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Preface

This book results from a meeting that took place in Cercedilla, Madrid, Spain in March 2002. The meeting was about new ideas that could lead us to better use of the solar spectrum with the ultimate goal of achieving superior photovoltaic devices and, consequently, a reduction in their price. The meeting, despite being short, was so fruitful and intense that it was considered that the concepts discussed there should be preserved and made accessible to third parties in book form.

The result is a book that covers a variety of concepts: the economics of photovoltaics, thermodynamics, multi-junction solar cells, thermophotovoltaics, the application of low dimensional structures to photovoltaics, optics and technology. Time will tell whether many of these ideas and concepts meet expectations. For the moment, they are presented here to stimulate other researchers.

Thanks to all the people that attended that meeting and thanks, particularly, to those that accepted the challenge of writing their chapter. Thanks also to the Polytechnic University of Madrid for hosting the meeting and to the European Commission, to the Spanish ‘Ministerio de Educación y Cultura’ and to ISOFOTON for providing financial support. And many thanks to the Institute of Physics Publishing and to Tom Spicer and the team in particular for publishing this book, for their patience in receiving the manuscripts and for their careful printing.

We are sure that the contributors also wish to acknowledge their families for allowing them some spare time to contribute to this book and, in their name, we allow ourselves to do so.

Antonio Martí and Antonio Luque

Chapter 1

Non-conventional photovoltaic technology: a need to reach goals

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1.1 Introduction

This book is the result of a workshop celebrated in the splendid mountain residence of the Polytechnic University of Madrid next to the village of Cercedilla, near Madrid. There, a group of specialists gathered under the initiative of the Energy R&D programme of the European Commission, to discuss the feasibility of new forms for effectively converting solar energy into electricity. This book collects together the contributions of most of the speakers.

Among the participants we were proud to count the Nobel Laureate Zhores Alferov who, in the early 1980s, invented the modern III–V heterojunction solar cells, Hans Queisser who, in the early 1960s, together with the late Nobel Laureate William Shockley established the physical limits of photovoltaic (PV) conversion and Martin Green, the celebrated scientist, who, after having established records of efficiency for the now common silicon cell, hoisted the banner for the need for a 'third generation of solar cells' able to overcome the limitations of the present technological effort in PV. Together they closed the workshop.

This chapter will present the opening lecture that presented the motivation for the gathering. The thesis of this document is that present technology, despite the current impressive growth in PV, will be unlikely to reach the low cost level that is necessary for it to replace a large proportion of fuel-based electricity production. As a consequence, new forms of solar energy conversion must be developed to fulfil society's expectations for it.

We want immediately to state that our thesis is not to be considered to be in conflict with the PV industry as a whole nor with the mainstream of PV development. On the contrary, we think that the support of present PV technology and the expansion of the industry based on it is a must for any further step forward in the development of solar energy conversion. Furthermore, we cannot totally discard the notion that it might reach the necessary prices and goals. When talking about the future, we can only talk about likely scenarios and about recommended actions to ensure that we help towards building a sustainable future.

Accordingly, this chapter will present the stresses that advise us of the necessity for the development of renewable energies (and, among them, solar electricity), the volume of installation that will be necessary to mitigate such stresses and the forecast exercises that allow us to support our thesis (i.e. that incumbent forms of PV are probably unable to reach the necessary costs for achieving the goals of penetration defined as relevant). Then, the ways to change this situation will be briefly sketched and forecasted. For additional information other authors in this book will explain the different options in more detail. However, the collective conclusions reached at the end of the Workshop are presented in an appendix.

1.2 On the motivation for solar energy

The most obvious reason for supporting the development of a new form of energy is the exhaustion of existing ones. Will this situation occur, at least within the next half-century? Let us look at the answer given by the Royal Dutch/Shell Group [1], the big oil corporation:

> Coal will not become scarce within this timescale, though resources are concentrated in a few countries and will become increasingly complex and distant from markets. Costs of exploiting and using them will eventually affect coal's competitiveness.
>
> Oil production has long been expected to peak. Some think this is now imminent. But a scarcity of oil supplies—including unconventional sources and natural gas liquids—is very unlikely before 2025. This could be extended to 2040 by adopting known measures to increase vehicle efficiency and focusing oil demand on this sector. Technology improvements are likely to outpace rising depletion costs for at least the next decade, keeping new supplies below $20 per barrel. The costs of bio-fuels and gas to liquids should both fall well below $20 per barrel of oil equivalent over the next two decades, constraining oil prices.
>
> Gas resource uncertainty is significant. Scarcity could occur as early as 2025, or well after 2050. Gas is considered by many to be more scarce than oil, constraining expansion. But the key issue is whether there

> can be timely development of the infrastructure to transport remote gas economically.
>
> Nuclear energy expansion has stalled in OECD countries, not only because of safety concerns but because new nuclear power is uncompetitive. Even with emission constraints, the liberalisation of gas and power markets means this is unlikely to change over the next two decades. Further ahead, technology advances could make a new generation of nuclear supplies competitive.
>
> Renewable energy resources are adequate to meet all potential energy needs, despite competing with food and leisure for land use. But widespread use of solar and wind will require new forms of energy storage. Renewable energy has made few inroads into primary energy supply. Although the costs of wind and photovoltaic sources have fallen dramatically over the past two decades, this is also true for conventional energy (direct quotations to Shell report reproduced here with permission from Shell International Limited, 2001).

Thus, in summary, no global energy shortage is expected to appear in the next 50 years but for Shell:

> Demographics, urbanisation, incomes, market liberalisation and energy demand are all important factors in shaping the energy system but are not likely to be central to its evolution. By contrast, the availability of energy resources and, in particular, potential oil scarcity in the second quarter of the century, followed by gas some time later, will transform the system. What will take the place of oil—an orderly transition to bio-fuels in advanced internal combustion engines or a step-change to new technologies and new fuels?

Therefore, we can expect an important transformation in the energy system caused, to a large extent, by oil scarcity. It is true that this scarcity will affect the energy used for transport, which is not at the moment electric, more directly while here we are dealing with electric energy. However, this may well not be the situation when fuel cells have been developed and penetrate, to an important extent, the transportation system. In any case, the transformation of the energy system will certainly affect electricity production, in the sense of extending its proportion in the final use of energy.

However, the second reason, perhaps publicly perceived as the most important today, for public support of the development of new forms of energy is sustainability. According to the Intergovernmental Panel of Climatic Change (IPCC) [2] in its Third Assessment Report (TAR), based on models corresponding to six scenarios (plus an additional one corresponding to the preceding Second Assessment Report (SAR)), they present a number of statements that are considered robust findings:

> Most of observed warming over last 50 years (is) likely due to increases in greenhouse gas concentrations due to human activities. (See figure 1.1.)
>
> CO_2 concentrations increasing over the 21st century (are) virtually certain to be mainly due to fossil-fuel emission. (See figure 1.2.)
>
> Global average surface temperature during 21st century (is) rising at rates very likely without precedent during last 10 000 years. (See figure 1.1.)

An additional feature of climatic change is associated with the inertia of the climatic system. Even if we immediately stop the emission of greenhouse gases, the quantity of CO_2 will continue to rise as well as the temperature. However, the social system also has inertia and reductions in greenhouse gas emission cannot occur immediately. A semi-qualitative diagram is presented in figure 1.3. For instance, attempts to stabilize the concentration of CO_2 in the atmosphere require actions to reduce the emission of greenhouse gases to well below the present level. The earlier we start to reduce the emission level, the lower the level of stabilization achieved will be but stabilization will still take one to three centuries. Temperature will stabilize even more slowly and the rise in the sea level due to thermal expansion and ice melting will take millennia.

In contrast, the reduction in 'greenhouse gases' other than CO_2 is easier and can be achieved within decades after the emissions are curbed.

An agreed model has been used to determine the conditions which would lead to a fixed final CO_2 concentration in the atmosphere (stabilization). Based on this, the IPCC TAR states that

> stabilization of atmospheric CO_2 concentrations at 450, 650, or 1000 ppm would require global anthropogenic CO_2 emissions to drop below year 1990 levels, within a few decades, about a century, or about 2 centuries, respectively, and continue to decrease steadily thereafter to a small fraction of current emissions. Emissions would peak in about 1 to 2 decades (450 ppm) and roughly a century (1000 ppm) from the present.

Reaching these goals requires a form of energy production virtually free from CO_2 release. Only nuclear power and renewable energies have this characteristic. The large extent of this necessary reduction implies that such sources must eventually be fully developed, both in cost and storage capability.

Other characteristics of the coming climate are, according to the IPCC's official opinion in its TAR,

> Nearly all land areas very likely to warm more than the global average, with more hot days and heat waves and fewer cold days and cold waves.
>
> Hydrological cycle more intense. Increase in globally averaged precipitation and more intense precipitation events very likely over many areas.

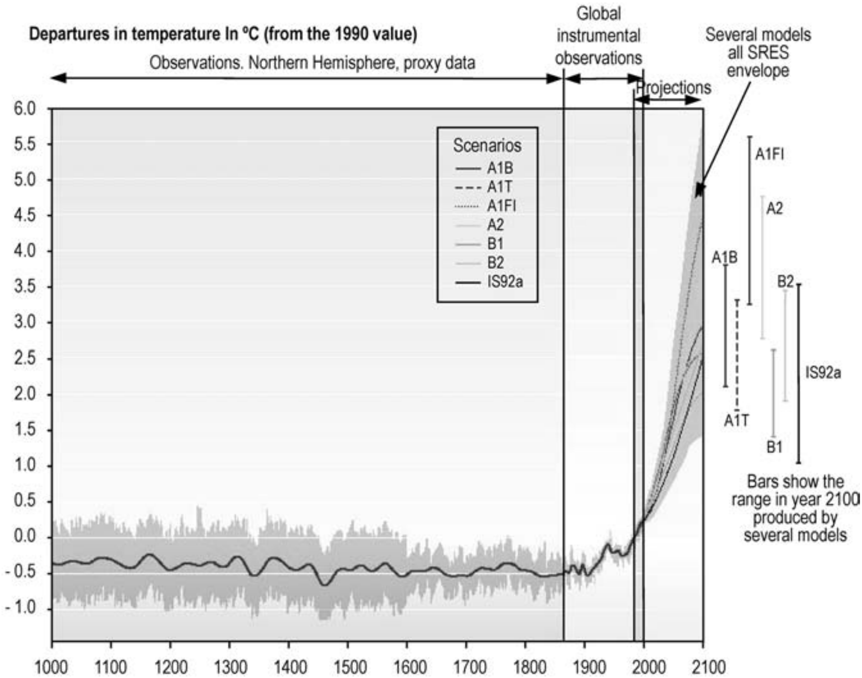

Figure 1.1. Variations in the Earth's surface temperature: years 1000 to 2100. From year 1000 to year 1860 variations in average surface temperature of the Northern Hemisphere are shown (corresponding data from the Southern Hemisphere not available) reconstructed from proxy data (tree rings, corals, ice cores and historical records). Thereafter instrumental data are used. Scenarios A are economically oriented, (A1FI, fossil fuel intensive, AT non-fossil, AB balanced), scenarios B ecologically oriented. Index 1 represents global convergence; index 2, a culture of diversity. The scenario IS92 was used in the SAR. For instance, scenario B1 which is ecologically oriented in a converging world is the most effective to mitigate the temperature increase (© Intergovernmental Panel on Climate Change. Reproduced with permission).

> Increased summer drying and associated risk of drought likely over most mid-latitude continental interior.

But undertaking the ambitious task of stabilizing the CO_2 content is only worthwhile if the consequences of the climatic change are adverse enough. In this respect, the IPCC TAR, while recognizing that the extent of the adverse and favourable effects cannot yet be quantified, advances the following 'robust findings':

> Projected climate change will have beneficial and adverse effects on both environmental and socio-economic systems, but the larger the

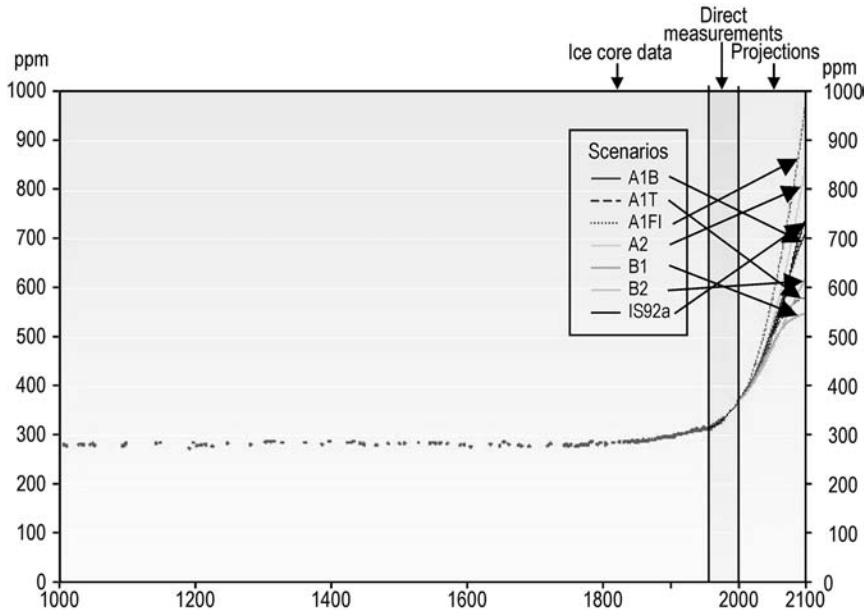

Figure 1.2. Atmospheric CO_2 concentrations (© Intergovernmental Panel on Climate Change. Reproduced with permission).

changes and the rate of change in climate, the more the adverse effects predominate.

The adverse impacts of climate change are expected to fall disproportionately upon developing countries and the poor persons within countries.

Ecosystems and species are vulnerable to climate change and other stresses (as illustrated by observed impacts of recent regional temperature changes) and some will be irreversibly damaged or lost.

In some mid to high latitudes, plant productivity (trees and some agricultural crops) would increase with small increases in temperature. Plant productivity would decrease in most regions of the world for warming beyond a few °C.

Many physical systems are vulnerable to climate change (e.g., the impact of coastal storm surges will be exacerbated by sea-level rise and glaciers and permafrost will continue to retreat).

In summary, a climatic change has already been triggered by human activity. Nature has always possessed a fearsome might. We might rightly say that we are awakening her wrath. By mid-century, the consequences, while certainly

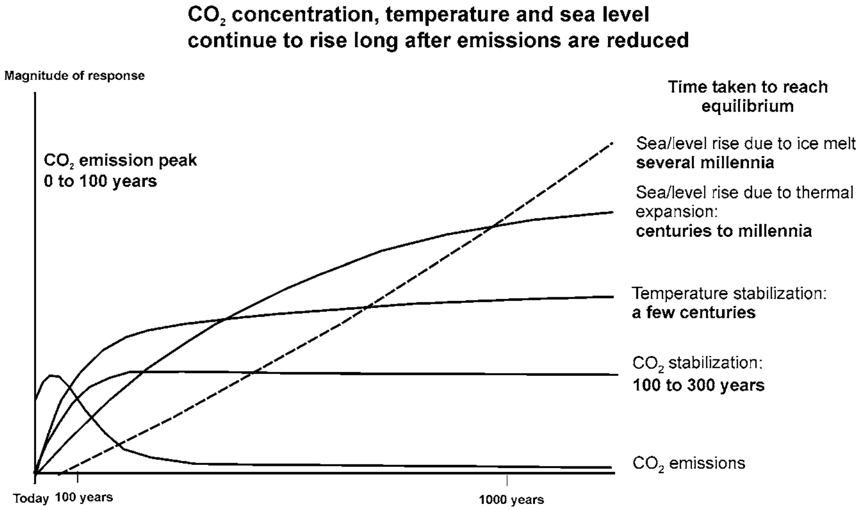

Figure 1.3. Generic illustration of the inertia effects on CO_2 concentration, the temperature and sea level rise. Note that stabilization requires a substantial reduction in CO_2 emissions, well below its present levels. In the long term, the use of non-polluting energies is a must to reach stabilization (© Intergovernmental Panel on Climate Change. Reproduced with permission).

not pleasant, might perhaps not be sufficiently dramatic globally but they will become so in the centuries to come if we do not immediately initiate a vigorous programme of climatic change mitigation. Intergenerational solidarity requests us to start acting now.

1.3 Penetration goals for PV electricity

In this section we are going to present some results from the Renewable Intensive Global Energy Supply (RIGES) scenario. This scenario was commissioned by the United Nations Solar Energy Group on Environment and Development as part of a book [3] intended to be an input to the 1992 Rio de Janeiro Conference on the Environment and Development. This supply scenario was devised to respond to one of the demand scenarios prepared by the Response Strategies Working Group of the IPCC (who also presented its own supply scenario). The chosen IPCC demand scenario was the one called 'Accelerated Policies'.

In this demand scenario, the growth of Gross Domestic Product (GDP) is assumed to be high in all of the 11 regions into which the scenario is divided. It is, thus, a socially acceptable scenario in which the growth of the poorest is not sacrificed to environmental concerns. Advanced measures in energy efficiency are also assumed.

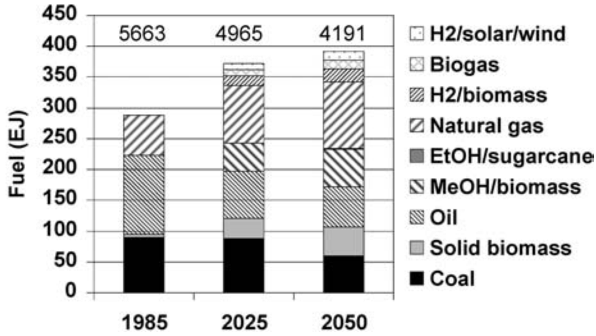

Figure 1.4. Fuel supply in RIGES. The number above the columns gives the carbon emission as CO_2 in Mt of C (elaborated with data from appendix A in [3]).

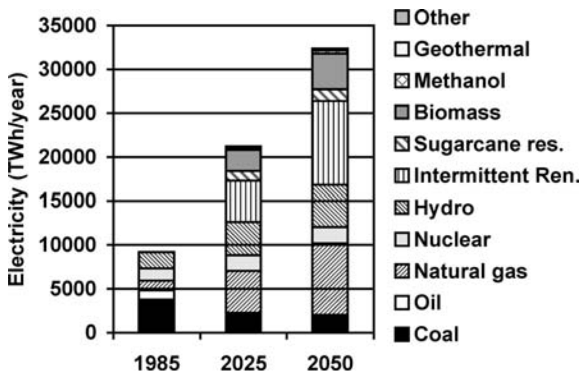

Figure 1.5. Electricity supply in RIGES. The fuels used for electricity generation are included in figure 1.4 (elaborated with data in appendix A from [3]).

In all the IPCC demand scenarios, not only the 'Accelerated Policies' one, much of the final use energy is provided in the form of electricity; therefore, it is electricity that experiences the highest growth while other fuels grow more moderately. All scenarios extend until 2050.

The results of the RIGES scenario separate other fuels from electricity. This avoids any discussion of how to translate the electricity from renewable sources (like hydroelectricity) into an 'equivalent' primary energy that contributes to the final use of the energy without affecting its production. These results are presented in figures 1.4 and 1.5.

The first result to note is that an increase in energy use can be obtained, with an intensive use of renewable energy sources, together with a decrease in CO_2 releases from 5663 Mt of carbon in 1985 to 4191 Mt in 2050. This decrease in CO_2 releases is obtained thanks to a moderate increase of only 36% in primary energy consumption, and an extensive use of renewable energies, that in 2050, will reach 41% of the total fuels used. The large proportion of natural gas, with its large content of hydrogen instead of carbon as the combustible element, also helps this result to be reached.

At the same time, the increments in the final use of the energy are largely satisfied by the 3.5-fold increment in electricity consumption supplied in 2050, mainly by renewable sources (62%) with fossil fuels providing 31%, the remaining 7% being nuclear and geothermal (the latter only 0.6%), that do not release appreciable quantities of CO_2. It is of interest to note that intermittent renewable sources, namely solar and wind power, amount to 30% of the total quantity of electricity generated and constitute the largest contribution to the global electricity supply.

But does this picture constitute a prediction of the energy situation by the middle of the 21st century? Not at all! Scenarios like this represent a set of self-consistent variables that may constitute a picture of the reality but there are other sets of parameters representing alternative and equally possible pictures. However, there are many more pictures with non-self-consistent sets of parameters that cannot occur. The study of scenarios tries to discard such impossible patterns and to focus on the self-consistent ones.

1.4 Will PV electricity reach costs sufficiently low to permit a wide penetration?

Reaching the penetration level assigned in the preceding scenario exercise implies that PV electricity has to reduce its cost to levels that makes it possible for it to compete with other electricity production technologies. Indeed, an energy technology is not adopted on cost considerations alone. Its choice has largely to do with why this technology is more convenient than the competing technologies. Modularity and image (which leads to generous public support for its installation), not price, are the origin of the impressive growth that PV sales have experienced in recent years. But prices must come closer to those of other technologies for any real massive penetration to be viable.

In figure 1.6 we present the evolution of PV module sales. We have witnessed, in the last five years, an explosive growth that almost nobody dared to foresee. The continuous curve represents an annual growth rate of 30%. The broken curve represents the model described later.

We have modelled the growth of the PV module market and the evolution of PV prices [4]. On one side, we have considered the learning curve that states that, for many goods, prices are reduced in a similar proportion every time the cumulated production of the good is doubled (the ratio of prices is the inverse of

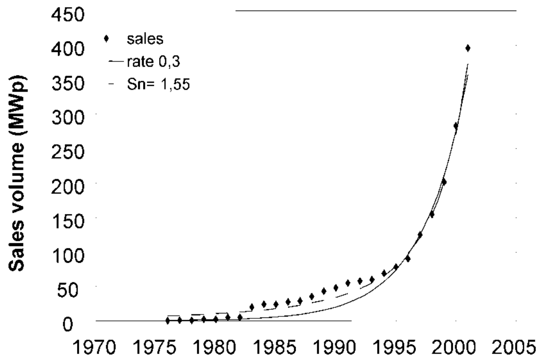

Figure 1.6. Annual sales of photovoltaic modules and model interpolations (from [4]. © John Wiley & Sons Ltd. Reproduced with permission).

the ratio of cumulated markets raised to the power n),

$$\frac{p}{p_0} = \left[1 + \frac{\int_0^t m \, \mathrm{d}t}{M_0}\right]^{-n} \tag{1.1}$$

p being the price and m the annual market at time t (p_0 and m_0 are the corresponding values at the initial time of consideration). M_0 is the accumulated market at the initial time of consideration.

In the case of PV, the price reduction is 17.5% ($n = 0.277$) in constant dollars every time production doubles. This law allows us to forecast the price of the modules at any future moment if we know the cumulated sales at this moment or, alternatively, if we know the annual sales.

In many studies the annual increase in sales is considered to be constant, i.e. the sales each year are considered to be those of the previous year multiplied by a constant. This is what has been done to achieve the continuous curve in figure 1.6; in this case, the annual rate of growth has been taken as 30%. However, we have preferred to link this growth to an economic variable. This is the demand elasticity S defined as the opposite of the logarithmic derivative of the annual market with respect to the price (or the ratio of the relative increment of the annual market for a very small relative decrement in the price):

$$S = -\frac{p}{m}\frac{\mathrm{d}m}{\mathrm{d}p}. \tag{1.2}$$

The broken curve in figure 1.6 represents this model when adjusted for best fitting with the real market data ($Sn = 1.55$). The fit is better than the exponential model. Combining equations (1.1) and (1.2) leads to

$$\left(\frac{m}{m_0}\right)^{\frac{1}{Sn}} = 1 + \frac{\int_0^t m \, \mathrm{d}t}{M_0}. \tag{1.3}$$

For *constant Sn*, the solution is

$$m = m_0 \left[1 - t \frac{m_0}{M_0} (Sn - 1) \right]^{-Sn/(Sn-1)}. \tag{1.4}$$

This equation shows an asymptote for $t = M_0/[m_0(Sn - 1)]$. This asymptotic behaviour means that the market's rate of growth increases every year and this, in fact, has been observed in recent years. However, this cannot last for long. In fact, with the previously mentioned data, the asymptote is located in 2009 ($t = 0$ is 1998). It is clear that Sn cannot be taken as a constant. In fact, there is no reason for it to be so. While there is much empirical evidence for many products that n is constant as long as there are no drastic changes in technology and this is the case for PV where 90% or more of the market is dominated by flat crystalline silicon modules. However, there is no rule that sets S as a constant. Consequently, S has been considered to be variable according to the following simplified pattern:

$$\begin{array}{llll} \text{if} & (pm < C_s(t) \quad \text{and} \quad p_c < p) & \text{then} & S = S_i \\ \text{if} & (C_s(t) \le pm \quad \text{and} \quad p_c < p) & \text{then} & S = S_s \\ \text{if} & (p \le p_c) \quad \text{then} \quad S = S_c & & \end{array} \tag{1.5}$$

where $p(t)$ is the module price. The meaning of this expression is that S takes a high initial value S_i when the total annual expenditure pm in PV modules is below a certain threshold $C_s(t)$, then, when this threshold is reached, S decreases to a stagnation value S_s. Finally, if a certain price of competence p_c is reached, S takes another high value S_c of competence.

The explanation of these conditions is as follows. $S = S_i$ today because people are willing to buy PV modules regardless of their high price as they find one or several convenient characteristics in PV electricity. This has always been so, as is rightly stressed by Shell in its cited report [1]:

> A technology that offers superior or new qualities, even at higher costs, can dramatically change lifestyles and related energy use. Widespread introduction of electricity in the early twentieth century prompted fundamental changes in production processes, business organization and patterns of life. Coal-fired steam engines powered the early stages of industrialisation, replacing wood, water and wind. The internal combustion engine provided vastly superior personal transport, boosting oil consumption.

One such superior quality is certainly a sense of freedom and solidarity and, to no lesser extent, image. PV is a clean technology that gives prestige to its owner (whether an individual or a corporation), more than many other sumptuary expenditures. Furthermore, it is modular. The general expenditure to enjoy this good is not very high. It can be afforded in many homes and you can 'do it yourself' so boosting the sense of freedom from large utility corporations.

Furthermore, the government may satisfy the wishes of the population concerning clean energy with low total cost but high symbolic value. For a stand-alone technology, it is generally reliable and easy to handle, thus reducing maintenance greatly with respect to the alternatives. For developing rural areas, it adds to the preceding advantages the approbation of donor organizations that often support rural development.

However, this generally favourable public acceptance will change when the operating costs really start to affect the economy. Then the opposition to delivering funds for this expensive alternative will increase and any increase in the market will require a real price reduction, i.e. S_s will be lower.

Again, when due to experience, the price has been reduced sufficiently so as to compete with the incumbent electricity generator, the situation will change and S_c will increase because the advantages of PV electricity will no longer be hampered by the price drawback. Yet this model is not intended to study this competition phase, only to detect in its onset—a final vertical asymptotic behaviour—the end of the validity of this study.

An interesting result is that it is virtually independent of the value selected for S_s (as long as $S_s n < 0.45$) and S_c (as long as $S_c n > 1.4$), which are the values of S to be used for the long-term future. For the short-term future, the use of the historic value of S_i seems justified. This leads us to an apparently obvious conclusion: the future markets of PV modules, in monetary terms, will amount, for a long period, to what society is willing to pay for a good that is purchased by its unique characteristics and one which is not competing with any other one equivalent.

To simplify, the level of expenditure that society is willing to pay wordwide for PV modules is assumed to be

$$C_s(t) = C_{s0}(1 + \kappa t) \tag{1.6}$$

which is growing at the rate of the total GDP of the industrialized countries as forecast in RIGES, C_{s0} being parametrized and the parameter κ taking the value $\kappa = 0.056$ year^{-1}. Of course, many other patterns are possible but a proper parametrization will cause them to be within the limits studied.

We present in figure 1.7 the growth of the market for several values of the parameters. The value of $C_{s0} = 5$ billion dollars corresponds to devoting to PV 0.1% of the GDP of the industrialized countries. It is assumed that only one-third of this amount, i.e. five billion dollars, is devoted to the purchase of modules. Additional curves have been drawn with C_{s0} twice and half the preceding value.

The evolution of prices is represented in figure 1.8. Note that the price considered by us [5] to be necessary for competition with conventional electricity, 0.35\$ Wp^{-1}, is not reached until 2050. As for the 1\$ Wp^{-1} barrier, in the most optimistic assumption in our study, it is reached in 2012, for an annual market of 18 GWp and, in the most pessimistic, it is reached in 2027 for an annual market of 7 GWp. This study does not foresee that it can be reached within this decade, as is the goal of some R&D programmes.

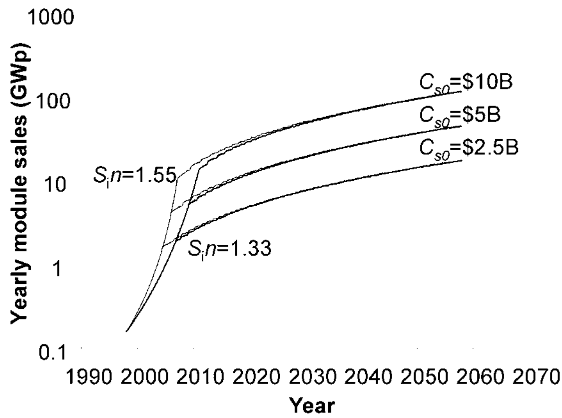

Figure 1.7. Annual module sales, in power units, for several values of the parameters. Note the good predictive behaviour of the model so far. In 1998, when the market was 159 MWp, the model predicted 362 MWp for 2001. The recorded market has been 381 MWp (from [4]. © John Wiley & Sons Ltd. Reproduced with permission).

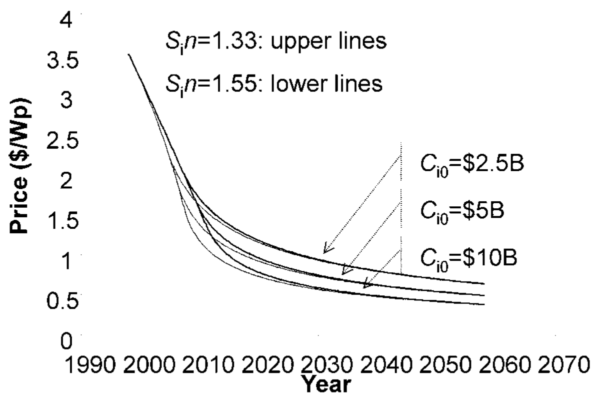

Figure 1.8. Prices predicted by the model for several values of the parameters. The competition price, assumed to be 0.35$ Wp^{-1}, is not reached within the period of study (from [4]. © John Wiley & Sons Ltd. Reproduced with permission).

This relatively disappointing price evolution is due to the low learning curve or rate, which, as we have already said, in PV is only 17.5% in constant dollars. It is higher than that of wind power, 15%, but much smaller than semiconductor memories, some 32%.

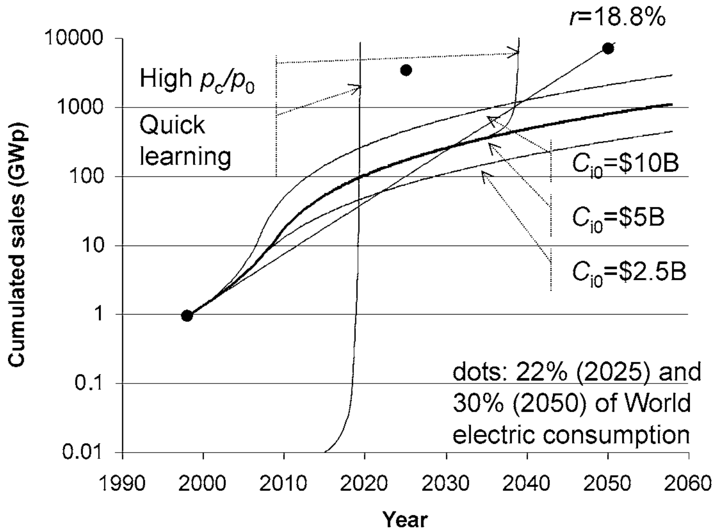

Figure 1.9. Cumulated sales of installed PV capacity based on the model described in the text (from [4]. © John Wiley & Sons Ltd. Reproduced with permission).

1.5 The need for a technological breakthrough

With the help of the indicated model, we draw in figure 1.9 the cumulated market that, given the fast growth of PV and the long expected lifecycle of the modules, is almost the same as that of PV installed power. In this diagram we have also indicated (by dots) the installed PV capacity necessary to provide (in good climates) the annual intermittent electricity programmed in RIGES. We observe that our model leads, depending on the value of C_{s0}, to 4.5–29.1% in the amount programmed for 2050. Furthermore, it is more expensive than incumbent electricity sources.

Of course, for a sufficiently high value of C_{s0}, the required cumulated sales would be reached. This value is 20 billion dollars which should be compared with the 5 billion of our central case. This would imply devoting up to 0.4% of the GDP of the industrialized countries to the development of PV electricity. In this case, the price of competence $p_c = 0.35\$\ \mathrm{Wp}^{-1}$ is also achieved by about 2050. The question is whether society is willing to support so heavily for so long a cost-ineffective technology that will eventually become cost-effective.

Even with less support, PV electricity might become cost effective if, for some reason, modules of $0.7\$\ \mathrm{Wp}^{-1}$, instead of the $0.35\$\ \mathrm{Wp}^{-1}$ considered so far, can lead to cost- effective generating plants. This might happen by a misjudgement on our part, if we have fixed too stringent a condition for the cost-competitive module price or, what is the same, by a modification in the costs of commercialization that permit higher cost modules for a given price of the installed PV generator but also by an undesired increase in the global price of electricity in constant dollars. However, the situation is expected to be the opposite: prices of incumbent electricity will decrease, as they have done historically.

If 0.7$ Wp^{-1} modules become competitive, the cumulated market will follow the pattern of the curve labelled 'high p_c/p_0'. In this case, the price for competition would be reached by 2038 in the central case represented in figure 1.9. Even for the lower case (not drawn), the price of competence would be reached by 2045, before the end of the half of the century.

However, relying on cost reduction by experience is a risky way of approaching the problem. Taking risks for radical innovation is less risky, we believe.

Based on its scenario 'Dynamics as Usual', Shell tells [1] a tale of a possible energy history in the 21st century:

> In the first two decades of the century, renewable energy grows rapidly in OECD countries, within the framework of established electricity grids and strong government support... Deregulated markets provide opportunities for branded 'green energy', which gain 10% of demand in some regions....
>
> Governments support a spread of renewable technologies to address public concerns about health, climate and supply security. Renewables experience more than 10% compound growth—with photovoltaic solar and wind growing at over 20% a year. By 2020 a wide variety of renewable sources is supplying a fifth of electricity in many OECD markets and nearly a tenth of global primary energy. Then growth stalls....
>
> Stagnant electricity demand in OECD limits opportunities for expansion. Although the public supports renewables, most are unwilling to pay premium prices. In spite of significant cost improvements, photovoltaic power gains only niche markets. And with little progress on energy storage, concerns about power grid reliability block further growth of wind and solar energy....
>
> Since 2025 when the first wave of renewables began to stagnate, biotechnology, materials advances and sophisticated electric network controls have enabled a new generation of renewable technologies to emerge. ... A range of commercial solutions emerge to store and utilize distributed solar energy. By 2050 renewables reach a third of world primary energy and are supplying most incremental energy.

For Shell, this is not the only scenario. Many others may exist, as they clearly state, but in another one they present, the so called 'The Spirit of the Coming Age', strongly based on the technological revolutions they perceive around fuel cells and H_2 technology, they also give crucial and similar weight to 'second-wave' PVs because, as they state at the beginning of their report, for the energy system,

> Two potentially disruptive energy technologies are solar photovoltaics, which offer abundant direct and widely distributed energy, and hydrogen fuel cells, which offer high performance and clean final energy from a variety of fuels. Both will benefit from manufacturing economies but both presently have fundamental weaknesses.

A similar message is the one implicit in our study. Silicon-based PV technology will permit a tremendous expansion in PV electricity but most probably 'in spite of significant cost improvements, photovoltaic power will gain only niche markets'.

Let us analyse why crystalline silicon cell technology will fail to reach lower prices. From a model point of view it is the low learning factor of only 17.5%, compared to the 32% of semiconductor memories. Why is this factor so low for silicon cell modules? We are going to advance a suggestion. The reason is related to the nature of solar energy. Solar energy reaches the Earth in huge amounts but it comes to us in a relatively dispersed form. For the exploitation of a resource this is very important. Mineral beds are only exploitable if the concentration of ore is above a certain limit. Solar energy is a unique kind of mineral bed. Unlike other mineral beds, it is available everywhere but, as in many others, its resource concentration is modest. Not so modest to make it non-exploitable but modest enough to make its exploitation relatively expensive. Almost every collecting material—including those that are used only for support or auxiliary mechanisms—is already expensive. Making them cheaper is certainly necessary but extracting the ore with more efficiency is as important. However, in the classic single-gap PV cell and, in particular, in the silicon ones, only the energy of the photons that are close to the semiconductor bandgap is extracted effectively. For the remaining photons, the energy is extracted rather ineffectively or totally wasted. Consequently, the possibility of greatly improving the silicon cell behaviour is limited. The top efficiency of a single-gap solar cell is limited to 40% under the very best conditions. In contrast, the PV limit of efficiency when this limitation is removed goes to efficiencies of about 85% under the same very best conditions. Improving the efficiency of multi-junction solar cells is an active area of research today: 32% has been reached and 40% is a medium-term goal. This should be compared with the 15% of most commercial silicon cells or the 25% of the best laboratory silicon cell.

But multi-junction solar cells are not the only way of making better use of the solar spectrum. The authors in this book will present proposals that might realize second-wave PV generators.

From our model viewpoint, innovations based on a better use of this solar spectrum should lead to a faster experience factor since more improvements are possible and more things remain to be learned. As an exercise, let us consider

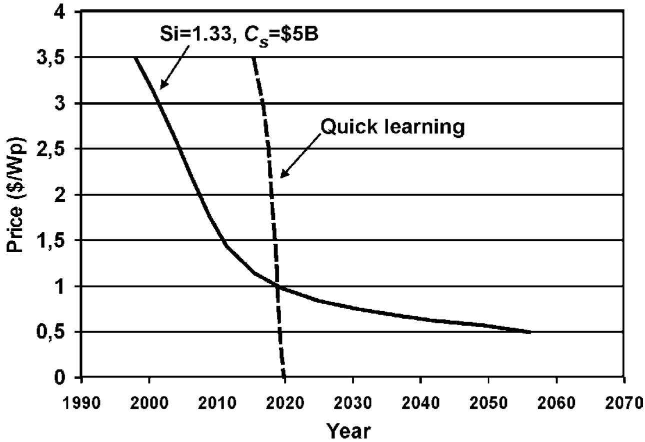

Figure 1.10. Cost evolution of a quick learning technology compared to the baseline case.

a solar converter learning at the rate of semiconductor memories (32%) that has been able to enter into the market and reach a cumulated market of 10 MWp by 2015 with a price in this year as high of 3.5$ Wp^{-1}. If this situation is reached, in four years such modules will be able to compete with incumbent electricity!

It might seem difficult to sell a technology that is so expensive compared with the concurrent silicon technology that, at that time, will cost only about 1$ Wp^{-1}, as shown in figure 1.10. Of course it would be better if the price of the new technology were to be smaller. However, most probably any new technology would start competing at a higher price and, therefore, it will have to have distinctive characteristics to make it attractive. Furthermore, someone will be forced to take an entrepreneurial risk to enable this product to expand. Anyway, from the model viewpoint, if the starting price were to be smaller, the price of competition would be reached slightly faster. We want, however, to stress again the importance of a fast learning curve, which is commonly associated with new technologies.

1.6 Conclusions

We are about to experience a revolution in energy. The social push towards deregulation, concerns about sustainability, the scarcity of oil by the second quarter of the century, the disrupting role of the ever present and modular PV technology, together with that of the hydrogen technology driven by fuel cells will all constitute the driving forces of this revolution.

Present-day silicon PV technology will be at the onset of this revolution. It will grow tremendously in this decade constituting one of the first big new economic activities of the 21st century. But then its growth will stagnate, as the cost-reducing capacity of present commercial PV technology is moderate.

One reason for this moderate cost-reducing capacity is in the poor utilization of the solar resource that is huge but dispersed. Only photons with energy close to the semiconductor energy bandgap will be used effectively. For the rest, their energy will be ineffectively converted or totally wasted.

A new generation (after silicon and single-gap thin films) of technologies making better use of the solar spectrum will constitute the second wave of the energy revolution announced by Shell. Its potential will be based on its stronger capacity for cost reduction by experience due to its higher limiting efficiency and to the fact that it will be based on novel and unexplored concepts.

This technology is not yet ready but, in this book, you will find the germ of many of the solutions which will form this second wave. For Shell, this will ripen in the second quarter of the century. We must do our best to start as soon as possible. The later we go to market, the more difficult it will be to displace the already established and cheap silicon technology. And we will need the support of silicon technology manufacturers, not their opposition, to succeed in marketing the potentially cheaper new technologies. This must be kept well in mind.

May the germ in this book blossom into actions leading to the establishment of the second-wave PV technology necessary to mitigate the adverse climatic changes and to permit higher equity in a world that must be based on enriching everyone.

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Chapter 2

Trends in the development of solar photovoltaics

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2.1 Introduction

Current civilization is based on mankind's economic and social experience of the organization of life, accumulated over thousands of years, resulting in increasing material consumption but also providing energy and information benefits. Radical alterations in the material base of civilization started at the end of the 18th century industrial revolution (just after the invention of the steam-engine). Since that time, scientific and technical progress has accelerated. To supply energy to power the various technical inventions, a powerful and gradually growing infrastructure leaning upon fossil fuel resources has been created. As it is easily converted into other types of energy, the consumption of electrical energy increases rapidly.

Nature has localized depositions of the fossil fuels necessary for operating thermal and atomic power stations. For this reason the maintenance and development of the fuel-powered complex has become a global problem and not only a technical one as, in many respects, it is also a political problem. However, mankind does not seriously concern itself with the fact that fuel resources are exhaustible and the ecological damage resulting from their use may, in the future, reduce their usefulness. Meanwhile, both these circumstances have already made themselves evident. The exploitation of new deposits of fossil fuels to replace exhausted ones becomes more and more difficult. The number of natural catastrophes is increasing and this is ascribed to the beginning of the 'greenhouse effect' resulting from the rise in the carbonic gas content in the atmosphere from the combustion of organic fuels. With an increase in the number of atomic power stations, the risk of technological catastrophes with serious consequences is growing.

At the present time, there is a growing conviction that the power industry of the future has to be based on the large-scale use of solar energy, its manifestations being quite different. The Sun is a huge, inexhaustible, absolutely safe energy source which both belongs equally to everyone and is accessible to everyone. To rely on the solar-powered industry must be considered not only a sure choice but also the only alternative for mankind as a long-term prospect. We shall consider the possibilities for converting solar energy into electricity by means of semiconductor photocells both retrospectively and for long-term planning. In both scientific and technological aspects, these devices are ready to be considered as a technical basis for large-scale solar photovoltaics of the future.

2.2 Starting period

Edmond Becquerel first observed the photovoltaic (PV) effect in a liquid–solid interface in 1839. W G Adams and R E Day in London carried out the first experiments with a solid-state photovoltaic cell based on selenium in 1876 [1]. It took more than a half of century for the creation of the first solar photocells with an efficiency barely exceeding 1%. These were thallium sulphide photocells with a rectifying region [2]. The investigations were carried out under the leadership of Academician A F Ioffe, who, in 1938, submitted a programme for the use of solar photovoltaic roofs to supply energy for consideration by the USSR government.

However, for the introduction of photovoltaics (even if we ignore economic considerations) essentially the devices needed to be more efficient. A decisive event in this direction was the creation in the USA in 1954 of silicon-based photocells with p–n junctions that were characterized by an efficiency of about 6% [3]. The first practical use of silicon solar arrays took place not on the Earth but in near-Earth space: in 1958, satellites supplied with such arrays were launched—the Soviet ‘Sputnik-3’ and the American ‘Vanguard-1’.

It should be noted here that the achievements in the theory and technology of semiconductor materials and semiconductor devices with p–n junctions provided the scientific basis for the creation of the first solar cells. At that time semiconductor devices were mainly applied as converters of electric power into electric power of a different kind (alternating currents into direct ones, HF generation, switching, and so on) or in electronic circuits for information processing and translation (radio, communication, and so on). In addition to the ‘classical’ semiconductor materials—germanium and silicon—materials from the A^3B^5 family group were synthesized. One such material—indium antimonide—was first reported by researchers at the Physico-Technical Institute (PTI) in 1950 [4]. Also at the PTI, at the beginning of 1960s, the first solar photocells with a p–n junction based on another A^3B^5 material, gallium arsenide, were fabricated. Being second in efficiency ($\sim$3%) only to silicon photocells, gallium arsenide cells were, nevertheless, capable of operating even after being significantly heated. The first practical application of improved gallium arsenide

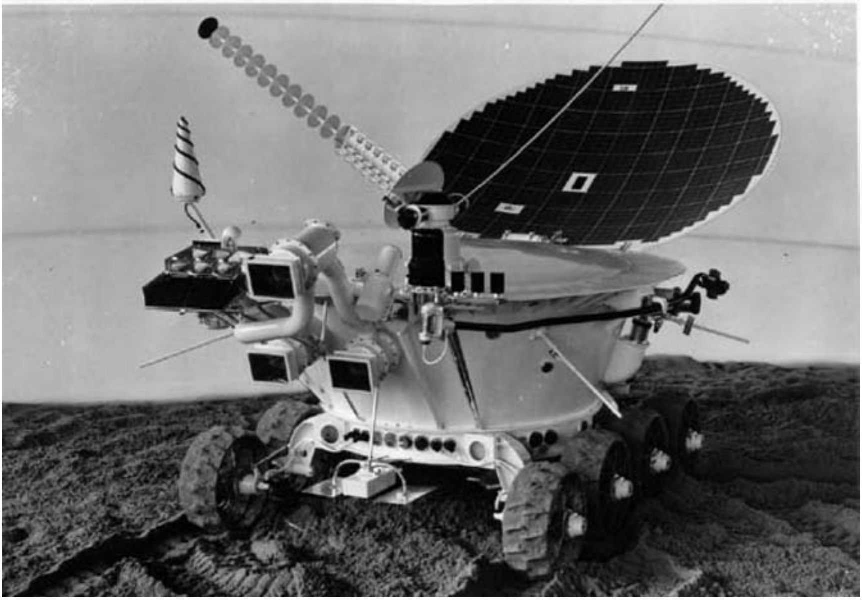

Figure 2.1. At the beginning of 1960s, it was found that p–n homojunction GaAs solar cells had a high temperature stability and were radiation resistant. The first applications of such cells took place on the Russian spacecrafts 'Venera-2' and 'Venera-3', launched in November 1965 to the 'hot' planet Venus and on moon-cars (see photograph), launched in 1970 ('Lunokhod-1') and 1972 ('Lunokhod-2').

solar arrays to supply energy was even more exotic than in the case of silicon ones (figure 2.1). They provided the electricity for the Russian space probes 'Venera-2' and 'Venera-3' operated in the vicinity of Venus (1965) as well as for the moon-cars 'Lunokhod-1' (1970) and 'Lunokhod-2' (1972).

2.3 Simple structures and simple technologies

The practical introduction of A^3B^5 materials opened a new page both in semiconductor science and in electronics. In particular, such properties of gallium arsenide as the comparatively wide forbidden gap, the small effective masses of charge carriers, the sharp edge of optical absorption, the effective radiative recombination of carriers due to the 'direct' band structure as well as the high electron mobility all contributed to the formation of a new field of semiconductor techniques–optoelectronics. Combining different A^3B^5 materials in heterojunctions, one could expect an essential improvement in the parameters of existing semiconductor devices and the creation of new ones. Again, the contribution of the PTI (Ioffe Institute) can be seen to be valuable. Here, in the second half of 1960s and the first half of 1970s, pioneer work on the fabrication and investigation of 'ideal' heterojunctions in the AlAs–GaAs system was performed with the main purpose of making semiconductor injection lasers more perfect. Heterolasers operating in the continuous mode at room temperature were fabricated and these first found application in fibre-optical communication systems. Ways for using multi-component A^3B^5 solid solutions for the creation of light-emitting and photosensitive devices operating in different spectral regions were also pointed out.

One of the results of the study of heterojunctions was the practical realization of a wide-gap window for cells. This idea had been proposed earlier and had the purpose of protecting the photoactive cell region from the effect of surface states. Defectless heterojunctions using p–AlGaAs (wide-gap window) and (p–n)GaAs (photoactive region) were successfully formed; hence, ensuring ideal conditions for the photogeneration of electron-hole pairs and their collection by the p–n junction. The efficiency of such heteroface solar cells for the first time exceeded the efficiency of silicon cells. Since the photocells with a gallium arsenide photoactive region appeared to be more radiation-resistant, they quickly found an application in space techniques, in spite of their essentially higher costs compared with silicon cells. An example (figure 2.2) of a large-scale application of the heteroface solar cells was a solar array with a total area of 70 m^2 installed on the Russian space station 'Mir' (1986).

Silicon and gallium arsenide, to a large extent, satisfy the conditions of 'ideal' semiconductor materials. If one compares these materials from the point of view of their suitability for the fabrication of a solar cell with one p–n junction, then the limiting possible efficiencies of photovoltaic conversion appear to be almost similar, being close to the absolute maximum value for a single-junction photocell (figure 2.3). It is clear that the indubitable advantages of silicon are its wide natural abundance, non-toxicity and relatively low price. All these factors and the intensive development of the industrial production of semiconductor devices for use in the electronics industry have determined an extremely important role for silicon photocells in the formation of solar photovoltaics. Although considerable efforts have been expended and notable advance has been made in the creation of different types of thin-film solar arrays, crystalline silicon (both in single- and poly-crystalline forms) still continues today to make the main contribution to the world production of solar arrays for terrestrial applications.

Until the middle of the 1980s, both silicon and gallium arsenide solar photocells were developed on the basis of relatively simple structures and simple technologies. For silicon photocells, a planar structure with a shallow p–n junction formed by the diffusion technique was used. Technological experience on the diffusion of impurities and wafer treatment from the fabrication of conventional silicon-based diodes and transistors was adopted. The quality of the initial base material in this case could rank below that of the material used for semiconductor electronics devices. For fabricating heteroface AlGaAs/GaAs solar cells, as in growing wide-gap AlGaAs windows, it was necessary to apply