PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt. Res. Appl. **8**, 93–111 (2000)

Millennium Special Issue

The Promise of Concentrators

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This paper addresses the issue of why concentrator systems have not gained a significant market share. The history of concentrator development is reviewed, and the status of existing concentrator efforts outlined. A critical look at the requirements to propel concentrators to a prominent market role in large-scale power production is presented. Various concentrator and flat-plate PV system approaches are compared by computing the expected cost of energy, and conclusions are drawn as to what the best course of action will be. Concentrator systems are projected to be the lowest-cost, lowest-risk PV option for medium and large PV power plants. Copyright © 2000 John Wiley & Sons, Ltd.

INTRODUCTION

The allure of concentrating sunlight as a means to dramatically reduce the cost of photovoltaic solar energy systems has been felt since the beginnings of terrestrial photovoltaics. Much effort has been expended to develop cost-effective concentrating systems. From a commercial point of view, the reality has fallen quite far short of expectations. The purpose of this paper is to take stock in the status and promise of concentrating photovoltaic systems in order to understand if they may yet play a significant energy role in the new millenium. It is assumed that the reader has access to the cited literature. In order to save space, most material in cited references will not be repeated here in detail. This is thus not a review paper, but a call to action to the photovoltaic community to help make concentrators a commercial reality.

EARLY HISTORY OF CONCENTRATORS

Spurred by the 1973 oil crisis, research on concentrating PV systems began in earnest in 1975. In the US, Federal efforts were funded through the US Department of Energy (DOE) and its precursor, ERDA, and managed by Sandia National Laboratories. The US budget for concentrators was $1.25 million in 1976. This grew over the years, peaking at $6.2 million in 1981. The then newly-established Electric Power Research Institute (EPRI) also recognized the potential of concentrators and initially based its photovoltaic program on high concentration silicon (initially with a thermophotovoltaic radiator). Later, multi-junction amorphous silicon flat-plate was added. The first project integration meeting for the Sandia Program was held in 1978, and already at that time there was a variety of approaches being tried, including reflective, refractive and luminescent concentrators. Over time, many large companies worked on concentrating systems. Researchers at Motorola, RCA, GE, Martin Marietta, E-Systems (later Entech), Boeing, Acurex, and Spectrolab all tried their hand at developing these systems. More fundamental research was supported at universities, particularly Stanford, Arizona State, and Purdue. The EPRI concentrator program involved Stanford University, Black and Veatch, Bechtel, GE and the Research Triangle Institute. In Europe and Japan, concentrators were viewed less favorably because of the

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Received 16 June 1999
Revised 3 October 1999

perceived low direct-normal solar resource there. Nevertheless, important programs developed at the Catholic University of Louvain, the Polytechnical University of Madrid, and Ioffe Physical-Technical Institute in St. Petersburg.

Several successful large-scale demonstration projects resulted from this effort, most notably the 350 kW Soleras Project in Saudi Arabia and the 300 kW Entech system atop a 3M parking structure in Austin, Texas. The Soleras system operated continuously from 1981 until recently, when it was dismantled.[1]

During the early 1980s, the urgency of the energy crisis passed as oil prices plummeted. Both oil and natural gas proved much more abundant than previously expected. Accordingly, the concentrator program was scaled back. Most of the participants dropped out once Federal funds became scarce. Nevertheless, there remained a dedicated group pursuing this dream. In order to give concentrators 'one last chance', DOE created the Concentrator Initiative in 1990. This initiative was comprised of four cell manufacturers (ASEC, Spectrolab, SunPower, and Solarex) and four module manufacturers (Entech, Solar Kinetics, Alpha Solarco, and SEA Corp.).† The status of the technology and commercial activity as of 1992 was reviewed by Eldon Boes and Antonio Luque in their excellent article 'Photovoltaic concentrator technology'.[2] The reader is referred to this article for technical details of the various concentrator approaches. The Concentrator Initiative was terminated in 1992, but SEA Corp's promising extruded Fresnel lens approach was funded for several more years. From 1975 through 1992, the total funds expended worldwide on trying to develop concentrating PV was probably over $40 million. This is a small fraction of the total investment in flat-plate PV; nevertheless, no significant commercial success resulted from all this effort. Lured by the promise of concentrators, a number of dedicated companies continue to pursue concentrator system development today. These activities are discussed below in the section on 'Concentrator activities today'.

WHAT WENT WRONG

As a prelude to figuring out how best to resurrect concentrators today, it is instructive to examine what went wrong — why was there not more commercial success? It is easy to blame the problem on low natural gas prices, or perhaps the lack of political will to include external costs in electricity pricing, but these are just two of the many contributing factors to the biggest problem — no existing market. The second and related major failure has been the inability of the concentrator community to gather sufficient resources to convincingly demonstrate complete system reliability.

Why is there no market today? From the beginning, concentrators were envisioned for applications as large power plants, producing significant quantities of non-polluting, renewable energy. In this application they compete with conventional fossil fuel plants, which produce low-cost electricity. When the concentrator program was conceived, fossil fuel prices were invisioned to continue rising to the point where alternative energy systems would eventually be competitive. This did not happen. Basically, the electric power industry is very mature and pervasive. The consumer cannot tell from which source his electricity comes. By and large he doesn't care. Added to this is the burden of non-dispatchability — PV power comes when the sun shines, not necessarily when it is needed. Concentrating PV power simply costs too much (although not as much as flat-plate PV). How much too much will be discussed later.

The reason for the lack of a market for concentrating PV has been obscured by the parallel success of flat-plate PV. Sometimes people conclude that there must be something flawed with the concept if it cannot succeed like flat-plates have. Flat-plate PV modules, however, have found a ready market for small, remote power sources. The smaller and remoter the better. There are many existing markets where PV modules provide very cost-effective power compared to the alternatives. In each case, however, the value of the system comes from some aspect other than saving of fossil fuel. In the case of emergency roadside phones, for example, the value comes from saving the conduit and wiring cost of distributing small amounts of electricity to the phones. A similar conclusion applied for the powering of navigational

† ASEC is now Tecstar and SEA Corp. is Photovoltaics International, LLC.

aids, remote telecommunications stations, etc. Another market for flat-plate PV is providing power in remote areas of developing countries for lighting, refrigeration, water pumping, etc. None of these markets is particularly suitable for concentrators. For all these applications, an important attribute is very high reliability and near zero maintenance. Initial module cost is not that important. For example, for small systems the total cost including installation, storage, and ancillary equipment is usually over \$15/W, of which the PV module costs around \$5/W. Offering a \$2/W concentrator module and tracker would only lower the overall cost of \$12/W. This is not a sufficient cost differential to entice most customers to accept the added complexity of concentrating systems.

Another market application which is gaining favor is building-integrated PV. Integrating PV into building roofs and facades reduces some of the installation cost, particularly if the module displaces roofing or siding material. It is very difficult to design concentrating systems suitable for this market, although some single-axis tracking approaches can be mounted on the flat roof of some industrial buildings. In any case, roofing material will not be displaced by the roof-mounted concentrator.

There is an existing, but small, market for medium-sized remote PV power systems (systems over 100 kW) which is a natural entry-point for developing the concentrator market. This market is small because PV is not currently strictly cost-effective in this application. Most such installations are demonstration projects. With a few exceptions, concentrators have not been chosen for these installations because of concern over the reliability of concentrator systems, and the fact that concentrator costs are high (usually comparable to flat-plate costs) due to their very limited production volume. The concentrator industry is thus in a sort of chicken and egg situation. The addressable market is small, so the resources available are not sufficient to reduce cost and improve reliability. So sales are small, etc. Flat-plate systems have broken out of this conundrum by addressing the small remote market, where they are cost-effective. Presenting suggestions on how concentrators can exit this conundrum is the subject of this paper.

WHAT WENT RIGHT

While concentrators have not yet gained market acceptance, it must be concluded that many things actually went better than expected during development of the technology. First, cell efficiencies are now much higher than originally projected. Early expectations were that concentrator cell efficiencies would be similar to flat-plate cell efficiencies. In fact, commercially available concentrator cell efficiencies are greater than that of flat-plate cells. For example, SunPower markets silicon concentrator cells with over 26% efficiency (resulting in Fresnel module efficiencies of 20% at normal operating conditions), whereas typical flat-plate module efficiencies are in the 13% range. The reason for their superior efficiency is that concentrator cells can be much more complex than flat-plate cells. This is because their high power density allows for higher cost per unit area. Early concentrator cells were basically flat-plate cells redesigned for higher current density. Later, designs developed specifically for concentrator applications emerged. These typically had very advanced light trapping, localized contacts, passivated surfaces, complex emitter profiles, etc.[3] Many of these concepts have been successfully applied to one-sun cells; however, the resulting high-efficiency cells are mainly for record setting purposes. Such a cell holds the record one-sun efficiency of over 24%.[4] Except in very specialized applications, such high-efficiency cells are cost-effective only in concentrator systems. Multi-junction cells based on compound semiconductors have achieved even higher performance. An AlGaAs–GaSb two junction mechanically stacked cell achieved 32·6% efficiency,[5,6] and more recently monolithic two-junction cells have exceeded 30%.[7] Such high performance compound cells are also very expensive and can be seriously considered only in concentrator systems (and space power). These high efficiency results became even more important in light of the fact that the non-cell system components are more expensive than was originally expected. These costs include module lamination, site preparation, support structure, installation, wiring, fencing, and similar area-related features. Roughly the first 10% of module efficiency goes to pay for these costs, meaning that a 10% efficient module would have to be free in order to produce competitive bulk electric power.

Another factor that turned out better than anticipated was the direct normal solar resource availability. Concentrating systems generally use only the direct portion of sunlight, that which comes from the direction of the sun and is not scattered by haze, clouds, etc. In the early days of the concentrator program, the direct normal resource was not accurately known. It was feared to be considerably less than the global radiation resource available to flat-plate collectors. Subsequently, it was found that in regions of good solar resource, the annual energy available to a two-axis tracking concentrator is actually greater than that for a flat-plate fixed at latitude tilt.[8] Even in a moderately cloudy climate such as that of Boston, a concentrator system receives 80% of the annual useable insolation that a fixed flat-plate receives.

PROJECTED COSTS

Today, there is enough experience with concentrators that their cost and performance potential can be estimated accurately. Boes and Luque project current dollar levelized electricity costs for PV concentrators to be in the 6–8 cents/kWh range for systems located in the Southwest US.[2] The lower value is for production volumes of 100 MW/yr with 25% efficient modules and the upper at production volumes of 10 MW/yr and 20% efficiency. All these assume a 6% annual capital discount rate. Correspondingly, higher numbers result from a 12% discount rate, specifically 10–13 cents/kWh.

Another recent and thorough study was completed by a joint EPRI/DOE task force which reported on rooftop PV, utility-scale thin-film PV, concentrator PV, and several solar thermal options in the report 'Renewable energy technology characterizations'.[9] This report found that concentrators have an early advantage over thin films and are projected to have similar costs by the year 2010, when projected electricity cost is in the 8–9 cents/kWh range. By 2020, the cost is projected to drop to 6–7 cents/kWh.‡

Independently, Swanson compared 10 concentrator and flat-plate options for their relative cost-competitiveness and came to very similar conclusions.[10] These calculations have been updated using recent DOE/EPRI numbers[9] for operation and maintenance costs. (The capital cost components assumed were remarkably almost exactly the same as in the DOE/EPRI report for the year 2010.) The results and details are presented in the Appendix. For PV plants in the 100 kW–10 MW size range, and located in high solar resource areas, concentrator systems are projected to have an electricity cost in the 7–9 cents/kWh range, besting all thin-film and silicon flat-plate options. Point-focus concentrators using 35% efficient multi-junction solar cells appear to be something of an ultimate PV technology, beating all other options in all applications except for small systems in cloudy climates. Close behind is silicon-based point-focus systems. Since silicon cells are available today, a logical development path is to pursue silicon-based point-focus systems in order to continue developing concentrator system technology and markets, and then transition to multi-junction cells as these become commercially available.

There is thus general agreement that well-developed concentrator PV systems will be able to sell electricity in the 6–10 cents/kWh range. Given that current wholesale electricity prices are in the 2–3 cents/kWh range, there remains the difficult issue of whether there is a market for such a plant, and if so, what that market is. This will be discussed below in the section, 'Surmounting the barriers to commercialization'.

CONCENTRATOR ACTIVITIES TODAY

Despite the past attrition in companies and institutions working on concentrators, there remains a considerable level of activity globally. Recently, new participants are also emerging. These are briefly discussed below in alphabetical order. Only the more well-funded activities are included. There are a number of small-scale, exploratory activities in addition to those discussed. The promise, quality, and

‡ These numbers are for an investor-owned power plant that is part of a larger corporate entity, with 35% debt and 65% equity. Slightly different results are obtained with different ownership scenarios.

vitality of research on concentrators will become apparent when reviewing the diversity and scope of this work. Most concentrators require tracking, but it is possible to obtain a small concentration with non-tracking, or static, concentrators. Static concentrators are really more similar to flat-plates than to the other concentrating options. As seen in the Appendix, static concentrators have the potential for costs in the same range as thin-film modules. This theoretical possibility has attracted a number of workers to the field, but to date there has been no clear, practical solution to converting this promise into reality. The challenge with static concentrators is to find an optical and module design which costs significantly less than the solar cell area it replaces.

Alpha Solarco

Alpha Solarco has been developing point focus Fresnel lens systems for a number of years. They were part of the DOE Concentrator Initiative, which culminated in a 15 kW demonstration array at Pahrump, Nevada. Currently, Alpha Solarco is reportedly developing a glass Fresnel lens to replace the previous acrylic lens made using the 3M 'Lens Film' process. This work is being performed with Chinese partners.

Amonix

Amonix, Inc. and SunPower Corporation are the two companies that licensed the high-efficiency point-contact solar cell from EPRI. This cell was developed at Stanford University under EPRI funding. Amonix has developed a 20 kW point-focus Fresnel lens array intended for the utility market. It has an innovative integral-backplane module design and greatly reduces the number of parts by incorporating the wiring and cell package as a part of the module back.[11] Systems have been installed at PVUSA and the Arizona Public Service's STAR facility. They recently announced that five more systems are under order.

Australian National University

ANU is developing a linear trough concentrator system. They are also developing a novel, rather simple silicon concentrator cell, which is expected to have 22–23% efficiency with only one non-aligned photolithography step. The cells are designed for operation at 30 $\times$ concentration. Work is underway on a 2 kW demonstration at Spring Valley, Australia. They expect the system to have a 15% overall efficiency.[12]

Ben-Gurion University

The Solar Energy Centre of the Ben-Gurion University of the Negev, Israel, is developing a very large dish PV system. This dish will have several experimental, water cooled PV arrays at its focus.[13]

BP Solar and the Polytechnical University of Madrid

A 480 kW concentrator project (the largest ever) has been built recently in Tenerife, Canary Islands.[14] It is called the Euclides Project and is part of the European Joule program. Euclides is comprised of 14 one-axis tracking reflective parabolic troughs, each 84 m long, with specially designed PV receiver modules built by BP Solar using buried contact solar cells operating at 38 $\times$ geometric concentration.[15] The reflector is a very light-weight and innovative space-frame design developed at the Polytechnical University of Madrid. The system uses passive cooling, accomplished with another innovative concept — heatsinks built of compression bonded, thin aluminum fins. The system has approximately 13% overall efficiency and is projected to produce power at 23 cents/kWh, half the cost of power from a crystalline flat-plate plant. This cost is projected to drop to 13 cents/kWh at a production volume of 15 MW/yr.

Entech

Entech, Inc. has been pursuing line-focus Fresnel concentrators since the start of the Federal PV program. They hold a fundamental patent on curved Fresnel lenses that have very high transmission (90%). These systems have improved over the years through demonstration projects at PVUSA, the 300 kW Austin 3M system, a 100 kW system at the Solar Park in Ft. Davis, Texas being developed by Central and South West Utilities, and a 100 kW system at the Energy Park near Dallas, Texas being developed by TU Electric. Entech was also part of the DOE PVMaT program to improve PV manufacturing processes. Entech systems use modified one-sun cells operating at 20 × . Their newest, fourth-generation modules have an efficiency of about 15% at standard operating conditions. Entech projects a levelized electricity cost of 7–15 cents/kWh at an annual production rate of 30 MW/yr.[16] Entech is generally considered the furthest along toward full commercialization of all the companies pursuing concentrator systems. They have stuck to a strategy of building large power plants (over 100 kW) and relied on demonstration projects to fund the development of the technology. As will be discussed below, despite the resulting appearance of lack of commercial success, this is probably the best approach at this stage in the technology's development.

Fraunhofer-Institut fur Solare Energiesysteme

The Fraunhofer Institute has been researching both concentrator cells and systems. GaAs cell efficiencies in the 24% range have been demonstrated. Fresnel module efficiencies of 19% were achieved.[17] Concentrator silicon cells are also being researched. An innovative one-axis reflective tracking concentrator design was demonstrated that achieves 300 × concentration through a refractive CPC-type secondary concentrator.[18] Professor A. Goetzberger, past director of the Fraunhofer-Institut fur Solar Energiesysteme, has been a long-time proponent of concentrating PV systems and has pointed out that the direct normal resource availability is surprisingly high, even in northern Europe.[19]

Ioffe Physical-Technical Institute

The Ioffe Physical-Technical Institute has a long history with compound semiconductor solar cell development, particularly for concentrator cells. Recently, they have been developing GaSb and AlGaAs cells for multi-junction applications.[20]

National Renewable Energy Laboratory

NREL conducts leading-edge research on high-efficiency, multi-junction solar cells. They have achieved a record 30% efficient GaInP/GaAs two-function monolithic concentrator cell operating at 150×.[7] Interestingly, the pioneering research on compound semiconductor solar cells conducted at NREL has found widespread application in high-efficiency space solar cells. It is curious to contemplate that when the concentrating PV industry is ready to accept high-efficiency multi-junction cells, the lowest cost route to securing their supply could be through the space solar cell industry, which will have had considerable manufacturing experience with multi-junction cells by then.

Polytechnical University of Madrid

The Polytechnical University of Madrid has had a long-term program on concentrators, of which the Euclides project mentioned above is only a part. This includes pioneering work in the optics of concentrators, as well as GaAs concentrator cells. Their work, particularly that on static concentrators, is well described in the textbook, *Solar Cells and Optics for Photovoltaic Concentration*.[21] Recently, a new type of concentrator has been invented and researched called the RXI concentrator.[22] This is a micro-concentrator that is very thin and yet has over 1000 × concentration capability with a large acceptance angle of 1·8°. This is very near the theoretical maximum for this concentration. It is designed to use small GaAs cells that are only 1 mm on a side and manufactured and packaged similarly to LEDs. Modules built using this approach will resemble flat-plate modules, yet potentially exhibit very high performance and low cost. Additionally, the large acceptance angle reduces the cost of tracking structure. Such modules could be applicable for certain markets currently served by flat-plate modules.

Photovoltaics International

Photovoltaics International, LLC, has developed an extruded acrylic single-axis Fresnel lens that promises very low manufacturing cost.[23] This system is designed to use modified one-sun cells and operates at about 10 × concentration. The design has gone through several generations as various problems (mainly strength to high wind related) have surfaced and been solved. They are nearing the point where larger demonstration projects are feasible. Projected costs for this approach are as low as 4–6 cents/kWh at 100 MW/yr production rate (not independently confirmed). One hurdle to overcome is securing a low-cost source of the modified one-sun cells, without increasing cell cost significantly over that of standard one-sun costs.

Solar Research Corporation

Solar Research Corporation, Pty. Ltd., is developing reflective dish concentrators and water-cooled close-packed PV arrays for use at the focus.[24] A single close packed silicon array produced more than 200 W with a reported efficiency (not independently confirmed) of 22% at 239 suns and a GaAs module produced 85 W with an efficiency of 18% at 381 suns. These systems will be deployed first in the Australian outback by an affiliated company, Solar Systems, Pty. The design has progressed to the point where full-sized prototype dishes have been tested and Solar Research Corporation is preparing for a larger system test.

SunPower Corporation

SunPower Corporation manufactures a variety of high-efficiency silicon concentrator solar cells. These include cells designed for point-focus Fresnel lens applications as well as cells designed for closely spaced arrays for use with large dishes and central receivers. Design concentration ratios vary from 250 × to 400 × . Peak efficiency is around 27% at 100 × , dropping to 26% at 250 × . These are backside contact cells derived from early work at Stanford University.[3] SunPower has built complete water-cooled dense arrays for dish and thermophotovoltaic applications. These cells are supplied to companies developing concentrating systems. (SunPower also manufactures high-efficiency one-sun cells for space and other high-value applications, as well as a wide variety of optical detector diodes.)

University of New South Wales

The University of New South Wales is best known for record setting one-sun cells and thin-film silicon research. They also have developed an innovative static concentrator, however, with 4 × concentration that is intended for rooftop applications. This concentrator uses an innovative grooved back reflector to enhance total internal reflection and, hence, achieve higher concentration than many other static concentrator designs.[25] This design appears to be one of the more practical static concentrator concepts that has been proposed, achieving good concentration in a relatively thin package.

University of Reading

The University of Reading, UK, is researching a variety of concentrating approaches including point-focus Fresnel modules,[26] and novel reflective trough modules.[27]

Tokyo A&T University

Tokyo A&T University has been researching two- and three-dimensional refractive static concentrators. These are designed to accept most of the diffuse light and, hence, are suitable for cloudy climates.[28] The two-dimensional lens has a concentration of 1·65 × and the three-dimensional lens around 2 × . While it might be concluded that this modest concentration is hardly worth the effort, it must be remembered that these systems use standard one-sun cells and the cell cost, which dominates module cost, is correspondingly reduced by these factors.

SURMOUNTING THE BARRIERS TO COMMERCIAL SUCCESS

There are a number of barriers that have impeded the development of concentrators and made commercial success elusive. In this section these are examined and some suggestions made to best surmount them.

Inconsistent government policies

Government policy can be instrumental in the emergence of new technologies. When the technology has broad societal impact, it is incumbent on governments to become involved. Government programs designed to nurture the development of renewable energy, however, have come and gone with frequent changes in approach and policy. Sometimes they promote research, sometimes they promote market penetration. One large casualty of this inconsistency was Luz, which built the largest and most successful solar-electric power plants. The over 300 MW capacity of Luz was based on concentrating solar thermal technology. They were on a clear path to generating electricity at 6 cents/kWh. The financing of Luz' SEGS power plants was dependent on annual renewal of the renewable energy tax credit. When this didn't happen one year until too late for the plant to be built by year-end (another requirement of the tax law), Luz failed.[29] From a societal and environmental perspective, this was a disaster that could easily have been prevented by proper government policy.

The renewable energy policies of the 1970s were designed to jump-start renewable technologies. Wind power was able to take advantage of these policies. Today wind power is the fastest growing energy technology and supports a vibrant industry. Photovoltaics was not able to take advantage of these policies because the technology was not close enough to commercial readiness (i.e., it was still too expensive). It is ironic to think that today, photovoltaic power costs approximately what wind power did in 1975. Would similar policies to those in effect in 1975 jump-start the photovoltaic industry today as it did for wind then? It is hard to say because most of those government initiatives have since been cancelled. More recently, the DOE Concentrator Initiative enticed eight companies to gear up for concentrator work, only to be cancelled after two years. Somehow, the world must find the collective political will to wrestle more effectively with the issue of renewable energy.

There are successful historical programs upon which future renewable initiatives could be modeled. When the need to electrify the rural portions of the US became apparent in the 1930s, the Rural Electrification Act was passed and the job done. Electrifying the country was deemed important enough that the poor strict economics of stringing distribution lines to every farm was not an issue. There are many similar successful government infrastructure programs to point to. Certainly, the development of renewable energy today is as important as US rural electrification was in the 1930s. For portions of the world without a pervasive grid, renewable energy and rural electrification can go hand in hand.

Perceptions

Concentrator systems have suffered from a number of negative perceptions. There is the image that concentrators are too similar to utility power plants, whereas flat-plate systems free the consumer from the power grid. There is the misperception that concentrators only work in desert climates. Then there is the perception that concentrators are inherently unreliable. Reliability actually has been a serious problem with many concentrator systems (although not all, as the Soleras project demonstrated), but it is a reflection of the state of the industry and is not inherent in the technology. Overcoming the negative perception that concentrators are unreliable is probably the biggest remaining hurdle to widespread acceptance. The industry must accept that this can only be done by accumulating positive experience with demonstration power plants that have been well engineered.

The impact of these misperceptions is beginning to decrease and should not inhibit the industry in the future as much as it has historically. Organizations such as the Concentrator Alliance can help provide information to dispel myths. At the same time the true magnitude of the problems inherent in commercializing thin-film technologies is becoming more apparent, so people are becoming more receptive to alternatives such as concentrators. Nevertheless, the reliability issue cannot be ducked, it must be squarely faced and solved.

Competition from flat-plate PV

The issue of how concentrators do not fit well into the existing PV market has already been discussed. For the medium and large-scale markets that are hoped to eventually emerge, concentrators are in competition with future thin-film PV technology, as well as perhaps some advanced ribbon technologies. So far, it is the anticipated arrival of these products, coupled with limited resources available for PV development, that has stunted efforts on concentrators. Concentrators must compete on cost with flat-plates. The cost calculations presented in the Appendix project that the levelized electricity cost for medium-sized plants in good resource areas will be 7·4 cents/kWh for high-concentration multi-junction systems, 9·1 cents/kWh for high-concentration silicon cell systems, and 9·6 cents/kWh for thin-film systems. Concentrators definitely have the potential to be competitive on cost. (A recent DOE/EPRI report places thin-film and concentrators in a virtual dead-heat after the year 2010.[9]) Concentrators offer several other advantages over flat-plate systems. These are grouped together in Table I. The strategies of concentrator companies should be designed to take maximal benefit of these advantages.

Competition from fossil fuel power plants

In reaching for the ultimate goal of providing clean, renewable energy, concentrators compete head-on with existing fossil fuel-fired generators. Projected electricity costs from concentrator power plants are about three times the current cost of energy from natural gas power plants. Early concentrator plants will be twice as expensive again. There is nothing that can be done about this without government involvement, period. We need to decide as a society if environmental issues such as acid rain, global warming, and reduced health are important enough to subsidize this difference for a while. Factors of three can't be that big a deal in the broader picture. After all, the price of electricity varies by over a factor of three at various locals in the US. The high costs in the more expensive locals is often a legacy of stranded nuclear power plants, another government program that wasn't entirely successful.§ The low-cost locals benefit from low-cost hydropower, a government program that was successful.

Competition from other renewables

The real competition for concentrators is other renewables, particularly wind power, solar-thermal electricity, and biomass. Wind has a big head start and is already at costs below the lowest projections for concentrator PV. The projected costs for solar thermal are similar to that for concentrator PV. It will be

§ Interestingly, nuclear power and solar power are to a degree synergistic. Nuclear power is non-polluting (except for waste) and expensive. Solar is non-polluting and expensive. Nuclear is based load capacity, solar is intermediate load capacity (in summer peaking utilities).

Table I. Advantages of concentrating over flat-plate systems for large PV installations

Lower cost	GaAs dish concentrators are projected to produce electricity at 7·4 cents/kWh by 2010, whereas thin-film modules are projected to be at 9·6 cents/kWh. If thin-film module prices come down from the assumed \$75/m^2 to \$35/m^2 at 12% efficiency (29 cents/W), then thin-film electricity cost would equal GaAs dish cost.
Superior efficiency	Concentrators are the only option to have system efficiencies over 20%. This reduces land utilization as well as area related costs.
Higher annual capacity factor	Tracking provides for improved energy output. Once the expense of tracking is incurred with flat-plates, the leap to installing concentrator modules is small.
Less materials availability issues	Concentrators use standard construction materials for the bulk of their requirements. Flat-plate systems have serious concerns over material availability; silicon feedstock, or indium in the case of $CuInSe_2$.
Less toxic material use	Many thin-film concepts use quite toxic materials such as cadmium, etc.
Ease of recycling	The trend in modern mass-product manufacturing is to make a product as recyclable as possible. Concentrators are composed mainly of easily recyclable materials, steel, aluminum and plastic. Recycling flat-plate modules will be much more difficult.
Ease of rapid manufacturing capacity scale-up	Existing semiconductor manufacturing capacity is more than sufficient to supply projected cell requirements. The remaining manufacturing is comprised of rather standard mechanical components. This greatly reduces capital requirements compared to flat-plate.
High local manufacturing content	Aside from the cells, the remaining content of concentrator systems can be manufactured worldwide, and close to the final point-of-use.

an interesting race (if the race is allowed to happen). Concentrator PV must look to its particular features that might give some advantages. Particularly, concentrator PV is much less site-dependent than wind, and more amenable to distributed applications closer to load centers. Concentrator PV is perhaps lower in maintenance cost than solar thermal. Solar thermal has a distinct advantage in that it is capable of hybrid operation (running off both solar and natural gas). From a broad perspective, however, the details of these differences are not that important. All the renewable technologies still in serious contention are comparable in their projected costs. Given the importance of eventually weaning the Earth from fossil fuel, all must be nurtured. Eventually the market will decide the right mix.

The search for the best early applications

Since concentrators can't participate in the existing, cost-effective PV market, new applications must be found. Furthermore, there is little likelihood of reaching the current wholesale electricity cost. The good news is that projected costs are lower than retail electricity cost in most regions of the world. Clearly, any economical application must be either remote, non-grid-connected or dispersed and located near retail grid customers.

One promising application is utility end-of-line grid support in remote regions that are experiencing rapid growth. PV is particularly valuable in this application when the region load is driven by air conditioning so that the demand and resource are well matched.[30] This application requires the participation of utility companies as well as Federal support. Another potential application is remote power systems that are now being served by larger diesel generators. Typical installations are island power systems, large water pumping stations, remote military bases, resorts, and the like. By adding PV to these installations, diesel fuel is saved and engine operating time is reduced. Concentrator PV should be cost-effective in these applications within the very near future. For larger power plants there are two possibilities. Portfolio standards, in which a government mandated portion of new generation must be from renewable energy, is one and green power, in which customers chose slightly higher electricity cost in order to know that a certain fraction of their electricity comes from non-polluting sources, is the other. Both of these are showing promise.

CONCLUSIONS AND RECOMMENDATIONS

There is a vital and growing group of entities continuing to move concentrator PV technology toward commercial success. Concentrators have great potential to become the lowest-cost photovoltaic option, producing power in the 7–15 cents/kWh range, depending on system size and location. Concentrator companies should not try to imitate today's flat-plate applications. The most natural markets are for medium-sized systems for grid-support, green power, and portfolio standards, or remove PV–diesel hybrid applications. What then is needed for the industry to take its place as a serious energy supplier? The following might do it.

Refining the vision

The industry needs to develop and sell a coherent and compelling vision of how concentrators will benefit society. Concentrators don't fit the prevailing paradigm about the emergence of PV markets. This paradigm says that the small remote applications will be the basis of an expanding industry, which will reduce costs as experience and volume increase, which will increase the number of cost-effective applications, which will further increase the volume, etc. This cycle will proceed until costs are reduced to the point where PV is competitive with fossil fuel. This is sometimes called the diffusion model.[31] The concentrator community should develop its own vision of the diffusion model which might go something like this. First, remote island power in the range of 100 kW–1 MW; second, grid support power in the range of 1–10 MW; and finally green-power generation of 10–100 MW located fairly close to load centers. A clear vision is a prerequisite to developing the political support needed to fund the development.

Government support

Governments need consistent policies with long-term vision.[32] If the industry vision is compelling, governments can help in the form of support for green marketing, pollution credits, portfolio standards, tax credits and R&D funding. Increased concern over greenhouse gasses, should it develop, will obviously make government support more likely. Government has played a very significant role in developing and subsidizing all existing energy technologies: fossil fuels, hydro, and nuclear. Why should solar be different?

Infusion of significant capital, preferably from large, international corporations

The concentrator industry has been something of a garage-shop industry dependent on government contracts to date. Much greater resources are needed to provide the sophisticated designs, reliability testing, automated manufacturing, service infrastructure, marketing, and customer support needed to move to the next level. This capital is much more likely to flow if government policies are clear, consistent, and visionary.

Significant penetration of the remote diesel markets in the form of diesel–hybrid systems

This market appears to offer the best combination of immediate need and suitability to concentrator systems to serve as an initial beachhead. The industry must soon expand shipments enough to reach a critical mass before alternative renewable technologies become low-enough in cost to squeeze out further competition.

Further depletion or disruption of fossil fuel supplies

In the event that the above do not happen, or are insufficient, there always remains the eventual spark of reduced availability of fossil fuel. One may argue as to when this might occur, but let's hope we don't wait until it does.

Concentrators will never be the whole PV business — different products will evolve for different markets. High-efficiency concentrators will not be beaten, however, for low-cost, medium to large-scale power in good solar resource regions. Let government, academia, and industry work together to make it happen.

Acknowledgements

The author is greatly indebted to EPRI and the US Department of Energy (through Sandia National Laboratories and the National Renewable Energy Laboratory) for many years of support, and to his colleagues at SunPower who continue to strive to make concentrating PV a commercial and environmental success.

APPENDIX A: COST COMPARISONS

The purpose of this cost analysis is to determine if there is sufficient economic advantage to warrant continued pursuit of concentrator systems and to help identify the best market applications for early commercial products. How can one quantify the reluctance of customers to incur the added complexity of concentrating systems? For the purposes of this analysis, it is assumed that the purchase decision would be based solely on cost for systems in the 100 kW–10 MW range (to be termed medium-sized systems here). Such systems would often have diesel generators on-site and thus maintenance personnel should be conveniently available. Alternatively, they would be located near housing or industrial parts in locations where service could be provided through local contracts in a manner similar to that for air conditioning systems. For systems in the 2–100 kW size range (termed small-sized systems here), however, customers could reasonably purchase flat-plate systems and may not have easy access to maintenance. Typical applications might be remote homes or irrigation systems. In this case, it is reasonable to assume that concentrators will have to cost less than an equivalent flat-plate system to become the purchase of choice. For this analysis it is assumed that one-axis tracking systems must cost 10% less than flat-plate systems, and two-axis tracking systems must cost 20% less, because of their greater complexity and more obtrusive appearance. In the analysis below, therefore, concentrating system energy cost is increased by 1/0·9 and 1/0·8 for one-axis and two-axis tracking systems, respectively. This allows direct comparison with non-tracking options. This is termed the concentrator premium.

The market segments

Four different market segments are analyzed and compared. These are described below.

Medium-sized system, high-resource area
The first market is for a medium-sized system in a high-solar-resource area. Insolation data from Albuquerque, New Mexico is used, although the result is representative of any desert or high-insolation region. By medium-sized system, one in the 100 kW–10 MW size is considered, and cost components applicable to such as system are used. (Large-sized systems, comparable to utility power plants are not analyzed here.)

Small-sized system, high-resource area
For this case, cost components representative of a small installation in the 2–100 kW size are assumed.

Medium-sized system, low-resource area
This is the same as the medium-sized system above, except that the resource data from Boston, Massachusetts is used. This is representative of a low solar resource area with a high diffuse component to the insolation.

Small-sized system, low-resource area
This is the same as the small-sized system above, except that resource data from Boston, Massachusetts is used.

The candidate technologies

Ten different system approaches are compared. These are discussed below. Detailed cost assumptions are included on the spreadsheets in Tables AI and AII. It is not proposed that the cost data is the last word. The reader is encouraged to supply his or her favorite assumptions and, thereby, come to conclusions for which they are most comfortable.

Fixed flat-plate (FFP)
This is the standard silicon module, mounted facing south at a slope equal to the latitude.

1-axis tracking flat-plate (1-axis FP)
Standard silicon modules are mounted on a horizontal, north-south axis tracker. This is used in some larger installations for producing higher summer capacity factors.

2-axis tracking flat-plate (2-axis FP)
Standard silicon modules are mounted on a two-axis tracker which is always facing the sun during daylight hours.

1-axis tracking parabolic trough (Si 1-axis trough)
This is a polar-axis tracking reflective dish with 50 $\times$ concentration on a photovoltaic receiver.

Static concentrator
A static concentrator with a concentration of 4 $\times$ is assumed. It is mounted south-facing with latitude slope.

Thin film
The costs are for a generic thin-film module. Future module cost is assumed to be \$75/m^2 with an efficiency of 12. This gives a module cost of \$0.63/W — which is certainly thought to be an aggressive goal for thin films. Some forecast still lower cost. If significantly lower cost were to be achieved, then thin-film modules would probably completely displace concentrators.

Central receiver
In this concept, a field of mirrors directs light to a high-concentration, water-cooled photovoltaic panel at the top of a tower.

2-axis tracking static concentrator (2-axis static)
This is a static concentrator as above, but mounted on a two-axis tracker.

High-concentration silicon point-focus dish (Si dish)
This is a reflective dish using high-efficiency silicon concentrator cells operating at a concentration of 400$\times$.

Table AI. Detailed assumptions for medium-sized PV plants

Medium plant — Albuquerque	GaAs dish	GaAs 2-axis	Si dish	2-axis static	Si 2-axis Fresnel	Thin film	Static conc.	Central rec.	Albedo FFP	2-axis FP	Si 1-axis Fresnel	1-axis FP	FFP
Desert (Albuquerque) kWh/m^2/day	6·566	6·566	6·566	8·624	6·566	6·336	6·336	5·025	6·336	8·624	6·08	7·41	6·336
Diffuse (Boston) kWh/m^2/day	3·626	3·626	3·626	5·782	3·626	4·554	4·554	2·775	4·554	5·782	3·42	4·94	4·554
Albedo factor	1	1	1	1	1	1	1	1	1·3	1	1	1	1
BOS area (low) \$/m^2	70	70	70	70	70	70	70	70	70	70	70	70	70
BOS area (high) \$/m^2	140	140	140	140	140	140	140	140	140	140	140	140	140
BOS power (low) \$/W	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3
BOS power (high) \$/W	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6	0·6
Tracking (low) \$/m^2	35	35	35	35	35	0	0	35	0	35	20	20	0
Tracking (high) \$/m^2	67	67	67	67	67	0	0	67	0	67	40	40	0
Module (low) \$/m^2	90	115	90	115	115	75	85	30	85	75	90	75	75
Module (high) \$/m^2	160	230	160	230	230	150	160	60	165	150	160	150	150
Cell (low) \$/m^2	30,000	30,000	15,000	300	15,000	0	300	20,000	200	200	5000	200	200
Cell (high) \$/m^2	100,000	100,000	20,000	1000	20,000	30	1000	25,000	400	400	15,000	400	400
Cell efficiency (high)	0·3325	0·35	0·26	0·21	0·27	0·12	0·21	0·26	0·2	0·2	0·24	0·2	0·2
Cell efficiency (low)	0·285	0·3	0·23	0·17	0·24	0·08	0·17	0·23	0·15	0·15	0·2	0·15	0·15
Operating temperature	65	65	65	60	65	55	60	65	60	55	65	55	55
deta/dteta	2·20E-03	1·90E-03	2·20E-03	3·30E-03	2·20E-03	2·00E-03	3·30E-03	2·20E-03	3·30E-03	3·30E-03	2·40E-03	3·30E-03	3·30E-03
Concentration	1000	1000	400	4	400	1	4	400	1	1	50	1	1
Module transmission	0·85	0·85	0·85	0·9	0·85	0·95	0·9	0·85	0·95	0·95	0·9	0·95	0·95
BOS eff.	0·85	0·85	0·85	0·9	0·85	0·9	0·9	0·85	0·9	0·9	0·85	0·9	0·9
Conc. premium	0	0	0	0	0	0	0	0	0	0	0	0	0
O&M cost (low) ¢/kWh	0·8	0·8	0·8	0·8	0·8	0·2	0·2	0·8	0·2	0·8	0·8	0·8	0·2
O&M cost (high) ¢/kWh	2·0	2·0	2·0	2·0	2·0	0·8	0·8	2·0	0·8	2·0	2·0	2·0	0·8
Cost-diff low ¢/kWh	12·8	13·2	15·8	13·7	16·6	13·2	13·4	17·1	15·4	16·5	19·9	18·6	18·5
Cost-diff high ¢/kWh	30·0	31·8	32·4	37·5	35·4	41·1	37·7	34·9	39·6	42·7	52·2	48·0	48·2
Cost-desert low ¢/kWh	7·4	7·7	9·1	9·4	9·5	9·6	9·7	9·8	11·1	11·3	11·5	12·6	13·4
Cost-desert high ¢/kWh	17·5	18·4	18·8	25·8	20·4	29·7	27·3	20·2	28·7	29·3	30·3	32·7	34·9
Cost-low \$/W	1·59	1·64	1·99	2·71	2·10	2·16	2·19	1·66	3·18	3·32	2·38	3·20	3·05
Cost-high \$/W	3·70	3·94	4·02	7·49	4·42	6·69	6·14	3·33	8·18	8·58	6·27	8·30	7·89

Table AII. Detailed assumptions for small-sized PV plants

Small plant—Albuquerque	GaAs dish	GaAs 2-axis	Static conc.	Thin film	Albedo FFP	Si dish	2-axis static	Si 2-axis Fresnel	Central rec.	Si 1-axis Fresnel	FFP	2-axis FP	1-axis FP
Desert (Albuquerque) kWh/m^2/day	6·566	6·566	6·336	6·336	6·336	6·566	8·624	6·566	5·025	6·08	6·336	8·624	7·41
Diffuse (Boston) kWh/m^2/day	3·626	3·626	4·554	4·554	4·554	3·626	5·782	3·626	2·775	3·42	4·554	5·782	4·94
Albedo factor	1	1	1	1	1·3	1	1	1	1	1	1	1	1
BOS area (low) \$/m^2	100	100	100	100	100	100	100	100	100	100	100	100	100
BOS area (high) \$/m^2	200	200	200	200	200	200	200	200	200	200	200	200	200
BOS power (low) \$/W	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4
BOS power (high) \$/W	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7	0·7
Tracking (low) \$/m^2	35	35	0	0	0	35	35	35	35	20	0	35	20
Tracking (high) \$/m^2	67	67	0	0	0	67	67	67	67	40	0	67	40
Module (low) \$/m^2	90	115	85	75	85	90	115	115	30	90	75	75	75
Module (high) \$/m^2	160	230	160	150	165	160	230	230	60	160	150	150	150
Cell (low) \$/m^2	30,000	30,000	300	0	200	15,000	300	15,000	20,000	5000	200	200	200
Cell (high) \$/m^2	100,000	100,000	1000	30	400	20,000	1000	20,000	25,000	15,000	400	400	400
Cell efficiency (high)	0·3325	0·35	0·21	0·12	0·2	0·26	0·21	0·27	0·26	0·24	0·2	0·2	0·2
Cell efficiency (low)	0·285	0·3	0·17	0·08	0·15	0·23	0·17	0·24	0·23	0·2	0·15	0·15	0·15
Operating temp.	65	65	60	55	60	65	60	65	65	65	55	55	55
deta/dteta	2·20E-03	1·90E-03	3·30E-03	2·00E-03	3·30E-03	2·20E-03	3·30E-03	2·20E-03	2·20E-03	2·40E-03	3·30E-03	3·30E-03	3·30E-03
Concentration	1000	1000	4	1	1	400	4	400	400	50	1	1	1
Module transmission	0·85	0·85	0·9	0·95	0·95	0·85	0·9	0·85	0·85	0·9	0·95	0·95	0·95
BOS eff.	0·85	0·85	0·9	0·9	0·9	0·85	0·9	0·85	0·85	0·85	0·9	0·9	0·9
Conc. premium	0·2	0·2	0	0	0	0·2	0·2	0·2	0·2	0·1	0	0·2	0·1
O&M cost (low) ¢/kWh	0·8	0·8	0·2	0·2	0·2	0·8	0·8	0·8	0·8	0·8	0·2	0·8	0·8
O&M cost (high) ¢/kWh	2·0	2·0	0·8	0·8	0·8	2·0	2·0	2·0	2·0	2·0	0·8	2·0	2·0
Cost-diff low ¢/kWh	18·5	18·9	15·6	16·2	17·2	22·7	19·0	23·6	25·3	25·0	20·7	22·6	22·7
Cost-diff high ¢/kWh	41·7	43·7	42·0	48·5	43·3	45·6	50·6	49·1	50·4	63·5	52·7	57·2	57·7
Cost-desert low ¢/kWh	10·6	10·8	11·2	11·7	12·4	12·9	13·0	13·4	14·3	14·4	14·9	15·4	15·4
Cost-desert high ¢/kWh	23·9	25·0	30·4	35·1	31·3	26·1	34·6	28·0	28·7	36·6	38·1	39·0	39·2
Cost-low \$/W	2·35	2·40	2·55	2·66	3·53	2·90	3·84	3·02	2·48	3·02	3·40	4·59	3·95
Cost-high \$/W	5·26	5·52	6·85	7·93	8·93	5·77	10·25	6·24	4·91	7·68	8·63	11·66	10·05

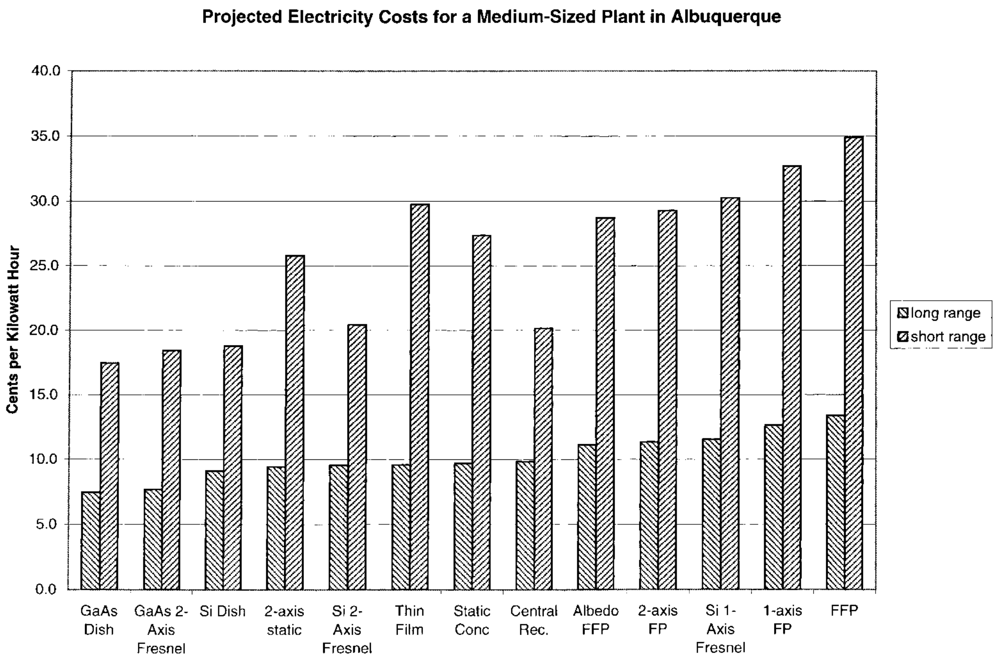

Figure A1. For the medium-sized plant in Albuquerque, the concentration options beat all the thin-film and silicon flat-plate approaches. The quickest path to the lowest cost would appear to be to start with the silicon dish, refine the concept and reduce dish and cell costs, and finally move to GaAs cells when they are ready (in 10 years or so). No other approach demonstrates as low a cost, both now and in the future. Static concentrators, mounted on two-axis trackers are a close second

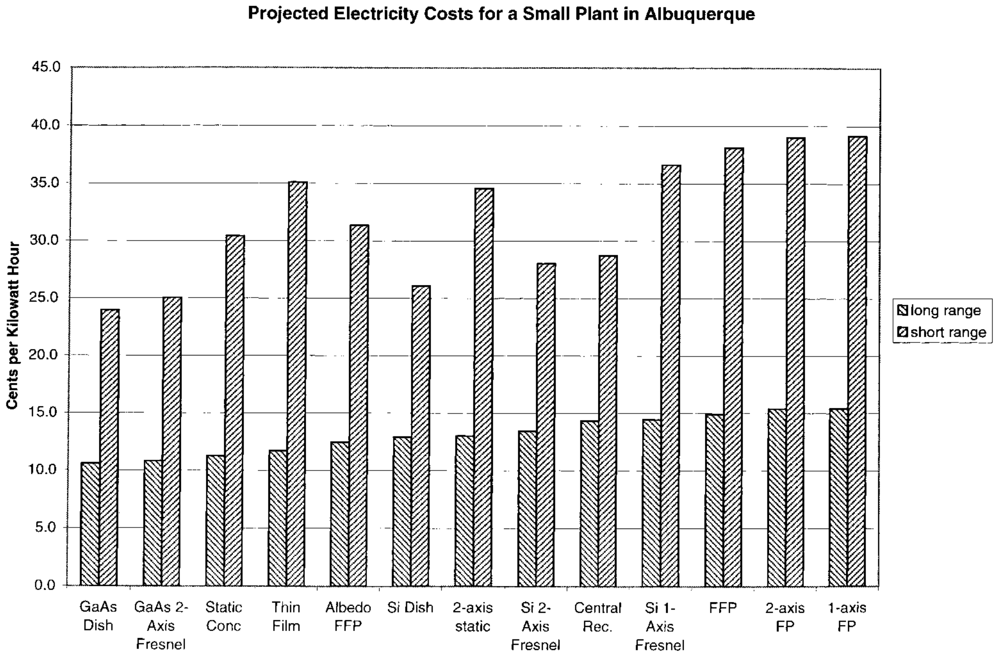

Figure A2. For small-sized plants in Albuquerque, the GaAs dish still has the lowest ultimate cost; however, the future thin-film and static concentrator have moved ahead of the silicon dish. The Si dish still represents the lowest present cost and can be viewed as a vehicle to develop the GaAs dish. Static concentrators remain the second best choice with thin films third. The bifacial silicon flat-plate option scores surprisingly well (Albedo FFP)

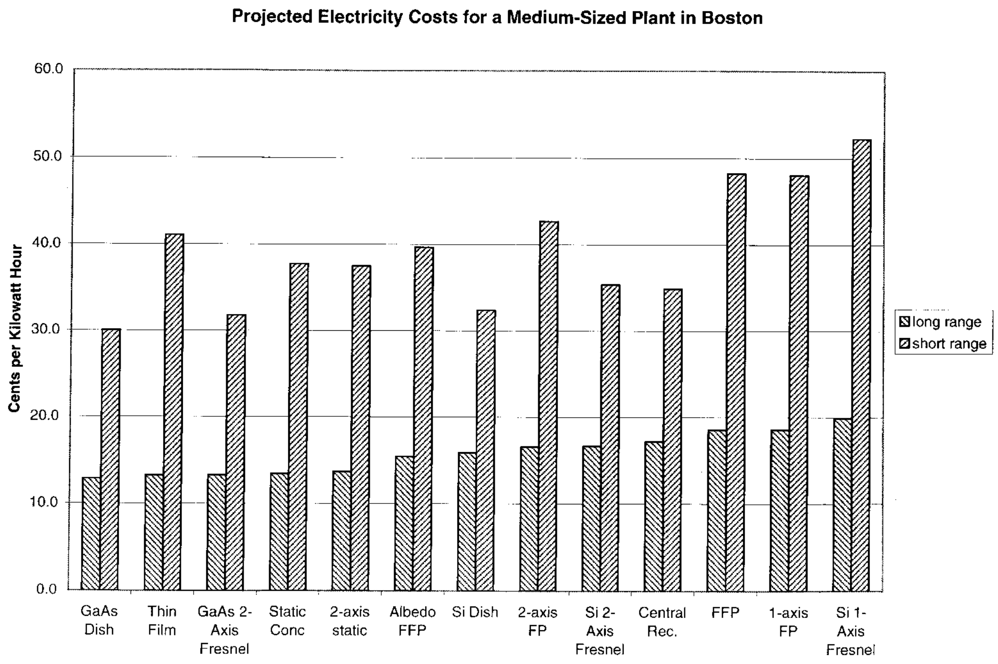

Figure A3. For medium-sized plants in Boston, the GaAs dish surprisingly maintains its lead, despite the lower direct normal solar resources. (In other words, a dish based on 35% efficient cells is something of the ultimate technology.) The thin-film approach is a close second place

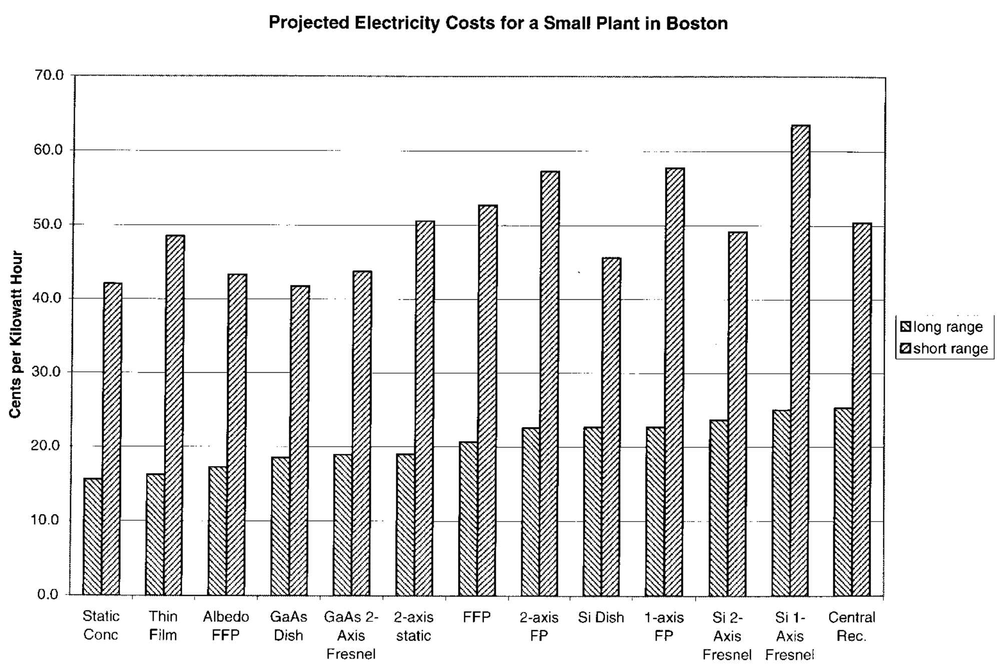

Figure A4. For small-sized plants in Boston, the non-tracking approaches finally take the lead. Nevertheless, the static concentrator remains ahead of the thin-film approach. Fourth place is taken by the GaAs dish. This is the only case where flat-plate silicon appears to beat the Si dish, although not after the transition to GaAs. Interestingly, bifacial wafered silicon moves up to third place and ahead of all concentrating options. Note that, in none of the target markets does wafered silicon appear to be the lowest cost option, now or in the future

High-concentration silicon point-focus Fresnel (Si 2-axis Fresnel)
This is a point-focus Fresnel system operating at a concentration of 400×.

High concentration GaAs point-focus dish concentrator (GaAs dish)
This is a system similar to the above, but the silicon cell is replaced with a very high efficiency, multi-junction cell based on III–V (gallium arsenide related) materials. The concentration is 1000×. This cell does not exist as a commercial product today; however, it is possible that it will in the future and that performance and cost will meet the target in 8–10 years.

High concentration GaAs point-focus Fresnel (GaAs 2-axis Fresnel)
This is a system similar to the above, but using 1000× Fresnel concentrators.

Results

The results of this calculation are shown on the following plots, Figures A1–A4, with some discussion in the captions. The associated input assumptions are on the spreadsheets in Tables AI and AII. The taller bar represents the 'near term' costs and the shorter bar 'long term' costs, where this is meant to be where the technology has the potential to go in 10 years. In the case of systems other than flat-plate silicon, the 'near term' cost is an estimate of what might be achievable with a serious development effort in several years' time. For the flat-plate silicon cases, 'near term' represents current costs. The technologies are sorted on the basis of future cost potential. The assumed levelized fixed charge rate is 10%. This is intended to be the current dollar fixed charge rate.

The reader should not construe these results as the last word in cost analysis. The intent is simply to compare various PV options using a uniform methodology and common set of assumptions. It is apparent that the leading candidates in every category are all similar enough in projected cost that a definitive ranking is not particularly meaningful. Improvements in any approach could easily catapult that approach to the lead. Nevertheless, the promise of concentrators comes through loud and clear.

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