Aesthetic PV Integration

Aesthetically Appealing PV Integration & Technology

Bachelor in Energietechnologie

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PROLOGUE

Our world is changing and it's changing fast.

There's no doubt that energy plays a big role in this process and will probably be the factor with the biggest influence when it comes to the destiny of this planet and its people.

This is why early 2013 I decided to study this subject and eventually graduate in.

My name is Maurits Dierick and I'm a student in Energy Technology at the Tomas More department of the Catholic University of Leuven (KUL), Belgium.

The final stage of the final year of our professional bachelor includes writing a thesis and do an internship in a company or organization that has a relationship to energy of some kind.

Since it makes no sense to try and make this planet a better place if you have no idea what it looks like, I decided to go on an international internship. My first choice was Canada because it still has a very large pristine wilderness and is investing heavily in renewable energy.

Unfortunately this turned out to be a very difficult path to tread which is why, in the end, I had to appeal to a distant cousin of my father, who owns an electric boat rental company in Vancouver, Canada.

Jonathan, the company owner, was very happy to help me out and I would like to thank him for making this possible.

I would also like to thank mr. Jef de Schutter, mr. Rob van Dun, mr. Erik Mondelaers, mr. Peter Alen and mrs. Sofie Mols for their collaboration and expertise.

RESUME

With an increasing public interest in solar energy technologies and a growing awareness regarding environmental problems such as global warming, combined with the endless amount of energy the sun gives us, solar energy technology has evolved rather quickly in the past decade.

Apart from fossil fuels and nuclear power, solar energy is a viable source of renewable energy with enough technical potential to cover a large part, or even the complete quantity of our energy needs.

In comparison with fossil fuels and nuclear power, solar energy is a more sustainable energy source although there are some concerns regarding rare metals being used in today's solar technology, e.g. indium, silicon, gallium etc. These metals are so far required to transfer solar energy into electricity.

In order for solar energy to be competitive on the energy market it has to be reliable, easy to install, cost effective, but also aesthetically appealing. These items cover the main part of my thesis. E.g. rigid solar panels as we know them don't always fit into practical situations such as small rounded surfaces. I think we could also agree on the fact that a massive amount of blue/black solar panels, would ruin the sight of a lovely pittoresque Italian village. Even though solar energy could be quite useful here.

As we all know, the energy output per m^2 is a lot lower for solar panels than it is for nuclear and fossil energy. This means a larger surface is required to produce the same power output. In the countryside where a lot of open space is available, this is not as much of a problem as it is in densly populated areas. This is where the practical and aesthetical aspects as mentioned before play their part.

I assume that by now, you can see why I ask myself if there are any solutions to this problem and if yes, what would the practical and technical consequences be?

In this thesis, I will describe how I used an unexpected tool from a small and expanding Canadian company as a test case for the installation of flexible solar panels for different applications.

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INTRODUCTION

North America is one of the biggest energy consuming area's on the planet. Electricity usage per head is on average around 250 kWh/day. This begs the question: would it be possible to hit that target with solar panels alone? Of course it is important to reduce the energy usage in the first place, before thinking about renewable production, but let's address the elephant in the room first.

In his book "Renewable Energy Without The Hot Air", David JC MacKay states the following: assuming a power density of 15W/m2, a simple calculation will tell us that we need an area of about 600kmx600km filled with photovoltaic panels to produce enough electricity for the 500 million people that live in North America.

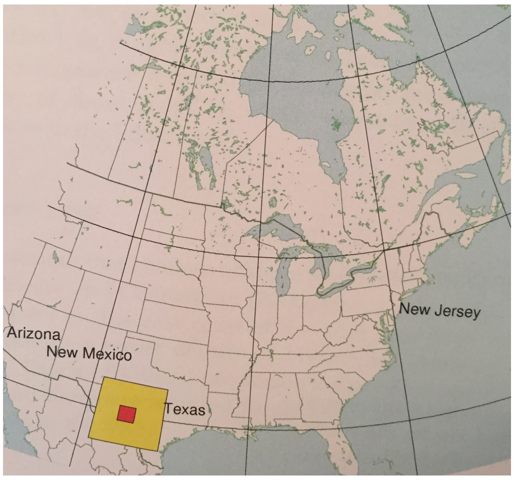


Figure 1: Area of PV panels required to cover energy needs [1]

On a map, this would mean that the entire surface of the state of Arizona would be completely filled with solar panels. Of course we can't just move the 6.7 million people living there. We could for example spread the required amount of solar panels over other areas in the sunnier, southern parts of the US. But that leaves us with new problems: the amount of solar panels and their ecological production footprint, the transportation of electricity, …

This is another key problem, which brings me to one of the main goals of this thesis: avoiding unnecessary transportation of electricity. Electricity transportation presents us with a problem, known to any energy expert as Joules first law, also known as Ohmic heating or resistive heating. It is the process in which the flow of electric current through a conductor produces heat and results in the loss of power.

An organization called Desertec is promoting a plan to use HVDC lines, which reduces the loss of power, to transport electricity produced in sunny southern countries to cloudier northern countries, but this would mean another huge cost.

The purpose of this thesis however, is to look for possibilities to produce as much as possible electricity "on site".

An obvious solution would be to decentralize the panels. This will get rid of the effects of Joules law for the biggest part but it brings us onto another problem I mentioned earlier: the aesthetic issues of PV panels.

Solar panels are often deemed too ugly and blamed for ruining the face of beautiful places and buildings, arguments you and I can probably familiarize ourselves with.

In this thesis, I will provide a number of solutions and map out the pros and cons of integrating solar panels, in order to decentralize production and make solar power production more appealing.

1 THE COMPANY

1.1 Joe's BBQ Boats

Small round barbecue boats are a familiar sight in popular touristic places all over Europe. However, when Jonathan, owner of Joe's BBQ boats, moved to Vancouver he noticed that there was no possibility to rent a BBQ donut in the city, even though barbecuing is very popular in Vancouver. As an entrepreneur, he ofcourse saw the possibilities and decided to take action. This meant that in the early summer of 2014, Jonathan and his friend could be found at the docks of Granville island marina, assembling the big, orange donuts.

As Vancouver is aiming to become the greenest city in the world by 2020, Jonathan of course wanted to contribute to this goal by swapping the classic petrol powered engines for Eco-friendly electric motors. Even though the manufacturer highly recommended against this decision, they insisted and are now one of the only businesses to achieve this with BBQ boats.

Figure 2: BBQ boats right after launch in 2014

Because Jonathan is a busy person and because the rental business has been doing well over the past years, he hired a manager to be able to focuss on the future of his company as well as expansion to other marinas.

2 THE PROJECT

2.1 Introduction

As stated in the prologue and resume of this thesis, it is extremely important to implement and decentralize energy production in order to reduce our energetical footprint.

The problem we have nowadays is that the commonly used solar panels are aesthetically unattractive and often unable to fit certain surfaces or applications, especially mobile applications.

Along with the interest of citizens, companies and governments, private and public investments in solar energy are booming. Numerous new and innovative startups like Solaxess (Swiss), GreenSun (Jordan) as well as Technical Research centres like the VTT (Finland), have been popping up all over the world. These institutes have been set up with only one goal in mind: develop new and innovative ways to make solar energy more attractive and implementable in a wide variety of applications. These start-ups are attracting financial investments from the worlds leading venture capitalists and even oil companies! Google, for example, largely funded Nanosolar in the US; whereas investors in the unfortunately deceased company Konarka, a manufacturer of printable plastic solar cells, included some of the world’s largest oil companies.

Roughly 2 billion people who lack access to the electric grid, as wel as companies and citizens of the developed world, where the electricity bill has become a serious economic problem, could benefit immensly from the advances that are being made by companies like the ones named above.

Another advantage of decentralization of energy production is the much lower sensitivity to mechanical failure, terrorist attacks or sabotage that lead to broad consequences. Something we unfortunately have to take into consideration these days.

In order to write this thesis, I have been in contact with many of these companies to find out the exact details of what they are doing and how it could benefit us in our daily lives. However, because most technologies described in this thesis are still being developed, many of these companies didn’t want to disclose their technology just yet.

In this thesis, I will give an overview of what these progressive innovations are, what their implementation could be used for and map out the pro’s and cons.

In the final chapters I theoretically applied the most appropriate solution to the BBQ boats to see if this could actually work for this application. I also listed a number of other examples throughout the thesis to show the countless possibilities for application of integrated solar energy production.

3 AESTHETICS AND WHY THEY'RE SO IMPORTANT

3.1 What is Aesthetics

Briefly described, aesthetics is the study of art. What does it consist of and what is the purpose behind it? Does it only consist of literature or paintings, a beautiful sunset or a brilliant engineering solution? These are some questions aimed at in the science of aesthetics.

Art is a way in which people express their personal and special feeling of aesthetics. It has existed for as far as recorded human history goes. It is unique to us because of the way we think. Art is a little understood tool that we as humans use to bring meaning to abstract concepts and gives us the possibility to define things that are a selective recreation of reality.

It is also a reason why many people tend to visit these beautiful villages in Tuscany and not the suburbs of Minsk, Belarus. Hard to define but nevertheless resulting in effective data. It is the reason why we wear jewelry, ties,.... There is no proven reason for this behavior, but we have a feeling it makes us more beautiful, valuable and happier.

3.1.1 A Brief Note of History

As we move towards a more renewable energy future we should recognize the inherent differences between the old and new means of energy production. For the largest part of the 20th century, energy production happened far from the daily events of life. The functional advantages dominated the eventual aesthetical side effects.

But as the days of gas and coal fired plants at the farthest edges of the city come to an end, we will encounter more and more energy production units integrated in the whole of residential and commercial units of our cities, as well as in objects we use on a daily basis.

Figure 3: 74th St. Coal Power Station Looking North. June 17, 1902 [2]

Figure 4: PV panels installed on a private home in Brooklyn Heights, New York [3]

Of course the need for large scale, ex-urban based power plants will remain, but they will be partly replaced by decentralized urban renewable energy production facilities.

But as we live in a world that cross-culturally attaches a great importance to design, it's obvious that as energy production comes in closer proximity with the cities and the buildings it powers, issues of aesthetics are becoming more and more debated.

3.1.2 Why Integration is Important

Figure 5: Elithis Tower Dijon, France [4]

Approaching the whole integration of energy production holistically, we will see that there is a difference between micro and macro production. Macro production units should be designed in a way that they would integrate with their surroundings and even go as far as triggering a positive response to the visual experience.

Micro production units will also be designed to integrate better with the fabric of our urban community in the same way that buildings and public art is designed to be integrated as a permanent addition to the greater image of our cities. Proof of this can be seen all around us, wind turbines are designed to have a futuristic look and their pylons are often painted in surrounding matching colours. As I will explain in the next chapters, a lot of companies these days are responding to this trend by developing aesthetically appealing solar panels in different colours and shapes.

This means we must embrace micro-installations as something more than just a source of energy. Whether we want it or not, they're becoming part of our lives.

Aside from the essential large renewable energy production units in our landscape and oceans, we will need to reduce our energy usage to move towards a zero carbon future. This concept of 21st century zero-impact design has taken off rapidly. A good example is the construction of zero-emission buildings, where the first examples have started to emerge. (see figure 5)

4 SOLAR ENERGY

4.1 History

In 1839, Edmond Becquerel, a 19 year old French physicist discovered that there is a creation of voltage when exposing a material to light. Little did he know that this discovery would lay the foundations for the solar energy production we know today.

The next big revolution took place around 1905 when Albert Einstein, famous for a wide variety of milestones, submitted his paper on the photoelectric effect. In this paper he explained how light can "liberate" the electrons on a metal surface.

However, it wasn't until 1954 that photovoltaics as we know them today were born. David Chapin, Calvin Fuller and Gerald Pearson of Bell Labs developed a device that could transfer sunlight into electricity. The first prototypes were only able to reach a 4% efficiency but later they pushed the technology and were able to reach up to 11%.

Despite the developments made in the years following, solar energy was not commercially viable yet. It might be hard to believe but the initial push came from the oil companies, who by that time and because of the oil crisis in 1973, started to realise the potential of this technology and the limited supplies of oil. Backed by Exxon, a Texas based oil company, Dr. Elliott Barman was able to design a solar cell that could produce electricity at 20$/W in versus the previous rate of 100$/W.

Years later, in 1993, the Pacific Gas & Electric Company completed the installation of a 500-kilowatt, grid-supported PV system in Kerman, California. In the following decade enormous improvements on cost and efficiency were achieved because of large investments. However, it wasn't until right after the polysilicon shortage from 2005 until the end of 2008 before electricity prices generated by solar panels started to compete with the price of retail electricity.

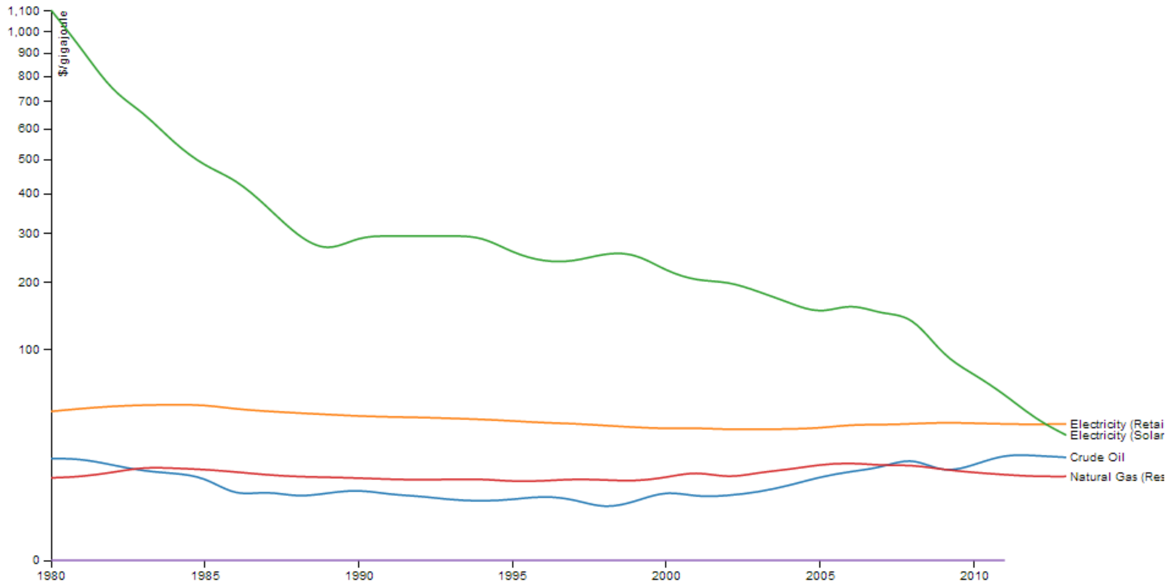


Figure 6: Timeline of electricity price per source [5]

4.2 The Basics of Photovoltaics

In order to understand the importance of solar energy and the difficulties that lay ahead, one needs to understand the basic principle.

Photovoltaics is the direct conversion from light to electricity on an atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When these "free electrons" or "photoelectrons" are captured, an electric current results that can be used as electricity (DC).

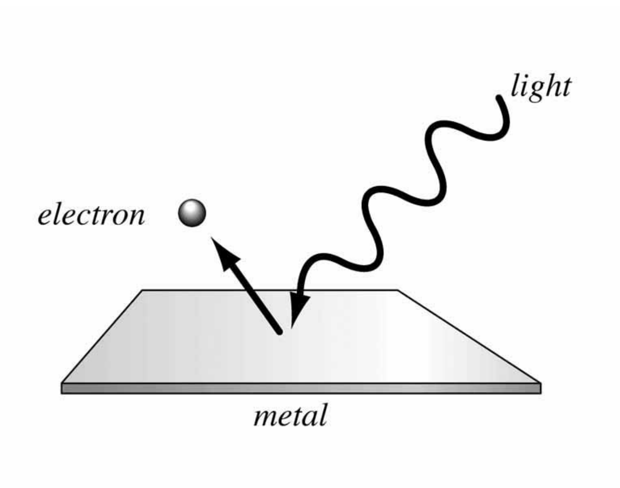


Figure 7: Light releases electrons from metal

Photovoltaic modules, commonly called solar modules, are the key when it comes to converting sunlight into electricity. They are made of semiconductors, a material that conducts electricity in some conditions but not others. These semiconductors are very similar to those used to create integrated circuits for electronic equipment. The most common type of semiconductor currently in use is made of silicon crystal. When looking at the periodic table we see that silicon is part of group 14. This means that it has 14 electrons, 2 in it's first shell, 8 in it's second shell and only 4 electrons in the third shell. These last 4 electrons are called the "Valence electrons".

In 1916, W. Kossel and G.N. Lewis discovered that atoms of all elements tend to achieve noble gas configurations, which means 8 Valence electrons on the outer shell. This is also the case for silicon:

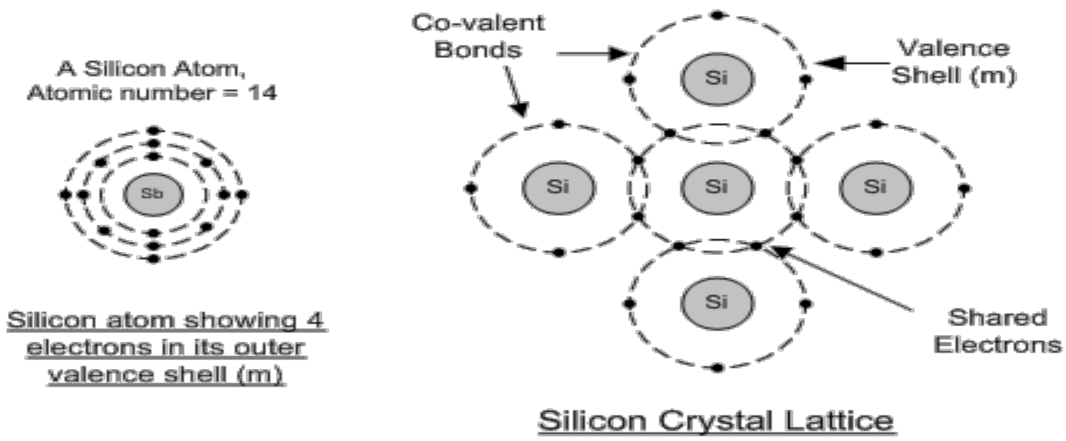


Figure 8: Silicon atom and Silicon atom structure

This balance leads to the development of a crystalline structure which is vital for such a solar cell, however, pure silicon in its crystalline form is a bad conductor of electricity since electrons are unable to move freely. This means adding impure elements that have either less or more valence electrons to create P- and N-type layers. This process is called “doping”.

In order to create the P-type layer, silicon is mixed with boron (the dopant) because it only has 3 valence electrons in it’s outer layer. When mixed into the silicon lattice, socalled “holes” are formed. In these holes the silicon has nothing to bond to. The absence of an electron creates the effect of a positive charge, hence the name P-type.

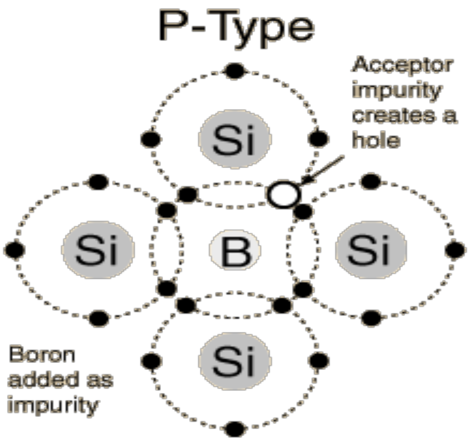


Figure 9: P-type doping

To create the negative N-type layer, phosporus is added to the silicon lattice in very small quantities. Phosporus has five Valence electrons and since this fift electron has nothing to bond to in the silicon lattice, it is free to move around.

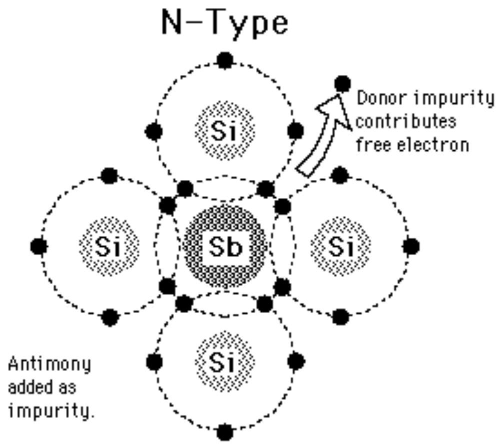


Figure 10: N-type doping

These two layers of impure silicon are then stacked upon eachother which results in an electric field. The free electrons in the N-layer rush to the other side to fill the holes in the P-layer. Of course the free electrons are unable to fill all the holes, otherwise the entire arrangement would be wasted. This phenomenon takes place mainly where the two layers meet, forming a field. Gradually, the process reaches a point of equilibrium and there exists an electric field dividing the different sides. This field serves as a kind of diode, permitting and even forcing electrons to drift from the P to the N half, instead of the other way round.

This is where the the sun comes in. As explained in the first paragraph of this chapter, energy of light results in dividing the electrons in the N-type layer. Each electron carrying a sufficient amount of energy will usually only free just a single electron, leading to a new hole as well. If this occurs close enough to the central electric field, the field is likely to shift the electron to side N and the hole to side P. This results in even more unbalance. If an external conductor is presented, electrons make use of this path to travel to the P side to combine with openings sent by the electric field, carrying on work in the process. This flow of electrons is the current and the electric field of the cell results in the formation of a voltage.

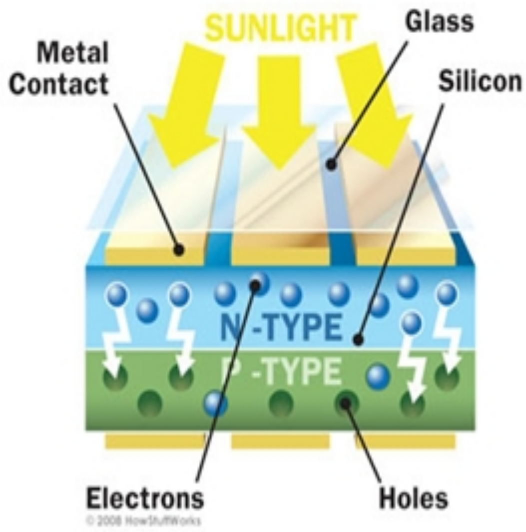


Figure 11: Solar cell structure

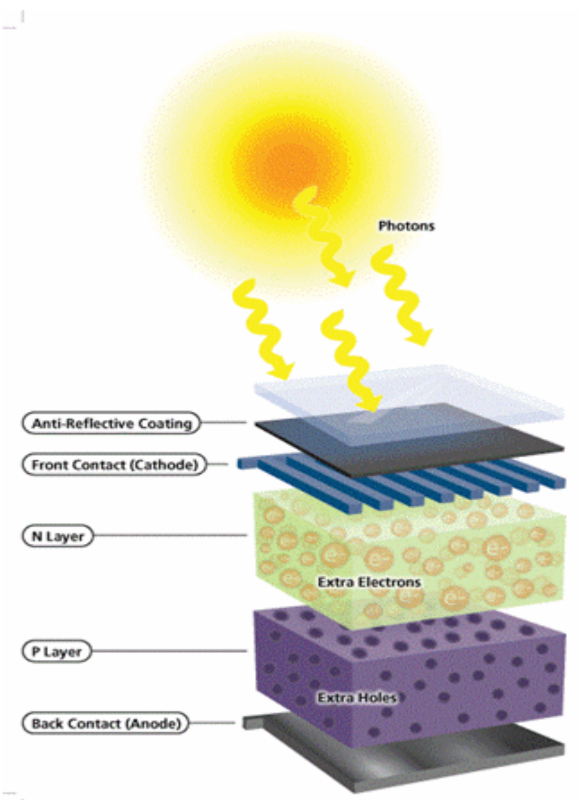


Figure 12: Solar panel structure

Silicon is also a very shiny substance, which would result in high losses due to reflection of light if it weren't for an anti-reflective coating.

The final step is to install a clear glass plate to protect the vulnerable cells from the elements.

I now explained the basic structure of a single solar cell. One cell however will only generate a very small amount of electricity. It is therefore crucial to connect a number of solar cells into a structure. This is called a photovoltaic module. Modules are designed to supply electricity at a certain voltage, for example the commonly used 12 volt system. The current produced is directly related to the amount of light striking the module.

Multiple modules can be wired into an array as can be seen in figure 13. In general, the larger the area of a module or array, the more electricity it will produce. Modules can be connected in both series or parallel arrangements to produce any required voltage and current combination.

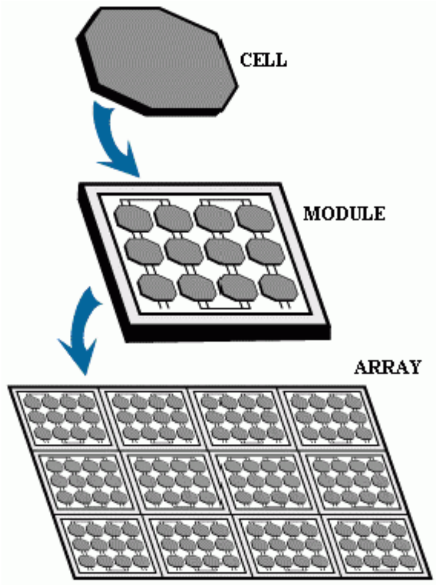


Figure 13: Cell – Module - Array

4.3 Monocrystalline vs Polycrystalline

Besides knowing the basic operation principle, it's also important to know that there are two different kinds of photovoltaics currently dominating the market: polycristalline and monocrystalline.

Both monocristalline and polycristalline solar panels serve the same function: turning energy from the sun into electricity. They're also both made out of silicon and both can be a good choice for your home, figure 14 compares the two:

	Monocrystalline	Polycrystalline
Cost	More expensive	Less expensive
Efficiency	More efficient	Less efficient
Aesthetics	Solar cells are a black hue	Solar cells have a blue-ish hue
Longevity	25+ years	25+ years
Major manufacturers	Canadian Solar SunPower LG Hyundai SolarWorld	Hanwha Kyocera Hyundai SolarWorld Trina

Figure 14: Comparison table monocristalline vs polycristalline panels

As stated in the comparison table on the previous page, monocrystalline panels are a bit more efficient, in general they reach efficiency up to 20% where polycristalline panels hardly reach 15%. (Christian QG, Tamesol, September 2016 [6])

The differences between monocrystalline modules and polycrystalline modules derive from the process in which they are created. Monocrystalline solar panels are made from a single crystal seed, either found in nature or created in a laboratory. As a result, they have a more uniform and smoother appearance than polycrystalline modules. Polycrystalline solar panels, on the other hand, are created from blocks of crystals which give the module a metal-flake effect.

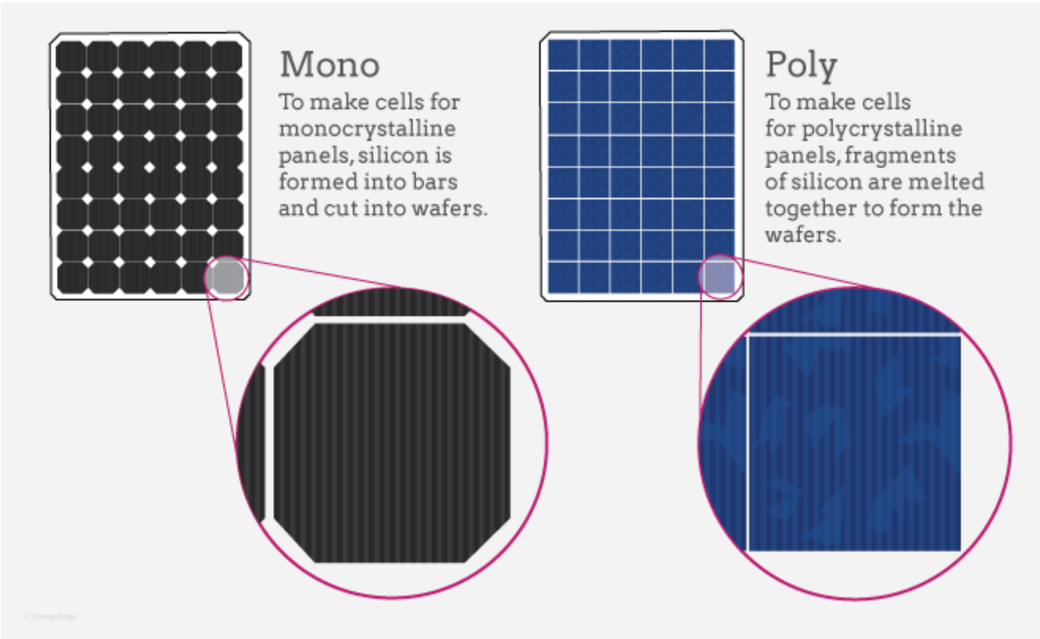


Figure 15: Monycristalline vs Polycristalline cells

4.4 Energy Loss in a Solar Cell

In this last chapter of the basics of photovoltaics, I will shortly describe some of the most important energy losses. This will make it easier to understand why the innovations described in the next chapters are so important.

In order to understand why efficiency rates are generally low, we have to start by analysing light. Visible light is only a part of the electromagnetic spectrum. Electromagnetic radiation is made up out of a range of different wavelengths and therefor different energy levels, with the visible spectrum appearing to us as the colours of rainbows. This means that the light that hits the cell contains photons with a wide range of different energies. It turns out that some photons don't have enough energy to alter an electron-hole pair (N-type layer). These photons will pass through the cell as if it were transparent. Only photons with a certain amount of energy, measured in electron volts (ev) will be able to knock an electron loose. If a photon has more energy than this required amount, the extra energy is lost. This effect can count for roughly 70% of the total efficiency loss.

Of course the electrons that are set free need to flow from one side to the other through an external circuit. We can cover the bottom of the panel completely with metal but we can't do this with the part that faces towards the sun. Otherwise it would cover the cells from sunlight. If we put the contacts only at the sides of our cell, the electrons would have to travel an extremely long distance to reach the contacts. Remember, silicon is a semiconductor - it's not nearly as good as a metal for transporting current. Its internal resistance is fairly high, and high resistance means high losses. To minimize these losses, cells are typically covered by a metallic contact grid that shortens the distance that electrons have to travel while covering only a small part of the cell surface. Even so, some photons are blocked by the grid, which can't be too small or else its own resistance will be too high.

Then there are of course the ohmic losses in the conductors and losses due to overheating, which are not to be overseen.

Solar panels are tested at a temperature of 25°C. For every degree above this reference temperature, the efficiency drops. Manufacturers provide a coëfficient to calculate these losses.

For example, the temperature coefficient of a Sharp Solar Panel NU-U230F3 is -.485% per 1 degree Celsius. So, for every degree above 25°C, the maximum power of the Sharp solar panel falls by .485%, for every degree above, it increases by .485%.

This being said, I hope this chapter has given a bit of insight on the technical difficulties and also opportunities that lay within the development of flexible, coloured, transparent,…. solar panels.

5 THIN FILM SOLAR PANELS

5.1 General

Customers who buy solar panels these days are mostly interested in the energy yields per purchased watt peak power over a certain period in true outdoor conditions. Solar panels however are usually sold with their peak power performance (WP). This is a reference power output, tested under labratory conditions (STC), among other things, this means a very high radiation level (1000W/m^2) and a module temperature of 25°C.

As you can imagine, these conditions are very rarely achieved in the real world, module temperatures often get as high as 60°C and the total hours where the radiation level reaches 1000W/m^2 is barely 1% of the total sun-hours per year. Diffuse light for example exists when the sky is cloudy or during the morning and evening. In a greater part of the world, diffuse light dominates the majority of solar irradiation (over 50% in Nothern and Central Europe). This of course results in a much lower output from these panels.

It is therefore crucial to predict what the actual output will be when panels are used in standard outdoor conditions and evaluate their behaviour. A study performed by Hans-Dieter Mohring for the Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW) Baden-Württemberg [7], proves that thin film solar technology consistently outperforms it's crystalline rivals in these conditions. This means that thin film technology could serve a lot of applications where normal PV wouldn't perform at all.

Between 2001 and 2009, over 100 companies entered the thin film production industry. The technology, previously only associated with the thin strip of PV cell that powered your calculator, has since seen a major development-leap. Growing from a mere 14MW in 2001 to 2141MW in 2009, the market is projected to reach over 22,000MW in 2020.

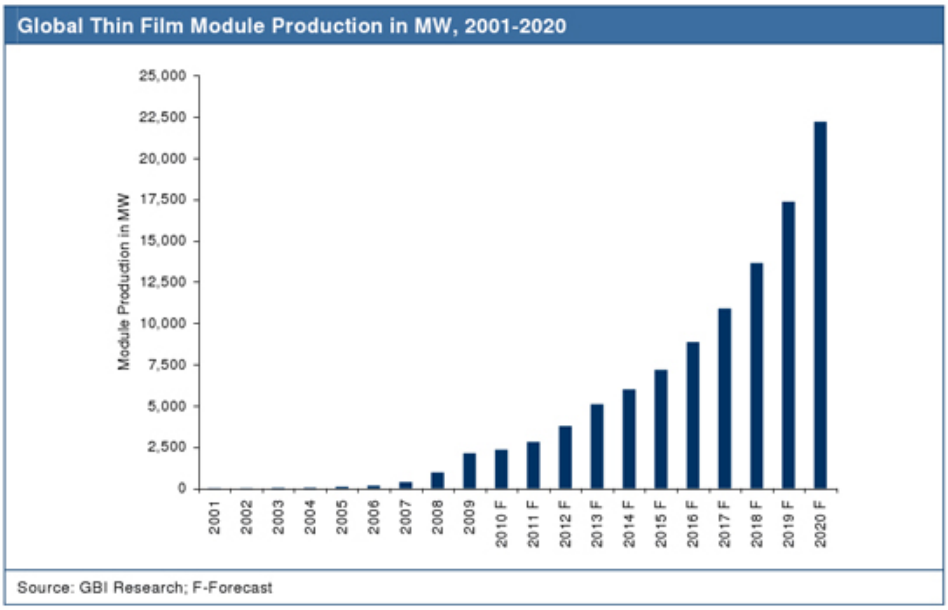


Figure 16: Global thin film production in MW, 2001-2020 [8]

The technology has also been able to get hold of a large part of the market share in the photovoltaïc industry. Over the past years, the market share grew from 2.8% in 2001 to 25% in 2009, and is estimated to increase to roughly 48% in 2020. It is not hard to believe that at this rate, thin film technology will surpass the currently dominiating silicon technology in the near future. [8]

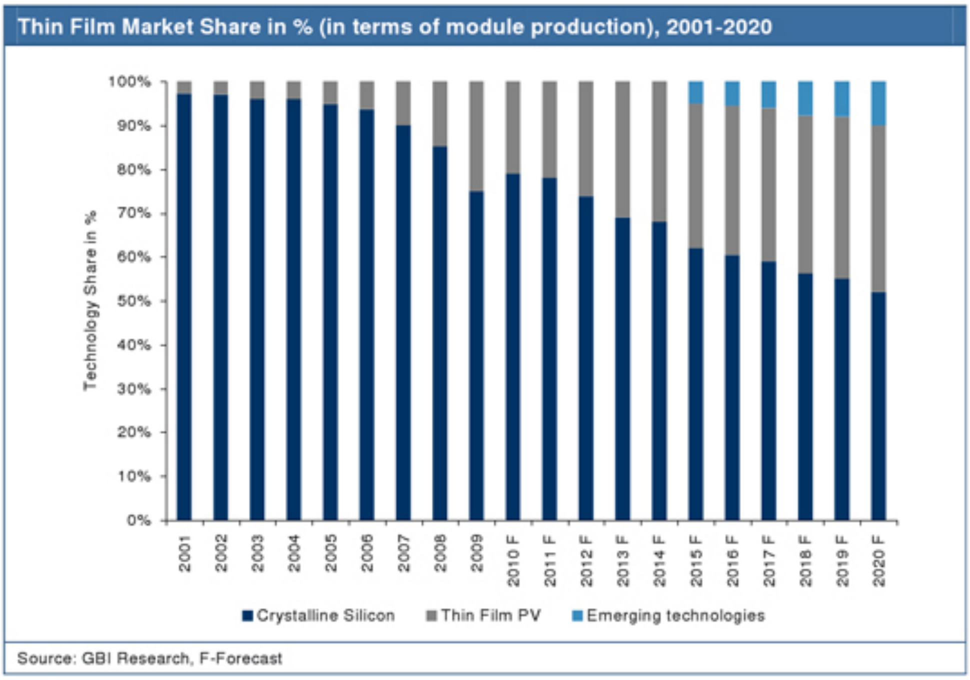


Figure 17: Thin film market share in %, (in terms of module production); 2001-2009 [8]

Compared to the traditional wafer-based silicon, thin film technologies yield products of comparable performance but with significant advantages in manufacturing: (the next chapter goes into further detail regarding these topics)

- Lower production material consumption (direct & indirect)
- Not depending on silicon supplies (except for a-Si thin film)
- Easier production process
- Integrated, monolithic circuit design – no assembly of individual solar cells into final products.
- No loss in efficiency at high temperatures (sometimes even increased efficiency).

This results in a much lower production cost than traditional solar panels. As shown in the figures below, the traditional production process contains twice as many steps compared to the thin film production process. These steps are also much easier to automate.

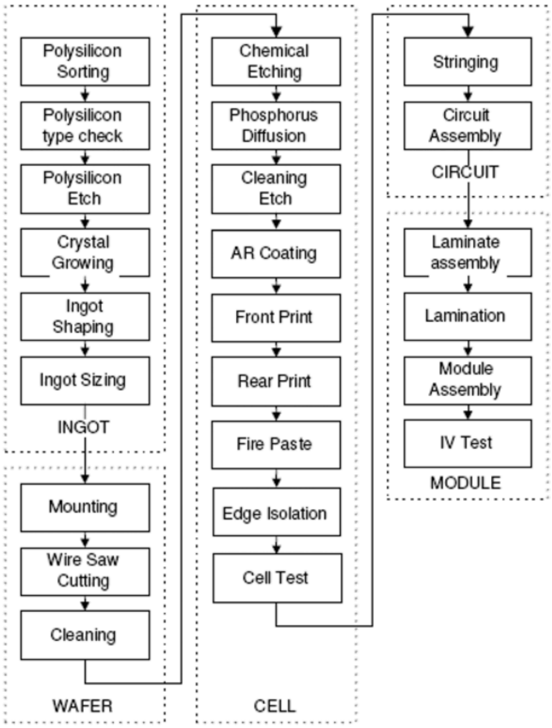


Figure 18: Manufacturing process of crystalline silicon modules

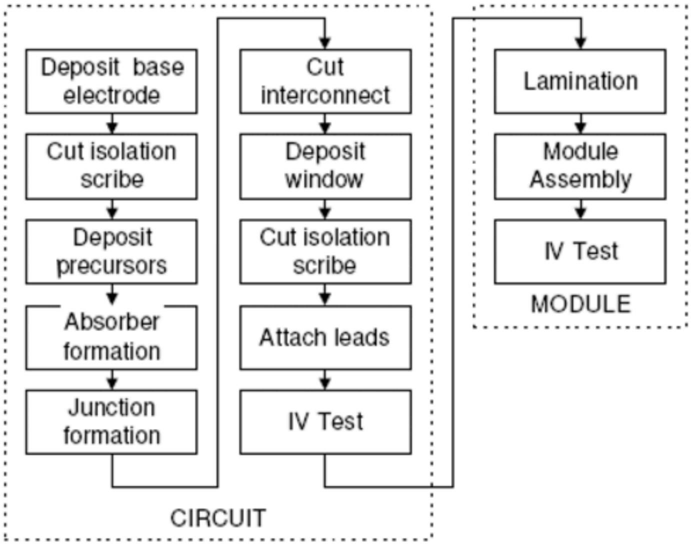


Figure 19: Manufacturing process of thin film modules

Fewer steps in the manufacturing process and the fact that thin film technology requires much less material than normal silicon panels, result in a much lower EPBT (Energy Pay Back Time). Where silicon solar panels take around 3 years, thin film technology only needs 1 year to recoup the energy needed in the production procedure.

There are three types of thin film solar panels, based on the semiconductor that is being used.

- CIS/CIGS (Copper Indium (Gallium) Selenide)

  These are the most popular among the thin film solar panels. The difference is simple, CIGS contains Gallium which prevents the aurora effect from ocurring and has a very high absorption level. This aurora effect gives the CIGS a matt appearance where CIS panels have a more glossy look. Efficiency levels for CIGS exceed CIS because of this Ga absorber layer. Market share in 2015 was 37% of the thin film industry.

- CdTe (Cadmium Telluride)

  CdTe solar panels are panels where Cadmium Telluride has been used as an absorber layer. Even though this technology looks very promising when it comes to general carbon footprint and efficiency levels. The usage of the toxic Cadmium Telluride may limit the production capacity due to a skeptical public opinion and limited supplies. Market share in 2015 was 36% of the thin film industry.

- a-Si (Amorphous Silicon)

  Amorphous silicon panels are the thin film, non-crystalline variant of normal wafer-based panels. Even though amorphous silicon panels are the most environmentally friendly, their low efficiency and the rising popularity of CIS/CIGS and CdTe, has caused a loss in their significance, resulting in a very low market share. Market share in 2015 was 27% of the thin film industry.

5.2 CIGS Thin-Film Technology

Among alternative, thin-film technologies, CIGS is the most advanced and the most efficient. Modules with CIGS ($Cu(In,Ga)(Se,S)_2$) are very efficient in converting light into electricity.

CIGS (Cu(In,Ga)(Se,S)2) is a calcopyrite material. These materials have got very desirable properties for PV-application, for example the tetragonal lattice structure. The nature of the surface of these materials is critical to determining the properties of the heterojunctions that collect current in the devices and can determine whether or not carrier recombination at the heterojunction limits device performance. (Heterojunctions are found in materials with unequal bandgaps (⇔ homojunctions)). By adding a Ga based p-type conductor (see structure in next chapter), the band gap can be increased from 1.0 to 1.73 eV and thus increase the electrical conductivity. The absence of such a buffer layer will result in a drop of open circuit voltage (Voc) and poor efficiency, among others, due to the large negative conduction-band offset at the CIGS/ZnO interface.

CIGS technologies are relatively well positioned in the field of solar technologies with present record efficiencies of 22,3% for small cells and 16,5% for production modules. As can be seen in figure 20, recent progress at cell level (black triangles) paves the way for mini-modules (red squares) and eventually towards total area module efficiencies of 18%. Expectations for the near future state that by improving laboratory technology, low cost CIGS modules can provide electricity below €0,05/kWh and will be of significant matter when it comes to CO2 reduction (figure 22).

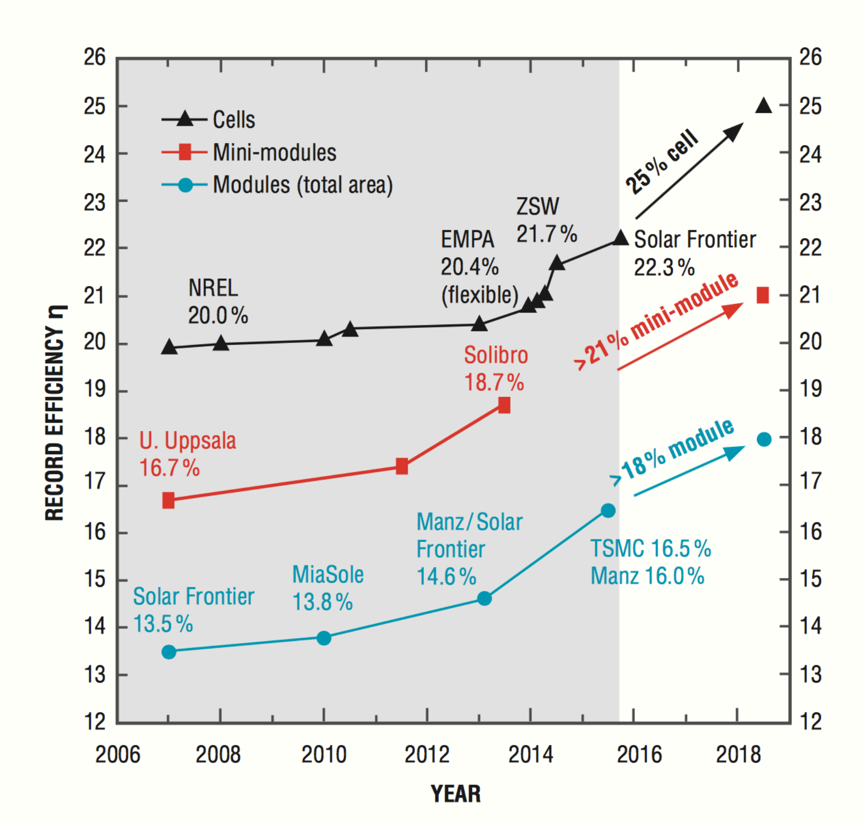


Figure 20: Evolution of record efficiencies highlighting a steeper increase since 2014; 2016-2019 projections based on current R&D projects. [9]

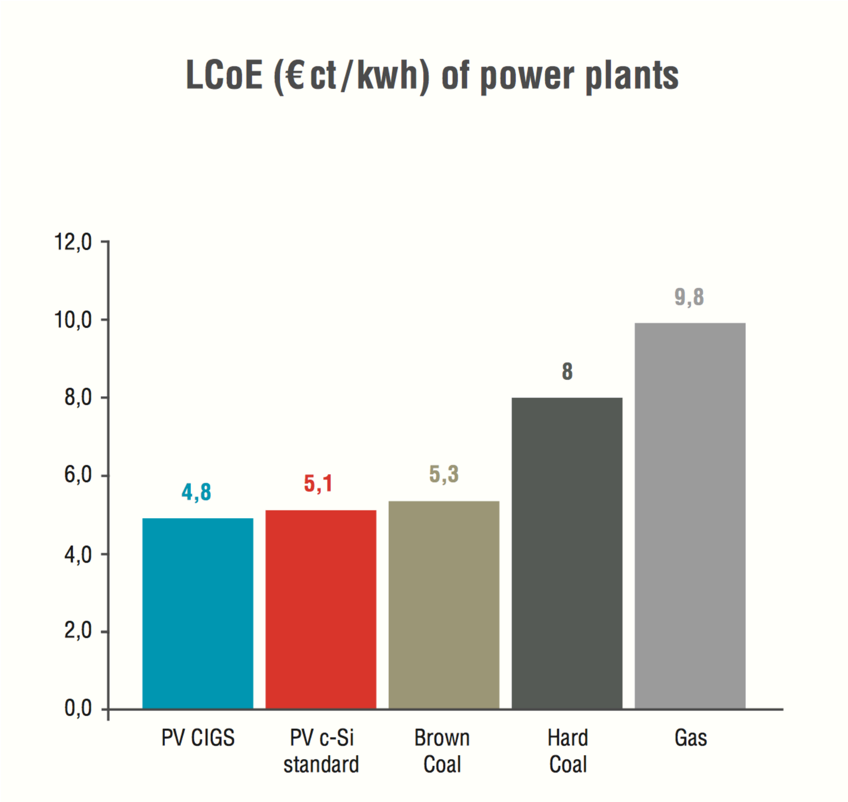


Figure 21: Levelized cost of electricity for different technologies [9]

Because CIGS contains gallium, which has a higher absorbency range and a higher sensitivity to light than any other material, CIGS solar panels generate much more electricity from the same amount of light compared to other technologies. The magnitude of this advantage is shown in figure 22 below.

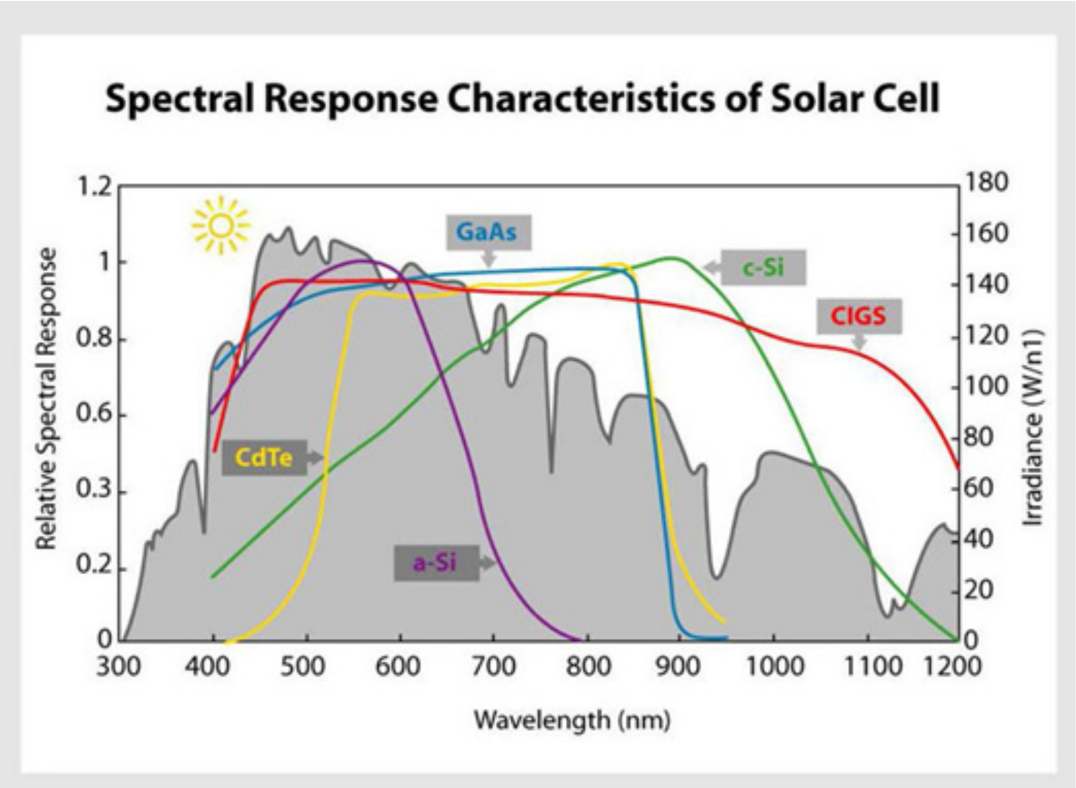


Figure 22: Spectral Response Characteristiscs of Solar Cell

As stated before, this makes CIGS solar modules a lot more efficient in northern or southern countries or places where the sun barely shines at its brightest.

The spectral irradiation power density changes with the air mass factor (AM). As shown in the figure below, the air mass factor corresponds directly with the distance sunlight has to travel through the atmosphere.

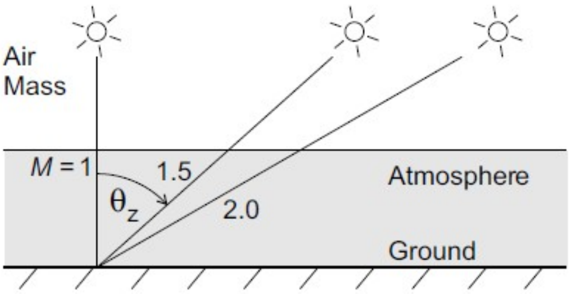


Figure 23: Air Mass Factor

AM = 1 therefor means a vertical angle and thus the shortest possible distance through the atmosphere (midday at the equator). AM >1 means a lower angle of irradiation, meaning mornings, evenings and places north or south of the equator. As the AM factor increases, the absolute AM value increases, resulting in longer wavelengths.

This shift of energy towards the infrared zone makes the sun appear red in the mornings and evenings.
The same principle counts for orientation. CIGS panels are much less sensitive to orientation than any other PV-technology.

Because of the structure and the way CIGS panels are built, they're much less sensitive to being partially overshadowed. Normal a-Si or c-SI panels use silicon wafers connected in series. This means if one of these cells is overshadowed, it cannot generate electricity, resulting in a weak link and a massive drop in module performance. This is problem is partially solved by using socalled bypass-diodes but implementing these complicate the manufacturing process and make it more expensive. Because of the unique structure of CIGS panels, shadows will only affect the overshadowed part of the module and will not influence the rest of the module's performance.

5.2.1 Production of CIGS Thin-Film

The diversification of production and design of CIGS modules offer different possibilities, depending on the purpose of the module. To keep things simple, we will focuss on the most common CIGS manufacturing structure.

In this manufacturing process, soda-lime glass of 1-3mm thickness (normal glass), is used as a back substrate. It has been proven that the sodium in the glass increases the open circuit voltage substantially. Many companies (like NanoSolar) use lighter and more flexible substrates like metal foils.
A molybdenum (Mo) metal-layer, which serves as a back-contact, is then sputtered onto the glass/metal substrate. This layer will reflect most of the light that went through the module back into the CIGS absorber.
In the next phase of the manufacturing process, a p-type CIGS absorber layer is added onto the molybdenum layer. The most common way is a vacuum-based sputtering process where CIG is sputtered onto the molybdenum and blended with a selenide vapor to create the final CIGS structure.

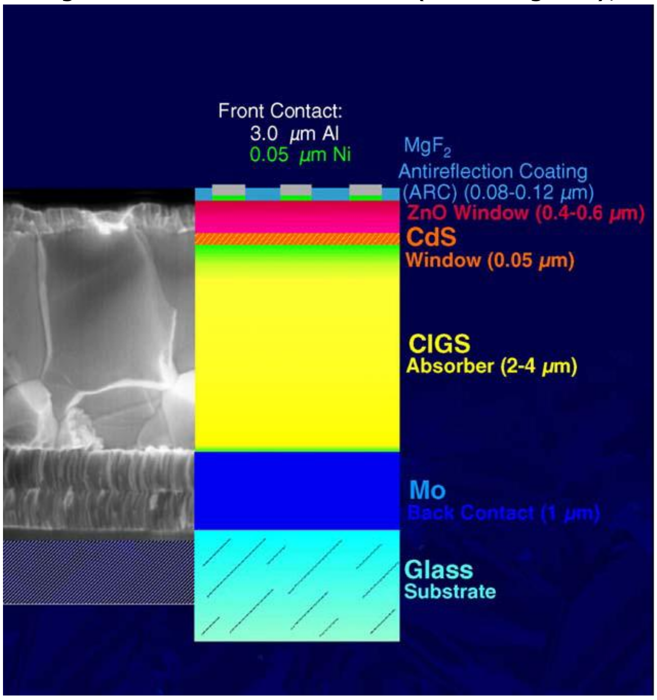


Figure 24: Structure of a CIGS cell

Nanosolar however uses a non-vacuum based process that mixes the materials into a liquid and then deposits the nano-particles onto the substrate after which it is sintered. (Sintering: heat treatment applied to a powder compact in order to impart strength and integrity)

On top of this p-type absorber layer, an n-type buffer layer is added. This usually consists of cadmium sulfide (CdS), applied using the chemical bath deposition technique.

The buffer is then covered with a thin zinc-oxide layer (i-ZnO), capped with a thicker aluminum (Al) doped ZnO layer. The i-ZnO layer is used to protect the underlying CdS layer from damage during the ZnO:Al sputtering process. The ZnO:Al layer serves as a transparent conducting oxide to collect and move electrons out of the cell while absorbing as little light as possible.

To automate this process, most producers, including Nanosolar use a process called "Roll-to-Roll manufacturing". This name refers to the process of applying coatings and other techniques to a roll of flexible material. The advantage is that there are no bottlenecks in this process, resulting in a much higher production line efficiency. It also means much less energy is needed for the production of these modules, resulting in a very low energy payback time. If we take carbon footprint into account, thin film solar technology provides promising evidence of a truly sustainable energy source.

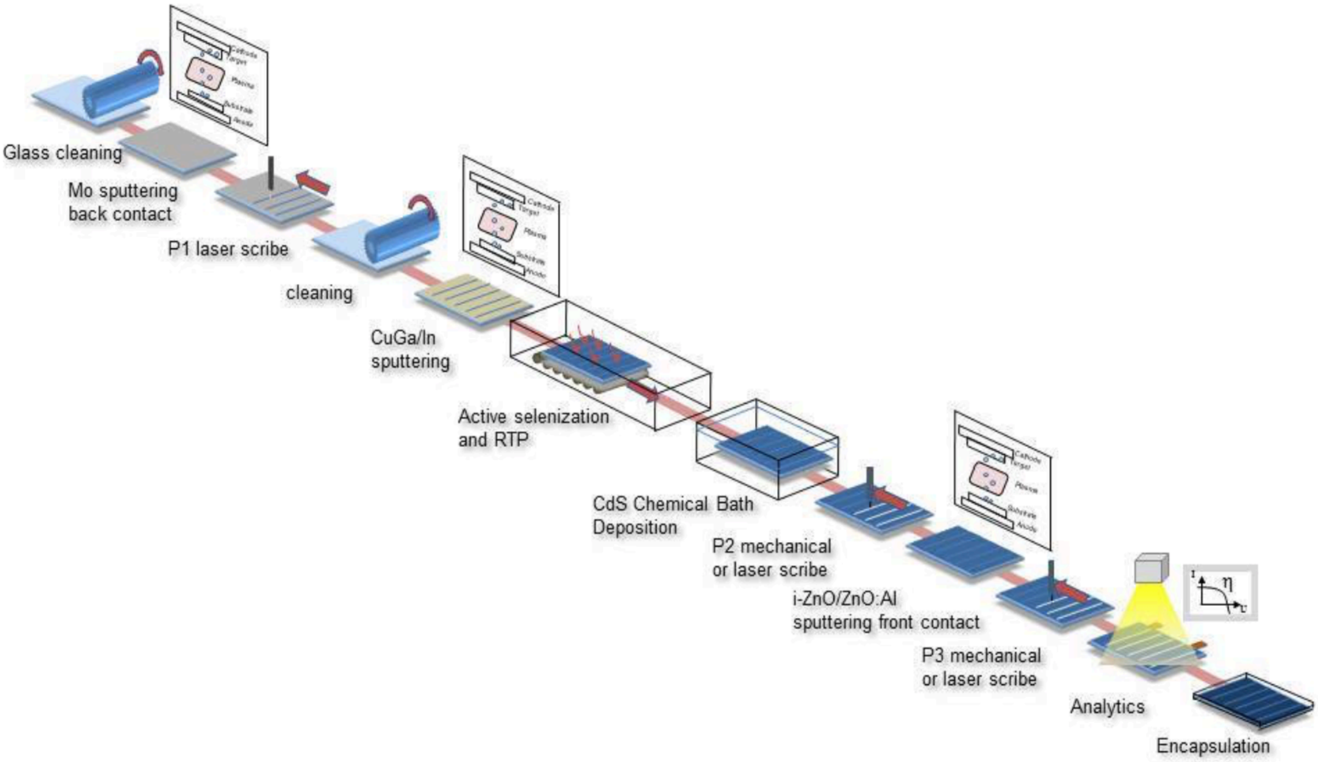


Figure 25: Roll-to-Roll production of CIGS PV-modules.

Figure 26: Roll-to-Roll manufacturing line at the NanoSolar facility in California.

5.2.2 Reliability

The word 'reliability' can mean two things in the case of CIGS PV-modules. On one hand it could mean the reliability of the module itself and on the other hand it could mean the reliability of the production capacity in the long term.
In this subchapter I will discuss both.

5.2.2.1 Reliability of the module

Because common silicon modules have been around for decades, it is easy to determine the exact lifespan of a module in certain conditions. Failure rates for silicon modules are as low as 1/10.000 per year, which is very impressive. However, CIGS and thin-film technology in general are still being developed so projections on the lifespan of these modules will have to be made.

The degradation of CIGS PV modules outdoors is complicated by various packaging methods (flexible or rigid), interconnect options (cell to cell interconnects or monolithic integration), the different manufacturing methods used to fabricate films in the CIGS stack, the corresponding material and interfacial properties of the semiconductor layers.

Since very few CIGS technologies have reached the 'ready commercial product –state', true long-term field tests haven't been excecuted yet. Whereas well built silicon panels are known to work efficiently for over 25 years, it's hard to make viable projections regarding the CIGS lifespan, yet current test-results look promising.

Because of the importance of long-term stability, I will give an overview of some test that have been excecuted by the NREL (National Renewable Energy Laboratory).

Following test results are extracted from a paper by Johan Wennerberg for the Faculty of Science and Technology of the university of Uppsala, Sweden.

In this paper, the CIGS modules are exposed to 2 different accelerated tests: a damp heat test and a dry heat test.

5.2.2.1.1 Damp Heat Test

The damp heat test is done according to the IEC1646 thin film module qualification standard. This test includes a visual inspection, insulation test and performance tests at various light and- and temperature conditions. In addition, modules are exposed to various mechanical tests like a load test, twist test and a hail test. In order for the module tob e IEC1646 approved, it has to meet the following criteria:

- The degradation of Pmax at STC does not exceed the prescribed limit after each test
- After the final light soaking, the maximum power output at STC in not less than 90% of the minimum value specified by the manufacturer
- No test sample has exhibited any open circuit or ground fault during the tests
- There is no visual evidence of a major defect
- The requirements of insulation and wet leakage current tests are met

If two or more out of eight test modules do not meet the requirements, the design shall be deemed not to meet the qualification requirements. Out of these 2 tests, the damp heat test is the most important since humidity penetration in the long term is believed to be a major cause of module failure.

The damp test procedure is as follows:

- Preconditioning: before conducting the tests, the module is annealed (tempered, hardened)
- Testing: following test conditions are applied:
  - Test temperature: 85°C (+-2°C)
  - Relative humidity: 85% (+-5%)
  - Duration: 1000 h
- Recovery: the module is submitted to a recovery time between 2-4 hours

To pass this test, the module needs to meet following criteria:

- No evidence of major visual effects
- Insulation resistance shall meet the same requirements as for the initial measurements
- The degradation of maximum power output at STC shall not exceed 5% of the value measured prior to the tests

Results:

For non-encapsulated CIGS devices, it is observed that after 4-500 hours degradation in both open circuit voltage and fill factor start to occur. These parameters tend to saturate at around 20-40%, resulting in a 40% performance loss. Closer investigation shows that in humid atmosphere, Na-O-CIGS is formed on the surface of the CIGS layer. Since this is an irreversible process, it leads to surface oxidation which then leads to a decrease of the electrical properties of the CIGS semiconductor.

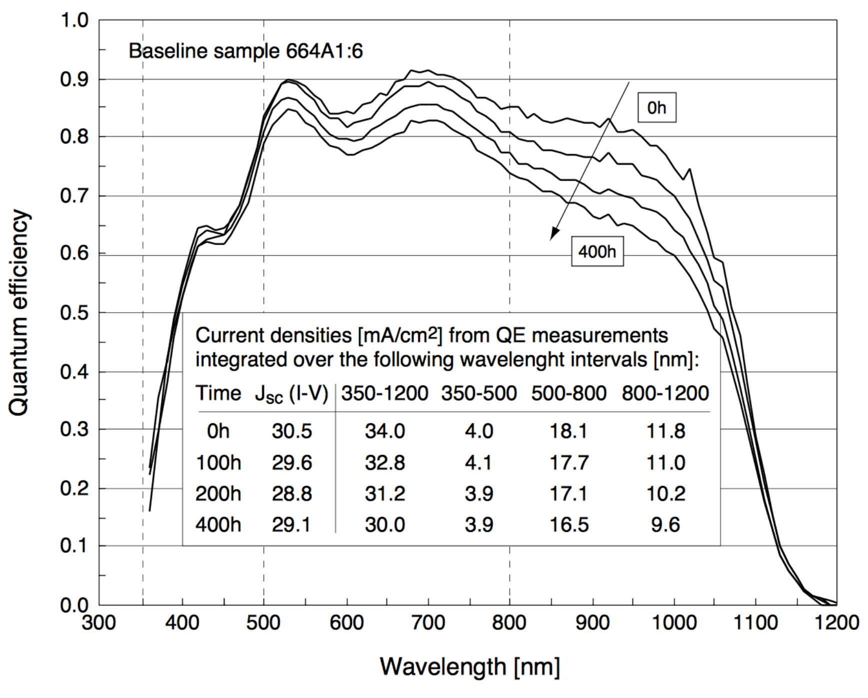


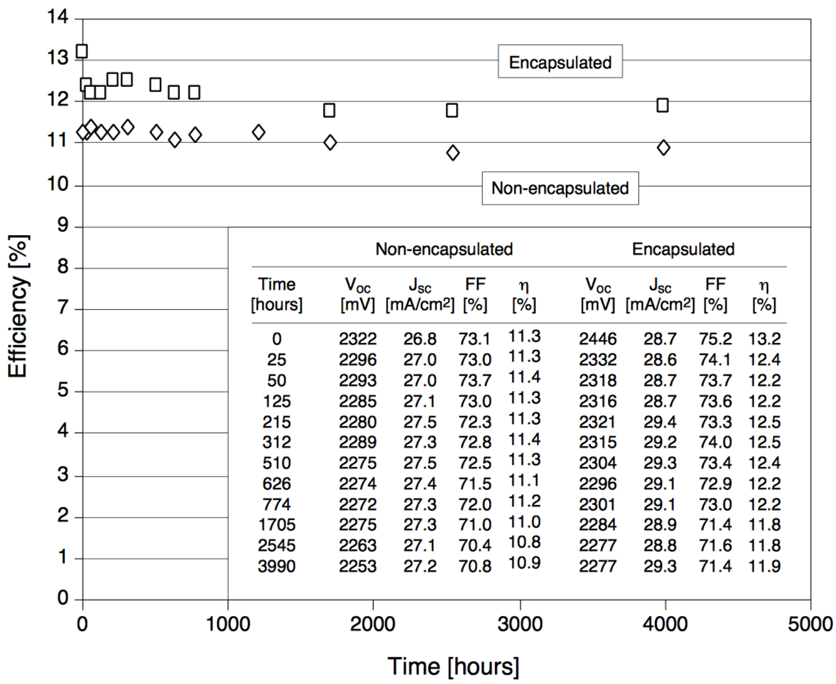
Figure 27: Quantum efficiency measurements of a baseline sample during accelerated ageing in damp heat conditions [13]

5.2.2.1.2 Dry Heat Test

Dry heat tests are performed under following conditions:

- Low pressure atmosphere: 85°C in a low pressure vacuum chamber with a temperature controlled hotplate
- For reference purpose, dry heat tests are also carried out in an argon atmosphere at 85°C

Results:



Time [hours]	Non-encapsulated V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]	Encapsulated V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
0	2322	26.8	73.1	11.3	2446	28.7	75.2	13.2
25	2296	27.0	73.0	11.3	2332	28.6	74.1	12.4
50	2293	27.0	73.7	11.4	2318	28.7	73.7	12.2
125	2285	27.1	73.0	11.3	2316	28.7	73.6	12.2
215	2280	27.5	72.3	11.3	2321	29.4	73.3	12.5
312	2289	27.3	72.8	11.4	2315	29.2	74.0	12.5
510	2275	27.5	72.5	11.3	2304	29.3	73.4	12.4
626	2274	27.4	71.5	11.1	2296	29.1	72.9	12.2
774	2272	27.3	72.0	11.2	2301	29.1	73.0	12.2
1705	2275	27.3	71.0	11.0	2284	28.9	71.4	11.8
2545	2263	27.1	70.4	10.8	2277	28.8	71.6	11.8
3990	2253	27.2	70.8	10.9	2277	29.3	71.4	11.9

Figure 28: Dry heat test of a naked and encapsulated mini-module in low-pressure air at 85°C [13]

As can be seen in figure 29 above, both voltage and fill factor exhibit initial changes, but performannce stabilizes at approximately 80%.

5.2.2.2 Reliability of the long term production capacity

As said previously, it is very important to have a good understanding of what the threats of this new technology are.

Normal PV panels as seen everywhere today use silicon as semiconductor. The problem however is that you need quite a lot of it for a single panel. Despite the fact that there are no silicon shortages at the moment, it looks like there might be in the future. With growing polysilicon demand in China, predictions are that by 2018 the shortage will be as high as 60.000 MT based on global PV end-market demand topping 95GW.

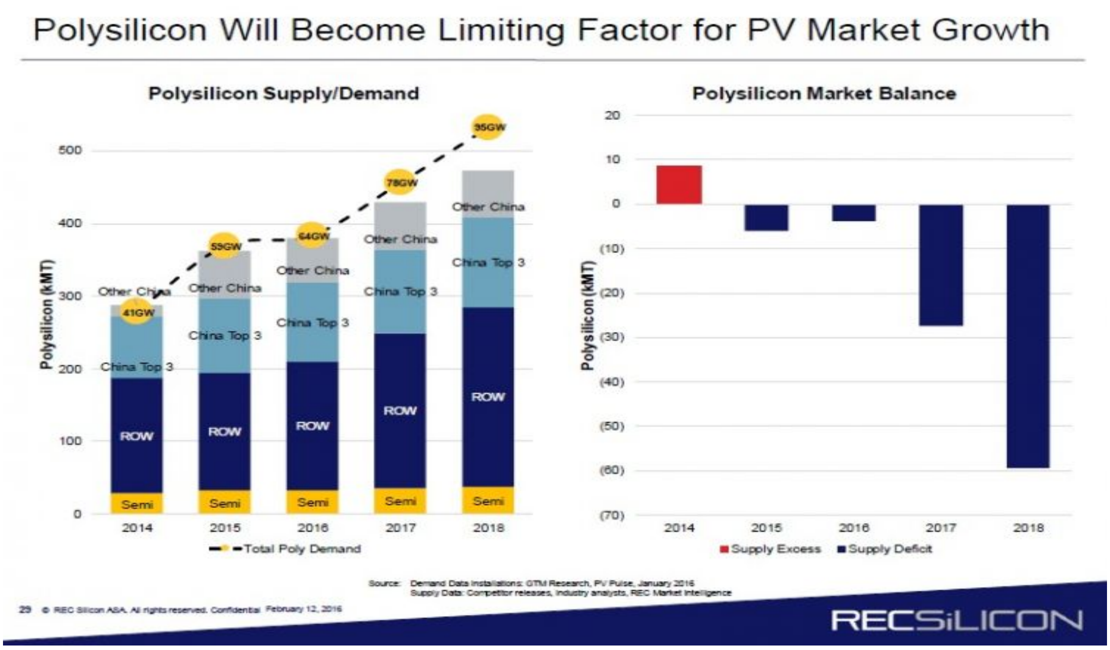


Figure 29: With Siemens-based polysilicon plants taking an average of four years to build (FBR around 2.5 years), polysilicon supply shortages could be nearly 60,000MT in 2018, based on global PV end-market demand topping 95GW. [10]

In CIGS modules however, things are different. CIGS modules contain indium and gallium. Both very rare materials, as shown in figure 30.

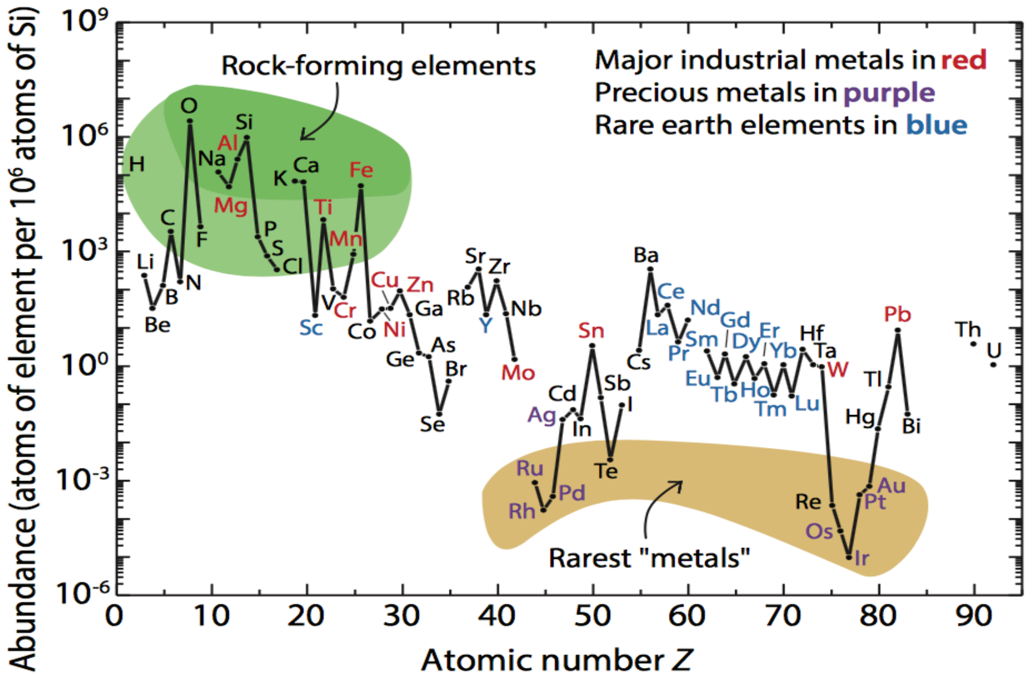


Figure 30: The abundance of elements (as atomic fraction) in the Earth’s upper crust. Data provided by the USGS [11].

Although indium is three times as abundant in the earth’s crust as silver, there are no significant ores of indium, it’s usually a by-product of zinc production. Indium is leached from slag and dust of zinc production and the metal further purified by electrolysis.

Estimations on the abundance of indium in the earth’s crust are around 0.05ppm for continental crust and 0.072ppm for oceanic crust. Consider that silver is being produced at a rate of 20.000 tonnes per year compared to aprox 1000 tonnes per year for indium. Silver is not perceived to be short in supply. Meanwhile, new ores and techniques are being discovered and developed.

So, even though indium is also used for LCD screens of smartphones, tablets, TV’s and computers, we shouldn’t be worried, according to the Indium Corporation. They say the only reason for the increase in price is due to a time-lag between the emerging demand and available supply. [11]

In the case of indium, recycling is also a very important aspect. The indium supply has been enforced by continued improvements in recycling programs. In the rapidly growing LCD market, upwards of 85% of non-deposited Indium is reclaimed and returned to the supply chain, using acid leaching, nanofiltration and liquid-liquid extraction techniques (Figure 31)

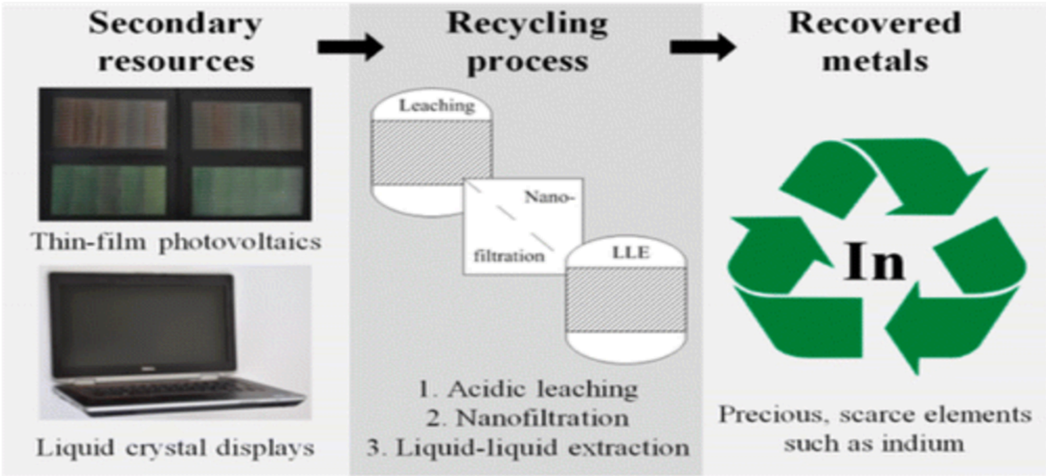


Figure 31: Recycling process of rare materials such as Indium

Similar to indium, gallium is also obtained by extraction. Like Indium, there are no primary gallium mines. Gallium is extracted from bauxite as part of the bauxite-alumina-aluminum refining flow, which most commonly utilises the Bayer liquor process. Historically, the low extraction volume was limited by the relatively small demand and relatively low prices, resulting in a low ROI for mining companies, which made the investment less attractive. For all practical purposes, gallium output is limited only by facilities investment and capacities. However, like indium, gallium production will rise as demand rises. The only concern is the time-lag which will result in a temporary peak in demand and prices.

5.3 CIGS SWOT Analysis

Strengths	**Weaknesses**
• **Good low light/less ideal angle performance** • **Good Shadow tolerance** • **Low manufacturing costs/easy to automate** • **Low energy payback time** • **Can be deposited on glass and flexible materials (easy to integrate)** • **No performance loss because of high module temperature**	• **Current reliability and stability test results are promising, yet more testing needs to be done.** • **Currently less efficient than common silicon technology** • **Facing technological challenges and innovations to make manufactuing process & equipment massively scalable.**
Opportunities	**Threats**
• **Promising test results and new technology developments will increase efficiency and exceed common silicon technology in the near future.** • **Possibility to integrate into many more applications to decentralize energy production** • **providing extremely low cost electricity**	• **The very well established silicon industry** • **Indium and gallium production industry will need to be developed => time gap between demand & supply => prices will skyrocket, resulting in more financial issues.** • **Economical history is not attractive to investors.** • **New technology => childhood diseases**

Table 1: CIGS SWOT Analysis

5.4 Application & Integration

Because of the relatively simple and easy to automate production process, costs of thin film solar panels are much lower than their alternatives. Anno 2016, a normal silicon solar module would cost around 4-5 USD per Watt for a normal residential installation, compared to the 0,40-0,70 USD per Watt for thin film panels. Add this to the efficiency advantages when it comes to diffuse light and it is easy to see why thin film technology will be starting to appear in a large number of different applications and take over the market.

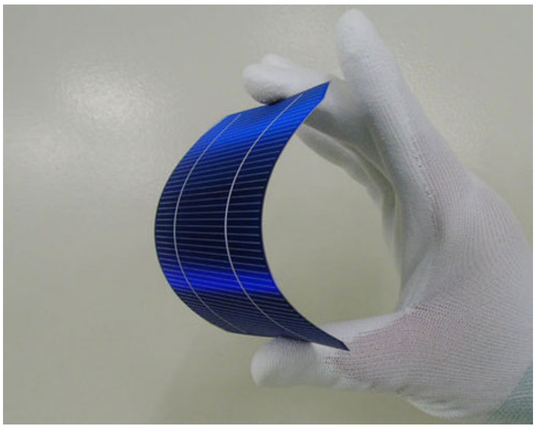


Figure 32: Thin film solar cell

The flexibility of these solar panels also allows them to be integrated in uneven surfaces where normal crystalline silicon panels wouldn’t fit.

Major producers of thin film solar panels like First Solar, Nanosolar, Mitsubishi and United Solar are in a race to reach the highest efficiency levels. However, it is The Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) that has set a new world record conversion efficiency for a copper indium gallium diselenide (CIGS) lab-sized solar cell, verified by Fraunhofer ISE of 22.6%. This aside, the current market leader, Solar Frontier (Japan) reached efficiency levels of 19,2%. [14] This new technology will be put into production in the summer of 2017, though efficiencies will be lower.

This again proves that thin film solar technology is gaining ground on convential silicon solar panels an taking over the industry, resulting in many new and innovative applications, examples are car roofs, decks of boats, tents, airplane wings,…

Even though mass integration of these panels has not occured yet, companies like Tesla, Ford, K-line and Fisker have been doing experiments and launched products to show that integrated solar technology can be aesthetically appealing and beneficial at the same time.

A good example of this are the Tesla Roofs for houses that have been announced in 2016. These roofs will be direct competition for normal roofs and are a perfect practical example of integrated solar technology.

Figure 33: Tesla’s solar roof [15]

Figure 34: Thin film solar technology integrated in army tent [16]

Figure 35: 2x100W Lensun thin film solar panels applied on the roof of a sail boat [17]

Figure 36: Recently Karma announced that the Revero's solar roof can now also charge the car's HV battery as well as the 12V [18]

In February 2016, Solar Frontier, the worlds leading thin film solar panel producer announced a collaboration with one of Japan's largest shipping companies, K-line.

K-line's new ship, the socalled "Drive Green Highway" would be integrated with advanced energy-efficient methods and design improvements to reduce its environmental impact. They will build 8 new ships each 200 meters long, 37,5 meters wide with a capacity of up to 7500 passengers. Each of these ships will be equipped with greenhouse-gas suppression technologies for their engines and a 150 kilowatt-peak thin film solar installation, existing of 900 panels on the roof of the ship. By combining these improvements they are aiming for a CO_2 reduction of 25%! The electricity from the solar panels will be used to power the LED- lighting on the car decks, which would normally be powered by a generator.

I agree that this will not save the planet right away but it is applications like this that will eventually add up to a big reduction of energy usage and greenhouse gas-emissions and most importantly, inspire other companies and organisations to take similar initiatives towards a more renewable future. [14]

"K Line is demonstrating how solar energy can improve the energy efficiency and reduce the ecological impact of the shipping industry," said Atsuhiko Hirano, CEO of Solar Frontier. "This is one example of the greater role that solar energy has to play in our future, supporting an ever broader range of technologies in a wider range of industries." [20]

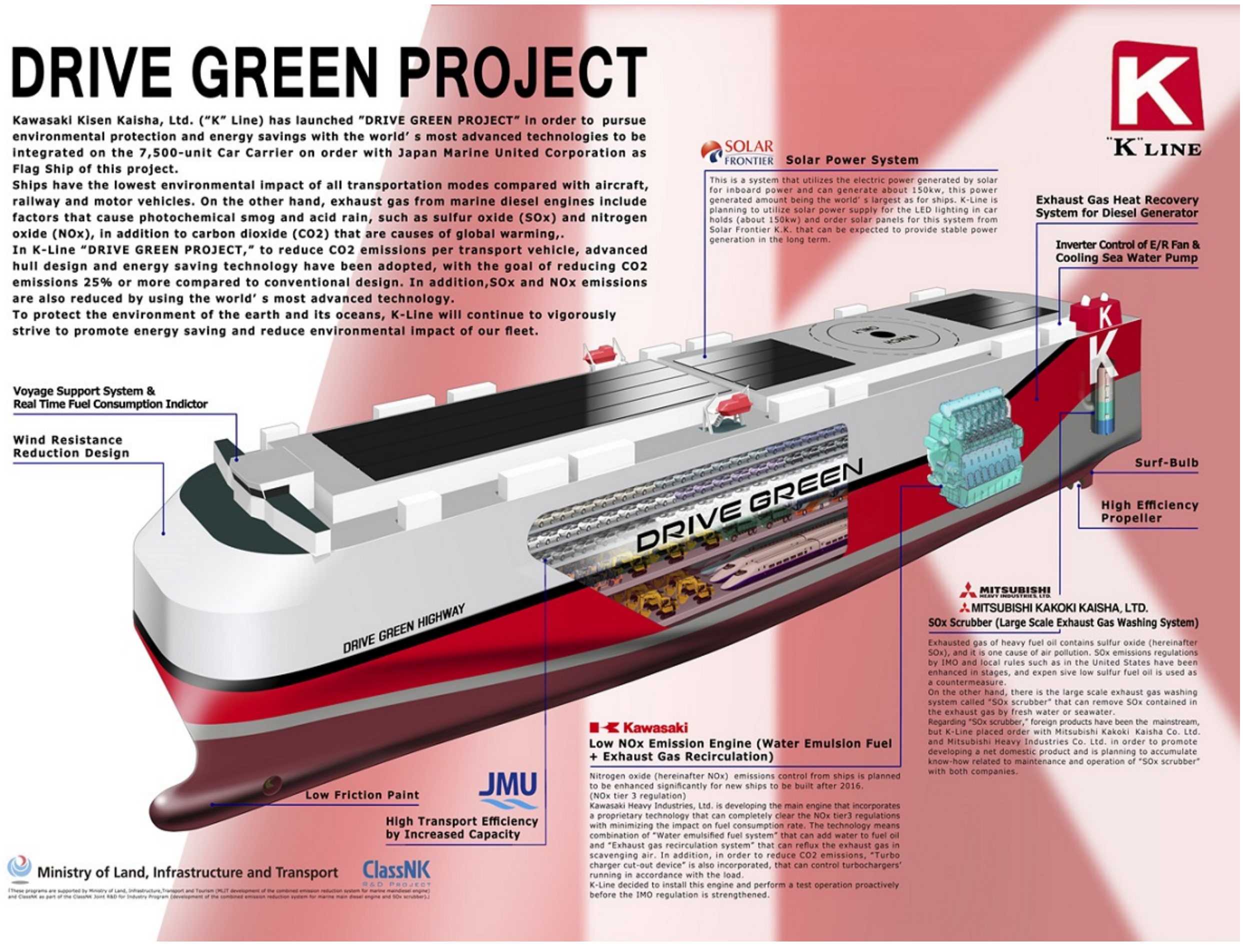


Figure 37: Drive Green Highway, the first of a series of similar vessels to be built under K Line's Drive Green Project (Image courtesy of Kawasaki Kisen Kaisha, Ltd.) [19]

6 COLOURED SOLAR PANELS

Even though thin film technologies might be very promising and easy to implement into a wide variety of applications, it doesn't (arguably) solve the aesthetic issue. To do this, we have to look at other solutions which completely, almost unrecognizably integrate into our surroundings. Because solar energy has proven its ability to compete with other, well established energy production methods and because energy demand rises, architects have long argued that solar panels are deemed to ugly to be used as a construction material. Of course many companies have responded to this demand and have come up with a series of alternatives.

The main question I will address in this chapter is wheter or not there is a loss in efficiency when changing the colour of a solar panel. I have also listed a number of examples.

6.1 Coloured crystalline silicon panels

In order to understand the difficulties of giving a solar panel a different colour, one must first understand the electro magnetic spectrum and the effects it has on the efficiency.

Shown below is a figure of the complete electro magnetic spectrum with the visible part highlighted. The most powerful (gamma) rays are to the left where as the longer, less energetic rays are on the right side of the spectrum.

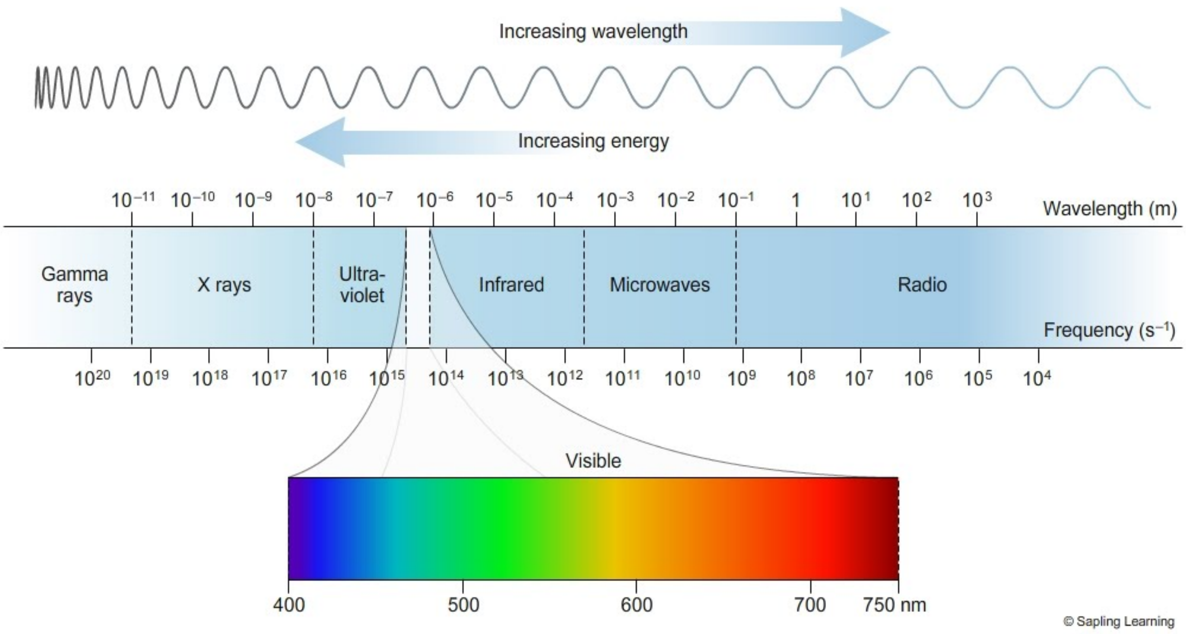


Figure 38: Electro magnetic spectrum

As we can see in figure 38 on the previous page, the visible light spectrum has a wavelength ranging from 400-750nm.

I explained in chapter 4.2 “The Basics of Photovoltaics” that in order for a semiconductor electron to move into the external load circuit, it needs to break free from the valence layer of the semiconductor atom. This means that only light photons with the right amount of energy are able to break these electrons free from their atoms and create a current. Put in terms of radiation, only the photons within the visible spectrum are strong enough to break electrons free.

In the solar energy distribution chart below, you can see that the largest part of the energy converted by crystalline solar panels lies within the visible spectrum. This is the mustard coloured area. The red coloured wavelengths don’t have enough energy and the yellow coloured have too much energy.

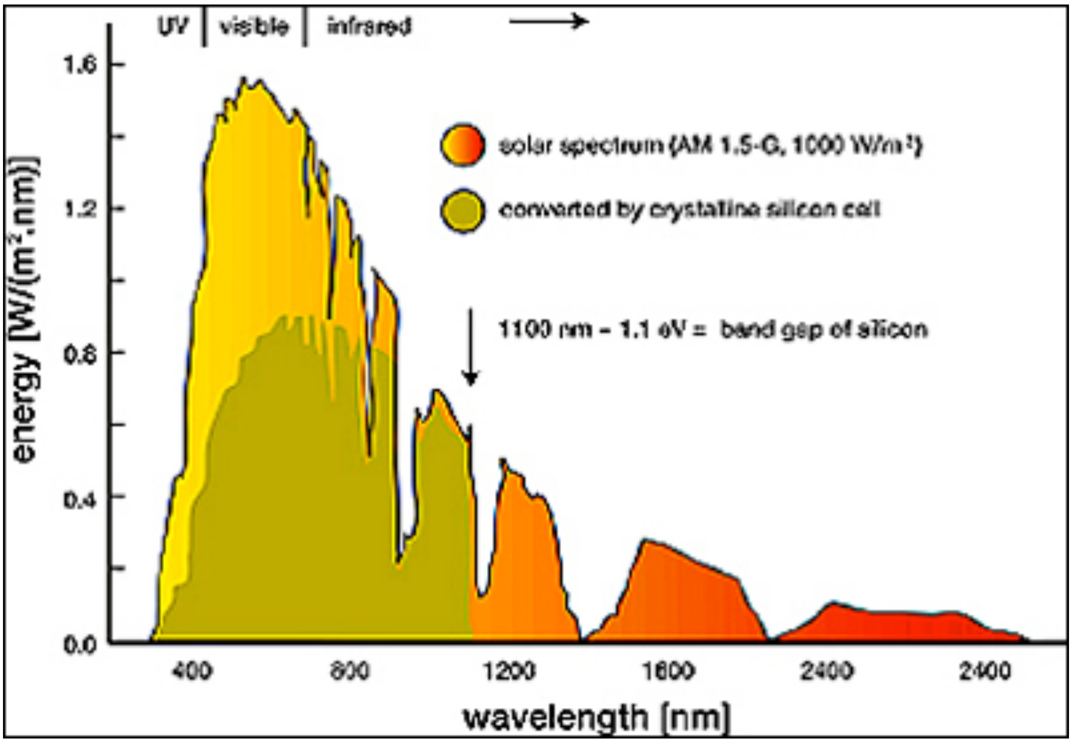


Figure 39: Solar energy distribution chart

An object appears to have a certain colour because certain wavelengths are reflected where others are absorbed. For example, white objects reflect almost all wavelengths which gives it it’s white appearance, while black objects absorb the entire visible spectrum.

This shows the difficulties that lie within coloured solar panels. It’s obvious that by placing a coloured glass cover on the solar panel, the tiny part of the spectrum that gives the colour will be reflected. This means it doesn’t penetrate through the glass which results in a lower energetic performance.

This means a good compromise needs to be found between the reflectance/transparancy of the glass and the efficiency loss.

Innovative solar companies like Swissinso, Solaxess and Onyx Solar have developed techniques to minimize this loss in efficiency. These techniques enable them to produce coloured solar panels with as little as 5% energy loss for yellow and green coloured crystalline panels (6% for thin film), 4% for blue crystalline panels (5% for thin film) and 2% for grey coloured panels (Thin film & crystalline).

The previously named company Solaxess has developed a film that makes solar panels appear white. The new technology consist of a plurality of transparent dielectric layers with different refractive (=light direction changing) indexes in order to reflect visible light while transmitting infrared light. The scattering of the visible light necessary to give a white appearance to a mirror-like surface is achieved by either placing the filter on a micro-structured surface or by placing on top of the filter a foil with embedded micro particles of a different refractive index. This means that this technology can only be applied to solar panels that are responsive to the IR part of the spectrum (like CIGS for example). Test on reference panels with an efficiency of 18,5% have shown that the effiency is taken down to 12% when applying the white filters. [21]

Of course this makes you wonder, if the efficiency is so much lower and the price so much higher, why would someone buy these panels over the much cheaper, much more efficient blue/black rivals?

The answer lies within the application of these panels. Normal panels aren't used for a lot of applications because they are deemed too ugly. This means that surfaces like the facades of buildings and constructions aren't being used to generate electricity at all. This makes 12% efficiency suddenly sound like a lot.

A counter argument could be the cost. If you apply solar panels with coloured films to existing buildings, the cost would be extra which would make it very hard to justify the investment. The goal of architects and development companies however, is to start using coloured solar panels as construction elements as can be seen in figure 40 below.

Figure 40: White photovoltaic glazings with a power output of 90 Watts/m2 – Collaboration between Solaxess and ISSOL [22]

6.2 Coloured thin film solar panels

Besides being flexible and thus easy to integrate, the colour and appearance of thin film technology will also determine its aesthetic ability. In order to be more compliant towards applications, solar technology has to blend in, as stated earlier.

Crystalline technology already offers many possibilities to be integrated into buildings (BIPV) but due to high costs, the market for these applications has not grown as expected. Thin film technology could mean a breakthrough in the built environment and because of it's flexibility it could also mean breakthrough of photovoltaic implementation in general.

However, to change the colour of thin film solar panels, different techniques are needed compared to crystalline solar panels. By playing with the thickness of the single amorphous silicon layer and by changing the encapsulation scheme, it is possible to change the colours of thin film solar panels. However, by changing the thickness of the amorphous layer, only a number of colours are possible. Changing the thickness too much results in high efficiency losses. Therefore different techniques to micro-pattern the surfaces are being tested and applied to allow new visual appearances and sometimes even increase efficiency!

This last technique is particularly interesting because it is also applicable on other thin film technologies (CIS/CIGS and CdTe), which have a lot higher efficiency levels because it traps the light inside the semiconductor layer.

Using a reactive mold-assisted etching procedure or laser-cutting techniques, it is possible to rapidly imprint larger area micro- and nano arrays onto materials. It is important to have the appropriate surface roughness to achieve good light scattering. When a surface is too roughly etched, voids or cracks may start to appear, resulting in a decrease of the performance.

This technology is still in the early development phase which makes is very hard to find details.

7 TRANSPARENT SOLAR PANELS

Another very interesting upcoming technology is transparent solar panels. However, since CIGS, CIS or CdTe are relatively new technologies, transparent technology has yet to be investigated. Therefore in this chapter, I will focuss on transparent silicon technologies

As you can imagine, many surfaces (especially windows) are transparent and simply can't be replaced by solar panels for aesthetical and practical reasons. To give an idea of the scale of this opportunity, 2% of the glass produced worldwide is being used for solar panels while 80% is used in buildings. Over the years, many companies have tried to make solar panels as transparent as possible as shown in figure 41.

Figure 41: Transparent solar panels (courtesy of solar constructions) [23]

These are made of crystalline silicon cells in between layers of glass. In many cases this is the ideal solution, it generates electricity with a high efficiency and it acts as a sunscreen at the same time.

However, in many applications, the orientation of surfaces like windows is not ideal and the need for better tranparancy exist. This is where thin film a-Si technology comes in. This technology holds several advantages over cristalline silicon that could be useful in a wide variety of applications. For a start, transparent a-Si thin film technology can be made by using a very small amount of powdered silicon, mixed with a transparent conductive oxide which is then vacuum layered onto a glass substrate to create a transparent semiconductor. Another very important advantage is that amorphous silicon thin film technology will outperform crystalline silicon technology when it comes to low light intensity and less ideal angles.

A test performed by Polysolar Ltd. under standard test conditions (STC) proves this. [24]

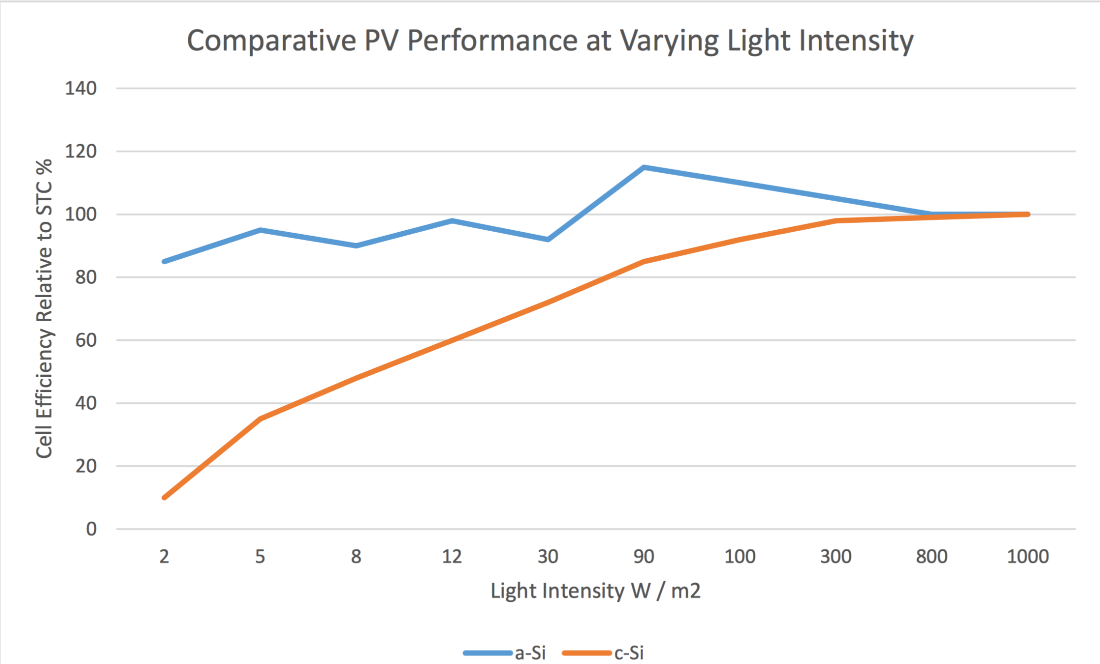


Figure 42: Low light performance a-Si vs c-Si (courtesy of polysolar Ltd.) [24]

Using thin film technology therefore means that not only south facing windows or surfaces can be used to generate electricity but also any other glass surface, even indoors! Also, because thin film cells are flexible, they can easily be used to be integrated into round windows or surfaces.

Figure 43: Transparent thin film windows used as roof and walls in a London bus shelter. The shelter produces 2000kWh per year.

However, even though these thin film windows are much more transparent than their cystalline rivals, it is still clearly visible that these are solar generating windows as you can see in figure 43. Admittedly, in southern countries where a lot of energy goes to cooling, semi-transparent windows can be useful. This brings us back to our initial aesthetics issue.

In recent years, researchers from Oxford University and Michigan State University have been investigating possibilities to make fully transparent, energy producing windows. It looks like they are on the right path. They completely changed the way a regular solar cell works. Normally, photovoltaïc solar panels generate electricity by absorbing the photons.

This new solar cell however uses a completely different approach. By using a *transparent luminescent solar concentrator* (TLSC) made out of organic salts, they are able to selectively harvest a part of the non-visible solar spectrum while letting the visible part pass through. These organic salts absorb certain near-infrared and ultraviolet wavelengths which they then emit to the edge of the plastic window where thin strips of conventional photovoltaïc cells convert them into electricity.

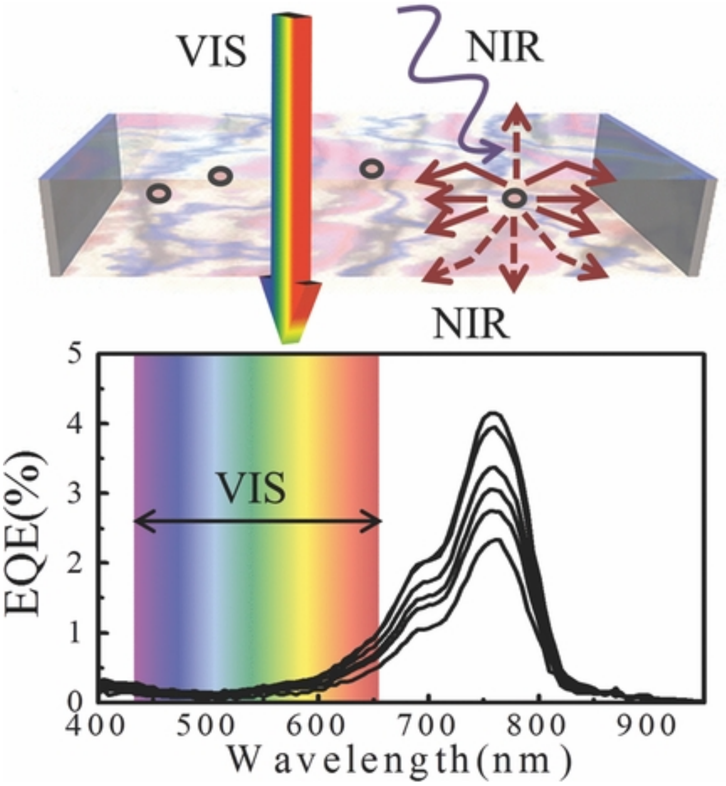


Figure 44: TLSC filters near-infrared wavelengths and emits these wavelengths to the side.

Unfortunately at this time, efficiency is very low at 1% while other transparent solutions as named before reach efficiency levels of 8%. However, reasearchers say that within the next couple of years, they should be able to reach efficiency levels of up to 10% using different technologies like CIGS. And remember, solar window technology opens up an enormous area to solar energy production.

8 APPLICATION OF THIN FILM SOLAR TECHNOLOGY ON THE BBQ BOATS.

8.1 Intro

Because the barbecue boats are so popular during hot sunny days, the company manages to rent each boat 3 times per day for multiple weekends per year. Because of this success and his entrepreneurial mindset, Jonathan wants to find a way to increase the amount of cycli and rent each boat 4 times per day.

At the moment, the boats that return from a cyclus have to be recharged and cleaned which takes over one and a half hours. Adding an extra cyclus means we would have to find a way to decrease the charging time or preferably eliminate it all together. The remaining time for cleaning is half an hour.

The boats are rented for periods of 2 hours (+30 min training session) at a rate of 275CAD during the week and 345CAD during the weekend. This means that in weekends, the boats could generate 690CAD extra, which is why Jonathan and I were wondering if we could use this money to improve the green image of the company even more by using solar power to charge the batteries.

Initially we wanted to decentralise the power production and minimalise the charging time by applying thin film CIGS solar panels to the hull of the boat so they could charge the batteries while they were floating around. (Attachment 1: Technical Datasheet Nanosolar Nanocel)

In order not to ruin the sight of the boats, we agreed to start by trying to make the solar panels as invisible as possible and thus installing them on the hull of the boat. Since the boats are circular, one half will always face away from the sun. Another important aspect is that the hull of the boat is donut-shaped and the angle towards the sun will not be ideal. This means we need solar panels that perform well in these less-ideal conditions and could adapt to the rounded surface of the hull. This means using CIGS thin film solar cells.

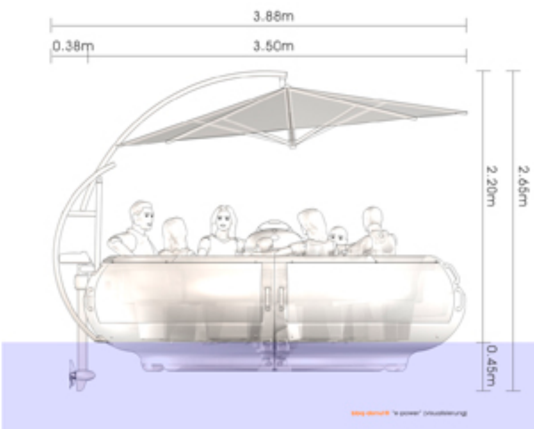


Figure 45: Profile sketch of the BBQ donut

However, calculating this turned out to be a near impossible task because of the lack of test equipment, knowledge and time. Therefore a decision was made to design 2 simple setups. An on-shore charger and a simplified version of the initial idea of applying the CIGS cells on the hull of the boat.

For the on-shore, I opted for a simple 'battery-switch' system where a solar setup would charge a new and easier to handle battery pack which could then be changed during the half-hour cleaning period. This system will have the advantage of reducing the charging time to almost 0. Additionally the panels who are placed in the marina could be used for other purposes outside the rental season, by renting the setup to the marina.

8.2 Energy Demand

The first step in dimensioning a solar system is knowing what the demand is. In this case the only electricity consumption comes from the 2HP (1,49kW) 24V Haswing engine. In this first solution, we want to be able to change the batteries quickly and easily during the half hour cleaning stop so we need to look at light and compact battery packs.

SPECIFICATIONS		
Voltage - Rated/Max	-	**DC 24V**
Depth Adjustment	-	**Depth collar**
Max Thrust	-	**2HP**
Prop Type/Size	-	**3 blade prop/11.8 inch diam**
Prop Speed at Full Power	-	**Max. 630 rpm underwater**
Battery Type (suggested)	-	**2 x 105AH deep cycle**
Max Boat Length/Load	-	**6.5m/700kg**
Power - Rated/Max	-	**1120W/1200W**
Amp - Rated/Max	-	**47A/50A**
Decibel Level (db)	-	**75db**
Shaft Type	-	**Aluminum**
Shaft Length	-	**38.5 inch/980mm**

Figure 46: Specification of the Haswing engine

Because these boats are meant to BBQ on the water, not only to cruise around, and because False Creek where the boats are rented isn't very big, we assume that on average the engines are only used for 50% of the time, be it at full throttle.

As you can see in the specifications above, the engine draws 47A at full throttle.

Before I calculate the energy demand, I have to address that the current batteries are too big to carry and require a lot of work to disconnect. We could easily install smaller packs that are easy to switch. Therefor I would opt for a special, purpose made battery.

The battery I've chosen is a lithium ion battery from the main electric outboard motor company in the world, Torqueedo. With 24,3kg, this battery is transportable and thus easy to replace. It is waterproof and fits perfectly in the battery compartiment of the BBQ boats. [25]

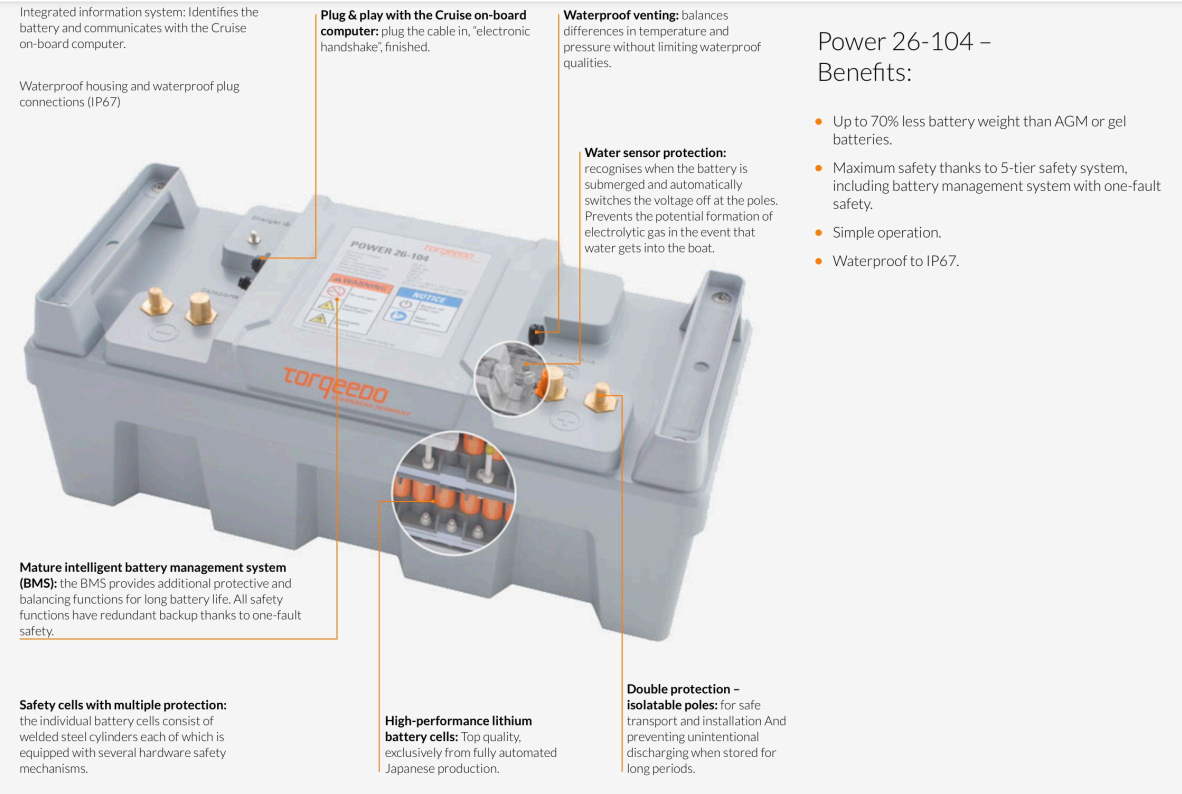


Figure 47: Torqueedo power 26-104 high-performance Li-Ion battery

Power 26-104 Technical Data

General features	
Capacity	2,685 Wh
Nominal voltage	25.9 V
Final charging voltage	29.05 V
Final discharging voltage	21.0 V
Nominal charge	104 Ah
Maximum discharge rate	180 A
Maximum discharge rate at nominal voltage	4,500 W
Weight	24.3 kg
Dimensions (L x H x B)	577.5 mm x 218.5 mm x 253.5 mm
Volume	32 l
Battery chemistry	Li NMC

Figure 48: Torqueedo power 26-104 high-performance Li-Ion battery technical data

As can be read in the technical specifications of the electric motor, the rated power is 1120W.

1120W x 0,5h = 560Wh

This is the energy that our engine uses over the half hour at full throttle and thus over the total rental period.

The capacity from the new batteries is 2685 Wh

This means after 1 rental cyclus the returning batteries contain around 2125Wh (or 20,86% discharge).

8.3 Irradiation

In order to make a decent projection of the actual energy yield of our solar setup, we need to take a look at the average solar irradiation.

Due to lack of time and equipment, I will use theoretical insolation data.

Natural Resources Canada provides acurate data regarding this topic on its website. (www.nrcan.gc.ca)

In the graph below you can see the average monthly insolation from the past 6 years (2010-2016). I extracted this data from an Excel file I found on the website and made a graph to give a clear overview.

The graph shows the average solar irradiation in $kWh/m^2/day$ for Coal Harbour, Vancouver.

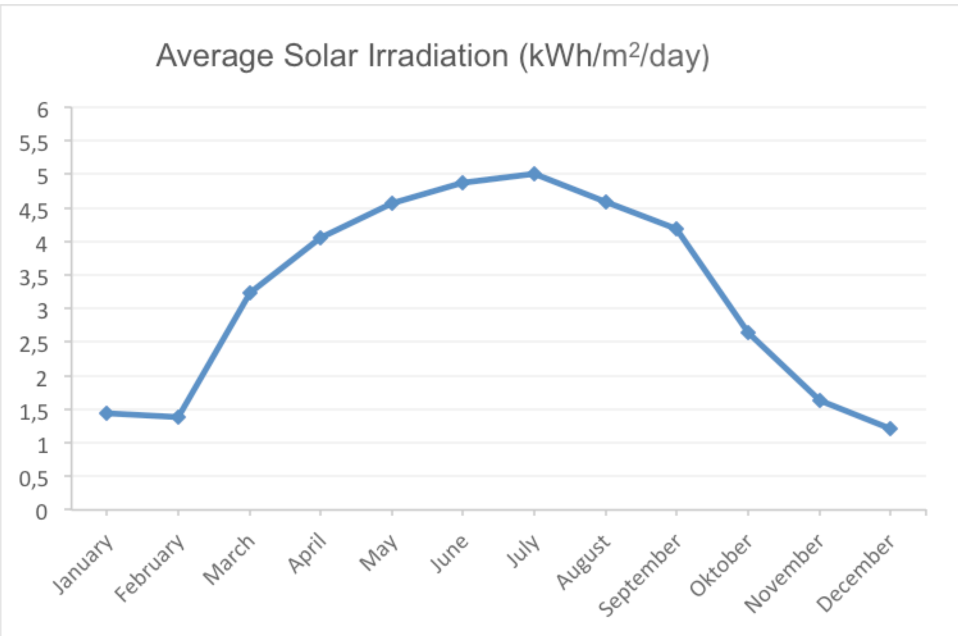


Figure 49: Average Solar Irradiation for Vancouver, Canada.

Because barbecueing on the water is an activity for warm sunny days, the available rental period is limited to just a couple of months per year.

With the exception of this year, a rental period starts in the beginning of april and ends at the end of september.

The average solar irradiation covering the 6 months of April – September is

4,55 kWh/m^2/day

Of course, the BBQ boats are rented per hour (not per day) and only when the sun is shining, therefore we must take a closer look at the data regarding sunshine hours.

Below is a chart containing the average hours of sunshine per month for 8 different cities in Canada. We will be looking at Vancouver and only take the months April – September into account.

Average Daily Sunshine Hours Canadian Cities Compared

Month	Vancouver, BC	Penticton, BC	Calgary, AB	Winnipeg, MB	Toronto, ON	Ottawa, ON	Fredericton, NB	Halifax, NS
Jan.	2.0	1.3	3.8	3.9	2.8	3.3	3.9	2.9
Feb.	3.0	2.8	5.0	4.9	3.9	4.4	4.7	4.0
Mar.	4.3	4.6	5.7	5.8	5.0	5.2	4.7	4.1
Apr.	6.1	6.5	7.3	8.0	6.2	6.3	5.3	4.5
May	7.4	7.6	8.2	9.2	7.4	7.4	6.6	6.3
Jun.	7.6	8.2	9.3	9.4	8.3	8.4	7.3	7.5
Jul.	9.5	9.5	10.2	10.2	8.9	8.9	7.7	7.7
Aug.	8.6	8.9	9.1	9.0	7.8	8.0	7.3	7.2
Sep.	6.6	7.1	6.9	6.0	6.3	5.7	5.7	5.4
Oct.	4.0	4.6	5.8	4.7	4.8	4.4	4.6	4.0
Nov.	2.1	1.8	4.1	3.1	2.8	2.8	3.3	2.5
Dec.	1.8	1.2	3.6	3.2	2.4	2.6	3.3	2.1

Figure 50: Average sunshine-hours for 8 cities in Canada

If we take the average from these 6 months, we find that the average sunshine hours per day are 7,63.

To find the actual irradiation per sunshine hour, we devide the ASI by the ASH:

4,55 kWh/m^2/day / 7,63 h/day = 0,595 kWh/m^2

8.4 MPP Tracker

In order to charge the batteries the best possible way, we need a Maximum Powerpoint Tracker. This is a device that will look for the optimal balance between voltage and current and thus charge the batteries with the maximum possible power delivery.

The tracker I've chosen is a tracer2215BN that will allow a max of 530W (24V)

Besides the fact an MPP tracker will benefit the total energy yield, there's also a loss that needs to be taken into account, as you can see in the graph below. [26]

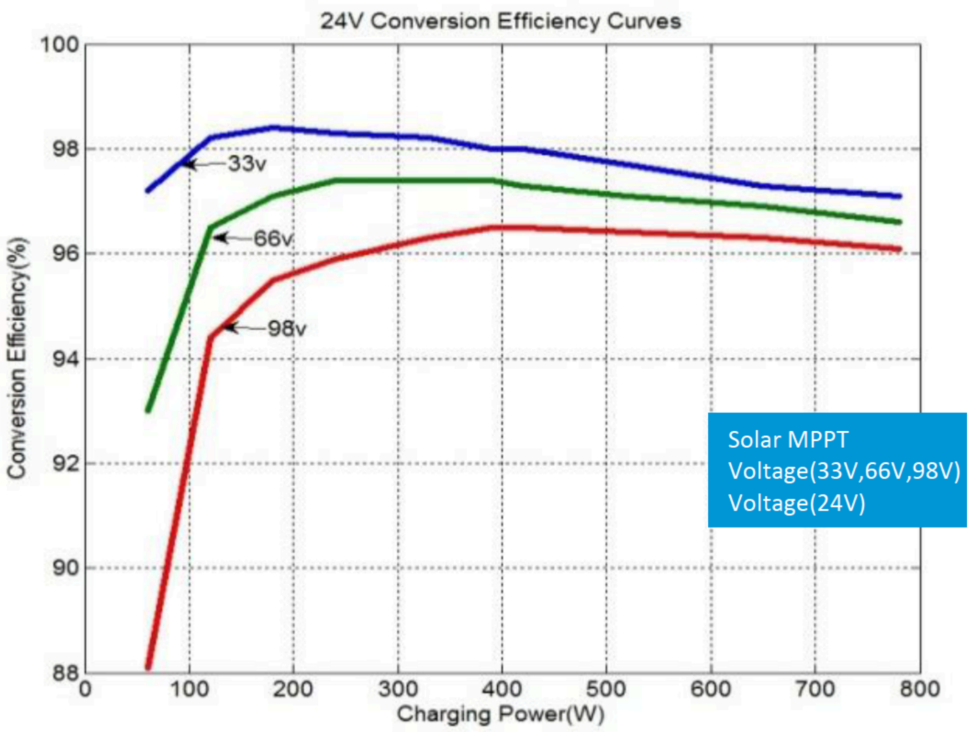


Figure 51: Tracer2215BN 24V conversion efficiency curves

In this case, the efficiency is around 98%, or a 2% loss.

This means we need to add an extra 2% to the total energy demand, to compensate.

560Wh + 2% = 571,2Wh

8.5 Conclusion

We now know the total energy demand over the 2 hours rental, 571,2Wh. We also know the average solar irradiation per hour and the electrical efficiency of our solar cells, 14%. [27]

Even though there is an extra 30 minutes for cleaning and 30 minutes safety training, this calculation will use 2 hours as charging time for the batteries.

The calculation looks like this:

0,596 kWh/m^2 x 0,14 = 0,083 kW/m^2 or 83W/m^2

The total energy demand per hour is 571,2/2 = 285,6 Wh

285,6/83 = **3,44 m^2**

PRICE:

One solar cell is 0,165m x 0,135m = 0,022275 m^2

This means we need 155 cells

Assuming the same price I paid for the lot I bought, this would mean around 581 CAD (see remarks at the end of the chapter)

The MPP costs 140 CAD

Because we need 2 batteries per boat, the price for those would be 7530 CAD

This means a total of 8251 CAD

This price estimate does not include installing costs or other materials.

If we assume this investment brings in an extra 690 CAD on a good weekend, and there are around 10 good weekends per year, this installation would pay for itself in 1,2 years. The rest is pure profit and an even greener company image.

8.6 Application on the BBQ Boats

We now know we need 3,44 m^2 solar cells to charge the batteries over a 2hr rental period.

The initial purpose however, was to apply these flexible solar cells to the BBQ boats. Another reason I chose these CIGS cells is because they are much less sensitive to less ideal angles than normal silicon panels. This makes them perfect for application to the BBQ boats. However, calculating the actual yield is almost impossible with the available resources.

As said before, the solar cells would only be applied to the top of the donut shaped hull for aesthetic purposes, as can be seen in the photo below. Any closer to the water surface could certainly damage the cells in the short term.

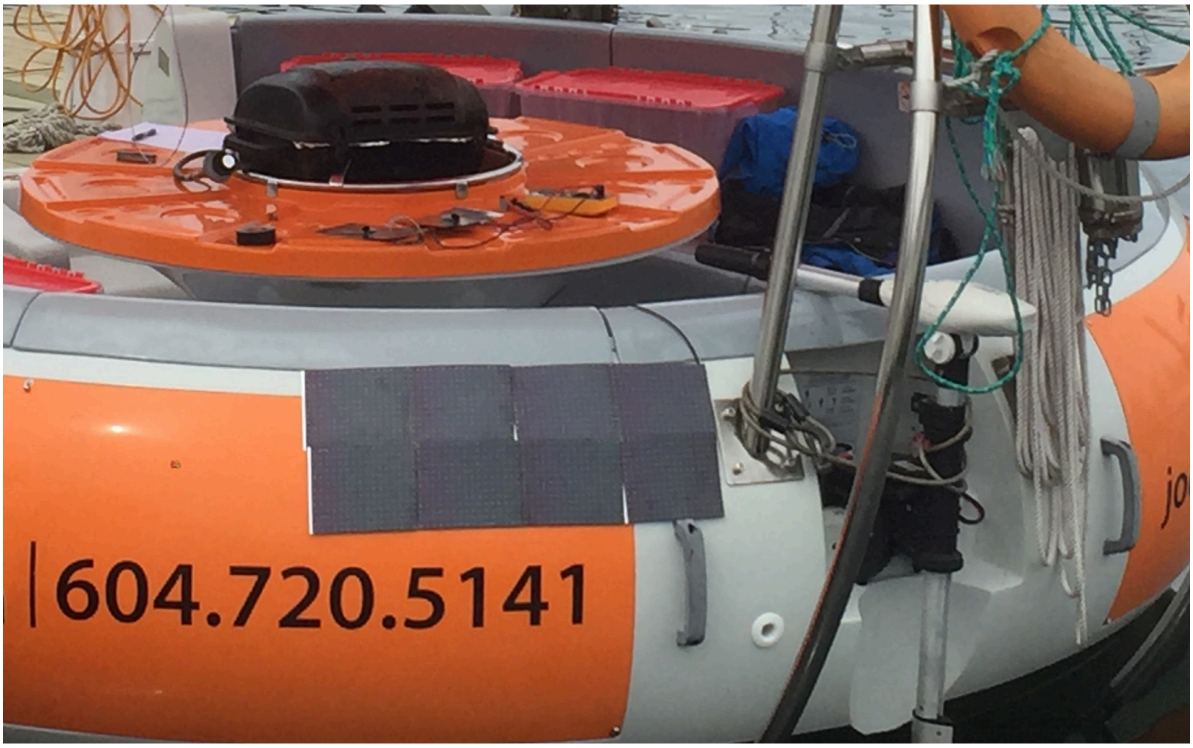


Figure 52: Example of Nanocells attached to the hull of the BBQ donut

I calculated that I could fit 49 cells on the top row and 50 cells on the bottom row.

All together this means a total area surface of 2,21 m^2

However, in contrast to the on-shore setup, these cells are all facing different directions and logically performing less. To be able to give an calculated estimate of the total yield of this setup, I measured the Voc of the cells, facing different directions under different angles. The approach of this measurement is not very scientific, but helps to give a good idea of the influence on the output. The values will be converted into relative percentages and applied to the electrical efficiency.

The measurement tool I used for this test is an Ohmeron MT489A multimeter.

Figure 53: Ohmeron MT4891 multimeter

The tests themselves are executed on a single Nanosolar Nanocell (attachment 1)

	N (0°)	E (90°)	S (180°)	W (270°)
Horizontal angle 1, 60°	0,28V	0,37V	0,40V	0,37V
Horizontal angle 2, 80°	0,30V	0,35V	0,38V	0,35V

Table 2: Voc measurements for different orientations and angles

**note that the voltage of the cell facing north (0°) is higher for the 80° angle. This could be an indicator that reflection of light on the water surface has a positive influence on the cell.*

Since η=14% under STC we have to convert these values to the values measured. The Voc according to the technical datasheet is 0,61V

	N (0°)	E (90°)	S (180°)	W (270°)
V(measured)/V(STC)x100 Horizontal angle 1, 60°	45,9%	60,7%	65,6%	60,7%
V(measured)/V(STC)x100 Horizontal angle 2, 80°	49,2%	57,4%	62,3%	57,4%
Equivalent η for 60° Equivalent η for 80°	6,4% 6,9%	8,5% 8,0%	9,2% 8,7%	8,5% 8,0%

Table 3: Relative loss in percentage and η

We now know the efficiency per angle and per orientation. If we devide each row by 4 we find that:

For 60° each orientation has 12,25 cells x 0,022275 m2 = 0,273m2

For 80° this number is 12,5 cells x 0,022275m2 per cell = 0,278 m2

	N (0°)	E (90°)	S (180°)	W (270°)
Horizontal angle 60° yield in kWh (0,273m^2 x 0,596 kWh/m2 x η)	0,0104 kWh	0,0138 kWh	0,0150 kWh	0,0138 kWh
Horizontal ngle 80° yield in kWh (0,278 m^2 x 0,596 kWh/m2 x η)	0,0114 kWh	0,0133 kWh	0,0144 kWh	0,0133 kWh
Total yield in kWh				= 0,1054 kWh

Table 4: Total energy yield calculation

As we can see, the total energy yield of the solar cells on the hull of the boat will generate 105,4 kWh. These measurements were taken on a very bright day with a temperature of 24°C.

The total demand of the engine is 571,2 Wh (incl the efficiency loss of the same MPPT), meaning after a 2 hour rental, the batteries will still need (571,2- (105,4x2))

= 360,4 Wh of extra charge per cylcus.

In this calculation I only took the 2 hours during the rental into account, however, when the boats are cleaned and during the safety instructions, the boats are also out in the sun, meaning we can add another hour to our calculation.

This brings the total to: 316,2 Wh and would reduce the extra charge needed to 255 Wh.

Over the day and thus 4 cycli, this means a total reduction in the battery of 1020Wh. This can be recharged using the standard shore-power charger during the night OR during low light hours before and after the rental.

PRICE:

Since we don’t need 2 batteries, we can save the expense of a second one.

Which leaves following costs:

Battery : 3765 CAD

MPP: 140 CAD

99 cells = 247,5 CAD

This price does not include installing costs or other materials.

A total of 4152,5 CAD means the installation would be profitable after 6 high season weekends.

REMARKS:

There are however a couple of things that need to be addressed.

- The solar cells are bought from a lot and are not available for consumers
- In the calculations above, I used actual SUN-HOURS because this is when the boats are actually rented. Normal light hours will exceed sun-hours but will result in lower energy yields.
- In these calculations, I did not take any other performance reducing factors like conductor resistance into account.
- The solar cells are not salt-waterproof in the long-term (there are solutions for this)
- Projections on efficiencies show that in the next couple of years, CIGS panels will become very profitable and in this case would be able to fulfill the entire demand.

CONCLUSION

Aesthetically appealing solar technology is starting to appear all over the world, albeit in small quantities. New technologies and production methods are being developed but it's easy to say they're not there just yet.

Looking at the facts and figures, I can conclude that competitive advantages in the market will be determined by a combination of cost structure and product attributes that locally drive the customer's choice. In other words, the new PV industry will exhibit multiple commodity categories with suppliers exploiting diversified product designs for different applications. However, for this to happen, larger investments need to be made and this can only happen when the technology is attractive enough.

Due to current silicon efficiency levels, prices and the current scarcity of the necessary raw material, this motion will take a couple more years.

Studying this topic over the past couple of months made me realize that the PV industry is on the verge of a revolution. The ultimate goal is to make solar harvesting surfaces that people don't even know are there.

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ATTACHMENTS

Attachment 1: Technical Datasheet Nanosolar Nanocell