Advances in the Photovoltaic Field through Light Manipulation

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By

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Diversity is another name for science because it leads to innovation.
Through innovation, people have been able to recognize and better understand many natural phenomena throughout history.
This is one such story.

TABLE OF CONTENTS

Preface viii

Notes for the Reader ix

Acknowledgements xiii

Chapter One 1
Light manipulation and innovation
General introduction and problems in photovoltaics 1
An optical system for cooling, light manipulation, and improvement of the photovoltage response of solar cells 3
The general principle of operation of the WFL system 8
References 14

Chapter Two 22
An overview of tested solar cells
Application of the WFL system and light manipulation to dye-sensitized solar cells 23
Application of the WFL system and light manipulation to monocrystalline, polycrystalline, and amorphous Si-solar cells 32
Application of the WFL system and light manipulation to solar cells based on synthesized doped and undoped Sb_2S_3 semiconductors 41
Conclusion 55
References 58

Chapter Three 65
Light effects from the perspective of experimental results
The solar spectrum and particle photon approach 65
Solar cell efficiency 69
Experimental results and deviations from conventional measurements caused by light manipulation 72
References 81

General conclusion concerning light effects 88
References 94

PREFACE

The term "discovery" in science in the past has usually been called the product of successful investigation. The tests were mainly performed with the help of constructions or aids in science, which today we call innovations in that aspect. Many scientific phenomena and effects in the past were unknown, so researchers were able to observe and try to explain them with the help of a designed and engineered aid (i.e., the whole experiment). People had to be much more inventive in performing experiments and designing the various aids mentioned in performing scientific experiments due to the lack of today's technologies and scientific instruments. This difference in the performance of scientific experiments has contributed to the possibility of looking at discoveries from diverse perspectives (we often say the possibility of looking at a problem from a completely different angle than usual), and this is exactly what leads to a better understanding of science and discoveries in general. As science developed, so did the new generation of instruments for their performance and measurement. With the development of instruments and digitalization, there was a need for uniformity in science. Uniformity has largely eliminated the innovative element of scientific research in terms of the fact that uniformity stands on the opposing side of diversity.

NOTES FOR THE READER

Through this part of the text, I would like to take you through a story whose meaning should be the will and desire to do something, as well as the fact that when you own it, then other mostly material things that you do not have will work in your favor and not to your detriment. In this part of the text, I will try to write in the simplest possible way without going into scientific details as much as possible, in the hope that this note can be understood by the general population, anyone interested in science and research, as well as anyone wanting to learn more about the use of solar energy.

This story related to work in the photovoltaic field began approximately decades ago with syntheses of the semiconductor antimony sulfide, Sb_2S_3. This semiconductor, which belongs to the V-VI group, is well-known to be suitable and quite promising as a material for application in the solar cell. We were extremely surprised concerning the insufficient knowledge about the mentioned semiconductor, which is considered, according to the scientific literature, to be promising for application in every respect of the electronic and optical properties relevant to the application. So, the first steps were to perform high-temperature organic synthesis for the purpose of understanding the growth mechanism and obtaining non-doped and doped Sb_2S_3 amorphous and crystalline nanoparticles of different shapes. Both the growth mechanism and the nanoparticle morphology are quite important for solar device applications. The kinetic control of the reaction allowed tuning of the electronic properties such as the optical bandgap of the nanoparticles, while the shape of the synthesized nanoparticles can play a significant role in electron transfer in the designed solar devices. For example, high aspect ratio nanowires are desirable for industrial applications, whereas small bandgap energy-designed materials are suitable as absorbers for solar cells (the main issue with this material is the optical band gap (found in the literature ranging from 1.7–2.2 eV), which is slightly higher than the ideal value (~1.4 eV) for a solar cell absorber). As a result, Sb_2S_3 with a small bandgap could be an intriguing semiconductor with unique optoelectronic properties. Unfortunately, as we already mentioned, many electronic and optical properties were not known at that time, nor were any reported syntheses of doped antimony sulfide nanoparticles. Therefore, our research related to the synthesis of applicable nanoparticles of this semiconductor, as well as the experimental characterization of the obtained material, had to go hand in hand with theoretical derivations. The theory had to be confirmed and help the experiments better understand the obtained material, i.e., the mentioned material in general. By combining experimental and theoretical results, confirmations, and help from both sides, we can know we are on the right track to learning things about materials for which we have insufficient knowledge. We will give just one example of the importance of the above-written piece in an understandable way to a broader audience of readers. Generally speaking, nanoparticles are synthesized in the domain of materials not only to have smaller dimensions but also to distinguish their unique electronic properties from those of bulk material. For those synthesized nanoparticles to fulfill the demand for different electronic properties compared to bulk materials, they must reach certain nano dimensions, which are different for different semiconductors. That effect is named the quantum confinement or size effect. In theory, quantum confinement effects become significant when one dimension of the nanocrystal approaches the de Broglie wavelength of electrons and holes in bulk semiconductors, $\lambda_e = h / (2m_{eff}\, kT)^{1/2}$, where m_{eff} is the effective mass of the electron (or hole for λ_h). λ_e and λ_h are typically 10–100 nm for most semiconductors. Unfortunately, we were unable to locate effective mass values for Sb_2S_3 in the literature. We discovered a lot of literature claiming to have observed quantum size effects when one dimension of a nanocrystal is quite large (50–100 nm, and even larger) and it receives a band-gap energy value of more than 1.7–1.8 eV. We are adamant that this problem be resolved. Furthermore, the excitons' Bohr radius, a_{ex}, which describes the characteristic separation of a bound electron-hole pair in a bulk semiconductor, is an important length scale. Excitons are quasiparticles composed of bound electron–hole pairs that are attracted to one another via the Coulomb potential. Because the exciton binding energy in most bulk semiconductors is low in comparison to kT at room temperature, electrons and holes are not bound. However, when the dimensions of the synthesized semiconductor nanoparticles are reduced to less than the a_{ex}, quantum size effects begin to play an important role. It was the theory combined with the experiments that provided us with the answer about the critical particle size that we have to reach to be able to invoke the effect, while all previous claims about the quantum size effect were reduced to an assumption. At that time, in the infancy of the development of materials for application in solar cells, in 2012 I gave a lecture at an international conference in Rhodes, where I met Prof. Dr. Daniela Vanmaekelberg from the University of Utrecht. Since I was a Ph.D. student and received my doctorate at Utrecht University, I knew the professor from previous collaborations with his group. Because of my work on the development of antimony sulfide semiconductor materials for possible use in solar cells, the professor invited me to attend the Quantsol workshop, organized by the European Society for Quantum Solar Energy Conversion, of which he is president. I was delighted with his invitation and joined the meetings the following year. The group was built by eminent professors who dealt with solar cells, materials, and theoretical physics. Until that time in our research, we mostly dealt with the synthesis and characterization of materials, both experimental and theoretical, and from that point, it was clear that we would have to go a step further toward the application and production of solar cells to show the application side of our synthesized material. Since then, our story related in the first place to the design of solar devices has begun.

Considering that no one in our institute was previously involved in the design of solar cells and that the infrastructure did not exist, in the initial steps, it was difficult. We only had instruments, such as a nano voltmeter and a multimeter, to measure the current-voltage dependence and the dark current. Because our first synthesized materials were crystal samples of antimony sulfide semiconductors, which morphologically included only elongated shapes such as wires, rods, and bars, many methods of film deposition, such as deep and speed coating, were not useful. Having no further infrastructure that could help us, we set out to manually design and build a system for dispersing synthesized nanoparticles and making films on the conductive glass that has been advanced over time. It should be emphasized that making perfect films from a synthesized semiconductor nanoparticle on a conducting glass as one of the electrodes is one of the first steps in making solar cells. Over time, there have been many attempts to improve the design of solar cells, which primarily refer to good contacts in the cell, cheap solutions for the second electrode, an attempt to replace the liquid electrolyte with the synthesis of cheap electrolyte carriers, and the cheaper and more economical synthesis of conductive polymers. We should only mention here in general that cheap technology and the design of solar cells are crucial because the market is always seeking, and always will, more inexpensive solutions than the existing ones. However, it should be emphasized that the ratio of cost to efficiency represents the true measure of an economic solution.

The next problem we encountered was a sun simulator, for which we did not have the resources to provide, so we had to solve the problems of illumination devices as well as cool the surface of the solar cell. We purchased halogen and tungsten lamps, whose spectra closely matched that of outdoor light, to illuminate the solar devices we built. It should be emphasized that in indoor measurements on experimentally made solar cells, various artificial light lamps are used, which simulate outdoor lighting well, xenon, halogen, tungsten, and others. These same types of light lamps are also found in sun simulators. To solve the problem of cooling the surface of the solar cell, we created optics with flowing water in which the water that serves for cooling is not in direct contact with the solar cell. Since the cooling system also contains an optical segment, convex lenses, we could change the intensity of light as well as their spectra, which can affect the current-voltage response of the solar cell. It should be emphasized that cooling the surface of solar cells and panels is extremely important, both at higher intensities and at lower intensities on a longer time scale, because of the devastating effect of temperature on the material from which solar cells and panels are made, and so for their longer life.

In the beginning, we were not even aware of how much this construction of the optics with indirect cooling of the surface of the solar cell or panel would help us manipulate the spectra at higher as well as lower light intensities, nor did we understand the significance of that. In addition, the issue of cooling the surface of the solar panel was significant for the life and durability of solar panels, especially at higher light intensities and concentration effects. At the time when we constructed optics, only sporadic scientific papers showed that even at lower light intensities (depending on the lamp used, which is usually associated with the difference in radiation spectra apart from another possible light effect), we could get better efficiency from solar cells than at higher ones. From that moment, we start working toward manipulating light intensities and spectra to obtain a better photovoltaic response or efficiency and try to comprehend the obtained measurements on different solar cells and understand the possible additional light effects.

ACKNOWLEDGEMENTS

The book was written entirely by the author, but some of the results represented in the book are the cooperation with other scientists and their universities through jointly published scientific papers. Although the book is dedicated to optics and light manipulation as well as reflectance on the solar cell's measurements, the beginning of this research starts with the development of materials for solar cells. That is why everyone with whom the author has worked from the very beginning deserves gratitude. The author wishes to express his heartfelt gratitude to all of the scientists who, directly or indirectly, assisted him in his work or influenced the author's opinion or attitude formation.

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CHAPTER ONE

LIGHT MANIPULATION AND INNOVATION

General introduction and problems in photovoltaics

Environmental exploitation caused by the traditional harvesting of energy (combustion of fossil fuels), as well as the fact that the overall reserves of global energy potential (natural gas, uranium, coal, oil) have been drastically reduced recently, lead to the immediate search for alternative energy sources.[1,2] Sunlight, biomass, wind, and marine energy are vital and renewable energy sources for the twenty-first century.[3-6] Their potential utilization is still unsatisfactory. Among these cost-free renewable sources of energy, solar energy is the most abundant. However, the use of solar energy compared to the potential is still negligible. In a single hour, the amount of power from the sun that strikes the Earth is more than the entire world consumes in a year. Light (or electromagnetic energy) can be harnessed for a variety of applications by converting energy from one form to another, of which the most important ones are generating electricity with photovoltaic (PV) cells and heating water. A solar cell, also called a PV cell, is a device that converts the energy of light into electrical energy through the photoelectric effect. In 2019, only 11% of global primary energy came from renewable technologies, and around 1% of global energy came from solar technologies. It is hard to believe that there is such a powerful source of energy as the sun without us being able to use it more efficiently than we have so far. Logically, there are things we do not understand well enough and, therefore, do not use effectively.

Most scientists in this field agree on a few facts about solar cells. One of them is that the low efficiency and high cost of currently used solar PV systems, a part of their reliability and durability, are one of the primary reasons for their reduced availability and usability.[7] For photovoltaics to become a more mainstream and pragmatic energy source, the efficiency of solar panels will need to improve drastically. This idea is in line with Goal 7 of the Sustainable Development Goals of the United Nations. It should be emphasized here that the reported maximum silicon (Si) solar cell efficiency is 29%, which is quite higher than the most efficient solar cells obtained in a laboratory, that is 25%[8] and large-area commercial, 24%[9,10] cells.[11]

It is clear that the most efficient crystalline Si-solar cells have almost reached their theoretical maximum efficiency, so it is not clear how efficiency could be increased "drastically'' with today's knowledge. For now, the theoretical solar conversion efficiency maximum is around 33.7% for a single p-n junction with a bandgap of 1.4 eV, determined by the Stockley-Queisser Limit.[12] Apart from the fact that efficiency is not the only limiting parameter, in reality, the efficiency/cost ratio must be considered. Also, the fact that the most efficient crystalline Si-solar cell has almost reached its theoretical maximum efficiency means that the competitive product has to be significantly cheaper, apart from their reliability and durability, with still good efficiency. Further, polycrystalline and monocrystalline Si solar cells are leading the photo-voltaic market, constituting more than 93% of the market with a development history of nearly 70 years. All the other types of cheaper solar cells (dye-sensitized, thin-film PV, organic, perovskite, etc.) that are currently on the market or will appear soon as cheaper products, will hardly manage to compete with Si-solar cells in terms of material abundance, safety, and improved technology. We do not have decades before all fossil fuel reserves disappear to upgrade and improve new solar cells made from a material that is not even remotely represented as silicon. So, any cheaper type of current or new solar cell or module design can serve more as a backup than a replacement for Si-solar cells. Photovoltaic (PV) energy is on the edge of becoming one of the main global sources of energy, and crystalline silicon will dominate the market with no sign of change in the near future. As was mentioned, in the last 20 years of development, the efficiency of crystalline Si cells has increased from approximately 21% to 26%, reaching an almost theoretical maximum.[13,14] After so many years of improvements, it is difficult to find a way in which efficiency can be drastically increased through the design of solar cells or panels. Furthermore, a major issue in photovoltaics is reliability and durability, with material properties such as temperature resistance (cooling the surface of solar panels to maintain room temperature) being required to meet a photovoltaic product's longer lifetime warranty. The exposure of the material from which the solar panels are made to high temperatures (in the absence of a permanent cooling solution) changes the electronic properties of the material, such as the energy gap on which the photo effect depends. Other officially stated problems, such as manufacturability (searching for disruptive new cheap materials), subsidies (a challenge to the photovoltaic industry regarding subsidy problems), and regulation (competitiveness of photovoltaics to other energy sources), have either been mentioned or have an indirect impact on the mentioned challenges.

It should also be noted that the efficiency of solar cells is not the only or most important parameter in designing PV devices (the only parameter by which one should judge whether or not something is promising), particularly when it comes to their performance in low light. We've been attempting to comprehend the significance of low light and how it can be used, primarily for the purpose of comprehending it and then developing efficient PV devices. Standard low-light conditions have yet to be established, but they are required to exist as guidelines for our research. As a result, the efficiency of the PV devices under standard testing conditions (STC) should not be compared to efficiency under conditions that have not established the low light standard testing conditions. If we do not understand why the same solar devices exhibit higher efficiency at lower light intensities than at higher ones, it means that those values are incomparable. In this regard, perhaps the solid efficiency of cells at low light intensities with low-cost technology in the majority of Earth's conditions could compensate for the higher efficiency in rare and extreme conditions of the established standard testing conditions, STC (irradiation of 1000 W/m^2, module temperature of 25°C, and standard spectrum AM 1.5).[15-21] In other words, there is a good chance that cells with the same efficiency as those operating under the extreme conditions of standard testing conditions (STC) can be designed to have a specific spectral distribution of low-intensity light. Light cannot be changed at different intensities, but different designed lens systems can change its distribution at different wavelengths. This knowledge will be incorporated into future cell technology as soon as one understands how to change the spectral light distribution and determines the most optimum one for the fabricated low-light intensity cells with high efficiency.

Therefore, finding ways to improve the operating characteristics and the general efficiency of the available and currently developed technology by expanding our general knowledge, on the one hand, and trying to solve all the other more technical problems mentioned, on the other hand, are the most important tasks.

An optical system for cooling, light manipulation, and improvement of the photovoltage response of solar cells

In this part, it will be explained the significance and importance of light manipulation through innovation (water-flow-lens (WFL) system) for better and more efficient output (enhanced electricity production) of the tested solar devices, presented in this book. Manipulating sunlight spectra and intensity through innovative design to increase the efficiency of solar devices is one way to expand our knowledge of the effects of light and make significant progress toward better solar energy utilization. By the term "manipulation," we primarily allude to light phenomena for which we do not yet have an explanation, such as the dominantly higher efficiency of solar devices than expected at lower light intensities and non-uniform or non-linear basic current and voltage characteristics of the solar cells, which at least depend on the light spectra and intensity as well. Only with a better understanding of the light effects, we will make progress in harnessing the sun's energy. It should be noted that the amount of solar energy flux that reaches Earth is determined by the geographical area's latitude. Annual solar irradiation exceeds 1600 kWh/m^2 in some parts of the United States, Africa, the Middle East, and Australia. Other parts of the Earth receive far less solar irradiation, so it is critical to research and develop solar cells that can operate at lower light intensities. Along with developing new solar cells, the goal of the research is to achieve high efficiency at low light intensities.

Our original construction of the optics, the WFL system, technically solves the manipulation of light spectra and intensities while simultaneously cooling the surface of solar panels. In many published scientific papers[22–34], we explained the necessity of such a construction as well as the importance of manipulating light through the design of the WFL system for more efficient output of existing solar devices, and that is why we consider ourselves pioneers in this field of light manipulation, especially at lower light intensities. The optical systems for cooling, light manipulation, and improving the photovoltaic response of commercial solar panels are designed and built so that certain natural external changes are monitored and controlled by solving several technical problems at the same time. Apart from changes in the light spectra and intensity, there are also additional effects of the interaction of light with different environments on the way light reaches the surface of the solar cells. Usually, each of the above-mentioned issues, such as cooling the surface of solar panels or increasing light intensities to increase electricity production, is considered and solved separately. However, effects in nature related to heating, changes in the angle, intensity, and radiation spectrum of the sun are combined effects that act in nature simultaneously. It should be emphasized here that the designed optical system with a flowing water system allows us to combine several technical solutions into one optical system, the WFL system. This primarily refers to technical solutions, surface cooling, increasing and decreasing light intensities, as well as light spectra manipulations that are achieved after the passage of external light through the optical part with flowing water on the carrier. As was mentioned, additional light effects and the interaction of light with different environments have been studied through different experiments. Cooling of solar panels is extremely important and cannot be left out. Since solar panels are not in direct contact with water, this WFL system is significantly safer for cooling and allows solar panels to live longer since they are covered with optics. Simultaneously, the system enables cooling depending on the speed of water flow and at a concentration effect, i.e., far higher light intensities than standard test conditions. Further, the manipulation of light spectra at lower (lower than the standard test conditions (STC) of 1000 W/m^2) as well as higher light intensities (higher than STC) causes significant increases in the efficiency of solar panels, leading to higher electricity production.

The importance of the essence of this design will be explained in more detail below. We already mentioned that there were two directions for improving the photovoltaic area, i.e., the production of a larger amount of electricity from solar panels. One direction is related to the design of new solar panels or materials from which solar panels are made, as well as the design of photovoltaic devices, in order to achieve cheaper, more reliable, and durable products than today's most commonly used silicon solar cells.[35-37] Because of the still too high price of currently used solar panels, this direction could be called a low-cost approach. As we already mentioned in this chapter, this approach is not realistic to achieve (in a sense of silicon replacing) due to the theoretical maximum efficiency of Si-solar cells in a very extensively developed technology in the last 70 years on one hand, and the abundance of silicon on the other hand.

The second direction covers finding a more effective way to use already designed panels in terms of reducing the cost of electricity production or better utilization. This second direction includes everything required to maintain and use solar panels at their maximum possible use[38], and these are surface cooling systems for panels[39-41], optics to improve the photovoltaic response of solar panels[42-44], and a crucially important segment, which includes manipulating light intensities and light spectra (aside from the additional light effects)[45–47] to produce more electricity. Our designed optics with flowing water belongs to the second described direction of improving the operation of solar panels and the production of a larger amount of electricity. To additionally emphasize, by the term “manipulation of light intensities and spectra”, we primarily allude to light phenomena for which we do not yet have an explanation, such as the higher efficiency of solar devices primarily at lower light intensities, which clearly at least depends on the light spectra. Moreover, when we say there is no explanation, we primarily mean the additional light effects, which we still do not understand, and the real nature of light, both particles and waves, which should be in accordance with the observed effects.

It is widely acknowledged and accepted that one of the requirements for the successful application of solar panels is that the surfaces of the panels be kept at a tested temperature of 25 °C. [48-50] It should be noted that the change in solar panel efficiency is not strongly related to the tested temperature and occurs at temperatures lower or higher than the tested one, expressed as a percentage of temperature coefficients, illustrating the change in solar panel efficiency with increasing or decreasing temperature. As defined by the Standard Test Conditions (STC), an elevated test temperature greater than 25 °C causes a drop in the conversion rate of between 0.40 % and 0.65 % per degree Celsius. [51,52] Apart from the cooling technique, the increase in electrical efficiency is determined by the size and type of solar panel device, as well as the season of the year and geographical location (light intensity, light spectra reaching the surface of the solar panel, and the angle at which light falls) and increases overall efficiency and electricity, respectively. In general, the intensity of solar radiation and the quality of semiconductors from which the solar panel was made are factors we can control, while variations in solar radiation or solar spectra reaching the surface of the solar module cannot be controlled.[53] Broadly speaking, various semiconductors used in solar cell modules have different band gaps, which represent an electronic characteristic of a given material. As a result, the entire spectrum of solar radiation is ineffective for photoelectricity, and only photons with energies equal to or greater than the bandgap of the PV material used are useful. The remaining photons in the solar spectrum will dissipate their energy as heat, lowering the output of the PV cell or module. Therefore, we need to eliminate the unnecessary solar radiation spectrum (to avoid heating) and maintain the cell surface at an ambient temperature. This cannot be done if there is no filter/cooling system with a liquid, which results in changes in light intensity and spectra as light passes through different environments.[26] In this manner, realistic, reduced light intensities and the impact of altered light spectra on the efficiency of commercial solar panels are realities, and we should try to understand them. However, if we want to get higher electricity production and better use of solar energy, we have to manipulate different light intensities and different light spectra and try to understand all the additional light effects. This cannot be implemented without an optical design like the WFL system (or some similar construction), a system with the effect of cooling, reducing and increasing the light intensity, and modifying the light spectra that reach the surface of the solar panels, apart from the additional light effects that it can cause. When we talk about lower light intensities and light spectra, it should be emphasized that their changes are very important, as well as the interaction of light with the environment, which is also sometimes very complex to understand. By constructing an optical system with flowing water, we have shown so far that by modifying the light spectrum, for the same light intensity (both at lower and higher light intensities), the system, therefore, constructed, increases the efficiency of solar cells, in the first place of silicon solar cells, dye-sensitive solar cells, and our designed and based on synthesized doped and undoped antimony-sulfide solar cells.

Apart from intensity reduction and changes in the spectra, there is also an additional relevant issue concerning the fact that when narrowing down the spectral distribution, conversion efficiency increases significantly.[54,55] But when we go down in light intensity, and the fact is that we do that with any filter/cooling system, then things are not so simple and must be viewed from another perspective. Huge changes in the efficiency of the same device at low and lower light intensities can be produced by different artificial light sources that simulate outdoor radiation and which, in fact, have broadly similar spectra. Additionally, most experiments performed at lower light intensities have been carried out by using artificial light sources so far. For this reason, combining outdoor and indoor experiments could be one way of understanding the behavior of PV devices at both realistic, different spectra and low or lower light intensities. Besides, a significant concentration-effect should be mentioned. Broadly speaking, optical components have been used so far to concentrate sunlight and focus it on solar panels, increasing the light intensity several times. In this way, the production of electricity increases[56-58], but the mutual effect with the cooling system at the same time on the surface of the solar panels is not solved. Our designed WFL system enables cooling depending on the water flow velocity and with a concentration effect. The joint effects are very significant because they, as such, combine to exist in reality and work together. In the described construction, we combine everything that has been proven over years of research to be the best way to improve the operation of solar panels and increase electricity production, which is water. As a proven best medium for cooling, water flow because it has been shown to increase the electrical yield, manipulation of light intensity as well as light spectra that produce a better photovoltaic response, and the effect of concentration, which always increases the electrical yield. It is significant to emphasize here that the simulation of combined effects achieved by simulating external conditions leads to the effect of an increase in current production even at lower light intensities with appropriate light spectra. Through experiments, the optical construction made in this way helps us try to go deeper into the nature of light, as well as additional light effects, and try to understand the ambiguity.

For instance, in photovoltaics, light is, in most cases, only discussed in the form of photons as particles. However, because of optics and the fact that light passes through different environments, we have every right to consider the phenomenon from the perspective of a wave point or the photon as a wave. Further, we noticed that the V_{oc} and I_{sc} without the use of the WFL system mostly obeyed the role that decreases with decreasing light intensity independently of spectra (there are also expectations observed for this rule without additional light manipulation). That role drastically changes after passing the light through the optical system. That should not be the case if we look at light only in the form of photons, but we discussed this issue in the last chapter of this book.

The general principle of operation of the WFL system

So how does the optical system operate? Briefly, the WFL system technically solves the manipulation of light or light spectra that reach the surface of solar panels at both higher and lower light intensities while indirectly cooling the surface of solar panels. Since the solar panel is completely covered with optics, the life span of use of solar panels is greatly extended, which is also a significant form of savings. Depending on the position of the optical part through which the cooling water flows (by approaching and moving the optics away from the solar panel, as well as moving the optical part at various angles in relation to the plane of the panel or module), we can manipulate both light intensities and light spectra. Depending on the position of the optical part, we can either have a concentration effect in which the light intensity increases, or a reduced light intensity with simultaneous indirect cooling. At both lower (than the standard testing conditions of 1000 W/m^2) and higher light intensities, when light passes through the optical system, at least the light spectra that reach the surface of the solar panel change. The change of light spectra even at lower light intensities provides a higher efficiency of solar panels, i.e., higher electricity production. Water that flows through the designed optics all the time indirectly cools the surface of the solar panels by cooling the outside environment. Depending on the light intensity, the water flow velocity can be changed, allowing the panel surface to be kept constant at the standard temperature for the panel operation.

In brief, the optical/lens system consists of two curved glass lenses (two convex surfaces in the spherical form) through which cold water circulates continuously, while the thickness of the water layer at the widest central part is the thickest (figure 1). Water pipes are integrated into the lens's inlets and outlets while the system remains completely closed and safe for use. Because the water layer is not in direct contact with the cell's surface, the cooling is related to maintaining an outdoor temperature.

Figure 1 shows photographs of the basic settings for indoor measurement with the WFL system using the halogen (A) and tungsten (B) lamps as the artificial light sources and outdoor measurement with natural radiation (C).

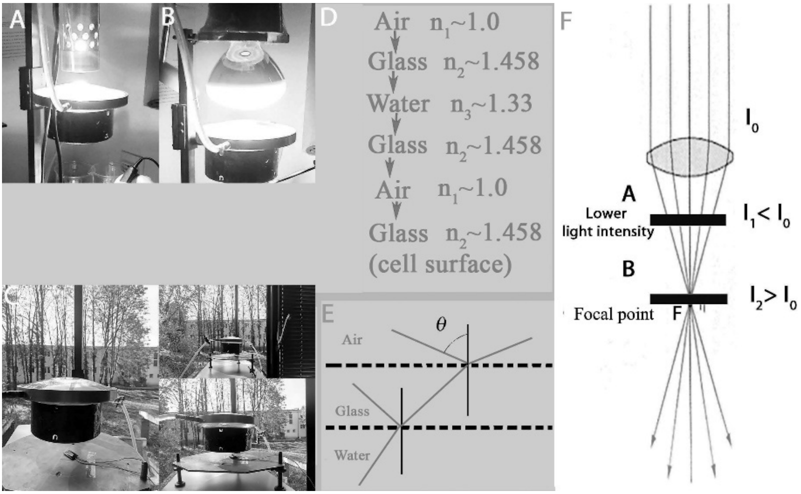

Figure 1. Photos of the basic settings for indoor measurement with the WFL system using the halogen (A) and tungsten (B) lamps as the artificial light sources and outdoor measurements with natural radiation (C). The solar cell is located under the holder of the optical part in the image at a different distance from the optics. The schematic structure is composed of the interface through which light passes, air-glass-water-glass-air glass (cell surface) with corresponding refractive indexes (D), and a ray of light striking the air-glass interface from the upper level, transmitting into the glass and then striking the glass-water interface (E). A schematic view of a lens and the two possible positions of the solar cell compared to the light source, with the lower light intensity than the incident light (A) and a concentration-effect (the higher light intensity) at the focal point (B).

In the figure, photographs of the WFL system used for cooling (flow glass water lens), reducing the intensity of light, and changing the light distribution (spectra) are shown. As well, figure 1D shows the schematic structure composed of the interface through which light passes, composed of the interfaces air/glass/water/glass/air/glass (cell) with a corresponding refractive index. The picture shows (figure 1E) a ray of light striking the air-glass interface from the upper level, transmitting into the glass, and then striking the glass-water interface. It can be noticed that at each interface, some of the rays reflect. Among other things, the behavior is affected by the incidence angle, Θ, which is affected by the reflection losses in the PV system.

Furthermore, it is well known that when a layer of water is hit by a solar ray or light, it selectively filters the various wavelengths of the light, acting as a chromatic filter. Red color (longer wavelengths) absorbs the most strongly, while violet color (shorter wavelengths) absorbs the least.

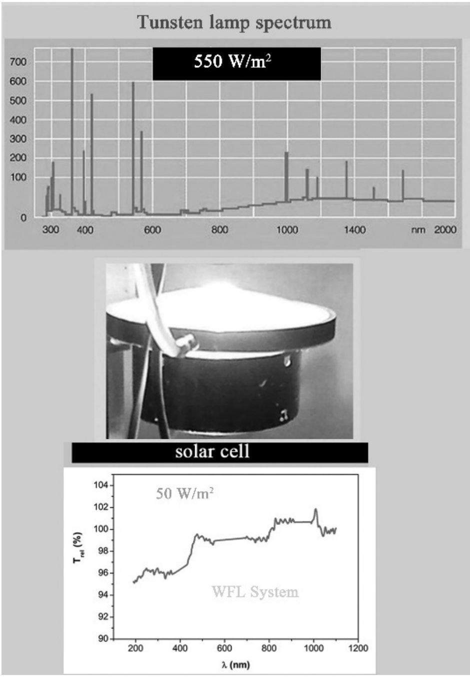

Figure 2. A schematic representation of the spectra of a high-pressure tungsten filament lamp, as well as a photograph of the WFL system used for cooling (flow water glass lens), reducing light intensity (from 550 W/m^2 to 50 W/m^2), and changing light distribution. The figure also depicts the wavelength dependence of the relative transmittance with the use of the WFL system compared to the transmittance of the tungsten lamp without it.

The wavelength dependence of the relative transmittance with the use of the WFL system, compared to the transmittance of the lamp without them, was used to confirm this effect in figure 2. The obtained results show minimal permeability in the UV region (up to 375 nm) and an almost constant value in the visible and NIR regions, with no significant difference in relative transmittance between 460 and 790 nm. It is important to emphasize that the minimum transmittance in the UV regions results in a better match between the tungsten lamp spectrum and the halogen spectrum. More about the evident difference between different artificial lights that have been used for performing indoor experiments and that quite well simulate outdoor radiation is discussed in the last chapter of the book. Here it will be only mentioned that by comparing the spectra of tungsten and halogen lamps, the mismatch is evident in the infrared (IR) and the ultraviolet (UV) parts of the spectrum. [59] We also have additional effects when building the WFL system, one of which is the depth of water in the thickest part of the constructed lenses. Given the thickness of our water layer at 4 cm, it has been proven and demonstrated[26] that the constructed WFL system eliminates a significant portion of the spectrum above 1000 nm. It is also worth mentioning that water causes an increase in the length of the radiation path in water, which is an important parameter for understanding the solar spectrum modification in water. Taking all of the mentioned effects of water into account, we can conclude that the dominant narrow energy part of photons from 550 to 600 nm arrives at the surface of solar cells. Water is also shown to reduce the impendence of incoming radiation and behave like graded glass. Furthermore, it should be noted that it is widely accepted that only water (mostly related to PV panels submerged in water) cannot increase the short-circuit current of the PV cell, regardless of the spectrum of the incoming radiation or the depth of the water. However, it has been reported that increasing water depth results in higher photoelectric efficiency for all tested commercial cells.[60-67] The photoelectric efficiency will differ because each material has a different energy gap, but greater water depth also means a different distribution of light spectra at any depth. So far, our experiments have shown that at low light intensities, the distribution of light cannot be ignored, and appears to be more dominant than the intensity of light itself. To understand this, we must first understand and connect the electronic properties of the material with higher and lower light intensities, as well as the light spectra reaching the surface of the solar cell or module. Furthermore, the behavior of solar radiation through a fluid such as water, heat transfer oils, therminols, fluids[68-71], and so on has been theoretically reported. However, there has been relatively little experimental work to date. About 40 years ago, J. D. Stachiw[72] focused on the possibility of obtaining a significant amount of energy in deep water. In 2010[73] and 2011[60], a systematic study of the behavior of photovoltaic (PV) cells in shallow water was conducted. Morel[74] investigates the effect of water on solar radiation, confirming previous findings and extending the comparison with seawater through numerical simulation.[62,63] These findings were then applied to solar pond technology and water desalination[75], as well as the spectral response and efficiency of silicon solar cells in the presence of a water layer[64]. In 2014, the first direct test of a submerged module's behavior was carried out. There have been reports of attempts to use PV underwater (UW) to increase the long-endurance power sources of UW autonomous systems and sensor platforms.[76] The Naval Research Laboratory (USA) is currently working to reduce the cost of solar cells matched to the UW spectrum by using organic solar cell materials.[67] Other attempts, primarily theoretical in nature, were made to investigate the thermal performance of PV module encapsulation and front covers.[77] Following that, these findings are applied to PV systems to improve their performance. The cooling of a concentrated PV system by immersing the solar cells in liquids[78], as well as the increased electrical yield via water veil on PV modules[79,80], are being investigated. According to the theoretical approach used for submerged PV modules[23], the integrated maximum response of the PV cells versus water depth decreases slightly for lower bandgap materials and increases significantly for higher bandgap materials. The plot of relative efficiency versus water depth, on the other hand, shows a significant increase in lower water depth for low bandgap materials and a slight decrease in lower water depth for higher bandgap materials. Variations in the response of PV modules to water depth may be related to different light distributions that exist at various depths of water. Even for each solar cell, there is either a constant increase or a constant decrease.

In principle, the reflection losses in a PV system are undesirable and affect negatively the efficiency of the solar devices. A ray impinging on the surface between two materials with different refractive indices (n), is divided into a reflected and a transmitted component. Numerous systems have been studied to reduce reflection losses (for instance, anti-reflective coatings (ARC) on the glass), but Krauter[77] by utilizing an optical model, evaluates increased optical transmittance for materials with ideal properties of $n = 1.33$. These ideal properties cannot be achieved with solid materials, but water, with a refractive index of 1.33, represents the perfect layer to achieve the predicted increase. Further, figure 1F presents a schematic view of a lens and the two possible positions of the solar cell compared to the light source, with the lower light intensity than the incident light (A), and a concentration-effect (the higher light intensity) at the focal point (B). Most of our reported indoor measurements with the WFL system were performed at lower or the same light intensities as the initial light source intensity (marked as I_0) and the position of the solar cell was in the shade ($I_1<I_0$),

away from the focal point. In general, far from the focal point, the intensity of light will always be lower than the initial light source. The distribution of light (spectrum), of course, always changes with the changing position of the WFL system.

Combining all these above-described effects and studying the influence of intensity and spectra, as well as possible additional light effects together with inevitable cooling, at the same time and not separately, is crucially important. In natural conditions, any changes in intensity and spectra have joint consequences, and temperature control of the surface of the solar cell or module is of essential significance in the credibility of the results and the maintenance of the solar system. To understand all those influences, some innovation is needed. The WFL system, handmade in our laboratory, enables cooling, decreasing, and increasing the intensity of light and manipulation of the spectrum. Besides, manipulation on the experimental level with the light intensity and spectra, together with some additional light effects that we do not understand, can help us to expand our knowledge concerning the interaction of light and to perhaps better comprehend the nature of light, for which there are still disagreements over different varieties of theory. The book discusses the possible reasons, such as light intensity reduction, changes in spectral distribution, the effect of interfaces, the effect of water on the solar irradiance spectra, and the fact that light, from our perspective, could be observed as a wave (because it passes through different environments before reaching the solar cell surface), for the better response of different PV devices, using the WFL system, compared with measuring without optics. It is evident that there is a range of energy gaps for all the different solar cells observed, where the use of the WFL system always improves the response of various photovoltaic devices.

In current photovoltaic power research, increasing conversion efficiency has always been a major challenge. As previously stated, this efficiency improvement can refer to designing materials with appropriate electronic properties, improving a photovoltaic device, or optical design. There have been numerous approaches to the design of materials and devices, including the synthesis of new active layer materials with enhanced carrier mobilities[81-83], the optimization of device architectures, the increase of exciton diffusion efficiency[84,85], and the creation of favorable morphologies for charge collection[86-89]. On the contrary, there has been very insufficient research into studying and manipulating incident light coupling into active layers, which has resulted in an increase in conversion efficiency. Micro-lens structures on the solar cell surface have been considered for light trapping.[90-93] Furthermore, a few reports have been published on optical designs to induce light trapping in PV cells, such as manufacturing on prism-shaped substrates[94], V-aligned solar cells[95,96], a patterned mirror-and-lens light trap[97], and the use of a pyramidal rear reflector[98]. It was also reported that a nano-waveguide system was proposed for solar energy conversion and amplification[99], as well as a two-stage dish-style concentration system to increase conversion efficiency.[100] Furthermore, a mixed dye[101] and ascorbic acid system[102] on photogalvanic cells were used to boost energy conversion. In addition, at a water depth of 4 cm[60], an innovative cooling PV technology consisting of submerging PV systems increases photovoltaic efficiency conversion by about 15%. All of these applications effectively increase light absorption in devices and boost performance by 10 to 30%. It should be noted that the designed WFL system has a water layer thickness in the middle of exactly 4 cm.

We mentioned that having such a powerful source of energy as the sun necessitates people's being able to use it more effectively than they currently do. This approach, through innovation, we believe, can broaden our knowledge of how to overcome this issue and more effectively use free energy.

References

[1] Shafiee, S., Topal, E., When will fossil fuel reserves be diminished? (2009) Energy Policy, 37 (1), pp. 181-189.
[2] Karpacheva, M., Malzner, F. J., Wobill, C., Büttner, A., E. Constable, C., Housecroft, C. E., Cuprophilia: Dye-sensitized solar cells with copper(I) dyes and copper(I)/(II) redox shuttles (2018) Dyes and Pigments, 156, pp. 410-416.
[3] Moriarty, P., Honnery, D., What is the global potential for renewable energy? (2012) Renewable & Sustainable Energy Reviews, 16 (1), pp. 244-252.
[4] Jung, S. H., Myung, Y., Kim, B. N., Kim, I. G., You, I.-K., Kim, T. Y., Activated biomass-derived graphene-based carbons for supercapacitors with high energy and power density, Scientific Reports, 8 (1), pp. 1915-1922.
[5] Darvish, A., Rafiee, F. M., Maximum efficiency of wind energy using novel dynamic voltage restorer for DFIG based wind turbine (2018) Energy Reports, 4 (2), pp. 308-322.
[6] Zhang, Y. Q., Sheng, S. W., You, Y. G., Wu, B. J., Liu, Y., Research on energy conversion system of floating wave energy converter (2014) China Ocean Engineering, 28 (1), pp. 105-113.
[7] Almosni, S., Delamarre, A., Jehl, Z., Suchet, D. et all., Material challenges for solar cells in the twenty-first century: directions in emerging technologies (2018) Science and Technology of Advanced Materials, 19 (1), pp. 336-369.
[8] Zhao, J., Wang, A., Green, M. A., 24.5% Efficiency silicon PERT cells on MCZ substrates and 24·7% efficiency PERL cells on FZ substrates (1999) Progress in Photovoltaics 7, pp. 471-474.
[9] Cousins, P. J., Smith, D. D., Luan, H. C., Manning, J., Dennis, T. D., Waldhauer, A., Wilson, K. E., Harley, G., Mulligan, W. P., Generation 3: Improved performance

at lower cost (2010) Proc. Photovoltaics Specialist Conference, San Diego, pp. 275-278.
[10] Smith, D. D., Cousins, P. J., Masad, A., Waldhauer, A., Westerberg, S., Johnson, M., et. al., Generation III high efficiency lower cost technology: Transition to full scale manufacturing (2012) Proc 38th IEEE Photovoltaic Specialists Conference (PVSC), Austin, Texas, pp. 001594-001597.
[11] Blakers, A., Zin, N., McIntosh, K. R., Fong, K., High efficiency silicon solar cells (2013) Energy Procedia, 33, pp. 1-10.
[12] Shockley, W., Queisser, H. J., Detailed balance limit of efficiency of *p-n* junction solar cells (1961) Journal of Applied Physics 32, pp. 510-519.
[13] Yoshikawa, K., Kawasaki, H., Yoshida, W. *et al.* Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26% (2017) Nature Energy 2, pp. 17032.
[14] Masuko, K., Shigematsu, M., Hashiguchi, T., Fujishima, D., Kai, M., Yoshimura, N., Yamaguchi, T., Ichihashi, Y., Mishima, T., Matsubara, N., Yamanishi, T., Takahama, T., Taguchi, M., Maruyama, E., Okamoto, S., Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell (2014) IEEE Journal of Photovoltaics, 4, 6, pp. 1433-1435.
[15] Randall, J. F., Jacot, J., Is AM1.5 applicable in practice? Modelling eight photovoltaic materials with respect to light intensity and two spectra (2003) Renewable Energy, 28, pp. 1851–1864.
[16] IEC-904-3, IEC Standard i.e. 1000 W/m2 AM1.5 normal to cell surface at 25 °C, 1989.
[17] Bucher, K., Site dependence of the energy collection of PV modules (1997) Solar Energy Materials & Solar Cell, 47, pp. 85–94.
[18] Roth, W., Schmid, J., Photovoltaically supplied devices of low and intermediate power range (1998) 8th EC Photovoltaic Solar Energy Conference, pp. 263–269.
[19] Pettersson, H., Johansson, H., Johander, P., Gruszecki, T., A design tool for dimensioning mobile solar-driven products, Electronics Goes Green 2000+, pp. 735-739, Berlin, 2000b.
[20] Nakajima, H., Solar array enrich consumer products (1979) JEE, pp. 26–9.
[21] Randall, J. F., Droz, C., Goetz, M., Shah, A., Jacot, J., Comparison of 6 photovoltaic materials over 4 orders of magnitude of intensity (2001) 17th EPVSECE, Munich.
[22] Lojpur, V., Mitrić, M., Validžić, I.Lj., The improved photovoltaic response of commercial monocrystalline Si solar cell under natural and artificial light by using water flow lens (WFL) system (2019) International Journal of Energy Research, 43 (8), pp. 3507-3515.
[23] Tina, G.M., Rosa-Clot, M., Lojpur, V., Validžić, I.Lj., Numerical and experimental analysis of photovoltaic cells under a water layer and natural and artificial light (2019) IEEE Journal of Photovoltaics, 9 (3), art. no. 8643369, pp. 733-740.
[24] Lojpur, V., Validžić, I.Lj., Influence of different light sources, light intensities, and water flow lens (WFL) system on dye-sensitized solar cell performances (2019) IEEE Journal of Photovoltaics, 9 (2), art. no. 8594565, pp. 492-498.

[25] Lojpur, V., Krstić, J., Kačarević-Popović, Z., Filipović, N., Validžić, I.Lj., Flexible and high-efficiency Sb_2S_3/solid carrier solar cell at low light intensity (2018) Environmental Chemistry Letters, 16 (2), pp. 659-664.
[26] Lojpur, V., Mitrić, M., Validžić, I.Lj., The role of low light intensity: A step towards understanding the connection between light, optic/lens and photovoltaic behavior for Sb_2S_3 thin-film solar cells (2018) Optics and Laser Technology, 101, pp. 425-432.
[27] Validžić, I.Lj., Popović, M., Lojpur, V., Bundaleski, N., Rakočević, Z., Confirmation of incorporation of Cu and Se ions in applied p- and n-type-doped Sb_2S_3 by photoemission spectroscopy (2018) Journal of Electronic Materials, 47 (4), pp. 2402-2410.
[28] Lojpur, V., Krstić, J., Kačarević-Popović, Z., Mitrić, M., Rakočević, Z., Validžić, I.Lj., Efficient and novel Sb_2S_3 based solar cells with chitosan/poly(ethylene glycol)/electrolyte blend (2018) International Journal of Energy Research, 42 (2), pp. 843-852.
[29] Lojpur, V., Mitrić, M., Kačarević-Popović, Z., Radosavljević, A., Rakočević, Z., Lj Validžić, I., The role of low light intensity: A cheap, stable, and solidly efficient amorphous Sb_2S_3 powder/hypericin composite/PVA matrix loaded with electrolyte solar cell (2017) Environmental Progress and Sustainable Energy, 36 (5), pp. 1507-1516.
[30] Lojpur, V., Tasić, N., Validžić, I., Different behaviors in current–voltage measurements of undoped and doped Sb_2S_3-based solar cells (2017) Journal of Applied Electrochemistry, 47 (1), pp. 117-124.
[31] Janošević, V., Mitrić, M., Bundaleski, N., Rakočević, Z., Validžić, I.Lj., High-efficiency Sb_2S_3-based hybrid solar cell at low light intensity: Cell made of synthesized Cu and Se-doped Sb_2S_3 (2016) Progress in Photovoltaics: Research and Applications, 24 (5), pp. 704-715.
[32] Validžić, I.Lj., Janošević, V., Mitrić, M., Characterization and current-voltage characteristics of solar cells based on the composite of synthesized Sb_2S_3 powder with small band gap and natural dye (2016) Environmental Progress and Sustainable Energy, 35 (2), pp. 512-516.
[33] Janošević, V., Mitrić, M., Savić, J., Validžić, I.Lj., Structural, optical, and electrical properties of applied amorphized and polycrystalline Sb_2S_3 thin films (2016) Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 47 (3), pp. 1460-1468.
[34] Janošević, V., Mitrić, M., Ležaić, A.J., Validžić, I.Lj., Weak light performance of synthesized amorphous Sb_2S_3-based hybrid solar cell (2016) IEEE Journal of Photovoltaics, 6 (2), art. no. 7347349, pp. 473-479.
[35] Husain, A. A. F., Hasan, W. Z. W., Shafie, S., Hamidon, M. N., Pandey, S. S., A review of transparent solar photovoltaic technologies (2018) Renewable and Sustainable Energy Reviews, 94, pp. 779–791.
[36] Roghabadi, F. A., Ahmadi, N., Ahmadi, V., Di Carlo A., Aghmiuni, K. O., Tehrani A. S., Ghoreishi, F. S., Payandeh, M., Rezaei Fumani, N. M., Bulk heterojunction polymer solar cell and perovskite solar cell: Concepts, materials, current status, and opto-electronic properties (2018) Solar Energy, 173, pp. 407-424.