 period, the UK Apollo team developed a computer-controlled plating process that deposited CdTe on a $1ft^2$ ($.09m^2$) substrate, in conjunction with a back contact process that relied on conformal coating techniques. The CdS film was produced via a thermal-chemical batch reactor process, where elapsed time and rinsing controlled the film thickness. The R&D effort eventually culminated in a 1-square-foot module with 10% aperture area efficiency (approximately 8 watts).

By the end of the 10-year R&D period, the Apollo technology fundamentals – chemical deposition of CdS and CdTe on tin oxide float glass substrate, application of back contact coatings, laser ablation of cells, and metallization – were identified and documented for a $1ft^2$ substrate using laboratory bench-type equipment. The encapsulation process relied on lamination and lead attachment techniques similar to that used by crystalline photovoltaic (PV) manufacturers. The R&D processes – and, by implication, the laboratory equipment – were documented as the core Apollo technology by 1996 and handed off to the Fairfield engineering team.

1994 to 1996: Acquisition of Fairfield Plant and Equipment

The Fairfield (Calif.) plant and equipment were designed by APS Inc. to produce 31” x 61” (78cm x 155cm) amorphous silicon PV modules using a batch process developed by its predecessor company.[26] However, APS infringed a Solarex patent in their deposition process and, as a result, ceased operation in 1995.[27] Subsequently, APS filed for bankruptcy, and the Fairfield assets were put up for sale. After a technical audit by BP Solar in 1996, it was determined that the Apollo technology could utilize about 50% of the APS equipment, primarily in the post-deposition processes. The Fairfield purchase was consummated in October 1996. The Fairfield a-Si plant was designed around a high-vacuum, plasma-deposition batch process. The only “wet material” in use at Fairfield was water for incoming glass washing, vacuum pump oil and various solvents used in the encapsulation process.

1997 to 1998: Technology Transfer, Process Specification, Equipment Procurement, and Staffing

Technology Transfer

In January 1997, a three-person team began the process of transferring the Apollo technology from the UK R&D group to Fairfield. During the initial stage of the technology transfer process, the team focused on engineering specifications for the Apollo process, so that equipment bid specifications could be prepared.

Review of the R&D laboratory process was used to define the cycle time and type – batch or continuous – for each manufacturing process step, including load/unload time. The manufacturing process was charted for a 14-by-61-inch substrate while taking into account existing equipment locations at Fairfield. The 14-inch width was dictated by the R&D team findings linked to voltage drop across the substrate during CdTe deposition. The 61-inch length for Apollo stemmed from the APS module footprint (31-by-61 inch) for existing equipment at Fairfield.

The processing of $0.55m^2$ (14-by-61 inch) substrates at Fairfield was considered an intermediate product from the outset, one that posed little risk for the R&D CdTe deposition process. The $0.55m^2$ module had a nominal 25W rating, which could be used for battery charging or in small arrays, but was not viewed as a power module. The rationale for producing the 25W module at all was to allow the plant to start operating in the shortest time possible, while the Fairfield technology team developed a CdTe deposition process for 24-by-61 inch ($0.94m^2$) substrate. The 24-inch product size emerged for several reasons. First, one person could manually handle a 0.94m2 size substrate; and a module could be handled by a two-person team, from a weight perspective. Second, off-the-shelf coating equipment to process 24-inch wide materials was judged to be widely available. Third, the R&D and Fairfield team had reason to believe the CdTe deposition technology could be pressed to accommodate 24-inch substrate, but larger widths presented significant technical risks; and, further, the plating tank size necessary to process 5-across 14-inch substrates could dimensionally accommodate 3-up 24-inch substrates. Finally, the deposition equipment would “fit” onto the Fairfield plant floor along with a second CdTe deposition train at a later time. From the outset, therefore, the technology transfer team considered the ramification of a larger substrate in preparing the specification for new equipment.

Process Specification

The translation of the R&D process for $0.09m^2$ substrates posed substantial challenges. The intermediate $0.55m^2$ substrate presented engineering challenges for even relatively simple heat-treat steps. Time-temperature profiles for manufacturing-size convection ovens had to be developed from the R&D bench-type ovens. Questions arose about ramp rates, soak time, cool-down, and surface temperature uniformity across single substrates of a “load” comprised of about 20 substrates in a batch, laminar flow oven. Such parameters had not been explicitly considered on the R&D level, presumably because the small $0.09m^2$ plate load did not elicit any fundamental technology questions.

Scale and edge effects were encountered in other processes as well. The CdS deposition process in R&D, for example, was based on "manual stirring" by a technician as two aqueous solutions were poured into a deep bench tank, followed by manual insertion of a small rack of CTO glass. At Fairfield the two solutions (cadmium-base and chelating) would be pumped into a reaction chamber many times larger, air would "stir" the solutions, followed by immersion of the substrate load weighing hundreds of pounds from a hoist. The batch reaction process requirements were carefully calculated, and then converted into equipment specifications for high-volume manufacturing. Similar scale issues were addressed across many other processes.

Equipment

When the engineering specifications were judged as complete, equipment procurement was initiated, which took place during the 1997-1998 period.[28] The approach taken was to obtain a modified version of "off-the-shelf" equipment from original equipment manufacturers (OEM) in order to minimize equipment design and delivery time. The main exception to this approach was the procurement of the CdS and CdTe reactors, each of which were one-off or engineer-to-order (ETO) pieces of equipment. The design and construction of the requisite Apollo deposition equipment by the selected OEM required considerable input from Fairfield's technology/engineering team. A prototype CdTe reactor was made prior to delivery of the main system to test the internal components. This unit had one eighth of the capacity of the main CdTe train and was operated in a semi-manual mode. However, the internal components and structure were identical in design to the production line. By July 1998, all equipment was in place, including the single CdTe prototype tank, so that process qualification trials could take place.

Recruitment of Technical Staff

As the Apollo project got underway at Fairfield in 1997, there was great demand for scientists, engineers and other skilled personnel throughout the "Bay" area in northern California. Initially, recruitment of technical staff was limited to the local region. It was quickly determined that personnel availability in northern California was inadequate for the proposed compensation levels; and sometimes qualified candidates simply could not be identified almost regardless of salary.

Apollo Technology – Legacy Manufacturing Plan: Circa 1997 – 1999

1997 Manufacturing Vision – Apollo Modules @ $\eta \sim 5.5 - 6.5\%$:[29] Initially, Apollo manufacturing volume was planned under the assumption that only supply constrained its consumption in the market. That is, if the Fairfield plant was capable of producing stable 25W_p modules over the 1998 to 1999 period, they would all be sold. Following on in 2000, if Fairfield produced stable 50W_p modules, they too would all be sold as well. The Apollo technology/engineering start-up team was convinced that the various equipment and process challenges were manageable, and that the endeavor would constitute a major breakthrough in thin-film module manufacturing. The Apollo team benefited from abundant offers of corporate support at the outset, which was usually forthcoming in disciplines such as financial, legal, purchasing and community relations.

Based on the outdoor experience of the R&D findings, the Fairfield team expected about 6% light-soak degradation by the Apollo module. The initial efficiency target in manufacturing was 5.9% for the $0.55m^2$ unit and 6.6% for the $0.94m^2$ unit, resulting in stabilized efficiency on order of 5.5% and 6.2%, respectively. The module features were straightforward – annealed glass to glass lamination using EVA, U-channel brackets, J-box connector, and 16AWG red/black wire harness suitable for interconnection in an array. These module features were those employed by APS for the a-Si 500kW array built for the PVUSA project. These encapsulation processes and equipment were carried over at Fairfield.

The manufacturing plan for the period 1998-2000 identified a number of risks that could impede the rapid start-up of Apollo production. These risks included the following:

1. Engineering Staff – timely recruitment within salary guidelines for essential engineering and other technical personnel needed for line start-up;
2. New Process Equipment – procured in reference to the cost estimates originally developed by the R&D team; this applied to both modified "off-the-shelf" equipment as well as the one-off, special-purpose deposition reactors and associated fixtures;
3. Facility Overhaul – modifications to accommodate multiple wet chemical manufacturing processes and supporting infrastructure;
4. Hazardous Waste and Environmental Control Equipment – retention of chemical solutions under normal and catastrophic conditions, spent solution capture and on-site/off-site treatment of hazardous chemicals, volatile organic compounds (VOC), and other materials (direct and indirect); securing necessary permits and approvals from local, regional, and state agencies;
5. Fairfield Equipment – modified or reconditioned to handle Apollo substrates and modules; legacy equipment of interest included glass washers, automated load/unload laser stations, metal sputtering unit, and encapsulation equipment such as EVA applicator, buss foil applicator, laminators, bracket applicator, laminate/bracket curing ovens, and conveyors;
6. Operator and Technician – timely recruitment from local labor pool and specific training, including skilled maintenance and process technicians;
7. Product and Process Reliability – reliance on earlier R&D studies, especially outdoor test array data, to forecast long term module electrical and environmental performance.

Start-up Challenges, Risk Management, and Revised Vision: 1997 – 1999: As it turned out, some of the aforementioned risks were significant drivers of project performance, either with respect to resource consumption, creation of major delays in the project timeline, or both. ***There was no expectation that new significant technology enhancements would be required for success.***

Technical Staff

Recruitment of engineering and technology staff was extremely challenging. The speedy recruitment of senior technology and engineering personnel in the local region was not successful. The overall project plan called for all new engineering staff, plus three "transfer" members from other units, to be onboard by April 1997; installation of all essential process equipment by the end of 1997; and start of qualification trials in early 1998.

The reality turned out differently. The first engineer was hired in May 1997, and the last came onboard in September 1997. Once assembled, however, the team charged ahead with the technical challenges. Higher than budget relocation costs and higher-than-planned salaries aside, the greater impact was a delay in acquiring, installing and qualifying process equipment; and in managing the extensive facility renovations. The start-up expenditure was set at about $200,000 per month. Hence, the delay in starting up the Apollo manufacturing line beyond the planned period (early 1998) was very costly.

Deposition Equipment

The Apollo CdS and CdTe deposition reactors were unique. In terms of scale, the batch reactors were quite large. In terms of equipment construction, the CdTe electro-chemical reactor required significant alignment precision, which is not normally associated with large and heavy substrates in a chemical bath. Alignment of the mass transport mechanism with the substrates and transport racks proved to be very difficult in terms of material selection and fabrication. Further, both types of reactors involved large thermal loads and the need to closely control the temperature profile.

In 1997, there were very few original equipment manufacturers (OEMs) with the requisite engineering and fabrication expertise needed for designing and constructing the sort of very large deposition reactors necessary for the Apollo process. The Apollo team identified a handful of firms in the USA. One was eliminated because all construction was done in the Far East, which would lead to excessive project and engineering oversight costs. A second company disqualified itself because they were located on the East Coast. The remaining three OEMs were in the Los Angeles area.

Three bids were solicited, but only two firms responded. The first bidder had marginal experience in manufacturing large-scale, automated chemical batch reactors at the time, and their bid was judged inadequate. The second OEM submitted a quote that demonstrated reasonably good technical understanding, and the proposed cost was close to that originally estimated by the R&D team. The third company, when pressed to submit a bid, said they would only consider a time and materials (T&M) design project for one year to come up with a design of what was needed, and the charges for the engineering effort would be equal to the second firm's bid for finished reactors.

The second OEM was awarded the contract for the CdS and CdTe deposition units in June 1997. The CdS deposition unit was delivered in December 1997 per the contract. The CdTe deposition system proved much more difficult. After many months, a special project manager and a mechanical engineer were assigned full-time to work on-site at the

OEM's place of business. In the end, the CdTe unit was delivered in August 1998 at a cost about double the original bid, and only prototype fixtures for one of the eight tank trains were provided. To fit out the other 7 tank fixtures, additional cost on order of another 50% was required.[30]

Facility Overhaul

The modifications needed to convert the "dry" Fairfield facility to accept the wet chemical processes for Apollo were challenging in several respects. Channels and conduits had to be cut into a solid concrete floor, along with discharge pipes to "catchment" tanks where pumps were needed to convey the spent solutions to a treatment facility especially designed to handle cadmium wastewater. Concurrently, various gas byproducts from processes involving hazardous gases and solvents had to be captured by flow hoods and conveyed to scrubber systems. Chemical holding tanks, containment dikes and seismic tie-downs were needed where yet-to-be-acquired process equipment was to be installed. Due to the large thermal load of the Apollo process, a new multistage boiler had to be fitted, along with significant upgrades for DI water service, compressed air, electrical drops, and air handling systems. Coordination of the various trades was daunting, as up to a dozen subcontractors were on-site along with crews numbering several dozen at times. Original estimates to put these new services in place were exceeded by wide margins as existing services had to be removed, in most cases, in order to install the new services. Moreover, the extremely short project timeline required reliance on design-to-build (DTB) contracts, as opposed to specification and firm fix-price quotations. DTB contracts can save time, but are generally more expensive and difficult to manage. An outside construction management firm was employed. Overall, the facility upgrades exceeded "stand-alone" construction estimates by about 100%.[31]

Hazardous Waste and Environmental Control Equipment

The project effort to identify, characterize, quantify and treat the hazardous waste by-products of the Apollo process was handled in an expeditious and cost-effective manner. There were a number of antecedents leading up to this outcome. First, the R&D team had carefully noted and documented the hazardous wastes produced in their UK laboratory, in response to strict corporate health, safety and environmental (HS) guidelines. Second, the UK member of the technology transfer team was well informed regarding the hazards associated with the Apollo process since he was the site HSE officer. Third, the Fairfield team was able to engage a BP pre-qualified environmental engineering firm in the Bay area. The environmental firm's study of hazardous-waste treatment was funded, in part, under a subcontract with NREL. Fourth, the first engineer hired at Fairfield was a quality-control specialist for a major chemical manufacturer and, as such, was very knowledgeable as to chemical hazards, waste treatment suppliers, and applicable regulations. In short, the requisite expertise, staff resources, and funding quickly fell into place.

The authority to construct (ACT) permit for air emission abatement equipment was issued in July 1997 by the Bay Area Air Quality Management District (BAAQMD). Following discussions with the local sewer district, the wastewater stream treatment prior to discharge was identified and established. All necessary environmental control equipment was ordered, installed, and qualified by mid-year 1998. There were no cost upsets, and permits to operate were eventually secured for start-up.

Fairfield Equipment

Renovation of existing APS equipment was scheduled on an "as-needed" basis over the years 1997-2000. The most significant upgrades, in terms of cost, involved the laser-ablation stations. By 2000, the existing Fairfield laser technology had insufficient power and other optical properties to reliably scribe Apollo substrates. The semiconductor and back contact material were considerably thicker in Apollo than that used by APS to produce a-Si material. Further, the use of tempered CTO substrates introduced flatness variations that necessitated beam optics with larger depth of field. The cost to upgrade all the laser stations and respective controllers was approximately $250,000 in 2001. Other "legacy" Fairfield equipment, such as glass washers and laminators, necessitated overhaul to replace aged parts, which was accomplished at modest cost within routine maintenance budgets. The buss foil applicator for a-Si APS modules was not usable for Apollo despite best efforts, eventually leading to the adoption of foil-tape prior to 1999, and then conversion to frit buss bars derivative of the parallel a-Si factory (Toano, Virginia). Other general-purpose conveyors and worktables were used as is. The edge-deletion equipment received a major overhaul to significantly enhance capture of ablated material, so as to trap cadmium particles. The metal sputtering system was used as is, although the metal target materials were modified over time to enhance performance of Apollo modules.

Operator and Technician Recruitment; & Product and Process Reliability

As it turned out, the first phase of the Apollo project from 1997-1998Q3 was mainly concerned with proving that the Apollo CdS-CdTe deposition equipment was capable of depositing a semiconductor film on large substrates. By the end of 1998Q2 the Apollo team was satisfied with the back contact process based upon studies using CdTe coated substrates from another company. Corporate leadership change in late 1997 did lead to inquiries regarding the financial and market underpinnings for the Apollo project. The earlier "supply constrained" premise did not survive close scrutiny by new marketing staff at Fairfield. There were new questions as to the technical feasibility of the Apollo CdTe deposition train. Responses to such questions were difficult in early 1998, as the equipment had not been delivered, much less installed and qualified. The financial viability of the Apollo enterprise was thoroughly analyzed with respect to alternative scenarios and their inherent risks. While the top-down management review was taking place, the Fairfield technical team continued efforts to improve the process, albeit with only a single prototype CdTe reactor.

The recruitment of a full complement of operators and technicians was set aside for the moment. Product reliability and environmental studies were also limited since Apollo CdTe deposition equipment was not yet installed at Fairfield. Both recruitment and product evaluation tasks became more consequential in the third phase of the Apollo project, following after the 1999 efficiency stretch and the Apollo commercialization stage-gate in June 2000.

Beginning in 1998Q2 the fabrication and assembly of the 8-tank CdTe deposition system was assigned to a special engineering team comprised of a senior project manager from BP, senior chemistry technologists from UK and Fairfield, and a Fairfield mechanical engineer. All members of this team were expected to work on site at the company building the CdTe deposition system.

The balance of the Apollo engineering and technology team continued efforts to refine and qualify the post-deposition processes. Progress in the development of the lamination and encapsulation process was limited as the appropriate engineering positions were not on board as yet. The installation of the equipment to control hazardous waste materials was continued.

Apollo Technology – Stage-Gate and Efficiency Stretch: 1998Q3 – 2000Q2

Stage-Gate #1: Equipment Capabilities – CdTe Prototype Reactor (Oct, 1998)

The first stage-gate demonstration was undertaken in October 1998. While awaiting the completion and delivery of the eight-pack CdTe deposition system, it was important to determine whether the prototype reactor unit was capable of depositing a CdTe film over the CTO-CdS substrate. As mentioned above, the OEM supplied a prototype reactor chamber that was expected to be the same as the 8 chambers in the production unit when delivered. There was a certain level of concern associated with the CdTe system, ranging from the mundane – did it leak cadmium solution – to the sophisticated – was a stoichiometric CdTe film deposited in the reactor – and the momentous – did the CdTe film exhibit semiconductor properties. The principal scientists responsible for the design of the CdTe reactor system carried out the demonstration. After several weeks, the prototype reactor performed as expected, albeit with much "hands-on" input by the scientists.

Stage-Gate #2: Process Capabilities – CdTe Prototype Reactor (Jan. 1999)

The second stage-gate demonstration was completed in January 1999. Shortly after the October stage-gate was completed, the full eight-pack CdTe deposition train was delivered and services connected. At this juncture, however, the individual reactor chambers were not completely fitted out. The decision was made to accept the equipment as is, because the OEM had been struggling with the build for some months. Before funds were released to completely fit out the eight-pack, it was important to demonstrate that the CdTe electrochemical process in the fitted-out prototype reactor was capable of producing viable product. The second stage-gate targets for a 200-plate lot included efficiency (average $\eta \geq 6\%$ & std dev $\leq 0.7\%$), overall yield ($\geq 80\%$) and related results.. This stage-gate was successfully completed.[32]

Stage-Gate #3: Process Capabilities – CdTe 8-Pack Reactor (April 1999)

The third stage-gate demonstration dealt with the eight-pack CdTe reactor and its process capability. The stage-gate #3 pass criteria were identical to those of stage-gate 2. Stage-gate #3 was successfully completed in April 1999.

Up to this point, the Fairfield team was working toward the start-up of the 0.55m^2 Apollo line in 1999. With the merger of BP Solar with Solarex, new questions were raised, namely, "which thin-film process had the best hopes for commercial success – the Apollo cadmium telluride at Fairfield, California, or the Millennia amorphous silicon at Toano, Virginia?" After technical discussions and exchanges of cost and performance data, it was concluded that neither thin-film technology had a clear cost advantage or a performance advantage as both produced modules with aperture efficiencies on the order of 6%. However, as the Toano plant was further along in terms of its production rollout, the Fairfield process became the "challenger" technology. The Apollo technology had to demonstrate a clear advantage in terms of product performance or cost in order to survive.

The Fairfield team was given a mandate to undertake an "efficiency stretch" project for the 0.94m^2 Apollo module, with the goal to significantly boost module power at a cost that demonstrated a clear and convincing comparative advantage. The Fairfield team sought the advice and assistance of the NREL thin-film staff as well as the scientists at the Institute of Energy Conversion at the University of Delaware. Both organizations provided excellent technical advice and supporting analyses that were extremely useful in progressing the Apollo CdTe technology at Fairfield.

Stage-Gate #4: High Efficiency > 6% Process Capabilities – CdTe 8-Pack Reactor (Sept. 1999)

The fourth stage-gate demonstration looked at the production of 0.94m^2 substrates with efficiencies in excess of 6% (~ 50Wp). At this stage, only the eight-pack reactor equipment was utilized. Based on supporting studies by NREL and IEC research scientists, the Apollo process team began looking at ways to improve the performance of the CdTe absorber layer. A post-deposition process was developed to facilitate grain growth, which resulted in overall module efficiency going from 6% to about 7% or ~60Wp with the 0.94m^2 size module.[33] The stage-gate 4 pass criteria were similar to those for stage-gate 3, and were successfully completed in September 1999.

Stage-Gate #5: High Efficiency > 7% Capabilities – CdTe 8-Pack Reactor (Dec. 1999)

The fifth stage-gate demonstration looked exclusively at the production of 0.94m^2 substrates with efficiencies in excess of 8% (~70Wp). This stage-gate addressed the stability of the Apollo module over 500 hours of light soak under load at controlled temperature (50°C ± 5°C) and irradiance (800w/m^2 ± 5%).[34] Stage-gate 5 was attained in December 1999.

Stage-Gate #6: Very High Efficiency ~10% Capabilities – CdTe 8-Pack Reactor (April 2000)

The sixth stage-gate demonstration looked at the production of 0.94m^2 substrates with efficiencies in excess of 8% (~70Wp). The technical challenge was to reduce the losses in the window or CdS layer. This was achieved by reducing the thickness of the CdS layer without compromising the electrical properties of the semiconductor. A process was developed whereby a high-resistance layer was placed over the CTO prior to CdS deposition. The CdS layer thickness was reduced by about half, which allowed more blue light to pass through to the CdTe layer and increased the quantum efficiency of the Apollo device. Module efficiency on order of 10% (~85Wp) was achieved for a significant number of units. This stage-gate was achieved in April 2000.

Stage-Gate #7: Commercialization of VHE Apollo Modules (June 2000)

This stage- gate was anticipated with eagerness by the Apollo technology team. The meeting was organized in June 2000 and involved marketing and corporate staff for the first time in many months. A number of issues were discussed, including the status of the technology, manufacturing capability, staff needs, product qualification and production ramp plan.

The outcome of the meeting was a directive to develop an overall business plan including product specification and qualification, manufacturing costs, staffing, capital expenditure, manufacturing ramp plan, sales forecast, and product stewardship plan. The next section will discuss the cost and schedule consequences that emanated from the commercialization strategy discussions.

Commercialization and Manufacturing: 2000 – 2002

Manufacturing Process Changes for 10% Modules:

The Apollo process and technology had evolved during the previous two and a half years as the result of the efficiency stretch improvements. The manufacturing process to produce modules with 10% efficiency (or 80 watts) had grown in complexity, however, through the introduction of new materials, new handling steps, and new equipment.

Figure 6 presents a simplified schematic for the “10% efficiency” Apollo process, which was expected to yield “80Wp modules” on average, as well as improved reliability. The efficiency gains involved process steps #02, #03, #05 and #07 in the schematic. Reliability gains came from change to heat strengthened glass (#01) and use of vapor barrier (#14). The schematic is simplified in that only 16 macro-processes are broken out. Underlying each of the 16 macro-processes is a bundle of discrete processes, numbering in excess of 42 to produce a glass-to-glass laminate. These 42 processes, in turn, do not reflect other offline procedures such as preparing solutions, process control measurements, operation of environmental control equipment, equipment setup and teardown, and similar procedures. Moreover, the 42 discrete procedures do not include the steps required to build the other module types (e.g., frame) desired by product managers.

As displayed in Figure 6, there were three major process subsets at Fairfield, namely Deposition Process (#01 - #08), Back Contact Process (#09 - #13) and Module Process (#14 - #16). A fourth major process subset – Environmental Control – is not depicted, but was just as critical to the successful operation of the Apollo manufacturing line.

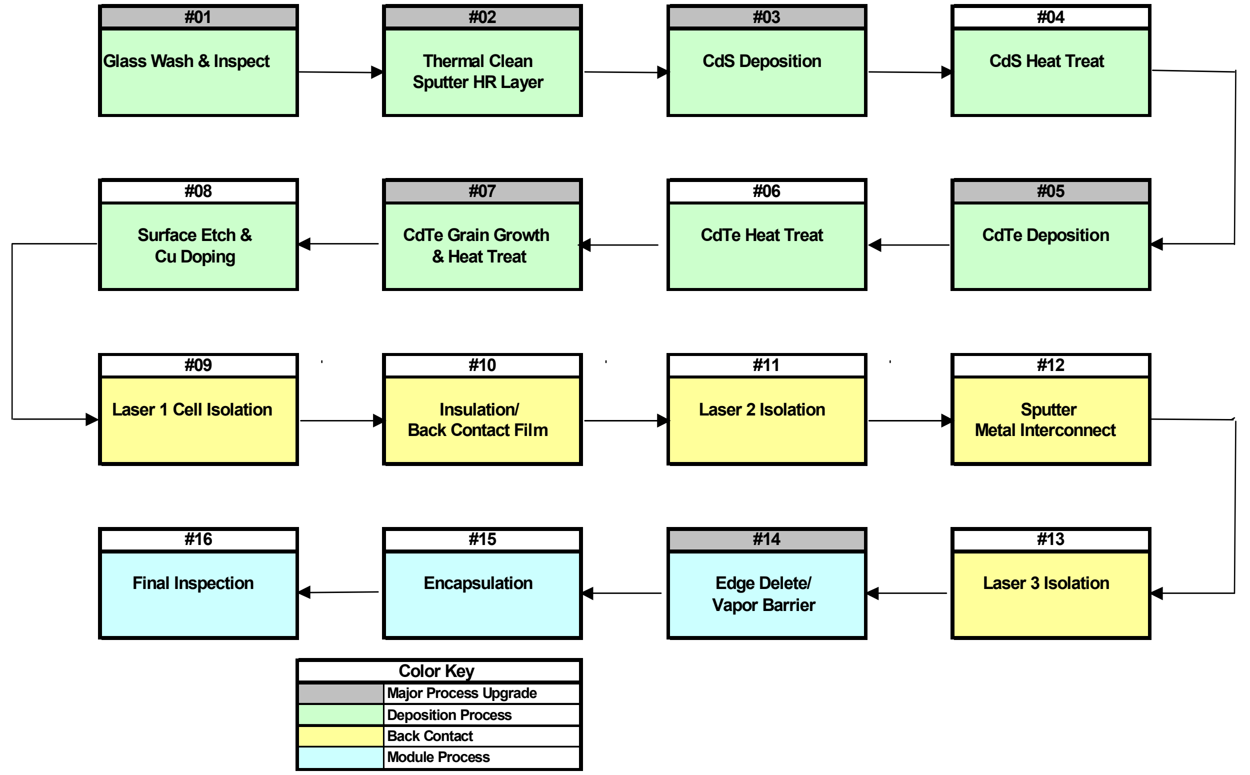
Specific engineers and technicians were assigned principal areas of responsibility, but everyone was expected to participate in daily and weekly meetings to troubleshoot yield, quality or performance shortfalls. Root cause and corrective action initiatives were daily occurrences as the manufacturing line began to ramp in 2001. As discussed later, line yield and environmental stress reliability matters consumed significant engineering, technology and production staff resources.

The process changes to improve aperture efficiency came at a cost in almost every circumstance, either in terms of material, direct labor or handling, cycle times, or new equipment. The type and approximate impact of the major changes are summarized below.

Process #02 Sputter HR Buffer Layer – this new process added nominal material costs for sputtered metal and masking tape. The more significant cost was higher direct labor costs and a bottleneck at the sputtering system station. The bottleneck eventually would impinge on capacity. The direct cost of the HR buffer layer at low volumes was roughly \$0.02 – 0.03 per W or \$2/m^2, and a scheduling workaround challenge.

Process #03 CdS Deposition – thinner window (CdS) layer was accomplished by using a shorter cycle time; which, in theory, lowered direct labor – but the resulting labor efficiency gain was minimal.

Figure 6. APOLLO SIMPLIFIED PROCESS FLOW - 10% EFFICIENCY [80Wp]



Process #05 CdTe Deposition – the efficiency stretch program concluded that a thicker CdTe layer improved device performance, which required a longer deposition cycle, and reduced plant capacity in units by approximately 25%. While the unit reduction was offset by higher electrical yields, it was concluded that fixed cost per unit or watt was adversely affected, and ways to shorten the CdTe cycle time were under consideration.

Process #07 CdTe Grain Growth – this process change had nominal material costs, but did require the addition of equipment costing about $300,000 and required more energy. The depreciation cost per watt was minimal at the targeted eight megawatt (8 MW) run rate.

Other Cost Impacts

There was a major unplanned cost upset during the 2000-01 period. It appeared as an extraordinary rise in the price of electricity in California. Due to a breakdown in the power delivery system in California, early forecasts indicated that utility costs on order of $0.07-0.10 per watt ($5 - $8 per m ^{2}) would be incurred at full-run rate. Investigations of how best to offset higher utility costs were set in motion, including installation of a large grid-connected Apollo array at the Fairfield site.

Product Plan and Impact

Following onto the commercialization stage-gate in June 2000, the Apollo venture came under the auspices of corporate gatekeepers for product design.

Heat-Strengthened Glass

One product design requirement was the use of heat-strengthened glass in the Apollo product. The Fairfield engineering team ran small lots through the deposition and encapsulation line. Fully tempered 0.55m^2 (14” x 61”) CTO glass lost about 50% of its surface compression, thereby falling into the heat-strengthen (HS) range (≤ 10k psi) after going through the Apollo process. Module electrical performance was acceptable. Other tests with HS rear glass (14-by-61 inches) indicated lower adhesion and some bubbles after lamination. Other process issues with heat-strengthened glass did eventually emerge.

With the above HS test results in hand, it was judged that CTO substrates could be tempered concurrent with “firing the frit buss” with modest additional costs based upon discussions with TF1 staff and their supplier. One alternative for the frit-buss – metal foil with two-sided tape -- was unreliable under environmental stress conditions. The product management team requested a cost comparison for annealed CTO and rear cover glass, tempered CTO and annealed rear cover glass, and tempered CTO and HS rear cover glass.[35] The approximate and initial cost differences are presented in **Figure 7**. The cost estimates for the HS-CTO and HS-Rear glass were guesstimates from the glass fabricator who would process truckloads with racks of annealed tin-oxide coated (CTO or TEC) and annealed clear (CLR) glass as shipped from the LOF float glass foundry.

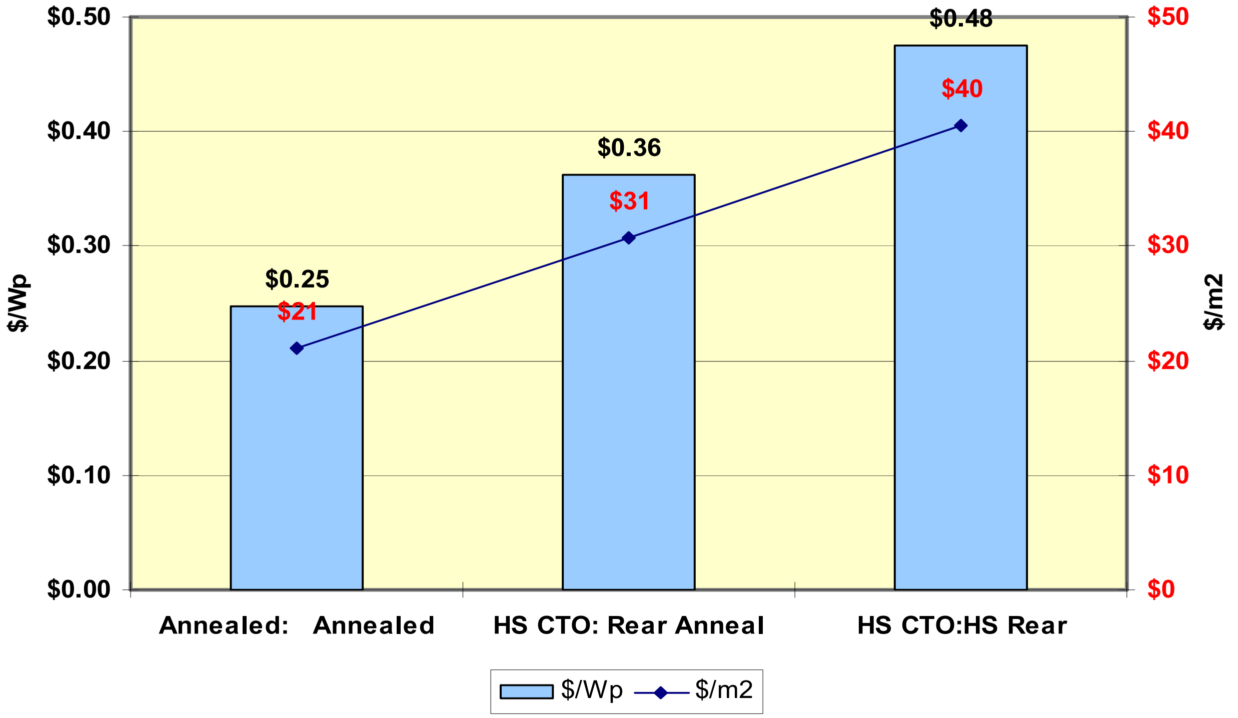


Figure 7. ANNEALED vs. HEAT-STRENGTHEN CTO & REAR GLASS

The base case – Annealed CTO and Annealed Rear – glass costs in the chart ($21/m^2) were gathered from local and internal sources. Subsequently, base case costs for annealed/annealed units were underestimated by 30% or so, while the HS/HS configuration costs were about 5% lower overall. All-inclusive quotes from the glass fabricator for scribing the CTO glass to size, edge seaming, washing, drying and racking for shipment to Fairfield was about $2.50/m^2. The "low ohm" CTO glass used at Fairfield was priced by LOF at about $15/m^2 for modest truckload quantities. For CLR glass, the raw glass with seamed edges was about $9/m^2 (vs. $3/m^2 as originally thought using in-house seaming process).

With the HS-CTO product, in addition to the cutting and seaming operations, the fabricator had to dispense conductive frit ($6/m^2) and cure the frit ($4/m^2) while tempering the CTO. Tempering the CTO glass, with one clear side and the other being tin-oxide coated, while holding flatness and compression specifications across the 0.945m^2 surface turned out to be a technology challenge for the fabricator and eventually a cost upset. Gaining agreement on how to measure surface compression using non-destructive means was difficult using available instrumentation. The HS process with CLR glass was more straightforward. A significant cost variable was the yield loss at the fabricator level. Over time it was anticipated that higher volume and more robust process control by the fabricator would secure lower unit costs, on order of 5 – 10% perhaps.

Despite the large "guesstimated" cost differences, it was decided to proceed with the HS-CTO and HS-Rear glass for Apollo because it was thought the final product would have greater acceptance and field reliability.[36]

Product Stewardship

Another issue considered by the Apollo Commercialization team was the question of product stewardship. At the Fairfield plant, substantial technical and financial resources were devoted to the abatement of environmental risks. The Fairfield plant had gained environmental (ISO 14001) certification. All employees were instructed regarding the proper methods and personal safety gear required by each operation where there was some risk of exposure to cadmium feedstock, as well as other safety and environmental hazards. The feedstock was present as cadmium solutions inside equipment hoods with separate air handling gear, which went a long way toward reducing workforce exposure. Early engineering studies concluded that finished modules and post-lamination line scrap easily passed the Toxic Characteristic Leach Procedure tests established by the U.S. Environmental Protection Agency (EPA), which meant such scrap could go into ordinary municipal landfills except in California. All Fairfield line scrap was disposed of as hazardous waste.

The issue of handling Apollo modules was addressed once again in anticipation of high-volume Fairfield manufacturing, and the shipping of large quantities of Apollo modules around the country and, in time, throughout the world. In general, the marketing plan for Apollo was to seek out partners who were large grid-connected installers. Preferably, these commercial arrangements would take place for projects of 50kW or greater. By limiting the distribution channels, it was thought the handling and return of scrap Apollo modules to the Fairfield plant could be achieved in an economic manner. Once reaching the Fairfield plant, any scrapped modules would be properly disposed.

Environmental standards were evolving and it was concluded that a "cradle-to-grave" (vs." cradle-to-cradle" advocated by some) stewardship program would be initiated.[37] On the basis of very preliminary cost estimates to ship modules from, say, India to California, warehousing and transit costs to a smelter operation where the scrap modules would be used as flux, an accrual charge of \$0.05 - 0.15/Wp (\$4 - \$12/m^2) may be necessary as a stewardship cost. A project was organized to scope the handling of local Apollo scrap and future material returns. Discussions were initiated with a smelter operator in the northwest.

Manufacturing Ramp Plan

The Apollo manufacturing line incorporated some major upgrades in terms of existing equipment, as well as the purchase and installation of new material handling and process equipment to improve operational efficiencies. Also, the eight-pack CdTe system had to be completely fitted out as only one tank had been upgraded for the efficiency stretch quest.

As the new equipment was brought onboard, the limitations of certain facility services also came into play. Upgrades to services such as boiler water distribution, pneumatic distribution, DI water and electrical services were initiated. The environmental abatement equipment also was upgraded in certain areas. Additional quality-control equipment for assessing deposition solutions, as well as wastewater streams became critical. The encapsulation line also required an influx of new (e.g., inline IV tester) equipment and the refurbishment of other equipment.

The encapsulation process and equipment capabilities were particularly significant as product qualification tests were undertaken. The glass-to-glass Apollo module, using HS substrate and rear glass, failed the 1,000-hour damp heat (1000hr DH) test. The newly hired encapsulation engineers had to identify a new edge and wire hole vapor barrier process to protect the Apollo thin-film, which was predisposed to moisture induced corrosion. Annealed glass off a float line is typically very flat. The HS process for glass introduces stresses that can introduce curvature onto the surface of the glass. A glass-glass laminate configuration will typically result in “gaps” between the CTO side and the Rear side. These edge gaps permitted ingression of water vapor that attacked the thin-film material and eventually lead to performance degradation in the module. Working closely with a specialty adhesives and sealants company, an extruded butyl sealant material was developed that, and once applied along the edge of the glass-glass laminate, acted to prevent DH failures through the edges. Another material was developed for the wire-hole pottant where leads were soldered to the conductive frit. The challenge here was to identify a material(s) that was impervious to water vapor, firmly encapsulate the wire solder interconnect and yet be flexible enough to not break the solder connection at the frit surface during thermal cycles. The vapor barrier process was a critical path item before a general product introduction was possible.

While the moisture barrier effort was underway, corporate product engineering simultaneously wanted to qualify various framed module configurations for Apollo. The framed module effort added greatly to the workload of Apollo encapsulation engineering staff. In addition to the major tasks associated with overcoming DH failures, Apollo technology staff was also instructed to consider new EVA material. A 1,000-hour damp heat test cycle lasted 6 weeks. Consequently, the conduct of dozens of test samples in various test cycles in test chambers at Fairfield, at Frederick MD site, and local environmental test houses kept several engineers and quality staff on their toes.

The fitting out of the eight-pack tank fixtures (e.g., mass transport comb) was also a considerable task. To accelerate final installation, an outside contractor was hired to organize a rigging and fitting crew. This process took several months to complete. Final installation of the tank fixtures had to take place inside the CdTe deposition reactor. Special safeguards were implemented to protect the installation team, as regular processing of test substrates was ongoing. Once a tank was fitted out, a process to plate out impurities was scheduled, which sometimes took a week or more. This was followed with qualification lots before the tanks were placed in service. The tank startup timeline extended over several months.

In addition to the hiring of several engineers and technicians in the last half of 2000, full production meant the hiring and training of 50-60 production employees. Attracting prospective process operators and technicians was woefully inadequate during the first quarter of 2001. Based on the advice of outside agencies, the starting rate for production employees was raised by about 10% across the board. This had an impact on labor costs; but, spread across all cost centers, it was not a major hit at the time. The generic answer to avoid higher unit costs was generally to ramp the planned volume and, hopefully, observe a corresponding change in units going to stores.

The Fairfield line began commercial operation in August 2001. Almost immediately, the line began to encounter difficulties with respect to yields. Some shakedown is always anticipated with start-up, but the yield losses increased right along with efforts to bring more CdTe tanks on line. The largest yield loss was at the CdTe deposition process either immediately as a visual defect (e.g., incomplete deposition) or later at IV test following the back contact process. Additional losses occurred in the encapsulation line due to electrical or visual failures, including excessive bubbles entrapped in the laminate, misalignment of top/bottom covers, appearance, and the like.

By the end of 2001, the cumulative line yield was only one-half of plan (65%), which was initially judged as being a reasonable target. The overall cost impact of the excessive yield loss is unknown, but a reasonable guesstimate would be about \$0.35/Wp or about \$30/m^2. This is a shocking cost increase, of course, and the entire technology and engineering team spent countless hours battling to regain control of line yield. Interestingly, studies of process variations did not suggest that the equipment was not working or was set-up incorrectly. Rather, the largest defect was visual at CdTe deposition, followed by electrical losses. The process finally achieved target yield at the end of January 2002, and operated until November 2002, when the line was shut-in.

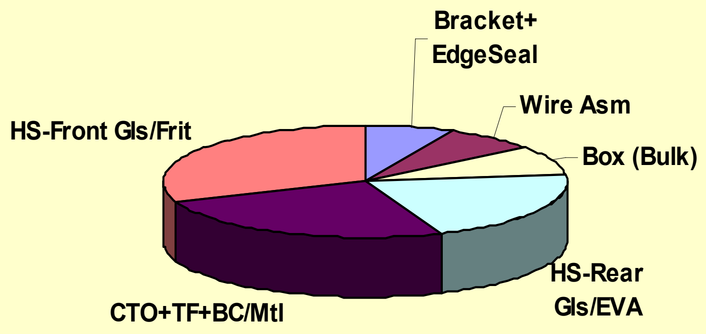
Thin-Film Costs

The cost to manufacture thin-film PV product has several major components as outlined above for the TF1 experience. Estimating the cost of manufacturing thin-film modules across a number of different companies during the past decade or so, there seems to be a striking similarity for the direct materials used in each instance, as well as direct-labor, manufacturing overhead and so-called fixed costs, such as plant management, engineering, facility costs, and assigned central support (HR, accounting, administration). Based on several production cost benchmark exercises for TF1 and Fairfield, the Apollo cost model developed for financial planning and forecasting purposes was similar to that for Millennia (TF1), not withstanding large differences in the fundamental technologies and how the thin-film device was produced.

One key driver to reducing unit costs, thereby moving closer to positive gross margin, was always higher module efficiency or peak watts (Wp) – the higher the Wp, the greater the divisor in any financial projection and the lower the unit cost. A second key driver for financial planning was greater volume of production, and the sooner the better, in order to spread sizable fixed plant, equipment and manufacturing support costs on per unit basis. A third cost driver is line yield usually followed by line efficiency and lower material costs. The planning analyst objective was usually focused on the “hockey stick” production ramp, thus achieving the more "straightforward" and less "technical" cost reduction. The volume-is-easy perception is often misplaced as greater volume during start-up oft times can dissipate the engineering focus and efficacy by introducing too many realities into the mix and may be less likely to achieve the "straightforward" gains. Allocation of technical resources during the start-up of a new technology is a challenge.

Figure 8 presents a pie chart of the typical material costs to manufacture a glass-to-glass thin-film (TF) module with dual-lead interconnects, U-channel brackets for system mounting, and packaging for shipment. Costs to produce units with extruded aluminum frames as used to manufacture crystalline-type products are greater than the simple U-bracket, on order of two times greater than the mounting bracket for the glass-to-glass configuration.[38]

Figure 8. Typical TF Direct Material Profile



Total material costs for an 80-watt module are estimated at \$0.85 per watt (\$68/m^2). The material composition of a finished TF module is displayed in **Figure 8** by rank from highest to lowest percentage of cost. The direct material item, percentage and cost per m^2 are as follows:

1. ~31% -- Heat Strengthen (HS) Front Glass (edge finish) and Frit buss (\$21/m^2), which is the substrate upon which the thin-film device is deposited;
2. ~25% -- CTO plus TF material (\$17/m^2) that includes all thin-film materials from CTO layer to semiconductor to back contact and metal;
3. ~21% -- HS-Rear Glass/EVA at (\$14/m^2) with edge seaming;
4. ~8% -- Box (bulk packaging) & labeling at (\$6/m^2);
5. ~7% -- Wire Assembly (\$5/m^2), comprised of J-box, pottant, wire leads with male/female connectors;
6. ~7% -- Bracket/ Sealant (\$5/m^2), for mounting the module and sealing edges from moisture.

The requirement for HS-CTO and HS-Rear glass for Apollo imposed a cost on order of \$4 - \$5 per square meter (~\$0.05/Wp). Both HS processes were additive to direct material costs for Apollo. The Frit/Temper process applied to CTO glass accounts for 75% of the total HS cost in Apollo, but was an essential process for "firing" the conductive frit buss collector in any event. If the frit buss system is eliminated, the HS costs could arguably be reduced. Other CdTe processes may achieve *in situ* heat strengthening of the TF product.

The Apollo CTO, CdTe semiconductor material, back contact and metallization cost is about one-fourth of total material cost in the above configuration. Adding the HS-Front Glass substrate, the percentage is about 56%[39]. The remaining cost elements, which comprise 44% of the total material cost, are also requisite in the production of crystalline modules in many instances. The ability to achieve greater material cost savings by reducing only the thin-film semiconductor material costs is limited.

Another way of looking at thin-film module costs is to recognize that their use in large power arrays imposes additional balance of systems (BOS) costs because the power density (Wp) per square meter is lower. In the case of the Apollo module, the power density is about 80W/m^2 given the overall 24"x61" footprint. By contrast the size of a BP multi-crystalline 80W module is only 0.65m^2, which is equivalent to approximately 123W/m^2. Hence, the multi-crystalline 80W module's power density is about 50% greater than the Apollo module put into production at Fairfield. Since BOS costs are approximately linear with overall array footprint, the Apollo module cost would have to be reduced on order of 50% to offset greater BOS material and installation costs. There is little prospect to achieve such large cost reduction for thin-film modules generally. The answer still comes down to power rating and power density. Prototype Apollo array calculations concluded that a sizeable total cost/performance shortfall would persist relative to higher power density crystalline Si units. The lower power density of the Apollo module, even if its module costs were significantly lower, still must confront the area-related balance of system costs for an array.

The discussion thus far only addresses thin-film direct material costs, which are typically much lower than crystalline Si direct materials due mainly to unit wafer/cell costs. Looking at post-lamination crystalline module assembly labor costs, there isn't a great difference with thin-film module assembly efforts. Both types typically involve soldering wire leads to the interconnect buss, mounting a J-box, IV testing, installing an optional mounting system (e.g., frame), cleaning, labeling, and packing. The crystalline tabbing, lay-up, and lamination process were very labor intensive in comparison to thin-film laser, metallization, edge-deletion, and lamination steps. Several companies have come forward with automation for the processing of crystalline modules in these areas. There may still be significant cost advantages for thin-film deposition, as opposed to wafer sawing and coating, but needs to be proved out, as some operations of this type appear to be narrowing the labor cost gap.

Generally speaking, the engineering, maintenance, and plant management costs would be quite similar for thin-film as for crystalline PV module manufacturing. Overall thin-film modules can cost less than x-Si on a direct material basis. However, to the extent thin-film units are to put into field arrays, the greater area required per system output target imposes substantial cost increases in BOS materials and possibly field installation labor as well. The Apollo module may have gained sufficient power density in time, but the possibility of commercial success was problematic pending success in the field. Full qualification of the Apollo product and manufacturing process was certainly years away.

Thin-Film Technology and Manufacturing Ramp

Manufacturing technology is different from R&D technology in one very important sense. While a handful of "superior" thin-film devices (or even a few hundred devices) may be produced in the laboratory, they are produced under very different circumstances. First, the equipment and materials used can be top grade, as cost savings on the order of pennies is not critical for a R&D demonstration. In any event, the quantities consumed in making the breakthrough devices will be modest. Second, the R&D laboratory staff will typically include highly trained and motivated individuals. Thirdly, the R&D timeline is such that compared to profitable factory operations, the rate at which the advanced devices are made is, in a word, "glacial."

The Apollo R&D team spent about 10 years developing the CdTe electrochemical process. The Fairfield engineering team was allotted 24 months in which to bring up a manufacturing line on a scale that was two orders of magnitude greater than the R&D device production rate. This relationship of R&D experimental time to targeted manufacturing start-up time has been observed in other companies as well.

The quantity of material to be consumed in manufacturing takes on a whole new dimension. In Fairfield, chemical solutions were delivered in totes that could only be handled with a forklift. CTO glass came in truckloads and was fabricated on a float line flowing at rate of 20 to 30 feet per minute, or about 20 tons of glass per hour. Manufacturing processes had to be controlled on a 24/7 basis and, more importantly, a means of monitoring the thin-film process so as to detect out-of-control situations before a ton of material (about 120 substrates) had to be scrapped. Equipment maintenance and calibration needed to be "95/95" capable of uptime and in six-sigma control. The large quantities of direct materials and the law of large numbers will undoubtedly produce out of specification values never seen or considered by the R&D team. Manufacturing engineers also have to develop a repertoire of "trouble-shooting" techniques to correct for unusual circumstances created by variations in materials, equipment, operators, and plant services.

Perhaps a better way of drawing the distinction between R&D levels of expertise and that in manufacturing is to consider the cycle time per module. A 10-megawatt thin-film line, producing an 80-watt unit over a 50-week period, has to produce a finished, quality module every 4 minutes working on a 24/7 basis. This does not take yield into consideration, so the 10MW cycle time is typically much more compressed. And, by the way, cost and product mix targets must be met while accommodating engineering trials to test better methods or to develop new products.

High-volume manufacturing of a commodity (for Apollo watts installed in an electrical grid) is a very tough game. It took a long time to assemble the first-rate engineering Apollo team at Fairfield. Eventually, the team would have successfully brought Apollo manufacturing up to an acceptable level. However, business plans for thin-film technology often exhibit negative cash flow for many years. Once major spending begins, it is difficult to convince investors to patiently wait for a return.[40]

End Notes

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[1] Original strategy proved infeasible because it assumed product attributes (manufacturing cost and efficiency) that were not achieved and also assumed power sales/financing terms and government concessions that were not successfully negotiated

[2] It was feasible to sell TF modules into markets where crystalline modules were the standard offering, but in traditional markets, TF prices had to be substantially below crystalline prices, and TF manufacturing costs were higher than originally targeted, resulting in negative cash flow.

[3] The initial strategy envisioned sales to a sister business unit developing, financing and operating central station PV power plants. In this case, certain market requirements did not apply, including UL certification and 20 year module performance warranties. This should not be taken to imply that the product would not have been safe in a large array context nor have lifetimes appropriate to the solar farm application, but rather that, for example, meeting standards appropriate to a 10 year warranty would have been acceptable.

[4] The report deliberately does not address the relative advantages and disadvantages of the TF1 manufacturing process in relation to a-Si manufacturing processes being developed or used by other companies. Analysis necessary to do so professionally and credibly was not within the scope of work authorized by NREL.

[5] The Chronar Corporation originally developed a batch plasma deposition process for making amorphous silicon substrates. After Chronar filed bankruptcy in 1990, the principal investor formed Advanced Photovoltaic Systems, Inc. (APS) and continued development of the a-Si deposition process at a Trenton NJ pilot plant. APS eventually transferred the technology and equipment to a special purpose plant in Fairfield, CA in 1992 – 93 and operated it in limited production until bankruptcy again intervened. Factory assets were eventually purchased by BP Solar.

[6] Process throughput is a measure of how many units are processed per unit of time. It a major factor in determining actual plant capacity, which in turn affects fixed costs per unit.

[7] First of a kind factories experiencing start-up and production ramp delays can incur significant additional capital expenditures.

[8] Module cost per Watt allows a first order comparison. Installed system costs depend on module efficiency as well as unit cost. The effect varies according to mounting structure, wiring and costs that scale with area, weight, etc.

[9] For example, see M.S. Keshner and R. Arya, "Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules, NREL Sub-contract Report NREL/SR-520-36846, October 2004.

[10] There is, as yet, little federal support of longer-term, higher risk plug-and-play product innovation and enabling technology.

[11] It is reasonable to ask and important to answer whether the cost experience reported and discussed applies directly to thin-film generally or other factories specifically. Of course it does not. The reader may choose to assume the Millennia and Apollo experience was an artifact of idiosyncrasies of the specific manufacturing processes and business contexts and has no other applicability. Or the reader may choose to infer general or specific lessons that apply in other cases based on his/her direct knowledge of the other cases.

[12] The initial commercialization strategy selected by the venture sponsors was very aggressive, resulting in considerable competitive advantage if successful, but also significant additional risk.

[13] See note i

[14] Initial plant cost estimates were based on aggressive assumptions regarding product efficiency, process speed, and total yield and were based on conceptual, not detailed engineering estimates. These various factors were not completely independent. Trade-offs became better understood based on pilot runs and on-going process development. The final choice, driven by the need to achieve targeted plant capacity, dictated additional chambers.

[15] At the time, manufacturers of coated glass did not aggressively respond to the nascent a-Si PV manufacturing industry (the validity of a large future market was not demonstrated) and may have priced their offerings accordingly.

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[16] The basis of the initial depreciation estimate is not available to the authors. The re-estimate did not, to the authors' knowledge, reflect an assumption of extended start-up at low production as actually occurred.

[17] Intial cost estimates were completed by an R&D organization based on conceptual rather than preliminary or detailed engineering. In a project context, considering the risks and unknowns, contingencies well in excess of those typical at this stage of project development for lower risk projects would have been appropriate, e.g. >50%. The choice between budgeting for the unknown and risking budget overruns is faced routinely in private and public sector undertakings: overruns and missed cost targets are by no means uncommon when pre-commercial technologies are involved.

[18] Project cost estimation theory and practice in other fields relies on the use of project and line item contingencies to account for the impact of changes needed to achieve a project's specification. Those who seek funding for scale up steps in PV development and manufacturing are faced with the dilemma of including contingencies in their estimates and thus jeopardizing their prospects for funding, or not including them and thus jeopardizing the ability to achieve projected costs.

[19] The problem of high area related costs incurred in using Millennia in rooftop applications was addressed in two ways. First, government commercialization grants were applied specifically to offer the modules at a discount that more than off-set the area related cost penalty. Second, an innovative module framing, interconnect and mounting system was developed that resulted reduced area related and installation costs to a bare minimum. This patented approach reduces crystalline residential rooftop system installed costs by 10 to 15% and is an important spin-off of the Millennia effort.

[20] Edge connector development was conducted under serious time pressure from the customer and also as a relatively new R&D target that had not been addressed previously. This context is not conducive to exploration of optimal solutions that involve significant technical risk. Parenthetically, it is the authors' view that government programs could effectively provide the context for exploration of higher risk and longer development cycle plug and play innovations, including radical innovations that would extend system modularity to the level of the DC module.

[21] Even the initial limited quantities of "pillow effect" product experienced minimal breakage when installed and in subsequent service. However, any reliability problems exceeding customer expectations (based on their experience with crystalline products) was considered excessive. Framed Millennia met this standard, and so continued sale into these applications was judged to be prudent and acceptable. However, BIPV applications of interest to numbers of potential customers, as well as other frameless laminate applications preferred by a number of existing customers, were restricted pending introduction of heat strengthened laminates.

[22] Estimates assumed tens of thousands of 0.8 m^2 units per year. Heat strengthening costs would be sensitive to production volume and glass area.

[23] Line yields for silicon solar cells in high volume production currently range from less than 90% to 95% according to presentations at the First International Symposium on Photovoltaic Mass Production. See http://www.epia.org/08Events/SEMICON2005/SE05_PRES1_07.pdf

[24] D. Shugar, "Strategies for Mainstreaming Grid-Connected PV This Decade", March 26, 2003, chart #11, http://www.nrel.gov/ncpv_prm/pdfs/33586100.pdf

[25] In retrospect, the factory is better viewed as the culmination of an RD&D process than as a self-justified commercial project. It could be inferred that "good money was thrown after bad" in pressing forward with incremental innovation to solve problems and improve overall results. The same could be said of much R&D conducted by US companies and laboratories.

[26] The Chronar Corporation originally developed a batch plasma deposition process for making amorphous silicon substrates. After Chronar filed bankruptcy in 1990, the principal investor formed Advanced Photovoltaic Systems, Inc. (APS) and continued development of the a-Si deposition process at a Trenton NJ pilot plant. APS eventually transferred the technology and equipment to a special purpose plant in Fairfield, CA in 1992 - 93.

[27] There were several "Solarex patents" related to the product (recipe) and process used to produce a-Si photovoltaic modules. Solarex developed an inline process for producing a-Si photovoltaic modules, and eventually scaled up the process at the Toano VA plant. When BP acquired Amoco in 1998, BP Solar also acquired Solarex and the Amoco share of a joint venture with Enron in the Toano enterprise. The Enron interest was eventually sold to BP Solar as well.

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[28] The specification of special purpose equipment for the first time is always subject to implicit risks. The Apollo technology team addressed the "known risks" in various ways such as requiring versatility where possible; but "unknown risks" are difficult since they may reveal themselves only after a large number of trials. Tests to correctly identify and remediate the defect become more difficult as the volume of product is increased. Unfortunately, the Apollo technology yielded a number of experiential challenges after start-up.

[29] Whenever module efficiency (η) is used, it references aperture area efficiency.

[30] Final design and delivery of the seven deposition tank fixtures was postponed until midway through 2000, following successful completion of the Apollo "efficiency stretch" and the "commercialization" stage gates over the April 1999 through June 2000 period.

[31] Some of the over budget costs of renovation are one time effects for the home plant. New plant construction would be bid with the Apollo requirements upfront and facility costs likely would be less for a mature technology. New technology startups, however, seldom have the luxury of securing a special purpose building from the ground up, so over budget modifications can be anticipated.

[32] This level of performance for Apollo was about the same as that of the a-Si product produced by Solarex at Toano VA on the TF1 line.

[33] In order to successfully process 24-by 61-inch substrates, the Apollo team worked in collaboration with LOF, the glass manufacturer, in order to obtain low resistance CTO lites at a reasonable cost. The low ohm CTO reduced voltage drop and allows for more uniform electrochemical deposition across the 24" width of the substrate. The low ohm TEC glass was priced at about $15/m2 for quantities of 1 – 2 truckloads per month. For volumes double this rate, unit costs would be about 5% lower

[34] Source NREL/SR-520-32883 report

[35] The glass-to-glass thin-film module is constructed such that the front glass, with the CTO and CdTe film, is attached to the rear glass, with EVA in between.

[36] The CTO was delivered in temper condition, but the Apollo process resulted in a relaxing of the surface compression to a HS condition.

[37] Some advocated a "cradle to cradle" stewardship where the cadmium material in scrap would be processed and used in manufacturing new material for making Apollo solar modules. Such an arrangement was considered, but only as a long-term goal.

[38] The frame configuration cost was approximately 2.5x greater than the bracket configuration due to more metal extrusion, more costly wire assembly and 50% reduction in units per bulk package.

[39] The cost values are presented with no yield losses. Generally the yield losses are typically greater for the front-end processes, which often take the form of low power, mechanical and visual losses. The front-end yield loss would apply to the HS Front Glass/CTO-TF Device, which represents about 56% of total material. The yield for lamination and encapsulation is typically higher, but any yield losses at final IV are still costly since it involves the next largest material category – HS Rear Glass/EVA.

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14. ABSTRACT *(Maximum 200 Words)*

This report examines two important generic photovoltaic technologies at particularly revealing stages of development, i.e., the stages between R&D and stable commercial production and profitable sales. Based on two historical cases, it attempts to shed light on the difference between: 1) costs and schedules validated by actual manufacturing and market experience, and 2) estimated costs and schedules that rely on technology forecasts and engineering estimates. The amorphous Silicon case also identifies some of the costs that are incurred in meeting specific market requirements, while the Cadmium Telluride case identifies many of the operational challenges involved in transferring R&D results to production. The transition between R&D and commercial success takes a great deal of time and money for emerging energy conversion technologies in general. The experience reported here can be instructive to those managing comparable efforts, and to their investors. It can also be instructive to R&D managers responsible for positioning such new technologies for commercial success.

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NREL; Robert Margolis; solar technology; photovoltaics; cadmium telluride; tandem amorphous silicon; thin-film technology; BP Solar; large-scale manufacturing; Apollo technology; Gerald Braun; Douglas Skinner

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