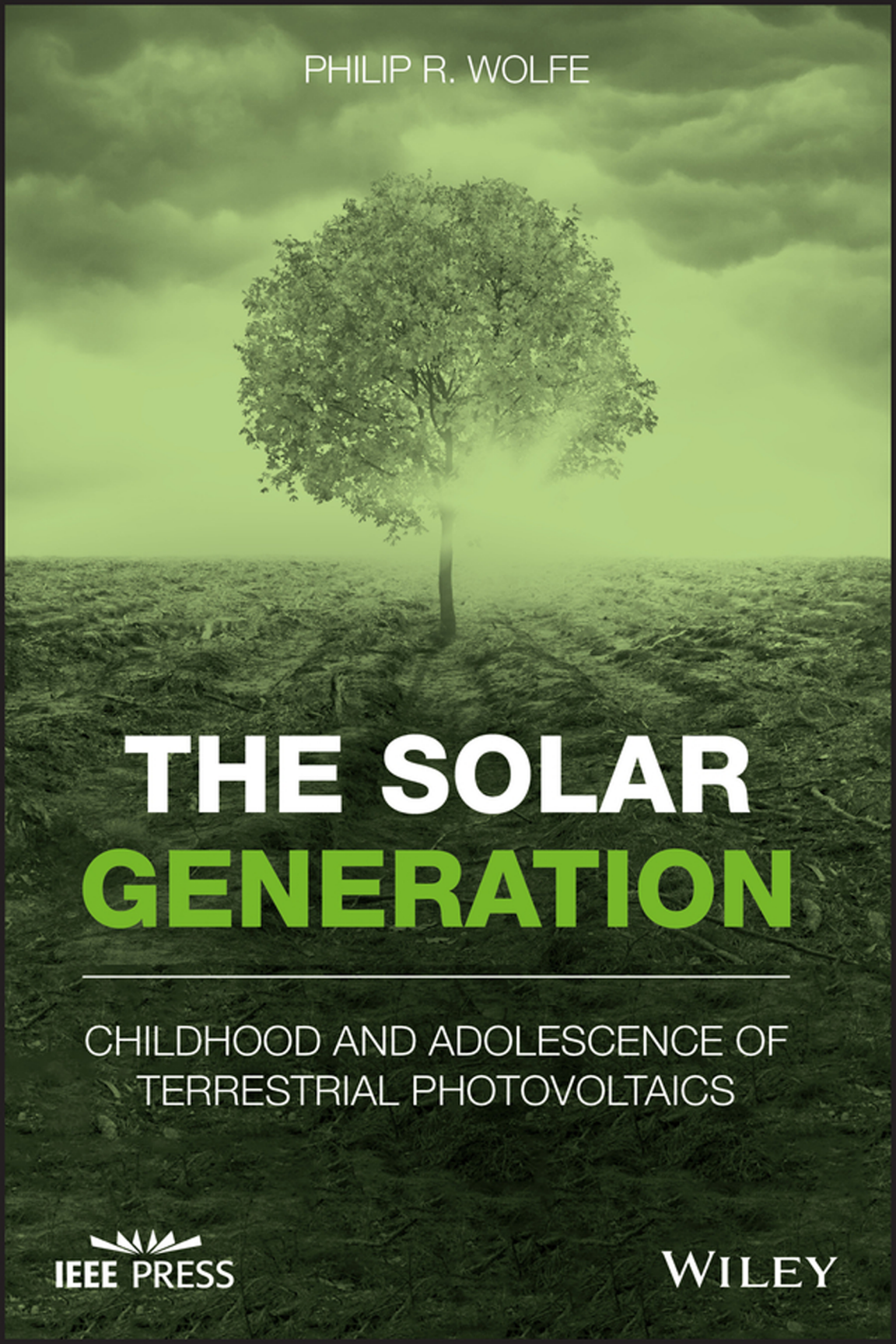




PHILIP R. WOLFE

THE SOLAR GENERATION

CHILDHOOD AND ADOLESCENCE OF
TERRESTRIAL PHOTOVOLTAICS


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The Solar Generation

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Childhood and Adolescence
of Terrestrial Photovoltaics

Philip R. Wolfe


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*This book is dedicated to all those
– described herein or otherwise –
who struggled against the status quo
to establish the terrestrial photovoltaics sector;
and build the foundations of
a major clean energy technology.*

*In memory of friends
Bill Yerkes,
Joseph Lindmayer,
Brian Harper,
John Bonda,
and those others who didn't live
to see the extent of their success¹*

¹ see Section 10.3.

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Foreword

Behold the blessed vision of the sun, no longer pouring his energies unrequited into space, but by means of photoelectric cells and thermopiles, these powers gathered into electric storehouses, to the total extinction of steam engines and the utter repression of smoke.

Rollo Appleyard, 1891 [1]

It is hard to imagine, now that solar power is an indispensable part of the global energy mix, that it was for so long discounted as an irrelevance. The accepted wisdom for several decades was that solar generation is an expensive, unreliable, small-scale niche application.

True, some of these criticisms had weight in the early years. At first a little imagination or faith was needed to see the true promise of a sustainable clean energy future. Fortunately, the early solar industry attracted pioneers with the vision to see beyond any temporary shortcomings. This book traces their journey as they laid the foundations for the significant business that solar energy has now become.

Solar cells had already been used to power spacecraft from the late 1950s, but widespread use on earth was an entirely different proposition. The terrestrial industry started with technology that was 1000 times too expensive, and production capacity maybe one billionth of what would be needed. This is the story of how far we got in the first quarter century.

It was not attained through the superhuman effort of one individual, but by collective achievement, even though it might not have felt at the time that everyone was working together. There was no single “father of solar power,” but rather dozens of inspirational individuals, and a lot of good companies, as you will discover.

You will see how many of the same names pop up in different places as companies, technologies, and applications rise, fall, and transform during the evolution of the sector. It is remarkable how the majority of these people, having

migrated into the industry from all walks of life, became captivated by the wonder of solar, and stayed with it for the rest of their working lives.

Who Needs This Book?

Solar energy today is a significant, but secondary, global contributor. I confidently predict that it will be the world's largest energy source within my lifetime.¹

Curious people, inside the sector and beyond, will want to know how it all began, and this book sets out to tell that story, from the start of solar power usage on earth to the time when widespread deployment was just beginning.

Why Me?

I had the good fortune to fall accidentally into the solar energy sector back in 1975, when it was just getting started. The companies and organizations, in which I was involved,² were associated with many of the leading solar businesses and researchers, particularly in Europe and North America.

However, as will become apparent, it is others who have made great achievements on which my own slight contribution has depended. I am lucky enough to have known many of the real movers and shakers and dealt with the leading companies.

Hopefully, I have managed to be objective, while preserving the benefit of having been there at the time. At the risk of a bad attack of schizophrenia, I refer to myself in the first person, as the author of this book; and to Philip Wolfe, in the third person, as a participant in the early PV era.

Volumes, Sections and Chapters, References, and Jargon

This book will be of interest to a wide range of readers and I have tried to structure it in the way that would be of greatest use:

Part I, the “biography” of terrestrial photovoltaics, tracks the evolution of research, technology, markets, prices, the industry, and so on.

Part II is called the “encyclopedia” with a Who’s Who of the most influential people and profiles of key companies, events, and developments.

¹ If I share my parents’ longevity, this may extend toward 2050.

² Mentioned in the profile in Section 10.2.

Part III is the reference section with glossaries, bibliography, and a really comprehensive index. You can find everything in there.

Each part is in chapters (listed in the contents summary above) and each chapter has a number of sections. A more detailed contents list is included in Chapter E of Part III.

I find that a forest of footnotes and references at the bottom of every page makes books harder to read. With a few exceptions, I have put such notes and references at the end. The reference numbers within brackets in the narrative relate to the reference list in Chapter B of Part III. A few pages have footnotes in numerals in superscript. Superscripted^{qv} after a name denotes people, organizations, and events individually profiled in Part II.

This is not a scientific textbook, and I have aimed to avoid using lots of acronyms, jargon, and formulas. If, however, you find yourself baffled about what an “MPPT” does, when “grid parity” is reached, or what the “Shockley Queisser Limit” limits, just go to the Glossary in Part III.

Name Checks and Acknowledgments

It has been such a pleasure writing this book and revisiting so many former colleagues around the world (see Chapter A in Part III). It has been more difficult trimming the list of those to be profiled to a sensible length. The intention was to select those who have been most influential, not necessarily those who were most visible. I have undoubtedly committed errors and omissions out of sheer ignorance. For all such cases, let us hope that enough people buy this book to justify further editions, when these mistakes can be rectified.

Hopefully, these pioneers will forgive me for naming them mostly without their professorships, doctorates, and so on. Where these do appear, they are at the level most prevalent during the timescale of this book – it may say Dr. here, but they are probably at least a Prof. by now! Many of the companies mentioned have longer names or adopt special typesyles; I ask their marketing departments, too, to forgive me for sticking to the parlance most commonly used at the time. Individuals profiled in Chapter 10 and organizations in Chapter 11 are annotated with “qv” when they appear in other parts of the book.

Many, many people gave me access to centuries of accumulated knowledge about photovoltaics during the writing of this book. It needs a whole chapter (Chapter A in Part III) to acknowledge them all. I must give a special mention to Bernard McNelis^{qv} for allowing me free rein in his extensive archive and photo library. Thanks also to Martin Green^{qv} and Dave Carlson^{qv} for checking the technological details, to Sabrina Wolfe for proofreading it all and helping me make it a much tidier and more literate work, and to Mary Hatcher, Editor, and

Vishnu Narayanan, Senior Project Editor. Finally, thanks to Alison Wolfe for sitting through many long PV reminiscences, and generally living with this book for all these months.

I have done my best to incorporate their suggestions, and to get the facts right, but the inevitable mistakes are all mine, not theirs. Readers finding substantive errors and omissions are encouraged to notify me through the book's website [234], so that these can be rectified in any future editions.

Part I

A Biography of Terrestrial Photovoltaics

“The silicon solar cell may mark the beginning of a new era leading eventually to the realization of one of the mankind’s most cherished dreams – the harnessing of almost limitless energy of the sun for the uses of the civilization.”

New York Times, 1954 [2]

Solar power has now become an indispensable part of the global energy mix, so it is easy to forget that less than a generation ago it was dismissed as an expensive, unreliable irrelevance.

By the last quarter of the twentieth century, the world had exploited apparently inexhaustible and cheap deposits of fossil fuels for more than 200 years, and saw no need for “alternative” sources of energy.

It was a crisis to this oil-dependent world that opens the story of terrestrial solar energy, told in this Part I. It is followed in Part II by fuller descriptions of the pioneering people, events, and organizations, which created this new energy sector. Finally, Part III gives a comprehensive reference section of sources and resources.

1

Origins of Terrestrial Solar Power

“Where shall I begin, please your Majesty?” he asked.

“Begin at the beginning,” the King said, very gravely, “and go on till you come to the end: then stop.”

Lewis Carroll [3]

If we were to begin at the beginning of the story of solar energy, we would go all the way back to the formation of the sun and the earth. Virtually all the energy we use comes straight from the sun; only atomic and geothermal energy use a resource that is not directly solar in origin. Sunshine fueled the growth of the organisms that gave rise to the earth’s coal, oil, and gas deposits. Today it grows the trees and crops for our biomass and biogas production. It is the source of the rain for our hydropower and wind for the turbines.

But let’s not begin this story in prehistory.

If we were to begin with when solar energy was first used to produce electricity, we would go back before Albert Einstein’s Nobel Prize in 1921, which many will be surprised to hear was for his work on photoelectricity [4], not quantum theory. We would need to look at the previous century’s achievements of the Becquerel family in discovering the phenomenon of deriving an electric charge from sunlight – the photovoltaic effect [5]. We’d look at the work of Bell Laboratories and others in the mid-twentieth century on early solar cells, and the first applications of photovoltaic (PV) devices in space in 1958. But I intend to cover the birth of photovoltaics only fleetingly.

Instead, this story begins with the “first oil crisis” of 1973–1974. That one event, more than any other, heightened mankind’s awareness that the energy sources it so desperately depended on were neither ubiquitous nor infinite. This led to dramatically increased interest in what at the time was called “alternative energy.” It also led to the formation of the International Energy Agency in 1974. Furthermore, the sudden increase in the oil price brought about by the crisis

started a progressive change in attitude about the value of energy, and made hitherto costly looking alternatives more attractive.

This congruence of factors led to what I consider to be the start of the terrestrial photovoltaics industry. This is when Joseph Lindmayer, Peter Varadi, Bill Yerkes, and Ishaq Shahryar left the US space solar industry to establish independent PV companies; and Elliot Berman persuaded Exxon to back his solar enterprise. It is when electronics and energy companies in Europe and Japan shifted photovoltaics out of their research laboratories and into business units. And it is when marketing of solar systems for use on earth really began, although there had been isolated earlier applications.

Having decided where to begin, the next decision is where to end. The end of a millennium is a notable juncture in any case, and 1999 was the year when cumulative solar photovoltaic capacity reached its first gigawatt (1 billion watts) [6]. It also proved to be a turning point for renewable energy. It was just into the new millennium when national feed-in tariffs were first introduced for solar power; and they, more than any other mechanism, created the climate for explosive growth in renewables generally and solar power in particular.

This book therefore focuses on terrestrial photovoltaics between 1973 and 1999. For convenience, I refer to this period as simply *our time frame*, *the early PV era*, or *the first solar generation*.

1.1 OPEC Oil Crisis

The first oil crisis was sparked in October 1973 when some members of OPEC proclaimed an oil embargo in response to American supply of arms to Israel in the Yom Kippur War. At the time petroleum consumption by industrialized countries was rising rapidly and the price of oil was about \$3 per barrel.

The Organization of Arab Petroleum Exporting Countries (OAPEC) comprised the Arab members of OPEC including Syria and Egypt, who had started the war. The embargo covered shipments not only to the United States but also to Canada, Japan, the Netherlands, and the United Kingdom.

The resulting strain on international relations led to intensive diplomacy headed by the Nixon administration's Secretary of State, Henry Kissinger. The prospect of a negotiated settlement between Israel and Syria eventually led to the embargo being lifted in March 1974, by which time the global oil price had risen fourfold to almost \$12.

OPEC members, led by Saudi Arabia's Sheikh Yamani, recognized the leverage they could exert and agreed to use the world price-setting mechanism for oil to increase their income. The continuing relatively high price of oil, and a keener appreciation of the concept of energy security, led industrialized nations to consider other energy options more actively.

1.2 Energy Security

Before this oil shock, the supply of fossil fuel was assumed to be virtually infinite. It was OPEC's constraint on supply that, albeit artificial, sowed the seeds for a more realistic view.

Although the expression "peak oil" wasn't coined until later, some analysts now started to consider the lifetime of available fossil fuel deposits and the dynamics between rates of discovery, exploitation, and consumption. Shell's M. King Hubbert had first postulated his peak theory in 1956 [7] and projected in 1974 that US oil consumption could by 1995 exceed the pace of new discovery [8]. The name Peak Oil was given to this phenomenon [9] in 2002 and this concept is now widely accepted, although the precise dates remain a topic for debate.

The concept of "energy security" has subsequently been broadened to take into account other factors such as the political stability of the regions where energy is produced, and risks associated with transporting it to the point consumption. Other threats such as terrorism also need to be weighed in the balance.

The second oil crisis provided further impetus to the growth of renewable energy. This started in 1979 when oil production in Iran declined after the revolution there, and it was exacerbated the following year by the outbreak of the Iran–Iraq war, which almost stopped production in Iran and severely curtailed Iraq's output.

So energy security, in the form of the availability and price shocks of the oil crises, provided the first major stimulus for terrestrial photovoltaics; and although the circumstances have changed, energy security remains a substantial driver today.

Let's briefly consider other significant drivers, even if their impact was not so weighty at the start of our time frame.

1.3 Climate Change

Climate science was still very much in its infancy in the early 1970s. The link between atmospheric carbon dioxide and methane with global temperatures was not widely recognized; or as a skeptic might put it, "climate change had not yet been invented."

Climate change considerations did not in practice become a substantial inhibitor to fossil fuel usage, or a main driver to the growth of renewables, until some two decades later. Toward the end of the twentieth century, climate change became the primary motivation for supporting renewables and creating the incentives that allowed solar energy to progress from adolescence toward adulthood.

1.4 Other Drivers of the Early Renewable Energy Sector

Along with the external drivers, summarized above, a number of internal drivers were also at play.

Key to the development of any new industry are the companies and people who get it started. From the very beginning, the terrestrial PV space was occupied by a broad cross section of independent and multinational companies. For the independents, we can presume that they were inspired by the concerns of their principals.

The motivation of the larger companies is not always so clear-cut. For many, it was an issue of strategic diversification or expansion, as further discussed in Chapter 7. But some seem to have viewed their involvement as market research, to keep tabs on this new sector – maybe even seeing it as a threat – and others seem to have seen it as a PR exercise.

Ultimately, of course, any new industry is all about the people. Tales of many intrepid PV pioneers will crop up during this story, and some of them are individually profiled in Chapter 10.

1.5 That Sisyphus¹ Feeling

Terrestrial usage of solar power was viewed with widespread skepticism for several decades. This resistance took many forms.

For a start, many people just did not believe that it could work. They thought it was some kind of trick; “you just can’t produce energy out of thin air.” This may be partly because PV is a solid-state technology – harder to understand, when all previous experience of electricity generation was based on rotating machinery.

Next came questions about reliability and longevity. Of course, any new invention needs to prove itself, and people want to see it in action before they commit. The whole field of semiconductor technology was only a few years old and people weren’t yet used to electronic devices, which are now so much part of everyday life.

More rational resistance came on the grounds of cost, and this will be addressed further as the book progresses. Remember that most traditional power generation involves plants where the upfront capital cost is relatively low, but the operating and fuel costs are high. Neither power engineers nor finance directors had economic models that could attribute fair value to the negligible running costs of a solar power plant.

Resistance was often particularly marked in more temperate climates. “Power from the sun? You’ve come to the wrong place!” Many assumed that PV

1 Mythical Greek king condemned by the Gods to eternally roll a boulder uphill.

technologies could work only in the sunniest places. It seemed incongruous that daylight is the only input required, and counterintuitive that systems are more efficient at low temperatures.

Finally, it doesn't take a conspiracy theorist to recognize that a successful solar industry threatens the business model of traditional energy producers. Political pressure was certainly brought to bear to slow the deployment of many environmental technologies. There are those who believe that similar tactics were adopted inside the industry as well.

All in all, there was a lot of resistance, and even more inertia, to slow the early progress of the industry. The effort required to secure and maintain the attention, political support, and funding felt like the unending struggle to push a boulder uphill.

2

What Is Photovoltaics?

Low value, expensive, unreliable, high capital cost, land hungry, intermittent energy

Solar and wind simply don't work, not here, not anywhere.

Australian politician Steve de Lacy [10]

This quotation so admirably encapsulates many of the attitudes prevalent in the early PV era; it justifies inclusion, even though it is much more recent.

Solar power is so familiar to us now that it is worth remembering the absolute wonder that would have been felt on first seeing a solar cell in operation. At a time when our electricity came from huge smoke-belching power stations, it was spectacular to connect a small flat gray disk to a fan and see the blades turn. Shadow the disk with your hand and the fan stops again! At the time it seemed like magic. It may be the memory of this first miracle that captivated so many of the early PV pioneers for the rest of their working lives.

Chapter 1 selected our time frame – the 27-year period from 1973 to 1999 – as PV's “childhood and adolescence.” I promised to cover the earlier period only fleetingly,¹ so here goes.

2.1 Prequel – The Birth and Infancy of Photovoltaics

The first published observation [5] of the photovoltaic effect was by 19-year-old French scientist Alexandre-Edmond Becquerel in 1839, possibly working with his father, the physicist Antoine César. Becquerel noticed that when light strikes certain substances, an electric charge accumulates. It seems strange to us today that they did not do more with this discovery, but the field of scientific endeavor at that time was a blanker canvas, and the talented Becquerels had so many fresh areas to explore.

1 John Perlin's book [13] is commended to readers wanting the fuller story of this period.

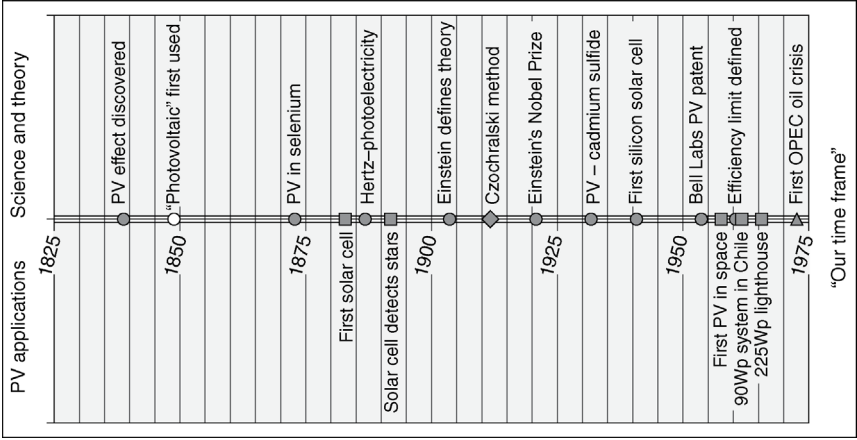


Figure 2.1 Simplified timeline of earlier photovoltaics development.

The word “photovoltaic” was coined in England a decade later by Alfred Smee [11]. The word – not quite interchangeable – “photoelectric” came into use following Heinrich Hertz’s 1887 discovery that ultraviolet light altered the voltage needed to produce a spark between electrodes [12].

In 1892, the Irish mathematician, George Minchin produced his own selenium photovoltaic cells for astronomical measurement of light from stars, although the first practical solar cell had been fabricated almost a decade earlier by the American inventor Charles Fritts.

Most scientists, however, were skeptical about the photovoltaic effect, because it didn’t fit with the understanding at the time of light simply as a wave; until Albert Einstein applied his knowledge of quantum theory to this field [4]. In fact, his Nobel Prize in 1921 was awarded “especially for his discovery of the law of the photoelectric effect.” Meanwhile, various researchers discerned the PV effect in other materials [14]. Despite all this fine science, Becquerel’s discovery went largely unexploited as a source of power for more than a century, as shown in Fig. 2.1.²

This lack of practical interest was in part due to the low conversion efficiency of these early experiments, where the electrical energy produced was often less than 1% of the incident light energy. As late as 1949, Vladimir Zworykin and Edward Ramberg concluded [15] that “It must be left to the future whether the discovery of materially more efficient cells will reopen the possibility of harnessing solar energy for useful purposes.”

2 This also shows Jan Czochralski’s breakthrough in the production of monocrystalline silicon – a method relevant beyond solely the solar sector.

The first progress in this respect came in the 1950s, when research teams at the electronics company RCA and at AT&T's Bell Laboratories developed working PV solar cells with up to 8% efficiency. In 1954, Daryl Chapin, Calvin Fuller, and Gerald Pearson at Bell Labs developed [16] a "Solar Energy Converting Apparatus," submitting a patent application [17] that was in due course granted.

Meanwhile, participants in the embryonic space program were aware that missions would be severely restricted if they had to take all their energy supplies with them in the form of batteries. The US Signals Corps' William Cherry encouraged RCA to work on solar cells and in 1958 the Vanguard I satellite [18] was the first practical application of PV, with less than 1 W of capacity. Later that year, Explorer III, Vanguard II, and Sputnik-3 all carried PV-powered systems. Early cells were small crystalline silicon devices, typically sized at just 1 cm square. Cost was not a primary issue; indeed, it was typically around \$1000/W of capacity.

With very few exceptions [19], nobody before the first oil crisis gave any serious consideration to PV for terrestrial use, although Philips, Hoffman Electronics and Sharp all undertook early installations.

2.2 Where Does the Energy Come From?

Solar energy is electromagnetic radiation emitted by the sun. Enough of it falls on the surface of the earth in 1 h to power it for a whole year. It has been estimated [20] that it would require about half a million square kilometers of solar systems to provide all the energy we need. This is about the area of Uzbekistan – although Uzbek readers should note that I say this only for comparison purposes, not as a proposition! Every location on earth receives sunlight for at least part of the year. The amount of solar radiation that reaches any one spot on the earth's surface varies with location, season, time of day, weather, landscape, and shading.

The sun strikes the earth's surface at different angles, ranging from just above the horizon (Fig. 2.2) to 90° directly overhead. The lower the sun is in the sky, the farther its rays have to travel through the atmosphere, becoming more scattered and diffuse. This distance through the atmosphere – or strictly the ratio of the distance to that when the sun is directly overhead – is called the "air mass."

The tilted axis of the earth's rotation affects the amount of sunlight at a particular location and time of year. Locations at around 40° of latitude receive more than twice as much solar energy in midsummer than midwinter, and this ratio increases to about 5:1 around 56° of latitude (Moscow, Edinburgh, or Cape Horn). In the tropics, summer-to-winter variations are smaller.

As the sun's rays travel further through the atmosphere, some are absorbed, scattered, and reflected by clouds, mist, and water vapor, sand, dust, smoke, and



Figure 2.2 PV anywhere on earth – even Antarctica [21] where the modules are vertical.

other pollutants, and of course the air itself. The solar radiation that reaches the earth’s surface straight from the sun without being diffused is called direct radiation. The light that has been scattered is called diffuse radiation and accounts for most light on cloudy days. The sum of the diffuse and direct solar radiation is called global radiation.

2.3 The Photovoltaic Effect

No generating station actually creates energy; it converts it from an existing energy source into a different form. We extract oil from the earth’s surface so vehicle engines can convert its chemical energy to motive power. We mine radioactive isotopes so nuclear power stations can convert atomic energy to heat and thence power. Now we can harvest sunlight by using solar cells to convert light energy into electricity (Fig. 2.3).

The solar cell is the primary active component of a solar power system. It is supplemented by other subsystems to condition and transport the energy and sometimes to store it. A solar cell produces electricity when the photons of light pass energy to negatively charged electrons in its semiconductor material,

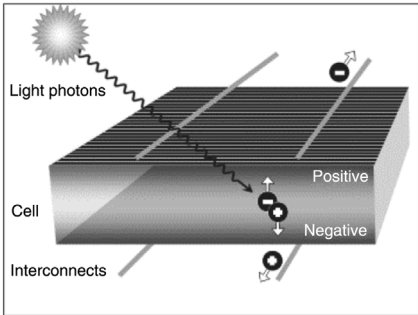


Figure 2.3 Photovoltaic effect in a solar cell.

allowing them to break free. The residual atom is then left with a net positive charge.

Because of the way solar cells are processed, the negative charges are attracted to one surface and the positive charges to the other. Conductive grids on the front and back surfaces of the solar cell collect these positive and negative charges. These contacts are in turn connected to wires to conduct the flow of direct current (DC) from the solar cell to power an external circuit.

We won't explore the technical characteristics in detail, but this summary helps understand how the PV applications described in the next chapter evolved.

2.3.1 Photovoltaic Operating Characteristics

The so-called current–voltage (or I – V) characteristic, illustrated in Fig. 2.4, shows how much current and voltage can be delivered by a solar cell at different levels of light intensity. The cell can operate at any point on the line, and the actual output therefore depends on the external circuit to which the cell is connected.

For example, the extreme right-hand end of the line shows the so-called open-circuit voltage (V_{OC}) – the potential that exists between the contacts at the front and back of the solar cell, when they are not connected to any external circuit and are therefore not delivering any current.

The left-hand end of the line shows the short-circuit current (I_{SC}), which flows if the solar cell contacts are directly connected together – that is, at a zero voltage. Note how solar cells are resilient and can be short-circuited without damage – don't try this with most other electricity generators!

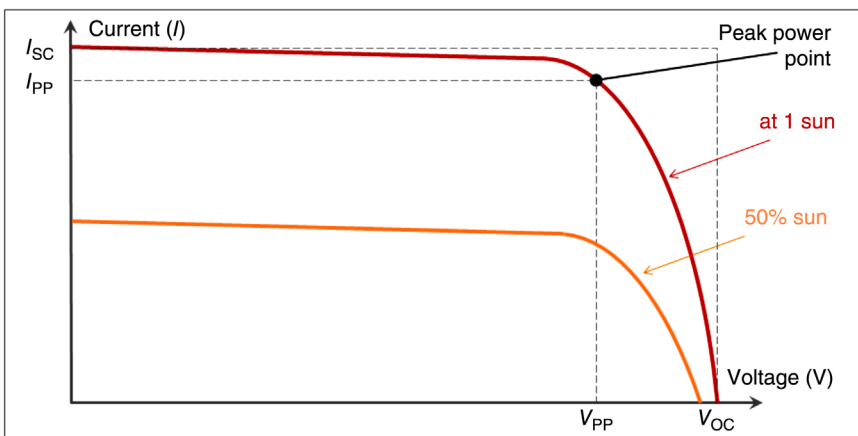


Figure 2.4 Typical I – V characteristics of PV cell at different light levels.

Any electrical engineer can tell you that power is the multiple of current and voltage. Solar cells therefore produce no power either at open circuit (where current is zero) or at short circuit (where voltage is zero). The point at which power is at its maximum is called the peak power point. This is also shown on the characteristic. The output at this point, known as “watts peak” (W_p) is the key parameter against which cells and modules are rated. As the name implies, there is a benefit from operating solar systems as close to this point as possible. The capacity of a PV cell, module, or system, quoted in W_p (or kW_p , MW_p etc.) is a rating of the power it delivers when operating at the peak power point under standard test conditions, explained in Section 12.3.

A measure of the electrical quality of the cell is called the “fill factor,” which is the ratio of the peak power to the product of the open-circuit voltage with the short-circuit current (i.e., the ratio of the areas of the two dashed rectangles shown in Fig. 2.4). The “squarer” the $I-V$ curve, the higher the fill factor.

The point on the characteristic at which the solar cell will operate in practice will depend on the external circuit to which it is connected. That circuit also has an $I-V$ characteristic; and the whole network will operate where the two characteristics meet. By way of example, a battery at a given state of charge operates at a fixed voltage, that is, a vertical line on the characteristic. The current with which the solar cell would charge that battery therefore varies with the intensity of light to which the cell is exposed.

There are many factors that affect the performance of solar cells of different types, and this book does not intend to address the science of these, although we touch on “bandgap” in Sections 4.4 and 4.7. Readers should look elsewhere [22] if they want a better understanding of this and parameters such as the “minority carrier lifetime” and “surface recombination.”

It is important to note that the PV effect is driven by the level of incident light energy. Solar cells therefore work whenever there is daylight, even on cloudy days. They do not need heat, and in fact work more efficiently at low temperatures.

2.3.2 Solar Cell Production

Here is a thumbnail sketch of how monocrystalline silicon solar cells are traditionally produced to achieve this clever task (a fuller account of solar cell technology is given in Chapter 3).

Monocrystalline silicon ingots are grown by introducing a small crystal at the top of a bath of pure molten silicon. As this is slowly rotated and pulled upward, the silicon solidifies in a sausage shape, with all its molecules aligned in a coherent crystal lattice. This is called the Czochralski process after the Polish chemist Jan Czochralski, who invented this method for producing crystalline metals in 1916 [23].

The ingot is “salami-sliced” into individual thin wafers, and these are placed in ovens, where small amounts of two chemicals (often boron and phosphorus)

diffuse into the two faces to selectively attract the positive and negative charges as described above.

Finally, conductive contacts are attached to the front and rear surfaces to collect the current produced. The cells are then usually connected together in strings and packaged for weather resistance and safety in solar panels, known as “solar modules.”

2.4 From Theory to Practice: Applying PV Technology

In hindsight, it may seem surprising that several decades elapsed after the discoveries at Bell Laboratories in the 1950s, before any widespread use of solar electricity. There are several reasons.

Scientifically, this was a very exciting era, especially because of dramatic progress in semiconductor technology. Many of the laboratories active in photovoltaics were also researching diodes, transistors, and other devices with more immediate commercial applications; so developments in the PV sector were often overwhelmed by the larger semiconductor industry.

At the Philips Physics Laboratory in the Strijp suburb of Eindhoven in 1955, for example, 19-year old apprentice Kees Ouwens was employed for making diodes and transistors. He sawed silicon rods into wafers, diffusing them as semiconductors and applying contacts. In the spring of 1956, he made a few solar cells in the same way, and had soon produced what was probably the first solar-powered transistor radio. But the next year he was back on the “day job” posted to the Philips UK subsidiary Mullard in the production of transistors.

Second, energy prices in the 1950s were extremely low. Although PV had a myriad of potential applications, most of these were already served by cheap alternatives based on fossil fuels. Except in space, where there were few other options, PV looked like an expensive alternative to existing energy sources.

There was therefore very little terrestrial deployment of photovoltaics, although a few pioneers did install development systems to see how they worked. The earliest such installations (of which I am aware) were for isolated mining sites in Chile and lighthouses and navigational buoys in Japan. Other off-grid and remote applications gradually started to emerge, as further described in Section 3.2.

Of course, the whole concept of photovoltaics was entirely foreign to the first prospective customers. Early marketers made solar gadgets – often little rotating fans, which they could give away to show that PV actually works. Lucas fabricated elegant mahogany boxes with two Solar Power Corporation P1002 modules in the lid, powering a fan and a light and some meters.

Arco Solar^{qv} invited customers to demonstrations at hotels where solar panels powered a pump in the swimming pool. When the clients walked in front of the panels, the pump would stop; when they moved away, it would start

again. “After they did that a couple of times,” says Peter Aschenbrenner [24], “you could ‘see the light go on.’”

2.5 What Is a Solar PV Energy System?

The photovoltaic cells described above are the active parts of a solar generator – which converts light energy into electricity. To meet the needs of energy users, other components are added to make a complete generating system.

2.5.1 Non-PV Solar Power Systems

Most, but not all, solar energy systems are based on photovoltaic cells, and when I use “solar power” or “solar energy” in this book, I am referring to PV. For the record, however, let’s quickly mention the other major forms of solar energy conversion.

Concentrated solar power (CSP) uses the sun’s heat to generate electricity. One of the two main methods for collecting heat at high temperatures for this application is to use so-called “power towers.” A large field of mirrors focus the sun’s rays onto a boiler at the top of a tower, as illustrated in Fig. 2.5.

An alternative CSP approach uses parabolic reflector “troughs,” which focus the sun’s rays onto a tube mounted at the focal point. The heat is collected in a transfer fluid circulated through these tubes. The SEGS (solar electric generating system) projects built between 1983 and 1990 at three sites in the Mojave Desert comprised nine solar power plants using parabolic trough collectors (Fig. 2.6).

Whichever thermal collector technology is adopted by these CSP systems, the heat then drives a steam turbine, similar to those used in traditional power stations. The early business of Flachglas Solartechnik^{qv} was the production of mirrors for concentrated solar power systems.



Figure 2.5 Not PV: concentrated solar “power tower” in Spain [25] at the Gema-solar project.