# Analysis, design and study of flexible solar systems

by

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A Thesis submitted for the Bachelor Degree

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GR

October, 2023

**Μέλη εξεταστικής επιτροπής συμπεριλαμβανομένου και του Εισηγητή:**

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«Είμαι συγγραφέας αυτής της πτυχιακής/διπλωματικής εργασίας και ότι κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος. Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του πτυχίου μου».

Ο Δηλών

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# Abstract

This thesis examines the several aspects of flexible solar systems within the broader framework of renewable energy sources. The imperative to address the pressing issues associated with the shift towards sustainable and clean energy solutions has prompted a more comprehensive investigation into the intricacies of flexible solar technology, encompassing its underlying design principles and its economic feasibility. This study aims to clarify these elements through a thorough academic investigation.

The present study focuses on the analysis phase, which involves a comprehensive examination of the technological complexities associated with flexible solar systems. The primary emphasis is placed on the organic photovoltaic systems capacity to adapt to diverse applications and conditions. The present inquiry explores the underlying concepts of photovoltaic technology, with a specific focus on assessing the efficiency and dependability of organic flexible solar modules. Moreover, the analysis takes into account the environmental consequences and sustainability considerations linked to flexible solar systems, highlighting their capacity to contribute to an ecologically conscious trajectory through a cyclical economic model.

The project primarily emphasizes on the design aspect, specifically exploring novel approaches to enhance the integration of flexible solar systems into pre-existing infrastructures. This study investigates innovative methodologies for system structure, orientation, and materials, with a specific focus on optimizing cost-effectiveness and enhancing total system efficiency. The research also examines the influence of several design characteristics on the extended-term effectiveness and resilience of flexible solar modules.

In addition to technical issues, the present study investigates the economic dimensions associated with flexible solar systems. A thorough evaluation of the costs and benefits is undertaken to determine the viability of using flexible solar technology on a broader scope. This evaluation incorporates several elements like installation costs, maintenance needs, energy generating capacity, and a possible return on investment. The objective of this study is to offer decision-makers significant insights into the financial feasibility of integrating flexible solar systems into portfolios of renewable energy.

The analysis of solar cell technologies and their comparison is of the outmost importance for all economic activity. Examining different technologies, each has its own strengths and weaknesses, which lead to the compartmentalisation of power producing applications, which is essential to both the consumer market and for utility companies.

# Περίληψη

Αυτή η διπλωματική εξετάζει διάφορες πτυχές των εύκαμπτων ηλιακών συστημάτων εντός του ευρύτερου πλαισίου των ανανεώσιμων πηγών ενέργειας. Η αναγκαιότητα να αντιμετωπιστούν τα επείγοντα θέματα που σχετίζονται με τη μετάβαση σε βιώσιμες και καθαρές λύσεις ενέργειας έχει προκαλέσει μια πιο διεξοδική έρευνα στις λεπτομέρειες των εύκαμπτων ηλιακών τεχνολογιών, καλύπτοντας τις βασικές αρχές σχεδιασμού της και την οικονομική της βιωσιμότητα. Αυτή η μελέτη στοχεύει στο να διευκρινίσει αυτά τα στοιχεία μέσω μιας λεπτομερούς ακαδημαϊκής έρευνας.

Η παρούσα μελέτη επικεντρώνεται στο στάδιο ανάλυσης, το οποίο περιλαμβάνει μια εκτενή εξέταση των τεχνολογικών περιπλοκοτήτων που σχετίζονται με τα εύκαμπτα ηλιακά συστήματα. Το κύριο βάρος τοποθετείται στην ικανότητα των οργανικών φωτοβολταϊκών συστημάτων να προσαρμόζονται σε διάφορες εφαρμογές και συνθήκες. Η παρούσα έρευνα εξετάζει τις βασικές έννοιες της φωτοβολταϊκής τεχνολογίας, με ειδική έμφαση στην αξιολόγηση της αποδοτικότητας και της αξιοπιστίας των οργανικών εύκαμπτων ηλιακών μονάδων. Επιπλέον, η ανάλυση λαμβάνει υπόψη τις περιβαλλοντικές επιπτώσεις και τις σκέψεις βιωσιμότητας που συνδέονται με τα εύκαμπτα ηλιακά συστήματα, επισημαίνοντας τη δυνατότητά τους να συμβάλουν σε μια οικολογικά συνετή πορεία μέσω ενός κυκλικού οικονομικού μοντέλου.

Το έργο επικεντρώνεται κυρίως στη σχεδίαση, εξερευνώντας καινοτόμες προσεγγίσεις για την βελτίωση της ενσωμάτωσης των ευέλικτων ηλιακών συστημάτων στις υφιστάμενες υποδομές. Αυτή η μελέτη ερευνά μεθοδολογίες για τη δομή του συστήματος, τον σχεδιασμό και τα υλικά, με ειδική έμφαση στη βελτιστοποίηση της οικονομικής αποδοτικότητας και της συνολικής απόδοσης του συστήματος. Η έρευνα εξετάζει επίσης την επίδραση διάφορων χαρακτηριστικών σχεδίασης στην αποτελεσματικότητα και ανθεκτικότητα των εύκαμπτων ηλιακών μονάδων.

Εκτός από τα τεχνικά ζητήματα, η παρούσα μελέτη ερευνά τις οικονομικές διαστάσεις που συνδέονται με τα ευέλικτα ηλιακά συστήματα. Πραγματοποιείται μια λεπτομερής αξιολόγηση των δαπανών και των οφελών για να καθοριστεί η εφικτότητα της χρήσης της ευέλικτης ηλιακής τεχνολογίας σε ευρύτερη κλίμακα. Αυτή η αξιολόγηση συμπεριλαμβάνει στοιχεία όπως οι δαπάνες εγκατάστασης, οι ανάγκες συντήρησης, η εν δυνάμει δυνατότητα παραγωγή ενέργειας και η πιθανή απόδοση επενδύσεων. Ο στόχος αυτής της μελέτης είναι να παράσχει στους αρμόδιους,

σημαντικές πληροφορίες σχετικά με τη χρηματοοικονομική εφικτότητα της ενσωμάτωσης των εύκαμπτων ηλιακών συστημάτων στο ρεπερτόριο των ανανεώσιμων πηγών ενέργειας.

Η ανάλυση των τεχνολογιών των ηλιακών κυττάρων και η σύγκρισή τους αποτελούν θεμελιώδη σημεία για όλη την οικονομική δραστηριότητα. Εξετάζοντας διάφορες τεχνολογίες, καθεμία έχει τα δικά της πλεονεκτήματα και αδυναμίες, οι οποίες οδηγούν στην καταμερισμένη εφαρμογή στην παραγωγή ενέργειας, κάτι που είναι ουσιώδες τόσο για την αγορά καταναλωτών όσο και για τις επιχειρήσεις υπηρεσιών δημόσιας ωφέλειας.

# Glossary

| | |
|---|---|
| OSC | Organic Solar cell |
| DSSC | Dye-Sensitized Solar Cell |
| PSC | Polymer Solar Cell/Perovskite Solar Cell |
| LCOE | Levelized Cost Of Electricity |
| PV | Photo-Voltaic |
| OPV | Organic Photo-Voltaic |
| TCO | Transparent Conducting Oxide |
| QD | Quantum-Dot |
| EV | Electric Vehicle |
| BIPV | Building Integrated Photo-Voltaic |

# Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor Dr. Kyriaki Kiskira for the continuous support of my thesis and for her patience and availability.

With our discussions, Professor Georgios Priniotakis assisted me to understand what steps I needed to follow to successfully complete my thesis. The insightful comments and the hard questions of Professor Michael Papoutsidakis widen my research from various perspectives.

I would also like to express the deepest appreciation to my colleagues who read and commented my thesis.

Lastly, my sincere thanks go to my family for their patience, encouragement and support. I am especially grateful to my parents, who supported me spiritually and economically for the completion of my thesis.

# Chapter 1 Introduction and review of Renewable Energy Sources

## 1.1 Introduction to Renewables

This chapter of my thesis surveys Renewable Energy Sources, as means of energy production. Energy production starting from the Industrial Revolution has been dominated by fossil fuels (Albert, M. J. 2021). As the population rises, so does the demand. Humanity risks polluting and damaging the environment, at a rate higher than that of the renaturation process which threatens to degrade the natural environment. The global electricity consumption has risen to 25,343 TWh in 2019 according to the EIA and it will continue to do so in accordance to the population trend. Renewables offer an alternative to burning fossil fuels to energy production. The philosophy behind renewables is the production of energy through the exploit of natural phenomenon like the photovoltaic effect, the flow of water or wind or the natural heat of tectonic plate movement (Ellabban, et al. 2014). The focus of this paper will only be on renewables that adhere to the philosophy of phenomenon potential energy conversion. Renewables such as biomass fuel will not be explored as they are not entirely similar either to renewables nor to fossil fuels. They serve as a form of fuel that follows the renewability principle but is burned exactly like a fossil fuel would be.

One of the most important aspects of renewable energy is its ability to reduce greenhouse gas emissions and combat climate change (Alrikabi, N. K. M. A. 2014). Burning fossil fuels, such as coal and oil, for energy not only depletes natural resources but also releases harmful gases into the atmosphere. In contrast, renewable energy sources like wind and solar power do not emit greenhouse gases during operation. By shifting to renewable sources, countries can decrease their reliance on fossil fuels, therefore reducing emissions and slowing the progression of climate change (Ellabban, et al. 2014). Moreover, many renewable energy sources have the potential to create new jobs and stimulate economic growth (Menegaki, 2008). Building and maintaining wind and solar farms, for example, requires a large workforce, and the manufacturing and installation of renewable energy systems generates jobs across various sectors. In addition to economic benefits, renewable energy can also increase energy security by diversifying a country's energy sources and reducing dependency on fossil fuels from other countries (Albert, 2021). Many renewable sources, such as wind and solar power, are also distributed and available in remote locations, making them ideal for communities that may lack access to traditional forms of energy (Fathabadi, 2017). Furthermore, renewable energy systems often require less maintenance and have lower operating costs than conventional power plants, reducing the long-term cost of energy for consumers and businesses alike.

In summary, the importance of renewable energy cannot be overstated. Not only does it offer an alternative to fossil fuels, but it also presents an opportunity to address climate change, create new jobs, enhance energy security, and promote sustainable development (Menegaki, 2008). As technological advancements continue to improve the efficiency and affordability of renewable energy systems, it is essential that governments and individuals alike prioritize the transition to clean energy sources.

## 1.2 Significance of Renewable energy application

Renewables provide a major advantage that is not at the forefront of the discussion. They provide the possibility of decentralized energy production as well as centralized (Fathabadi, 2017). It gives the option to any consumer or economic unit in general to produce its own need for electricity, independently (Robyns, Benoit, et al. 2021). The legal framework is not ripe globally to enable such a leap, but the systems of most countries respect this fact. Net metering is gaining momentum and early investors have jumped on the opportunity to lower their utility costs and better yet, make a profit (Darghouth, Naïm, et al. 2016). Renewable energy also gives the centralized electricity the possibility to maintain the utility status quo with the caveat of having to change from a physical fuel storage to an energy storage device . Either way, there are double the possibilities, as opposed to coal, nuclear or natural gas power plants that were never used outside of Grid-scale installations. These systems never provided the economic incentive for consumers to self-produce electricity.

## 1.3 Types of renewables

Renewable energy sources are becoming increasingly important as our society moves towards a more sustainable future. There are several types of renewable energy sources that are currently being used, including wind, hydropower, tidal, geothermal, and solar (Ellabban et al. 2014). Wind energy is generated by wind turbines, which convert the kinetic energy of wind into electrical energy by spinning a generator. This technology has become more efficient and cost-effective in recent years, making it a popular choice for generating renewable energy. Hydropower is generated by the movement of water, either from falling water or from waves and tides. This source of energy has been used for decades, but advances in technology have made it even more effective and accessible. Tidal energy is a form of hydropower that harnesses the power of tidal currents to generate electrical energy (Ellabban et al. 2014). Geothermal energy is generated by the heat within the Earth's crust, which can be used to produce steam that drives electrical generators (Alrikabi, N. K. M. A. 2014). Finally, solar energy is generated by capturing the sun's rays using photovoltaic cells, which convert the energy into electricity (Ellabban et al. 2014). Each of these renewable energy sources has its advantages and disadvantages, and they all require different techniques and technologies to access and harness their power. However, the benefits of renewable energy sources are clear: they are clean, abundant, and environmentally sustainable (Alrikabi, N. K. M. A. 2014). As such, there has been a growing interest in renewable energy sources around the world, and governments and private companies are investing significant resources in developing new and innovative methods for generating renewable energy (UN, 2020). Ultimately, the more we can harness the power of renewable energy sources, the more we can reduce our dependence on fossil fuels and move towards a more sustainable future.

### 1.3.1 Wind energy

Wind energy (also referred to as aeolic energy), power generation with the use of the wind’s flow. Wind turbines work on the principle of using wind to make electricity. Wind turns the propeller-like blades of a turbine around a rotor, which spins a generator, which creates electricity (EERE, 28/03/2023).

The most common technology used to harvest wind energy is the horizontal axis turbine (Wagner H.J, 2018). Recent innovations include the vertical axis turbine designs like the eggbeater-style Darrieus model and other groundbreaking designs like the vaneless ion wind generator or the Vortex Tacoma an Oscillating Cylinder (David et al. 2018).

Wind energy generation has the staple benefit of being available practically everywhere. It has also the added benefit of complimenting the most prevalent modern renewable, solar energy (Kumar, Y. et al. 2016). These two renewables compliment perfectly each other as they work in opposite weather conditions. The biggest negative of wind power is ist dependence on weather conditions which cannot be accurately predicted, hence the need for energy storage devices in these installations (Van Kuik G.A.M et al. 2016)( Blaabjerg et al. 2017). The levelized cost of electricity for wind energy is about 34$ (Tyler Stehly et al. 2022). Although the wind is rising there are few challenges that the current technology faces. Some examples are the output power prediction, the electricity market challenges and the socio-economic challenges (AHMED et al. 2020). The energy potential is approximately 75-130 TWyr/y (Perez et al. 2022).

### 1.3.2 Hydropower

Hydropower in all its forms makes use of the kinetic energy of water. The basic principle of hydropower is using structures to exploit the natural flow of rivers and the height differential to drive turbines. (Bagher A.M, 2015).

Hydropower plants consist of two basic configurations: with dams and reservoirs, or without any of the two (Kishor et al. 2017). Dams with large reservoirs available can store water over short or long periods to meet peak electricity demand (Kishor et al. 2017). The facilities can also be divided into smaller dams for different purposes, such as night or day cycles, seasonal storage or pumped-hydro for energy storage used for both pumping and power generation (Wagner et al. 2018). The other form of hydropower available is without dams and reservoirs, which automatically means producing at a smaller scale. This gave birth to a recent new sector of hydropower, micro-hydropower

(Moran et al. 2018). Typically, the facility is designed to operate in a river without interfering in its flow.

This is a more passive design in generating power in contrast to large scale hydropower as dams are usually intrusive structures (Moran et al. 2018). As a consequence, many consider small-scale hydro a more environmentally-friendly option according to IRENA.

The biggest advantage of hydroelectric power is its reliability. The stream of water is constant and controlled by the dam systems. There are little to no fluctuations of power supply which makes hydropower one of the few renewables that are not intermittent (Bagher A.M, 2015). There are though, a few disadvantages that come with the construction of dams in natural waterways, like the change of the water table which affects the local fish fauna (Williams, 2020). Most of the bibliography on the subject suggests that the biggest challenges that large hydropower faces are on the subject of natural preservation, as dams affect fish migration routes (Geist, 2021). The estimated LCOE of hydropower worldwide has remained stable at the cost of 0.05 U.S. dollars per kilowatt-hour in 2021 according to IRENA. The energy potential of hydropower is 3-4 TWyr/y (Perez et al. 2022)

### 1.3.3 Tidal Power

Tidal power makes use of the kinetic energy in the natural flow of sea waves. Tidal energy is created using the movement of shore tides and oceans created by the earth and moon movement, where the height differential of the water tides between their rise and fall, is a form of kinetic energy (Wang, Wang, 2019). Thus, tidal power is in the same scope as gravitational hydropower, which uses the movement of water to push a turbine to generate electricity (actionrenewables.co.uk, Accessed 13.03.2023).

The following is a classification of wave energy devices. First are Wave Activated Bodies. Second are Overtopping Devices. Last but not least are Oscillating Water Columns (Khan et al. 2018).

One of the many advantages of tidal power is its low upfront cost compared to the costly dams of hydropower, or installation of photovoltaics. That’s because the second generation of generators don’t require the construction of a dam to function (Millar, 2007). This also limits the environmental impact of the installation. Furthermore, although the technology resembles that of wind turbines, the turbines harvest energy from tides, which can be predicted years in advance as opposed to wind conditions or cloudy stretches that affect PVs. Thus, power generation can be programmed and supplemented accordingly (Khan et al. 2018). On the other hand, a drawback is the economic feasibility of the installations and the difficulty of maintenance operations which could be proven to be costly. Also, various installations are predicted to noticeably impact water quality by reducing both upstream and downstream current velocities while increasing those along the side of an array (Roberts et al. 2016). With an LCOE of £150 per MWh by 100MW installed, £130 by 200MW and £90 by 1GW the technology is positioned on the expensive side of renewable energy (Scottish renewables, 2017). As a technology still in its infancy tidal power faces the challenge of uncertainty due to too little data available. The cost factors and environmental impact remains to be seen, though the few projects that have been realized seem to give promising results. Energy potential of 0.3-2 TWyr/y (Perez et al.2022).

### 1.3.4 Geothermal Energy

Geothermal energy uses small underground pathways, such as fractures to conduct fluids through the hot rocks (Gallup, 2009). In geothermal electricity generation, this fluid can be drawn as energy in the form of heat through wells to the earth's surface (Gallup, 2009). At the surface, that energy is converted to steam, which drives turbines that produce electricity (energy.gov, 2023).

The main categories of technologies used for geothermal energy production are dry steam systems, flash steam and binary (NREL, 2023).

One of many advantages of Geothermal energy is the land required to run a power plant compared to other renewables (Kewen et al. 2015; Soltani, M. et al. 2021). Geothermal though is not without its faults, as risks of elevated seismic activities on sites are possible. Also, the economic element of lower efficiency is not to be overlooked (Anderson et al. 2018). The LCOE of Geothermal Energy in 2021 according to IRENA-was 0.07$/kwh. Maybe the most substantial of drawbacks that geothermal has is its availability. Geothermal is only feasible in very seismic countries that are on the intersections of tectonic plates (Figure 1). Energy potential of 0.2-3 TWyr/y (Perez et al. 2022).

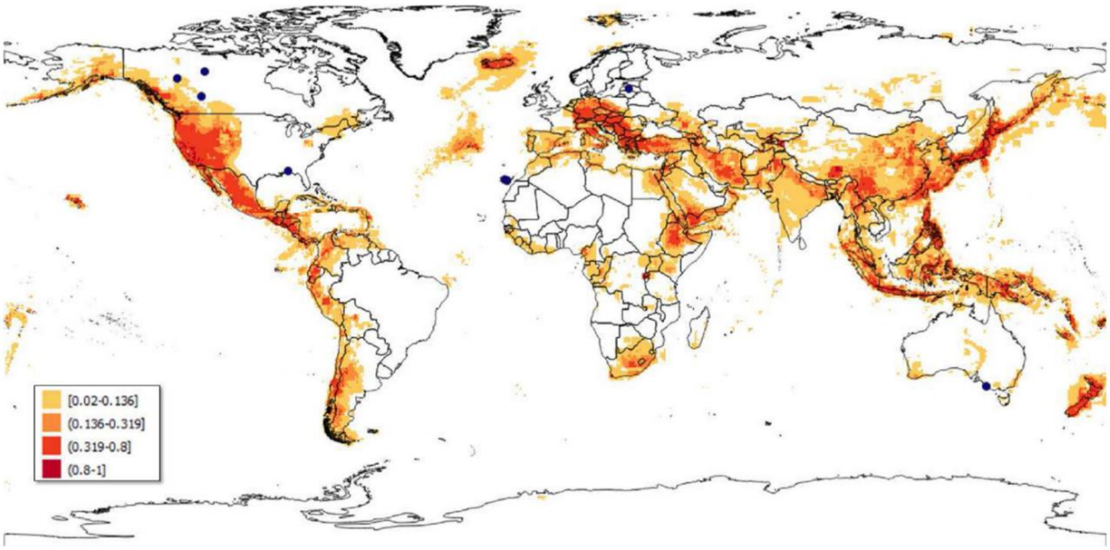


**Figure 1: "Predicting geographical suitability of geothermal power plants" Adapted from Giancarlo Coro, Eugenio Trumpy, 2020.**

### 1.3.5 Solar power

Solar, turning sunlight into electricity through the photovoltaic effect. When the sun shines onto a solar panel, energy from the sunlight is absorbed by the PV cells in the panel. This energy creates electrical charges that move in response to an internal electrical field in the cell, causing electricity to flow (energy.gov, 2023).

There are a few technologies that use sunlight as a power source, but we are only focusing on the energy production technologies of photovoltaics. We are only exploring the technology of systems that make use of the photovoltaic effect. With that clarified, there are four main types of solar panels. Monocrystalline, Polycrystalline, PERC and thin-film (Saga, 2010).

This type of energy production is rich in advantages such as the availability of solar irradiation, the low maintenance and high reliability of the systems, the overall low impact it has on its environment during energy production (Kabir et al. 2018). Another significant advantage of solar energy is its social benefits (Sampaio et al. 2017). The widespread adoption of solar energy could have a tremendous impact on accessibility and energy security, particularly in developing countries. Many remote areas of developing countries lack access to reliable electricity, which can impede economic growth and quality of life (Kabir et al. 2018). The disadvantages of solar PV installations are usually the volatility of the energy output which is reliant on meteorological conditions, the relatively large area that PVs occupy, a high initial cost of investment and a limited availability of systems in the market (Sampaio et al. 2017). The estimated LCOE for solar is 0.05$/kwh (IRENA,2022). Energy potential 23.000 TWyr/y (Perez et al. 2022).

# Chapter 2 The portrait of Solar Energy

## 2.1 The option of Solar power

Solar power is considered to be the most promising renewable source available for a myriad of reasons. We will explore just a few so that the choice is made clear. One of the main benefits of solar energy is its cost-effectiveness in the long run. Although the initial investment in solar panels may be high, the savings on electricity bills can extend for several years or even decades (Sodhi, Manbir, et al. 2022).

According to the National Renewable Energy Laboratory, the cost of solar panels has reduced by more than 60% in the past decade. As a result, more homeowners and businesses can afford to install solar panels and reduce their dependency on traditional electricity sources. Solar energy also helps to reduce carbon emissions and air pollution since it does not produce any greenhouse gases during operation. This is particularly important given the current climate crisis and the need to adopt sustainable energy sources to mitigate its effects. Additionally, solar panels are low maintenance and have a long lifespan, with warranties lasting up to 25 years (Sodhi, Manbir, et al. 2022). The technology is also versatile and can be installed on rooftops, parking lots, and even on floating solar farms. Furthermore, solar energy can create local jobs and stimulate the economy. According to the National Renewable Energy Laboratory, the solar industry employed over 240,000 people in the United States in 2020, with a projected growth rate of 7% for 2021 (NREL, 2021).

Finally, solar energy helps to improve energy security and stability, particularly in rural or remote areas where access to traditional electricity sources is limited. This is because solar panels can generate electricity even in areas with no grid connection and can store excess energy in batteries for later use. In addition, solar-powered microgrids can provide reliable and affordable electricity to communities during disasters or emergencies (Atamtajani, A. S. M. et al. 2021).

Overall, the benefits of solar energy extend beyond financial savings and can improve the environment, create jobs, and enhance energy security. As such, greater investment in solar technology is essential to transitioning to a more sustainable and resilient energy grid.

### 2.1.1 Cost of Solar power

Solar energy is one of the most economic options available as it's utility scale (grid-scale) LCOE (Levelized Cost of Electricity) is 0.048$/kwh in 2021. It has droped in cost by an exorbitant 86% of its 2010 price.

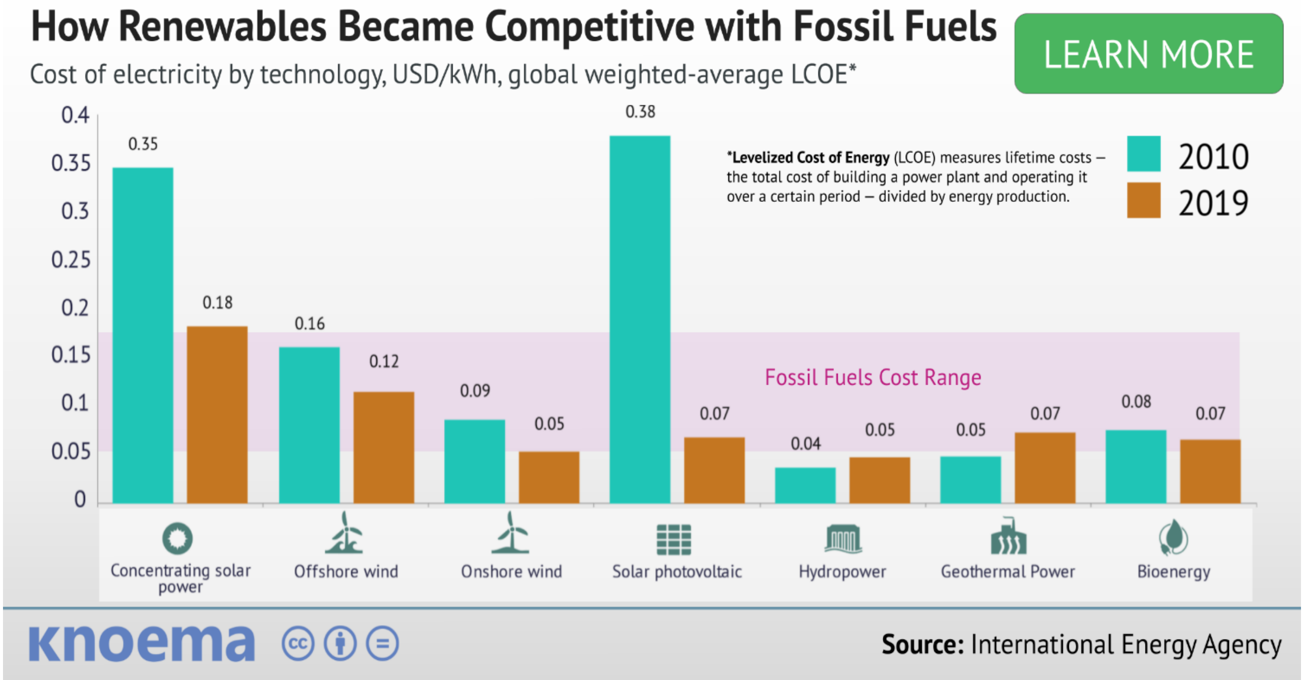


**Figure 2: "Levelized cost of electricity for different Renewable energy technologies" Adapted from "http://knoema.com/infographics/fmzvyg/a-decade-of-change-how-renewables-became-competitive-with-fossil-fuels, Accessed 15/07/2023**

The cost of PV installations is on par with the rest of renewable technology. The biggest edge of solar though is its maintenance cost as we see in Figure 3 which was last updated on 02/2016.

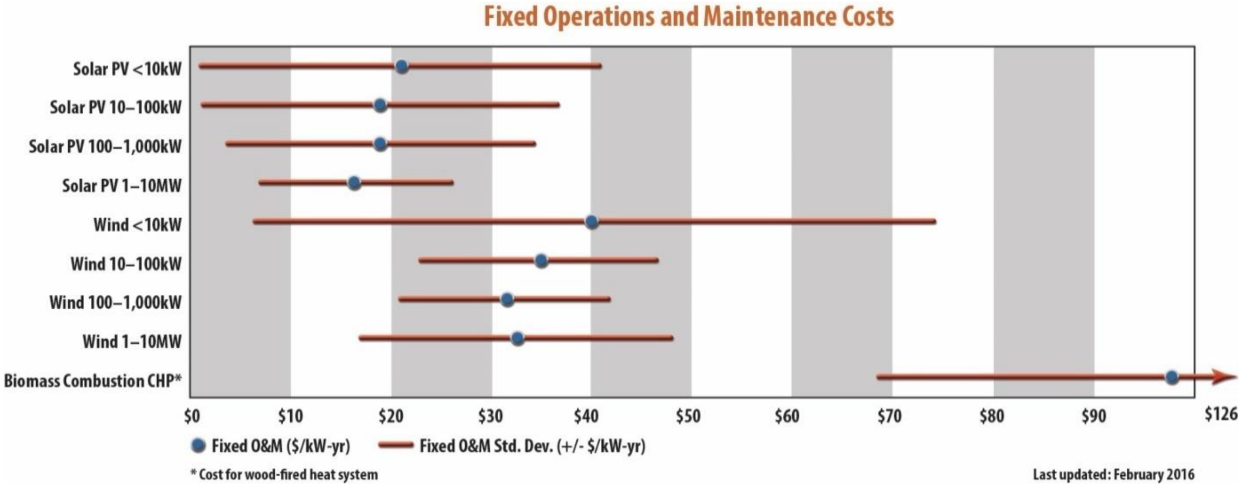


**Figure 3: "Fixed operations and maintenance costs for Wind/Solar for different kW ranges" Adapted from NREL https://www.nrel.gov/analysis/tech-cost-om-dg.html, Accessed 15/07/2023**

In summary PVs are one of the most cost-effective solution for grid scale electricity production. Its advantages though are present even in small-scale applications as the LCOE trend and operational costs apply evenly across scales (Figure 3).

### 2.1.2 Availability of Solar Power

The most evident benefit of solar energy is that it is economically practical and accessible to the majority of countries. The maps below show global population density and solar irradiance.

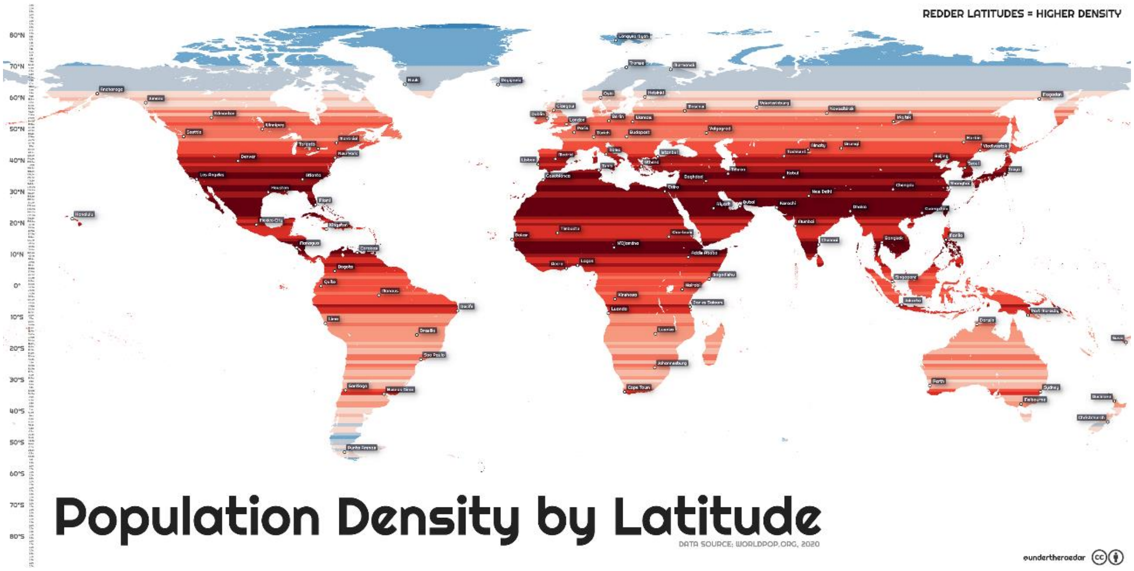


**Figure 4: “Population density by latitude” Adapted from https://www.visualcapitalist.com/cp/mapped-the-worlds-population-density-by-latitude, Accessed 16/07/2023**

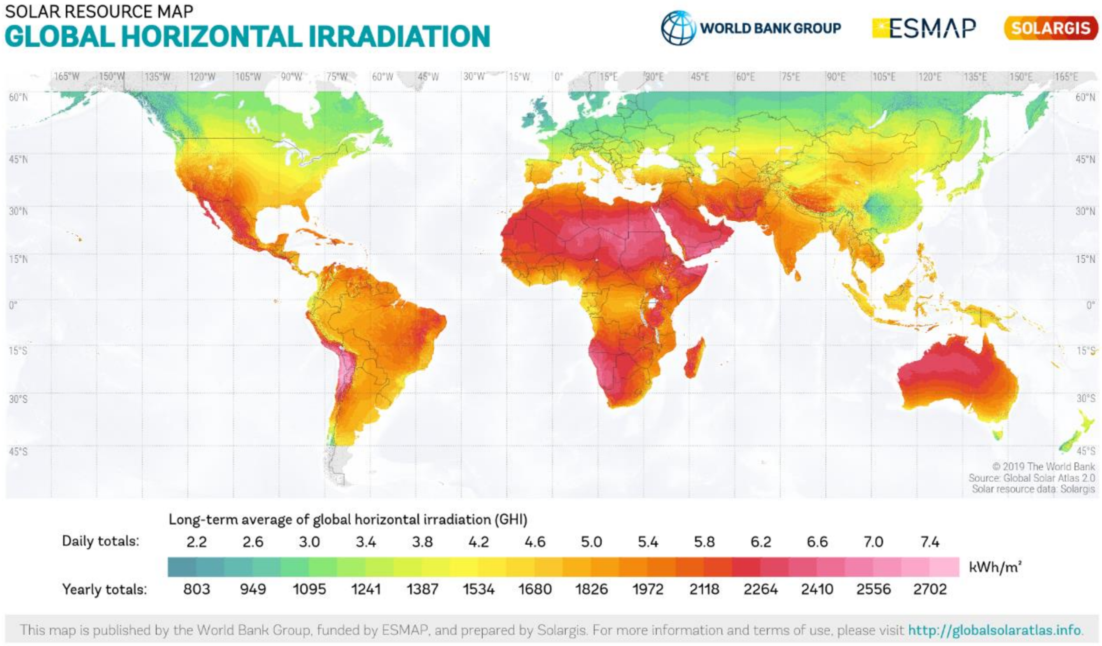


**Figure 5: “Global irradiation intensity by latitude” Adapted from https://globalsolaratlas.info, Accessed 16/07/2023**

The overlap between the maps is almost complete. Which means that for the majority of humanity, solar is an accessible solution to their energy needs (Kabir E. Et al. 2018).

## 2.1.3 Passive power production

Photovoltaics have the benefit of being completely passive in their energy production, having no moving parts. Their environmental impact during production is zero. Unlike hydro, tidal, aeolic and geothermal which all either have moving parts or interfere in significant ways in their environment. An example of direct environmental impact are dams which not only pose safety risks if not properly planned and maintained (Anderson et al. 2018).

PVs' problems arise at various stages of their lives, most notably at the end. It is a matter of material science and chemical engineering as some of the materials used for PV construction are rare or toxic (Rathore, N. and Panwar, N.L. 2022).

## 2.2 History and operating principle of photovoltaics

### 2.2.1 History of PVs

The photovoltaic effect was first discovered by Edmond Becquerel in 1839. In this experiment, silver chloride or silver bromide was used to coat the platinum electrodes; once the electrodes were illuminated, voltage and current were generated. (Palz, 2010)

The first solar cell was created in 1881 by Charles Fritts with an efficiency of 1-2%. He created it by coating selenium with a thin layer of gold. Only a few years later in 1888, inventor Edward Weston received two patents for solar cells – U.S. Patent 389,124 and U.S. Patent 389,425 (Smithsonian magazine, Accessed 29.03.2023).

Russell Shoemaker Ohl, a semiconductor researcher at Bell Labs, made the following significant development in solar cell technology in 1940. One of the silicon samples he was examining had a crack in the centre. He observed that when this particular sample was exposed to light, current passed through it. This crack, which had likely occurred when the sample was created, really defined the boundary between regions holding differing degrees of impurities. As a result, one side was positively doped while the other side was negatively doped. Ohl unintentionally created a p-n junction, the building block of a solar cell. An electric field is produced when excess positive charge accumulates on one side of the p-n barrier and excess negative charge accumulates on the opposite side. An incoming photon pushes an electron and cause current to flow when the cell is connected to a circuit. Ohl received a patent for his solar cell, which had an efficiency of 1%. The first practical silicon solar cell was created thirteen years later by a team of scientists working together at Bell Labs (APS , Accessed 29/03/2023).

In 1953, engineer Daryl Chapin, who had previously worked on magnetic materials at Bell Labs, was attempting to create a power source for telephone systems in remote, humid areas where dry cell batteries degraded too rapidly. Chapin researched several alternative energy sources and determined that solar power was among the most promising. He attempted to use selenium solar cells, but found them ineffective. Meanwhile, chemist Calvin Fuller and physicist Gerald Pearson were attempting to influence the properties of semiconductors by introducing impurities. Fuller gave Pearson a fragment of silicon that contained impurities of gallium. Pearson immersed it in lithium, resulting in the formation of a p-n junction (APS, Accessed on 29/03/2023). Then, Pearson connected an ammeter to the silicon and shone a light on it. The ammeter jumped substantially, surprising them. Pearson, who was familiar with Chapin's work, advised his friend not to invest any more time in selenium solar cells, and Chapin switched to silicon immediately. The three then spent several months working to improve the silicon solar cells' properties. One difficulty was establishing reliable electrical contacts with the silicon cells. Another issue was that, over time and at room temperature, lithium migrated through the silicon, causing the p-n junction to shift further away from the inbound sunlight. To overcome this issue, they experimented with various impurities before settling on arsenic and boron, which created a p-n junction that remained close to the surface. Additionally, they discovered that the boron-arsenic silicon cells made for good electrical contacts. They created a "solar battery" by connecting a number of solar cells after making a number of other design modifications. Bell Labs announced the invention in Murray Hill, New Jersey, on April 25, 1954 (Tsokos, K. A. 2010). They utilized their solar panel to power a small miniature Ferris wheel and a solar-powered radio transmitter as a demonstration. These first silicon solar cells were approximately 6 percent efficient at converting the energy in sunlight into electricity, a significant improvement over all solar cells that came before them (APS, Accessed on 29/03/2023).

### 2.2.2 Operating principle of PVs

Photovoltaic describes a material or device that can convert the energy contained in photons of light into an electrical voltage and current. A photon with a sufficiently short wavelength and high energy can cause an electron in a photovoltaic material to separate from the atom which holds it. In the presence of a nearby electric field, these electrons can be driven toward a metallic contact, where they can form into an electric current. (Masters, 2004)

Photovoltaic panels make use of the photovoltaic effect to produce current. A solar cell is a junction diode. A solar cell is constructed differently than a standard p-n junction diode. Initially, a thin layer of p-type semiconductor contacts a dense layer of n-type semiconductor (Fonash, 2010). Several finer electrodes are then attached to the p-type semiconductor. The path of light to the thin p-n junction is unimpeded by these microscopic electrodes. In addition, a current-collecting electrode is positioned beneath the n-type layer (Fonash, 2010). When photons reach the p-n junction between p-type and n-type semiconductors, a thin p-type layer facilitates their entry. The photons supply the p-n junction with energy, forming electron-hole pairs. This light disturbs the junction's thermal equilibrium, causing the free electrons to migrate to the n-type part of the junction. Similarly, the holes migrate to the p-type side of the junction. Due to a potential barrier, freed electrons on the n-type side cannot pass through the junction. This causes an increase in the concentration of electrons on one side (at the n-type junction) and holes on the other (due to the junction's barrier potential). This procedure permits the p-n junction to function as a battery cell.

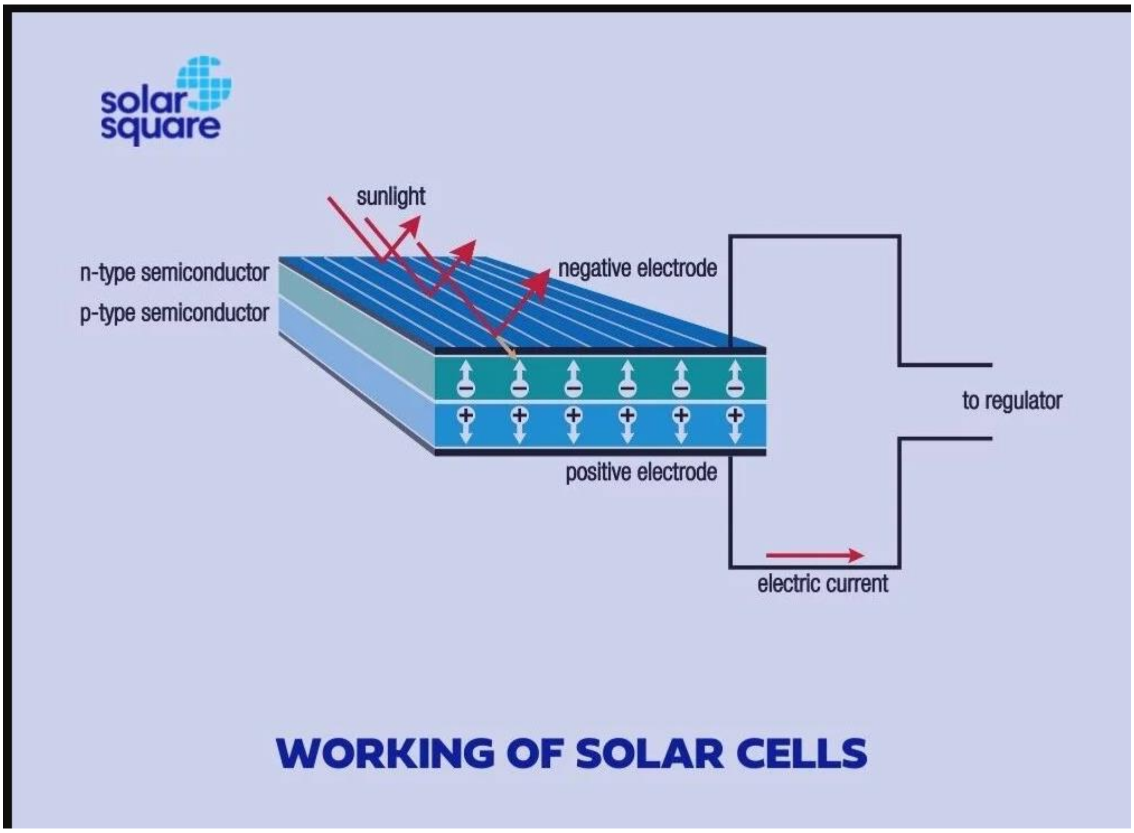


**Figure 6: "The working principle of a solar cell" Adapted from https://www.solarsquare.in/blog/solar-cell-construction/ June 20-2022, Accessed 17/07/2023**

## 2.3 Types of PVs

### 2.3.1 1st generation

Silicon is the most widely used material in commercial solar cell modules, accounting for approximately 90% of the market for photovoltaic cells (Jakhongir T.U, 2019). This achievement is due to several advantageous properties of silicon. For starter it is abundant, being the second most abundant element on earth following oxygen (Yaroshevsky A.A, 2006). Furthermore, it is generally stable and non-toxic and has a bandgap of 1.12 eV, which is nearly optimally suited to the terrestrial sunlight spectrum. Meaning that silicon is sensitized within the range of electromagnetic radiation emitted by the sun (Badawy W.A, 2015). Moreover, silicon photovoltaic cells are readily compatible with the silicon-based microelectronics industry as electronic circuits and all types of transistors are made of the same material (Sampaio et al. 2017).

Silicon solar cells are widely used in the solar industry due to their high efficiency, durability, and cost-effectiveness. The efficiency of silicon solar cells has steadily increased over the years, with modern cells achieving conversion rates of up to 23% (Lee,

Y. et al. 2015). Despite their advantages, silicon solar cells do have some drawbacks, such as their relatively low efficiency in converting certain wavelengths of light ,their high energy requirements for manufacturing and the thick (100e500 mm) silicon substrate cannot be bended and is opaque (Kim, S. et al. 2021). Silicon-based solar cells have a limited potential for application inflexible PVs because of their drawbacks (Kim, S. et al. 2021). However, ongoing research and development in the field of solar energy are helping to address these challenges and improve the performance and cost-effectiveness of silicon solar cells.

#### 2.3.1.1 Monocrystalline cells

As their name suggests, monocrystalline solar cells are manufactured from single silicon crystals using the Czochralski process. In large ingots, Si crystals are sliced during the fabrication process. Large productions of single crystals necessitate precise processing, as "recrystallizing" the cell is an expensive and multi-step process (Tyagi, V. V. *et al.* 2013). Between 17 and 18 percent is the efficacy of monocrystalline single-crystalline silicon solar cells (Sharma et al. 2015). Mostly mono-crystalline cells are in black color, because of high light interaction (Bagher A.M, 2015).

In an effort to reduce costs and increase production rates, the photovoltaic industry has developed novel crystallization techniques. Thus, cells composed of multicrystals emerged. Even though these cells are somewhat less efficient than monocrystalline cells, this technology is becoming more appealing due to the decreasing cost of production (Sampaio et al. 2017).

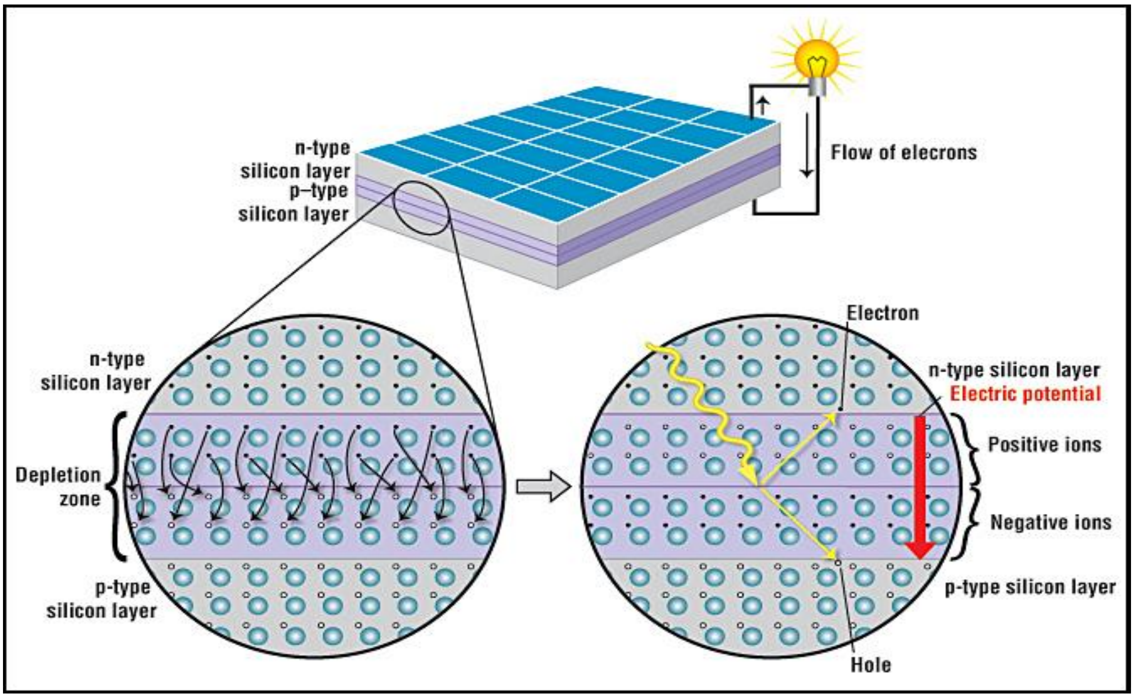


**Figure 7: "Molecular composition of a solar cell during the photovoltaic phenomenon" Adapted from https://www.acs.org Anthony Fernandez, Accessed 18/07/2023**

The passivated emitter rear localized (PERL) cell, the heterojunction with intrinsic thin layer (HIT) cell, and the back contact, back junction (BC-BJ) cell are representative of modern high-efficiency monocrystalline silicon PV cells. These PV cells contain several of the technologies that contribute to this variety of PV cell's high efficiency. The PERL cell is a research PV cell that contains front and rear surface passivation layers, an inverted-pyramid light-trapping surface, a rear localized p+ layer (BSF), a double-layer ARC, and a p-type float zone (FZ) monocrystalline silicon substrate (Saga, 2010). These innovations are all included to achieve the highest efficiency possible.

#### 2.3.1.2 Polycrystalline cells

In general, polycrystalline PV modules are composed of a number of distinct crystals that are interconnected within a single cell (Tyagi, V. V. *et al.* 2013). Unlike mono-crystalline solar cells that are made from a single crystal of silicon, poly-crystalline solar cells are made by melting multiple silicon fragments and then pouring the molten material into a mold to form a block (Sharma, et al. 2015).. This block is then cut into wafers, which are used as the base for the solar cells. The manufacturing process of polycrystalline Si solar cells, which is decreasing the temperature of a graphite mold containing molten silicon, is more cost-effective (Sharma, et al. 2015).

The production process of poly-crystalline solar cells results in a less uniform structure compared to mono-crystalline solar cells. The multiple silicon fragments in the molten material cool and solidify at different rates, resulting in a variety of crystal sizes and orientations within the block (Saga, 2010). This creates boundaries, or grain boundaries, between the different crystals that can affect the flow of electrons through the solar cell (Saga, 2010).

Polycrystalline Si solar cells are the most prevalent solar cells at present. It is estimated that they accounted for up to 87 percent of global solar cell production in 2019 (Jakhongir Turakul Ugli, T. 2019) . During the solidification of molten silicon, a variety of crystal structures form. Despite being marginally less expensive to manufacture than monocrystalline silicon solar panels, they achieve efficiencies of about 13-16% (Sharma et al. 2015).

In addition to lower manufacturing costs, polycrystalline cells offer additional benefits over monocrystal-line cells, such as a more aesthetically pleasing appearance, less energy consumed during their life cycle, a shorter energy return time, a reduced greenhouse effect, and a crystal structure that does not need to be perfect (Dhilipan, J. et al. 2022).

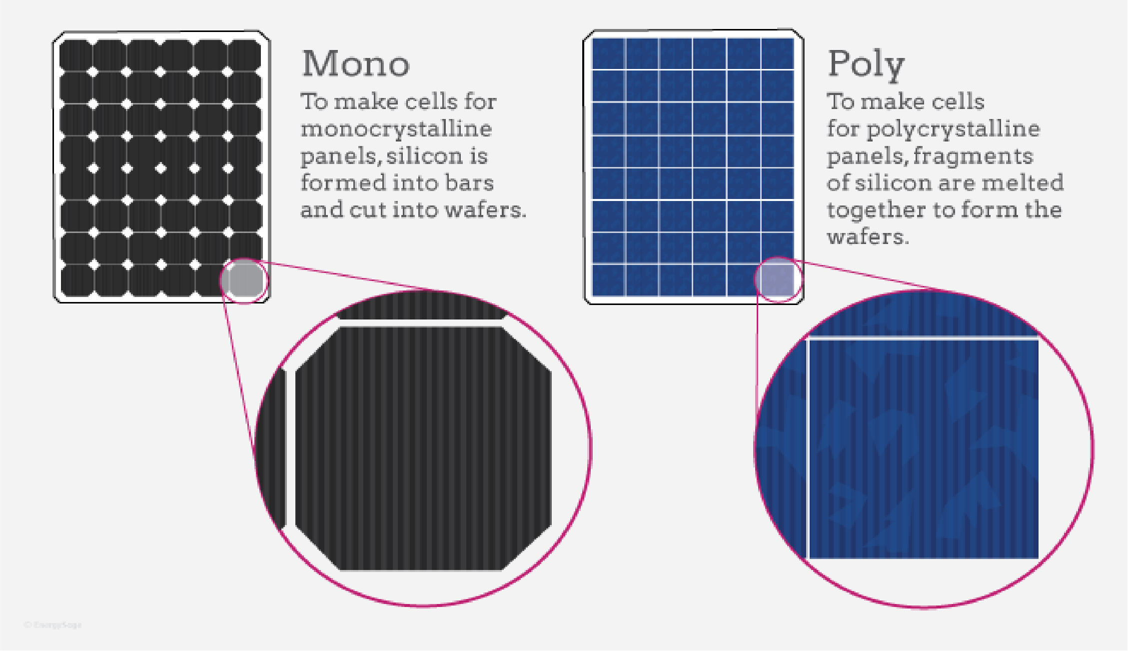


**Figure 8: "Monocrystalline and Polycrystaline solar cells" Adapted from https://ases.org, Accessed 18/07/2023**

# Chapter 3 Flexible Solar Cells

## 3.1 Flexible solar cells overview

Flexible solar cells are a type of solar cell that can be bent, twisted, or molded into various shapes without breaking or losing their ability to convert sunlight into electricity (Li et al. 2021). All flexible solar cells are second-generation and onwards PV technologies. These include but are not limited to most thin films, OPVs and perovskites (Efaz et al. 2021).

One of the main advantages of flexible solar cells is their ability to be integrated into a variety of products and applications, such as wearable devices, vehicles, and building facades (Lee, Ebong, 2017). Flexible solar cells can also be manufactured using roll-to-roll processes, which allow for low-cost, high-volume production (Li et al. 2021).

However, there are also some challenges associated with flexible solar cells. For example, the flexibility of the solar cell can make it more susceptible to damage from environmental factors such as moisture and heat, and the thin-film materials used in flexible solar cells can be less efficient at converting sunlight into electricity compared to traditional silicon-based solar cells (Lee, Ebong, 2017).

To achieve the result of a flexible solar cell all its components need to have flexibility, electrodes, the semiconductor material itself and the substrates. For the purposes of this paper, only the active semiconductor materials of the cells will be explored.

## 3.1.1 Second generation solar cells

### 3.1.1.1 Amorphous silicon (a-Si)

PV modules made of amorphous silicon (a-Si) were the first second generation industrially produced solar cells.  The technique used to produce amorphous silicon, or a-Si, solar cells differs from crystalline silicon in that the locations of the silicon atoms within the material are completely arbitrary with respect to one another. Or, in other terms, the silicon material that makes up the cell has a non-crystalline structure, or lacks a definite arrangement of atoms in the lattice (Tyagi, V. V. *et al.* 2013). Because of this randomness in the atomic structure, the electrical characteristics of the material are significantly altered, resulting in a wider gap (1.7 eV) than that of crystalline silicon (1.1 eV) (Tyagi, V. V. *et al.* 2013). They can be produced in an environment with a low processing temperature, which enables the use of a wide variety of polymers and other flexible substrates that are also relatively inexpensive. Processing these substrates requires a lower amount of energy overall. As a result, amorphous silicon a-Si solar cells are not only more affordable but also more readily available.

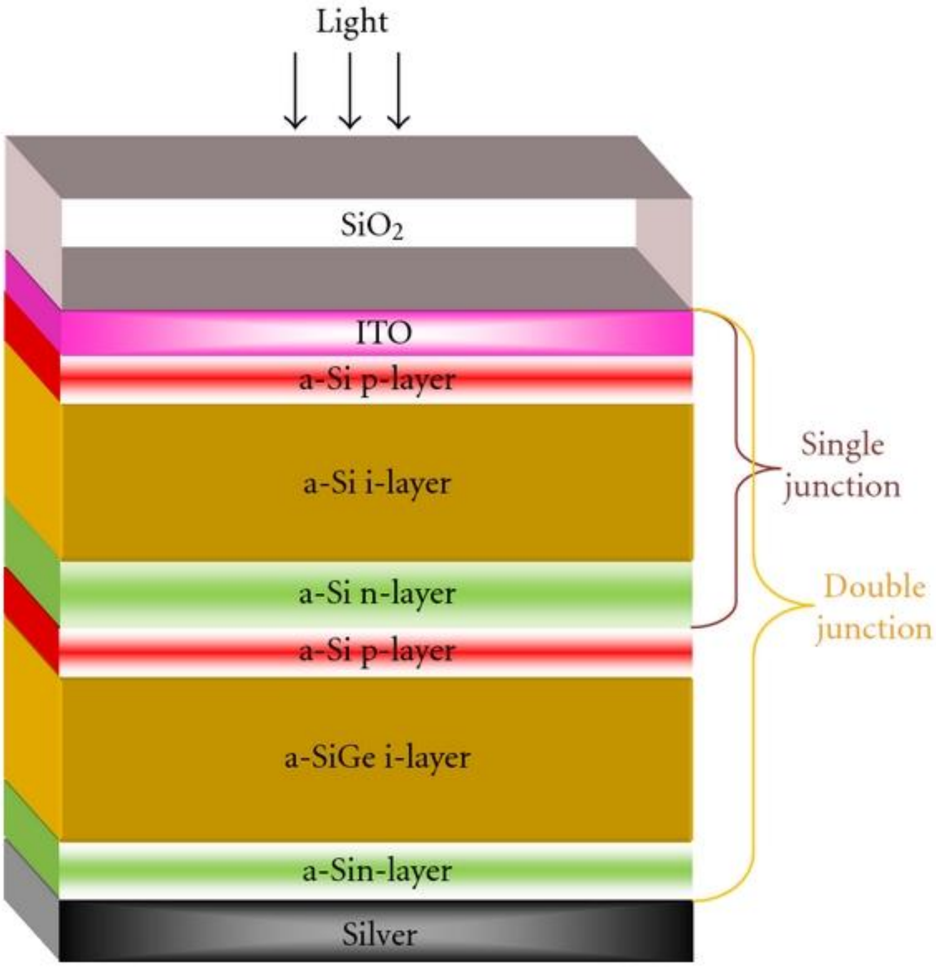


**Figure 9: "Effect of p-Layer and i-Layer Properties on the Electrical Behaviour of Advanced a-Si:H/a-SiGe:H Thin Film Solar Cell from Numerical Modeling Prospect" Adapted from Peyman Jelodarian, Abdolnabi Kosarian, 2012**

For some technical characteristics, this type of solar cell is typically fabricated on a fluorine (F)-doped tin oxide (SnO:F) glass substrate for single-junction or a periodically (honeycomb)-textured substrate (HTS) for micromorph (tandem) structure. Typically, successive silver (Ag) and gallium (Ga)-doped zinc oxide (ZnO:Ga) coatings are applied to the substrate to reduce reflective loss and increase conductivity (Efaz E.T et al. 2021).

Then, hydrogenated -Si (-Si:H) is typically deposited by plasma-enhanced chemical vapor deposition (PECVD) using CO2, phosphine (PH3), diborane (B2H6), silane (SiH4), and hydrogen (H2) as dopant gases. Transparent conducting oxide (TCO) film as the front window is subsequently deposited by radiofrequency (RF) magnetron sputtering from indium tin oxide (In2O3:Sn) or hydrogenated-indium oxide (In2O3:H)(IOH) (Erteza Tawsif Efaz et al 2021). Following the application of Ag as the grid electrode, a moth-eye-based anti-reflection coating (ARC) can be applied to enhance cell performance (Efaz E.T et al. 2021) .

The doped silicon material is coated onto the reverse side of the glass plate that serves as the substrate in the fabrication of these. The side of these solar cells that is used for conducting electricity is typically a silvery grey tint, while the side that is used for reflecting light is typically a dark brown color (Sharma et al. 2015). The low efficiency of a-Si solar cells is the primary problem with these cells. At the level of the PV module, there is an automatic decrease in cell efficiency. At the moment, the efficiency of commercial PV modules falls anywhere between 4% and 10% (Li X. et al. 2021). This range isn't too high. On the other hand, they can be easily operated at higher temperatures and are appropriate for shifting climatic conditions where the sun only shines for a limited amount of time. (Sharma et al. 2015).

Microamorph silicon cells are another sort of arrangement. These cells combine two distinct types of silicon, amorphous and microcrystal-line, one on top of the other in a single device. The upper layer of these cells consists of an extremely thin layer of amorphous silicon (a-Si), which converts light into electrical current. The longer wavelengths of the visible solar spectrum are best converted by the microcrystalline silicon found in the lower layer, which is also where the shorter wavelengths of the visible solar spectrum are found (Sampaio, 2017). This leads to better efficiency increases than amorphous silicon cells, ranging from approximately 8–9% more than amorphous silicon cells depending on the cell structure and the thickness of the layers.

### 3.1.1.2 Copper Indium Gallium Selenide (CIGS)

Copper, Indium, Gallium, and Selenium (CIGS) is a quaternary compound semiconductor composed of these four elements. CIGS are also semiconductors with direct band gaps. Comparatively to the CdTe thin-film solar cell, CIGS has an efficiency of 10% to 12% (Tyagi, V. V. *et al.* 2013). CIGS-based solar cell technology is one of the most feasible thin film technologies due to their exceptionally high efficiency and economic considerations. Techniques such as sputtering, evaporation, electrochemical coating technique, printing, and electron beam deposition are used to process CIGS (Srinivas et al. 2015). In addition, sputtering can be a two- or multi-step process involving deposition and subsequent selenium interaction, or it can be a one-step reactive process. Nevertheless, evaporation is comparable to sputtering in that it can be utilized in a single phase, two steps, or multiple processing steps (Srinivas et al. 2015). The substrates for CIGS materials include glass plate, polymer substrates, steel, and aluminum, among others (Li X, et al. 2021). The dramatic reduction in CIGS module production costs has increased the importance of balance of systems (BOS) such as module racking, and soft costs such as engineering and installation time which are key areas where light weight flexible CIGS solar cells offer advantages (Ramanujam, J. *et al.,* 2020). Solar energy production with low cost and high efficiency is the primary objective of manufacturers and scientists worldwide. Researchers from corporations, research institutions, national laboratories, and universities are examining how to increase productivity by any method.

The device is cost-effective. In 2010, the Center for Solar Energy and Hydrogen Research atZSW in Germany reported a CIGS cell with a total thickness of 4 m, including the metal contacts, and an efficiency of 20.3%. In 2013, the Swiss Federal Laboratories for Materials Science and Technology (EMPA) engineered a thin film CIGS solar cell with a 20.4% efficiency on a flexible polymer substrate. The narrow CIGS layer is adhered to a polymer substrate, allowing for the continuous roll-to-roll fabrication of the cells. A CIGS 20.4% efficient cell was manufactured using a static co-evaporation procedure (Powalla et al. 2018). Between the light-absorbing CIGS layer and the transparent ZnO front electrode, their cell made use of a Zn(O,S) buffer layer as opposed to the conventional CdS layer. The core of their technology is the high-vacuum cluster deposition system, which permits static co-evaporation of the CIGS absorber's constituent elements and sputter deposition of i-ZnO and ZnO:Al as window materials. Powalla et al also reported that the Cu(In, Ga)Se2 layer was intentionally doped with potassium, resulting in a 20.8% improvement in efficacy (Powalla et al. 2018). The novel doping procedure permitted a change in the CIGS absorber's composition towards a higher gallium content while preserving the absorber's efficacy. Additionally, the novel deposition procedure enabled a partial defeat of Voc saturation and a transition in CIGS absorber composition at higher gallium content. The saturation of Voc for higher Ga content had previously prevented the development of CIGS cells with a larger band gap. Solar Frontier finally obtained an efficiency of 22.3% by improving the CIS absorber layer and junction formation process (Lee and Ebong, 2017).

### 3.1.1.3 Cadmium Telluride (CdTe)

Cadmium telluride is one of the most promising approaches to low-cost and high-efficiency manufacturing which makes it a prominent candidate for the development of cheaper, economically viable photovoltaic (PV) devices and the first low-cost PV technology. As one of the most promising photovoltaic materials for thin film cells, CdTe is known to have an ideal gap (1.45 eV), a high solar spectrum absorption coefficient and chemical stability. These characteristics make CdTe the most appealing material for thin-film solar cell design (Tyagi, V. V. *et al.* 2013).

However, the toxicity of cadmium (Cd) and environmental concerns associated with its use pose a challenge for this technology(Sampaio, 2017). Cadmium is considered a heavy metal and a potential toxin that can accumulate in the bodies of humans, animals, and vegetation. The disposal of toxic Cd-based materials and their re-cycling can be extremely costly and detrimental to the environment and society. Consequently, a limited supply of cadmium and the environmental hazard associated with its use are the primary concerns with this CdTe technology (Efaz E.T et al. 2021). The other potential issue is the availability of Te, which can result in a dearth of raw materials and impact the price of the modules (Efaz E.T et al. 2021). First Solar, one of the world's largest manufacturers of photovoltaic solar modules, has launched a recycling program for deactivated photovoltaic (PV) cells, which are extremely popular in the field of thin films due to the efficiency of their production process. This program has the potential to reduce production costs, thereby making the price of this technology more competitive (Firstsolar, Accessed 16/05/2023).

CdTe is an outstanding crystalline compound semiconductor with a direct band gap, which facilitates the absorption of light and increases efficiency. Typically, it is formed by sandwiching cadmium sulfide layers to create a p-n junction diode. The manufacturing procedure consists of three stages: First, polycrystalline materials are used to synthesize CdTe-based solar cells, and glass is chosen as the substrate. The second process entails deposition, i.e., multiple layers of CdTe solar cells are coated on to the substrate using various cost-effective techniques. CdTe as mentiones before has a direct optimum band gap (1.45 eV) with a high absorption coefficient of over 5*1015/cm, as stated in. Therefore, its efficacy typically falls between 9% and 11%. CdTe solar cells can be manufactured on flexible polymer substrates. (Sharma et al. 2015).

The high absorption coefficient allows producing high efficient devices also with ultra thin absorbers, values exceeding 10% have been obtained with thickness below 1 μm and around 10% for only 0.5 μm (Ramanujam, J. *et al.,* 2020) . The CdTe thickness reduction could be a crucial point for increasing efficiency and stability of flexible devices. Both rigid and flexible CdTe solar cells perform best when made in superstrate configuration (Ramanujam, J. *et al.,* 2020).

### 3.1.1.4 Copper Zinc Tin Sulfide (CZTS)

Cu2ZnSnS4, also known as CZTS, is a prospective material for low-cost thin-film solar cells due to its suitable band gap energy of approximately 1.5 eV and large absorption coefficient of over 104/cm. All of this material's components are plentiful in the earth's crust and are non-toxic, making it the superior option with a record efficiency of 12% (Lee and Ebong, 2017). After the initial triumph of the CZTS-based solar cell (with its 0.6% light-to-electrical conversion efficiency) in 1996, significant progress has been made in this area of research, particularly in the last five years, focusing mainly on the preparation method of the cells (Vanalakar S.A et al. 2015).

According to Vanalakar S.A et al. physical methods such as RF magnetron sputtering, hybrid sputtering co-evaporation, and pulsed laser deposition, thermal evaporation, pulsar laser deposition, spray pyrolysis approach are used to fabricate CZTS thin films (Song, X. et al. 2014). Chemical methods such as electro-deposition, sol–gel, microwave, hydro-thermal, solvothermal, heated injection, and precipitation are also employed (Song, X. et al. 2014).

CZTS-based thin film photovoltaic technology has a significantly lower production cost than CdTe- and CIGS-based photovoltaic devices, respectively. Therefore, CZTS-based photovoltaic devices must be utilized on a larger scale. It is anticipated to be the next generation of thin-film photovoltaics due to its high performance, availability, low price, ease of fabrication, and adequate stability. The CZTS has a kesterite structure and a prospective absorber layer candidate for solar cells, making it more appropriate for low-cost thin-film photovoltaics (Dhilipan J et al. 2022).

Due to its direct band gap of approximately 1.5 eV, it has a higher absorption coefficient (Ravindiran, M., and C. Praveenkumar, 2018).

## 3.1.2 Third generation solar cells

### 3.1.2.1 Perovskites

Perovskite solar cells have emerged as a promising class of photovoltaic technology owing to their exceptional optoelectronic properties and low cost. The unique crystal structure of perovskites, which can be tailored by altering the composition of the constituent metal halides and organic cations, allows for efficient absorption and conversion of light into electricity. The rapid progress in perovskite solar cell research has resulted in a rapid increase in their power conversion efficiency from 3.8% in 2009 to over 25% in recent years (Basumatary and Agarwal, 2022).

Hybrid metal halide perovskites (organometallic halides), are the one of the most recent developing materials that have been employed in photovoltaic (PV) technology during the past several years. These are referred to as hybrid substances due to the fact that they include both organic and inorganic components (Stenber J., 2017). Both methylammonium lead iodide (CH3NH3PbI3 or MAPbI3) and methyl- ammonium lead bromide (CH3NH3PbBr3 or MAPbBr3), which have a bandgap of 1.6 eV and 2.3 eV, respectively, are the hybrid perovskite materials that are employed most frequently as an absorber layer in perovskite solar cells (PSC) (Basumatary and Agarwal, 2022).

Perovskite solar cells are fabricated by depositing a thin film of perovskite material on a substrate, which is typically glass or a flexible polymer. The perovskite material can be synthesized using various methods, such as spin-coating, spray-coating, or vapor deposition (Park, N.G, 2014). The perovskite material typically comprises a combination of metal halides, such as lead and iodine, and organic molecules, such as methylammonium or formamidinium cations. When light is absorbed by the perovskite material, it generates electron-hole pairs, which are then separated by the built-in electric field at the perovskite/substrate interface. The separated charges are collected by electrodes, and the resulting current is sent to an external circuit to power devices (Jung, H.S. *et al.* 2019).

Perovskite solar cells have several advantages over conventional silicon-based solar cells. Greater than 25% power conversion efficiency has been demonstrated. Low-cost production utilizing simple and scalable solution-based processes. Excellent optoelectronic properties, including a high absorption coefficient, a long length of carrier diffusion, and an able to be tuned bandgap (Jung, H.S. *et al.* 2019). Material composition and device architecture flexibility, enabling a variety of emerging applications, including tandem solar cells, building-integrated photovoltaics, and transparent solar cells (Bi et al. 2021). Despite these advantages, there are several challenges that must be addressed for perovskite solar cells to become a practical and competitive technology. These include its susceptibility to moisture and oxygen, perovskite material has limited stability under ambient conditions, which can degrade the material and reduce device performance (Stenberg J., 2017). Although efforts are being made to develop lead-free perovskite materials, perovskite solar cells commonly contain lead, which has the potential to be toxic. Hysteresis effects in the current-voltage characteristics, which can affect the precision of the power output measurement and impede the development of consistent and standardized testing protocols. Insufficient comprehension of the physical and chemical properties of perovskite materials impedes the optimization of device stability and performance. (Bi et al. 2021).

### 3.1.2.2 Dye-Sensitized solar cells (DSSCs)

DSSCs are a form of photovoltaic device that directly converts light energy to electrical energy. In contrast to conventional silicon-based solar cells, DSSCs do not necessitate high-purity materials or costly fabrication methods, making them an attractive option for cost-effective renewable energy (Tyagi, V. V. *et al.* 2013). DSSCs operate by sensitizing a wide-bandgap semiconductor, such as titanium dioxide (TiO2), with a molecular pigment that absorbs light in the visible and near-infrared regions of the solar spectrum (Gong, Jiawei et al. 2017).

As for DSSCs working principle, transparent conducting oxide (TCO) filmcoated glass substrates, dye, photoanode, electrolytes, and counter electrode (CE) are the fundamental components of DSSCs. Photoanode and counter electrode substrates were clear conductive oxide-coated glass. Coating this layer captures electrons from the photoanode (dyecoated TiO2) and transfers them to the counter electrode through the outside circuit. Thus, it collects current.The working electrode of DSSCs is a TCO substrate with dye molecules-adsorbed semiconductor oxide material as the photoanode. Most semiconductors employ anatase titanium dioxide (TiO2) with a band gap of 3.2 eV.

It's abundant, cheap, and non-toxic in the mantle (Iftikhar et al. 2019). Counter electrodes have three main purposes. The counter electrode accepts electrons to decrease the oxidized redox pair (Wu J. Et al. 2017). Through ionic transport material, solid-state DSSCs diminish the oxidized redox pair. It transports external circuit electrons into the inner cell's electrolyte solution. Electrons are recirculated by the counter electrode. It improves photoanode efficiency by reflecting non-absorbed light (Efaz et al. 2021). To satisfy these three processes, the criteria it needs to have are high catalytic activity, conductivity, and reflectivity. It also needs chemical corrosion resistance and a porous surface. High chemical and mechanical stability, counter electrode energy should equal redox electrolyte potential. TCO substrate adhesion. Composites have been studied because no material meets all these characteristics (Karthik, S.N et al. 2019). DSSCs also need electrolytes. Redox mediator in the electrolyte transfers charge or ions between the counter electrode and photoanode. Redox couples should not see visible light. They also need to be chemically stable and reversible. Charge carriers can spread faster with low viscosity. It cannot desorb pigment or scatter semiconductor material on the FTO plate (Wu J. Et al. 2017). The most common, stable, and efficient redox mediator is iodide/triiodide. Aqueous, organic, and ionic liquid solvents create DSSC electrolytes (Andualem et al. 2018).

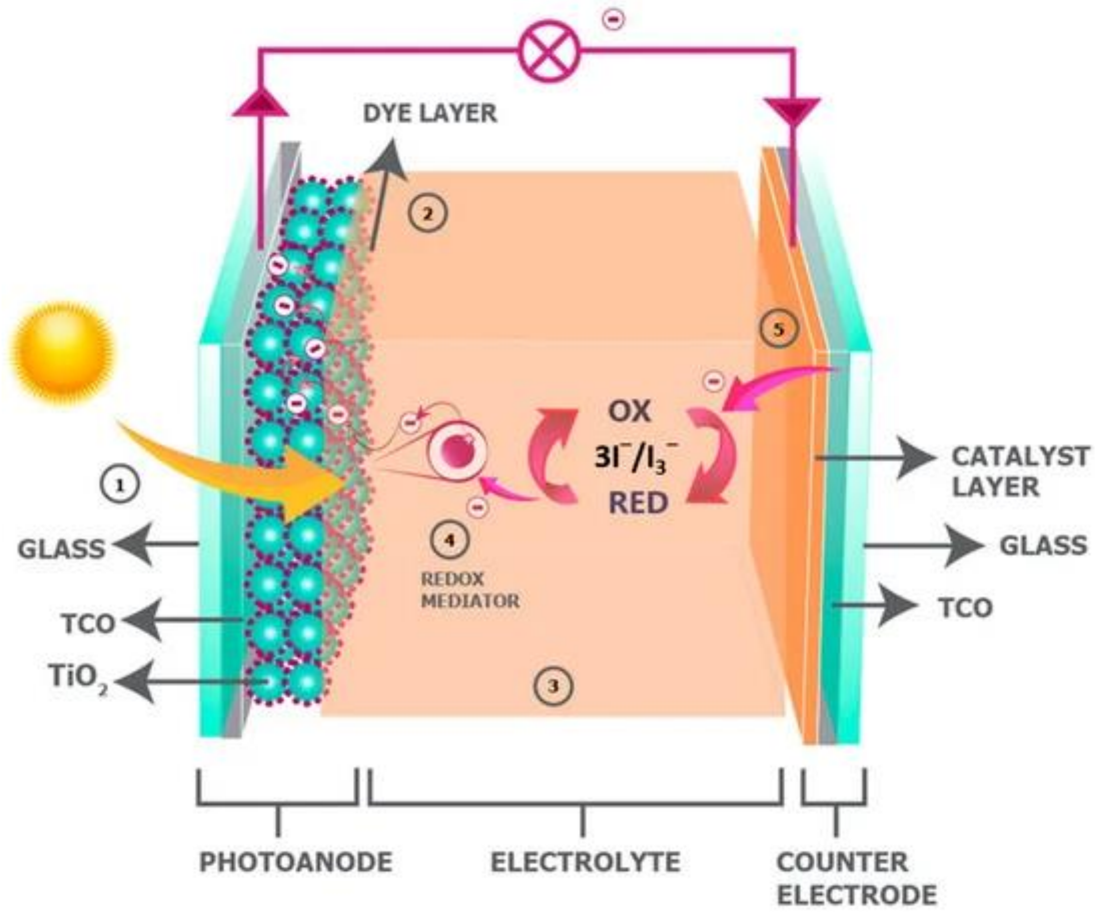


**Figure 10: “Dye-sensitized solar cell structure” Adapted from Iftikhar et al. 2019**

The efficiency of a DSSC is predominantly determined by the light absorption properties of the dye, the efficiency of charge separation and transport in the semiconductor, and the catalytic activity of the counter electrode for the reduction of the mediator (Al-Alwani et al. 2016). Efforts in the field of DSSCs have centered on enhancing the efficiency and stability of the devices, as well as investigating novel semiconductor and dye materials. Utilizing techniques such as surface engineering, nanostructuring, and co-sensitization, the performance of DSSCs has been enhanced. Despite the challenges of long-term stability and scalability, DSSCs have demonstrated tremendous promise as a renewable energy application technology (Al-Alwani et al. 2016).

### 3.1.2.3 Organic photovoltaics

Organic compounds also known as polymers, serve as conductors for the generation of electrical energy in organic PV cells. Due to the limitless supply of sunlight energy and the ecological benefits they have over standard inorganic ones, OPVs are regarded as the primary alternative to future electricity generation (Sampaio and Gonzalez, 2022). Acknowledging that organic semiconductors possess the potential to provide a more cost-effective and environmentally friendly method has influenced the rise in OPV research. OPVs also have the added benefits of being potentially semitransparent recyclable and easy to scale up (Efaz et al. 2021). They have proven to be a promising technology for renewable energy generation due to their potential for low-cost, solution-processed fabrication and flexibility (Tyagi, V. V. *et al.* 2013).

OSCs are composed of organic thin films that absorb sunlight and transfer it to electrical energy via a photoactive layer situated between two electrodes. The photoactive layer is composed of a mixture of an electron-donor (e.g., a conjugated polymer) and an electron-acceptor (e.g., a fullerene derivative) material, which enables efficient charge separation upon solar absorption (Kalyami N. Et al. 2018). The two electrodes (the cathode and the anode), are responsible for accumulating charge carriers and transmitting the resulting current to an external electrical circuit. The Electron Transport Layer (ETL) conducts electrons to the cathode (negative electrode), whereas the Hole Transport Layer (HTL) conducts holes to the anode (positive electrode) (Anrango-Camacho et al. 2020). The active layer in OPVs is typically made up of two distinct materials, an absorbing electron donor (D) (with a low ionization potential) and an electron acceptor (A) (with a high electron affinity) assembled in a two-layer arrangement (planar heterojunction - PHJ) or as a composite (Sampaio and Gonzalez, 2022).

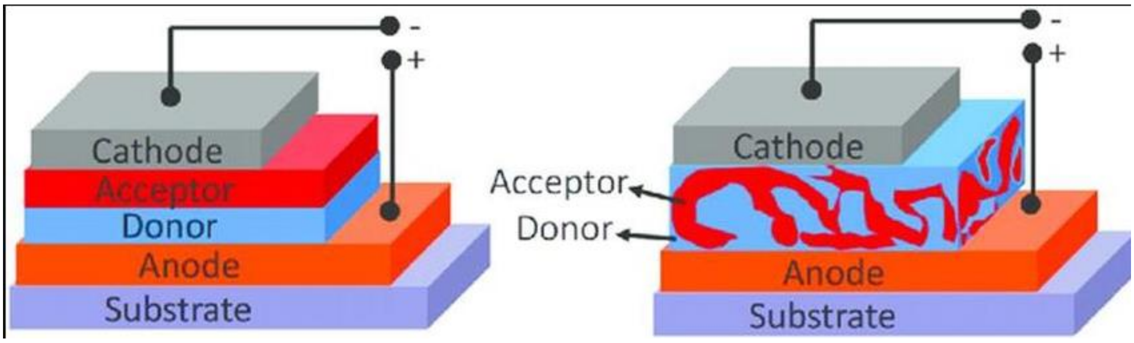


**Figure 11: "Organic Solar Cell structure" Adapted from Yilmaz, Efe Çetin et al. 2017**

Photons excite electrons from the highest occupied molecular orbital (HOMO) of the electron-donor material to the lowest unoccupied molecular orbital (LUMO) of the electron-acceptor material, producing electron-hole pairs (Sampaio and Gonzalez, 2022).

The electron-hole pairs must be separated and transported to the respective electrodes in order to generate a current. This is accomplished by the interface potential between the electron-donor and electron-acceptor materials, which causes the electrons to migrate to the electron-acceptor material and the holes to migrate to the electron-donor material (Marinova et al. 2017). This separation of charges generates an electric field that propels electrons and holes toward their respective electrodes (Marinova et al. 2017).

According several sources cited in this papers, bibliography, two distinct varieties of electrodes can collect electrons and holes: the anode and the cathode. Typically, the anode is composed of a transparent and conductive material, such as indium tin oxide (ITO), while the cathode is composed of a metal with a low work function, such as aluminum or calcium (Tong Y. Et al., 2017). The cathode collects electrons, while the anode collects holes. When electrons and holes reach their respective electrodes, they travel through the external circuit and produce a current. The OSC's power output is dependent on a number of parameters, including the efficacy of charge separation, the quality of the electron-donor and electron-acceptor materials, and the architecture of the device (Li X. et al. 2021). The highest efficiencies achieved are from bulk heterojunctions, not planar. The reason is that bulk heterojunctions have much higher contact surface area which maximizes the electron and hole transferring (Tong Y. Et al. 2017).

In recent years, OSC research has centered on the development of novel materials and device architectures to enhance their performance and reliability (Hou et al. 2018). For instance, tandem OSCs, which are comprised of two or more photoactive layers with complementary absorption spectra, have demonstrated potential for attaining higher PCEs. In addition, non-fullerene acceptors have shown promise for enhancing the stability and performance of OSCs (Hou et al. 2018).

### 3.1.3 Non-Flexible Design Philosophy Third-Generation Solar Cells

The solar cells in this category are considered not flexible, because their design philosophy was not focused to the flexibility characteristic. Both multi-junction and quantum dots design philosophy can be applied to flexible solar cells.

### 3.1.3.1 Multi-Junction Solar Cells

Multi-junction solar cells are a form of photovoltaic cell that can convert a greater portion of the solar spectrum into electrical energy than conventional single-junction solar cells. These cells are composed of numerous layers of semiconductors, each with a unique bandgap energy that enables it to absorb a distinct portion of the solar spectrum (R.R King et al. 2007). They are also known by the name of "Tandem solar cells". This so-called multi-junction technique can reduce thermalization loss caused by the absorption of a high-energy photon by a small bandgap and inversely a low-energy photon with insufficient energy to excite an electron in a high-bandgap material (Tyagi, V. V. *et al.* 2013).

The semiconductor's bandgap energy determines the wavelength of light it can absorb. Utilizing multiple layers of semiconductors with differing bandgap energies enables the cell to absorb a greater proportion of the solar spectrum. This permits greater efficacy and power output per unit of area. Solar cells with distinct bandgaps are arranged so that the solar cell facing the sun has the largest bandgap (Yamaguchi, Masafumi et al. 2021).

This top solar cell absorbs all photons with energies greater than its bandgap and transmits the less energetic photons to the solar cells below. The subsequent solar cell in the stack absorbs all photons with energies equal to or greater than its bandgap energy and transmits the remainder downward in the stack. Eight Only MJ designs have been able to surmount the detailed-balance limit of single-junction solar cells among all so-called third-generation solar cell strategies (Yamaguchi,Masafumi et al. 2021).

The high conversion efficiency of multi-junction solar cells is one of their most significant advantages. Multiple layers permit a greater proportion of incoming solar energy to be converted into electrical energy. In fact, multi-junction solar cells currently claim the world record for solar cell technology with the maximum efficiency (Baiju Adil and Yarema Maksym, 2022). In the future, ongoing research and development is anticipated to result in greater efficiency and cost-effectiveness. Currently, their high cost and complicated fabrication process prevent their widespread adoption (Baiju Adil and Yarema Maksym, 2022).

### 3.1.3.2 Quantum Dot Solar Cells

Quantum dot solar cells are a type of solar cell that utilize quantum dots as the active material. Quantum dots are nanoscale semiconductor particles that have unique optical and electronic properties due to their size and quantum confinement effects, thus make it a special semiconductor system with an ability to control band-gap of energy (Tyagi, V. V. *et al.* 2013). As a promising candidate for the next iteration of solar cell technology, quantum dot solar cells have received a great deal of attention over the past decade. Changing the size of quantum dots tunes the band-gap of colloidal metal chalcogenide nanocrystals, allowing for the creation of multi-junction solar cells and the effective harvesting of near-infrared photons (Lee and Ebong, 2017). The discrete energy levels of zero-dimensional quantum dots (QDs) make them a great option for intermediate band-based photovoltaic cells with a theoretical efficiency of 63% (Zheng et al. 2016). In general, QD-based solar cells can be divided into four categories, Schottky junction solar cells, p–n junction solar cells (both homojunction and heterojunction), hybrid QD–polymer solar cells, and quantum dot-sensitized solar cells (Zheng et al. 2016).

QDSCs are derived directly from DSCs, with quantum dots replacing organic pigment molecules as the light-harvesting material. Attractive photoelectronic properties of QDs were the initial impetus for research into QDSCs. A QDSC typically consists of a QD-sensitized photoanode, an electrolyte, and a counter electrode (Pan, Zhenxiao et al. 2018). Upon light irradiation, the QDs absorb solar energy and the electrons in their valence band (VB) are excited to their conduction band (CB), producing electron–hole pairs. Then, the electrons in the CB of the QDs are rapidly injected into the CB of a metal oxide (typically TiO2) electron acceptor, accomplishing charge separation (Badawy W.A, 2015). Through the TiO2 mesoporous film, electrons are transferred to the transparent conductive oxide substrate and then to the counter electrode via an external circuit (Pan, Zhenxiao et al. 2018). During this time, the reduced species of the redox couple in the electrolyte regenerate the oxidized QDs, while the electrons from the external circuit catalyze the reduction of the oxidized species of the redox couple. Other undesirable processes, also known as charge recombination, occur concurrently with these desired charge-transport processes and substantially diminish the solar cell's performance (Pan, Zhenxiao et al. 2018).

The efficiency of quantum dot solar cells can be enhanced by engineering the size and composition of the quantum dots to optimize their light absorption and charge transport properties. In addition, the use of multiple layers of quantum dots with different sizes and compositions, known as quantum dot heterostructures, can further improve the efficiency of quantum dot solar cells by broadening the absorption spectrum and reducing recombination losses (Selopal et al. 2020).

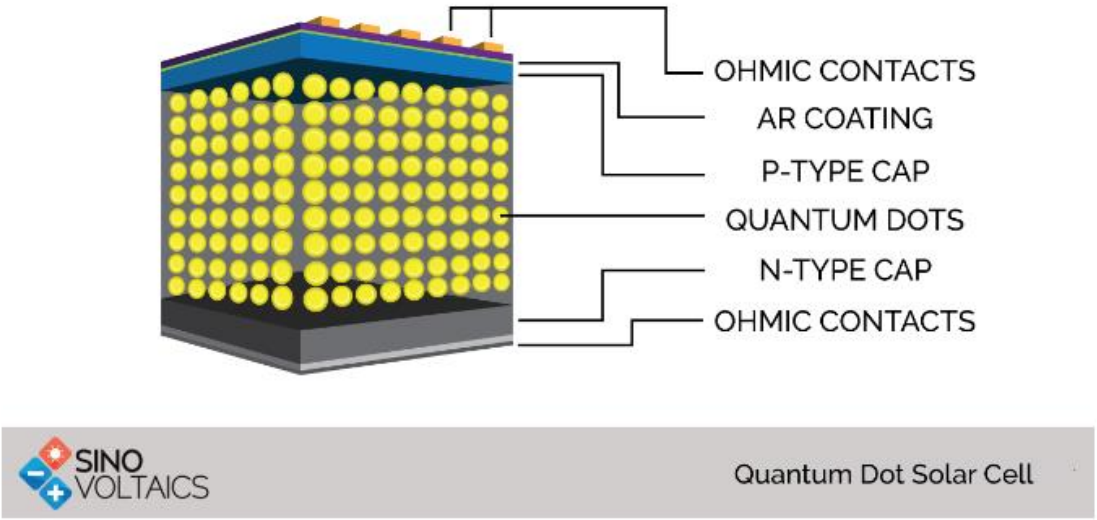


**Figure 12: "Quantum dot solar cell structure" Adapted from https://sinovoltaics.com/learning-center/solar-cells/quantum-dot-solar-cell/ accessed 09/05/2023**

# Chapter 4 A comparison of solar panel technologies

## 4.1 Categories compared

For the purposes of this thesis, we are going to be comparing only the technologies explored within it. Which means, tables 1 and 2 of section 5.3, will contain information specifically for the following technologies:

1. Silicon monocrystalline solar cells
2. Silicon polycrystalline solar cells
3. Amorphous silicon solar cells
4. Copper Indium Gallium Selenide (CIGS) solar cells
5. Cadmium Telluride solar cells
6. Copper Zinc Tin Sulfide solar cells
7. Perovskite solar cells
8. Organic solar cells
9. Dye-sesitized solar cells
10. Quantum Dot solar cells

Multi-junction solar cells are excluded as the nature of their design is to combine the aforementioned technologies. Therefore, an accurate comparison cannot be made. Some of the categories can be combined into a singular cell, for example, perovskites can be used in tandem with the rest of the technologies (Lal N. et al. 2017). With our collative elements set, the next step is to define the parameters of the analysis.

## 4.2 Parameters of comparison

Table's 1 and 2 objective is to provide a streamlined explanation of how the technologies differ in terms of the features they possess. The table has to adhere to the analysis of the fundamental technical characteristics of each and every technology.

### 4.2.1 Benchmarks

Efficiency, peak power, short-circuit current density, open circuit voltage, and fill-factor are some of the characteristics that are divided into separate columns and displayed in this category of attributes. To evaluate the performance of the solar cell, each of these parameters is considered. (Delft website, Accessed 25/07/2023).

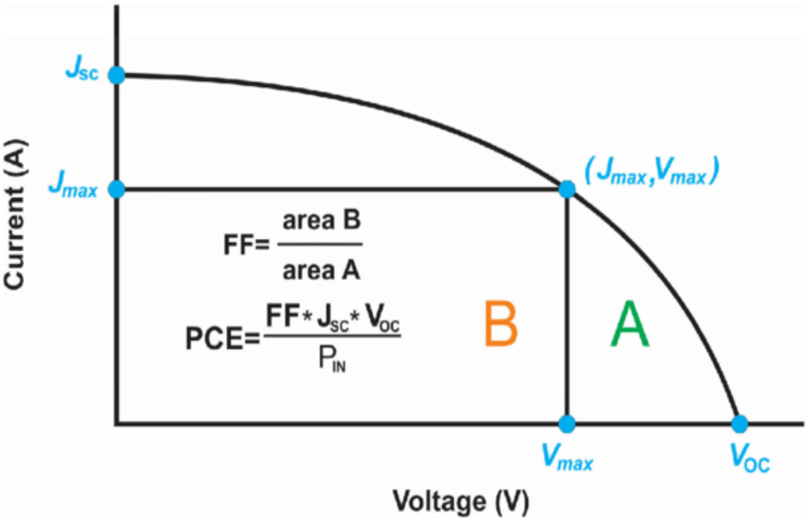


**Figure 13: “Factors of solar cell performance” Adapted from Dye-Sensitized Solar Cells: Fundamentals and Current Status - Scientific Figure on ResearchGate accessed 05/09/2023**

## 4.3 Benchmarks Tables and comparison

**Table 1 "Comparison of solar cell technologies by benchmarks"**

| | Highest Recorded Efficiency (PCE) | Bandgap | Fill Factor (FF) | Short circuit current density (Jsc) | Open circuit Voltage (Voc) |
|---|---|---|---|---|---|
| Mono-Si | 26.8% | 1.11ev | 80% | 42 mA/cm$^2$ | 764 mV |
| Poly-Si | 23.3% | 1.12ev | | | |
| a-Si | 14% | 1.65-1.78 ev | | | |
| CIGS | 23.6% | 1-1.7ev | 74.48% | 38.75 mA/cm$^2$ | 804.03 mV |
| CdTe | 22.3% | 1.44ev | 90% | 31 mA/cm$^2$ (Theoretical) | 840–880mV |
| CZTS | 14.9% | 1.4-1.5ev | 83,75% | 33.72 mA/cm$^2$ | 970 mV |
| Perovskites | 26.1% | 1-2ev (>1.4ev) | 85.3% | 28 mA/cm$^2$ | 1193mV |
| OSCs | 19.31% | 1.7-2.3ev | 50-70% | 21.4 mA/cm$^2$ | ~1000mV |
| DSSC | 13% | 1.5ev | 82-89% | | 700-740 mV |
| Quantum-Dot | 18.1% | Variable | 62% | 30 mA/cm$^2$ | 692 mV |

Table 1 compares the main figures that compose the total efficiency of a solar cell. Each technology has its own analogy of numbers which differentiates its from the next. The PCE is a composite number which is the sum of all the rest, which makes it possibly the most important measure of a solar cell. It reflects a total

Following table 1, is table 2 which compares general characteristics of the cells. Table 2 scrutinizes the different strengths and weaknesses each technology has and concludes at an appropriate area of application for the cell. Then, the information provide by Table 1 and Table 2 is explored, in order to elect the most suitable technology for the development of products.

**Table 2 “Comparison of solar cell technologies by characteristics”**

| | Positives | Negatives | Area of application |
|---|---|---|---|
| Mono-Si | • Efficient and widely used.<br>• Long lifespan. | • High production cost. | • Residential and commercial rooftop installations, solar farms, and space-constrained areas where high efficiency is essential. |
| Poly-Si | • Cost-effective. | • Slightly lower efficiency than monocrystalline silicon. | • Large-scale solar farms and utility-scale installations where cost-effectiveness is a priority. |
| a-Si | • Flexible and lightweight.. | • Lower efficiency | • Portable solar chargers, flexible and lightweight solar panels, and low-light conditions such as indoor electronics |
| CIGS | • Flexible and potential for high efficiency.<br>• Complex production processes. | • High toxicity | • Building-integrated photovoltaics, flexible and lightweight solar panels, and applications that require versatility. |
| CdTe | • Cost-effective with shorter energy payback.<br>• Common in utility-scale installations. | • Environmental concerns due to cadmium | • Utility-scale solar installations, especially in regions with abundant sunlight and cost considerations. |
| CZTS | • Abundant and non-toxic materials.<br>• Potential for low cost. | • Research stage, limited commercial availability. | • Emerging technology with potential applications in low-cost solar panels for residential and commercial use, but research is ongoing |

| | | | |
|---|---|---|---|
| Perovskites | • Rapidly advancing technology.<br>• High efficiency. | • Limited long-term stability, ongoing research. | • Emerging photovoltaic technology with potential applications across various sectors, including residential, commercial, and industrial installations. |
| OSCs | • Low-cost and lightweight.<br>• Tunable bandgap. | • Lower efficiency, sensitive to the environment. | • Wearable technology, portable electronics, and niche applications where flexibility and low-cost production are critical |
| DSSC | • Low-cost manufacturing.<br>• Flexible and suitable for low-light conditions. | • Limited long-term stability. | • Low-light conditions, flexible and lightweight solar panels, and applications where cost-effective solar cells are required. |
| Quantum-Dot | • Tunable bandgap.<br>• Potential for high efficiency. | • Research stage with scale-up challenges. | • Quantum dot solar cells are still in the research stage, and their potential applications may include advanced photovoltaics for specialized applications. |

Table 2 maps out the different profile of each technology and what applications emerge from their features. When examining different solar cell technologies, it becomes evident that there exists a diverse array of choices, each with unique merits and drawbacks. These technologies serve a wide range of applications and goals, necessitating a comprehensive evaluation to select the most suitable choice for a certain project.

Monocrystalline Silicon (Mono-Si) and Polycrystalline Silicon (Poly-Si) solar cells are widely recognized as the established leaders in the field of photovoltaics (Jakhongir T.U, 2019). The primary advantage of monocrystalline silicon comes in its exceptional efficiency, which frequently positions it as the frontrunner in this regard (Lee, Y. et al. 2015). These technologies are particularly suitable for applications characterized by spatial constraints, where maximizing energy production within constrained areas is imperative. Nevertheless, a significant downside of these products is their comparatively elevated production cost, which may discourage cost-sensitive initiatives (Kim, S. et al. 2021). The extended durability of monocrystalline silicon renders it a compelling choice for individuals seeking a secure and enduring investment opportunity. On the other hand, polycrystalline silicon cells provide a cost-effective solution and are frequently employed in extensive installations, thereby striking a balance between efficiency and affordability.

Amorphous Silicon (a-Si) solar cells are considered as part of the domain of thin-film technology. The aforementioned entities are renowned for their exceptional adaptability and inherent property of being relatively light in weight. These characteristics provide opportunities for distinct applications, particularly in scenarios where inflexible, traditional panels would be inadequate. Regrettably, the efficiency of a-Si is comparatively poor, rendering it less appropriate for energy-dense applications (Sampaio, 2017). However, these cells demonstrate exceptional performance in specific situations, including as their application in portable solar chargers and gadgets intended for use in low-light environments, such as indoor electronics (Dhilipan, J. et al. 2022).

Copper Indium Gallium Selenide (CIGS) solar cells also belong to the category of thin-film photovoltaic devices. The primary qualities of the subject under consideration lie in its capacity for achieving elevated levels of efficiency and its inherent flexibility (Mufti et al. 2020). Nevertheless, the intricate nature of their production processes might provide a barrier. Through continuous research and development efforts, CIGS cells are gradually addressing these obstacles and have the potential to establish a presence in the market, particularly in contexts that need adaptability, such as building-integrated photovoltaics (Mufti et al. 2020).

Cadmium Telluride (CdTe) solar cells are a type of thin-film photovoltaic technology that is well-regarded for its economical nature and efficient energy payback rate. Utility-scale installations frequently prioritize the use of these systems due to their significant advantages in terms of economic feasibility (Ramanujam et al. 2020). Nevertheless, there are ongoing worries over the potential environmental ramifications associated with the utilization of cadmium. As a result, extensive research efforts have been undertaken to explore and identify alternative materials that are more sustainable in nature (Ramanujam, 2020). The cost and applicability of CdTe in sundrenched places might outweigh its moderate efficiency and longer energy payback time when compared to silicon cells.

Organic solar cells, which utilize polymers as their active materials, have attracted considerable interest due to their lightweight nature and the ability to adjust their bandgap (Hu et al. 2020). These devices exhibit cost-effectiveness and are particularly well-suited for lightweight applications like as wearable technology and portable electronics. Nevertheless, because to their comparatively lower efficiency and susceptibility to environmental influences, they are frequently most suitable for specialized applications that prioritize adaptability and cost-effectiveness (Tong, Y. et al. 2020).

The field of perovskite solar cells is undergoing tremendous advancements, posing a significant competitor and ally, to the existing conventional solar cell technologies. Advantages of this class of materials encompass notable efficiency levels and the possibility of achieving cost-effectiveness in production (Wang, Y. et al. 2020). Nonetheless, the issue of their restricted long-term stability continues to be a matter of worry. The aforementioned cells are now at the research and development stage, yet, they have significant potential for many applications, spanning from residential rooftops to extensive industrial installations.

Dye-Sensitized Solar Cells (DSSCs) provide the advantageous characteristics of cost-effective production and flexibility, rendering them well-suited for deployment in environments with limited illumination and portable settings. Nevertheless, the restricted long-term stability of these entities may discourage their implementation in some situations (Mozaffari et al. 2017).

Quantum dot solar cells represent a nascent technological advancement characterized by a modifiable bandgap and the prospect of achieving notable levels of efficiency. The current state of affairs involves the continuation of research efforts, accompanied with the persistent obstacles encountered in the process of expanding manufacturing capabilities. Although the potential uses of these technologies are currently being investigated, they show promise for enhancing solar systems in specific industries (Sharma et al. 2016).

Copper Zinc Tin Sulfide (CZTS) solar cells represent a compelling technological advancement due to its utilization of abundant and environmentally benign ingredients. These entities possess the capacity for cost-effective manufacturing, rendering them appealing for both residential and commercial sectors. Nevertheless, CZTS is now in the research stage and its commercial availability is restricted (Islam, M. et al. 2021).

In essence, the selection of solar cell technology need to be in accordance with project objectives, financial constraints, and ecological factors. When making decisions, it is crucial to consider aspects such as efficiency, manufacturing cost, and long-term stability. Conventional silicon cells provide notable efficiency, although their affordability may pose a challenge, whereas thin-film technologies such as CdTe and CIGS present cost benefits albeit with somewhat reduced efficiency. The potential of emerging technologies like as perovskite and organic cells is considerable; yet, their long-term stability remains a subject of worry. Ongoing research and development efforts in these domains contribute to the continuous advancement of solar cell technology, hence enhancing its prospects for the future with heightened levels of excitement and dynamism.

## 4.4 The choice of Organic Solar Cells

Organic photovoltaics (OPVs), often known as organic solar cells, offer a compelling option for product design due to its three fundamental pillars: mass manufacturing capabilities, environmental sustainability, and economic sustainability (Zhang, S. et al. 2016).

To begin with, it is worth noting that organic solar cells possess significant benefits in terms of their capacity for mass manufacture. The production of these cells may be achieved by cost-effective and efficient methods, such as roll-to-roll printing and solution processing. The scalability and cost-effectiveness of the aforementioned production processes render organic solar cells a compelling option for the purpose of large-scale manufacturing, which in turn results in a decrease in the cost of production per unit and enabling the effective incorporation of solar power into a diverse range of goods (Kavlak, et al. 2018).

Furthermore, the incorporation of environmental sustainability is an imperative factor in contemporary product design. Organic solar cells are manufactured from organic elements, which are generally recognized for their superior environmental compatibility compared to the heavy metals employed in alternative photovoltaic technologies. The aforementioned materials exhibit ample availability and lack toxicity, hence mitigating the environmental impact associated with the manufacturing process of solar cells (Zhang, S. et al. 2016). Furthermore, the manufacturing procedures employed in the production of organic solar cells frequently include the utilization of a reduced number of harmful substances and result in diminished emissions of greenhouse gases. This aligns with the worldwide urge to mitigate the environmental consequences associated with energy technologies (Luthra, et al. 2015).

Economic sustainability is a crucial foundational element. The economic viability of organic solar cells is promising, as they are fabricated using inexpensive components and can be produced on a large scale. The cost-effectiveness of solar power integration in diverse items can substantially decrease the initial investment, hence augmenting the viability of product design (Sun et al. 2018). Furthermore, the emviromentally conscious nature of organic solar cells is in line with the objective of integrating renewable energy to a wider spectrum of customers, hence promoting economic and enviromental sustainability through long-term reduction in carbon emissions (Riede et al. 2021).

In summary, the selection of organic solar cells for product design is supported by three key factors from an academic standpoint: their capacity for large-scale production, their environmental sustainability, and their economic sustainability (Zhang, S. et al. 2016). The potential of these cells to be produced on a large scale at a low cost, their utilization of environmentally sustainable materials, and their affordability render them a promising option for product designers aiming to incorporate renewable energy solutions into their products while considering both sustainability and economic factors.

# Chapter 5 Concept products of organic solar cells

## 5.1 Design and concept philosophy

The aim of this section is to introduce two concepts of products, that capitalize on the advantages of organic solar cells. One of the most difficult tasks of any new technology or product is to penetrate the market. It took practically a century for solar panels to become relevant in energy production as the world turned to renewables very recently. The solar industry though is dominated by silicon solar cells. So, the task that any new solar cell technology faces is to antagonize or differentiate itself from the industry leader.

With this in mind, three conceptual products will be proposed, to antagonize and differentiate OSCs from silicon solar cells. The reality of the matter may lie in the middle though as its often the case. A combination of these products may be better still than any of them individually. The basic advantages of polymer solar cells are:

- Flexibility
- Low production cost
- Abundant materials
- Non-toxic
- Fast and efficient production

These characteristics paint the picture of a technology that in its production and use, resembles closely the electronics industry. The principles of very cheap production, abundant materials and replace instead of repair are the cornerstones of the modern electronics market. This thesis won’t delve in the intricacies of business-consumer relationship or economic policy and politics, instead it focuses on the strategy needed to enter the market of solar energy production. The most harmonic way to enter any market is to make the product desirable to investors. Investors are human and the less friction a concept creates with their pre-existing experiences, the more likely is for them to embrace it. Which means that if the electronics industry works in a certain manner in this era, the best chance of a new electronic product is to abide by it.

The products as detailed below, include these principles in their design, as its their technology and material's nature. The total design of the products not only takes into consideration economics, it also provides a sustainable cyclical life-cycle for all the materials involved in the process. The three products namely are:

1. A foldable and easy to transport portable solar panel.
2. A solar umbrella or "active sun shade" for vehicles.
3. A window tint membrane for electric vehicles.

All three of these applications make the most out of organic solar cell technology. The portable solar panel which already exists in the form of a thin silicon device, can benefit greatly with the integration of organic solar cells. The biggest benefits of the differentiation is cost which falls greatly with the use of organic cells and the weight of the device itself.

The active sun shade/solar umbrella follows the axis of thinking as the previous concept product but maximizes its orientation to cost minimization. The product's silicon counterpart is already in the market, which proves that it is a viable consumer product, its success dependent on production factors, research and marketing.

Last but not least, the solar window tint for vehicles has the potential of complementing the automotive industry car window production. It serves as a tertiary product for car glass, which has the potential to provide a huge boost for EV energy economics. The integration of another power production system to electric vehicles can be very attractive to manufacturers, as range is a major obstacle of widespread adoption. The electronic vehicle market is still in its infancy and each system developed to support it can lead a step closer to the general integration of the technology by the market.

In the following section, the life cycle of an organic solar cell will be explored in-depth. It is a crucial assessment of its sustainability, as the materials and production processes involved with the solar cells need to be completely cyclical.

## 5.2 The life cycle of a polymer solar cell

The biggest part of the cradle to grave life-cycle analysis of the aforementioned products, is identical to that of an OSC. With that clarified, the best approach to this particular analysis is to establish the general production process of the cells, and then add steps in each product's section, in accordance to its design.

### 5.2.1 Raw material extraction

This phase is chosen as the first step of the cycle, not only for its precedence inside the production cycle of the product. But also, because its importance as the origin of the enviromental sustainability of a product 37. (Guine, J. B. et al. 2002). Modern research puts a huge emphasis on the idea of sustainable or otherwise cyclical economies. It is important to phase out materials that aren't enviromentally friendly and take action to phase them out, like it has been done before with Chlorofluorocarbons (Montzka, S. A., et al. 2021). The most common materials used in organic solar cell manufacturing are PET – polyethylene terephthalate, ITO – indium tin oxide, PEDOT:PSS – poly(3,4-ethylenedioxythiophene), active layer (usually a polymer:fullerene blend), Al – aluminium (Krebs et al. 2010).

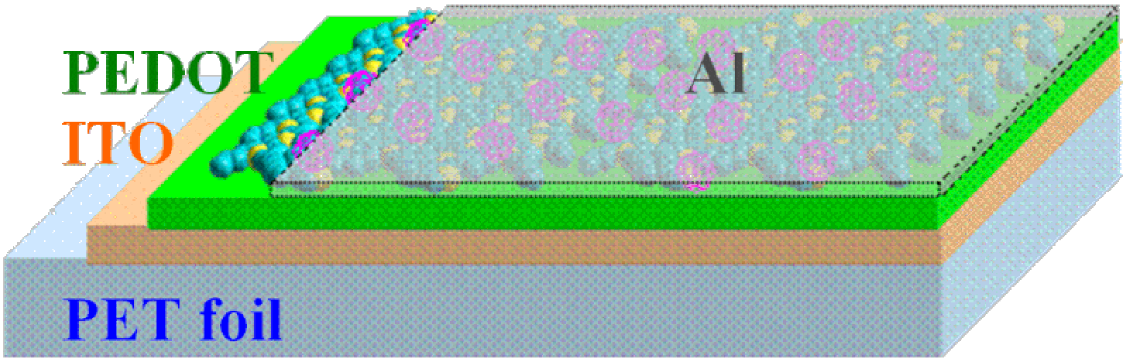


**Figure 14 Adapted from Kivirus at English Wikipedia, Public domain, via Wikimedia Commons**

PET is 100% recyclable and near infinitely, which makes it a closed-loop (Shen et al. 2011). The only thing that can limit the closed-loop recycling of PET is the lack of PET available for recycling due to low levels of collection and insufficient waste management infrastructures. ITO is reusable after the end of life of most OPV's. PEDOT:PSS – poly(3,4-ethylenedioxythiophene) is also a recyclable material. Not only that but it is a self-healing polymer that regenerates (Babeli Ismael et al. 2020). Aluminum is well researched and one of the best examples of closed-loop recycled metals (Green JAS, 2007;Schlesinger, Mark E, 2013).

In conclusion, the most widely used materials in OPV production are completely recyclable and most of them in near infinite cycles. This makes the cells (cartridge) very efficient cost wise and more importantly enviromentaly friendly.

### 5.2.2 Manufacturing and processing

The most valuable contribution that the flexibility of polymer solar cells provide, is the option of roll-to-roll manufacturing. Each printing technology will be explored as part of the production cycle. The three steps are:

1. Wet film formation
2. Processing during or post formation
3. Lamination

Espinosa et al. 2011 described the manufacturing process in six distinct steps as seen in Fig.15.

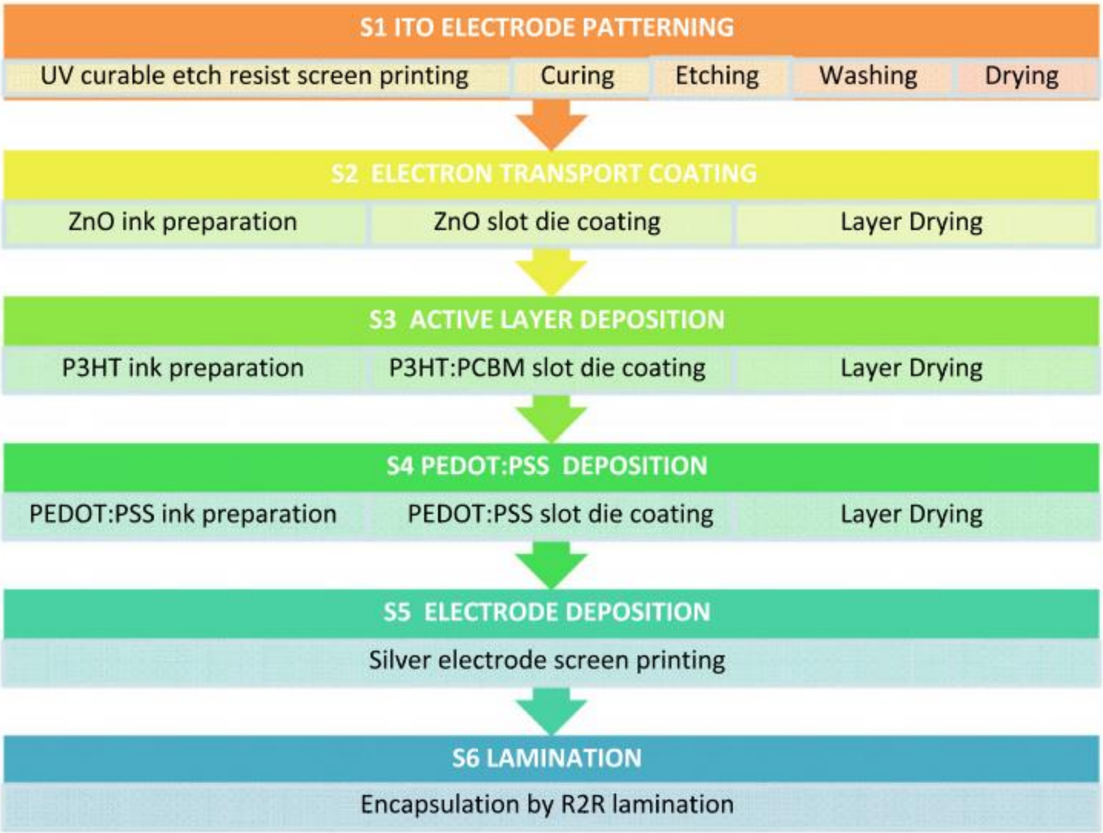


**Figure 15 Adapted from Espinosa, Nieves, et al. (2011) "A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions."**

For the sake of being concise, the process methods will be described in the three broad phases stated in the beginning of this section.

#### 6.2.2.1.Wet film formation

There are four types of wet film formation through contact printing techinques explored for OPVs. These are flexographic, gravure, screen and rotary screen printing (Aziz, Ismail, 2015).

Gravure printing can print low-viscous inks at up to 15 m/s, however ink rheology, web speed, and impression cylinder pressure affect print quality. As the web is brought into contact with the gravure cylinder by pressure from the softer impression cylinder, surface tension transfers ink from small engraved cavities producing the design to the web (Roth et al. 2014). The gravure cylinder's cavities determine the imprint's form and thickness. The ink bath constantly fills the gravure cylinder's engraved cells, and a doctor blade removes extra ink to keep it in the cavities (Søndergaard, Roar, et al. 2012). Gravure printing for solar cell preparation is very rarely used (Søndergaard, Roar, et al.

2012). Flexographic printing is an R2R method that varies from gravure printing in that ink is transferred from a relief rather than cavities. Rubber or photopolymer printing plates create the design. Fountain rollers continually transfer ink to the ceramic anilox roller with etched cells/micro cavities (Roth et al. 2014). This collects ink for transmission to the printing cylinder relief that transfers it to the web.

Roll-to-roll flexographic printing is a relatively new technology for organic solar cells, but it has been used to process modified PEDOT:PSS18, a wetting agent on the active layer, and conductive grids (roll-to-roll) with a line width below 50 μm, which could be used as electrode structures for ITO-free organic solar cells (Søndergaard, Roar, et al. 2012).

Screen printing, unlike flexographic and gravure printing, creates a very thick wet layer and dry film (Søndergaard, Roar, et al. 2012), which might be beneficial for printed electrodes with high conductivity. 10–500 micron wet layer thicknesses are usual. Flat-bed and rotary screen printing exist. Both approaches use the same premise. The squeegee pushes ink paste through the mesh hole to create the desired pattern. Both methods work differently. Flat-bed screen printing has low-cost masks and allows one print at a time with modifications between prints. This aids development and lab work.

Rotary screen printing uses a spinning cylinder with a fixed internal squeegee to keep the ink confined (Søndergaard, Roar, et al. 2012). As a true roll-to-roll printing technique, rotary screen printing outperforms flat-bed screen printing in speed, edge definition/resolution, and wet thickness. However, the mask is much more expensive. Two-dimensional printing offers the highest wet thickness (> 300 micron). Rotary screen printing is less suitable for laboratory work than flat-bed because of the mask expense, the sensitive operation, the difficult adjustment, and the time-consuming cleaning. Screen printing of active layers and printing of polymer solar cell front and back electrodes have been both successful (Aziz, F., & Ismail, A. F. 2015).

Meniscus coating creates a continuous wet layer along the web without contact between the coating head and the web, while all printing methods allow two-dimensional lateral printing. Coating is created by feeding ink to a "coating head"-web meniscus. Most coatings cover the substrate equally, making them zero-dimensional. Wet thickness control produces uniform layers better than printing. Most roll-to-roll polymer solar cell production uses slot-die and knife coating (Wengeler, L., et al. 2011). Since laboratory doctor blading results are identical, roll-to-roll knife coating can be employed. An ink reservoir before the knife feeds the meniscus as the web passes. A slot and pump delivers ink to the meniscus in slot-die coating, allowing web speed or ink supply to change wet thickness (Roth et al., 2014). The coating window is mostly defined by ink and web surface properties, but coating geometry limits wet thicknesses. Web speeds of a few meters per minute can traverse closely spaced stripes. Several large polymer solar cell demonstrations have addressed this.

Lastly, contactless wet film formation. Organizing film forming processes by coating and printing categories is difficult, and several OPV techniques have been designated without considering the definitions above. Inkjet printing is regarded as an emerging method for the manufacture of solar cells due to its advantageous characteristics such as a high material utilization rate, cost-effectiveness, and flexibility (Sumaiya et al. 2017) . The utilization of inkjet printing has facilitated the development of an active layer composed of Poly(3-hexylthiophene):[6,6] phenyl C61-butyric acid methylester (P3HT:PCBM) in polymer solar cells. The future prospects of inkjet-printed organic solar cells (OSCs) are promising. However, it is imperative to overcome the obstacles associated with the utilization of the inkjet printing technology. Ongoing research efforts are focused on enhancing the efficiency of inkjet-printed organic solar cells (OSCs) and addressing challenges such as the coffee ring effect, restrictions in viscosity, film homogeneity, and nozzle clogging (Sumaiya et al. 2017).

Either technique from the above could be suitable for the manufacturing of the layers used in the conceptual products.

#### 6.2.2.2.Processing

Søndergaard, Roar et al. 2012, gave two examples of roll-to-roll processing. Double slot-die coating technique, that the author describes that it gives access to complex segregated wet films with a complex topology laterally and horizontally. The second example they provide is the differentially pumped slot-die coating technique developed by Alstrup et al. 2010 where two or more ink solutions are mixed and supplied to a modified slot-die coating head.

Post wet film formation processing includes Film drying. Traditionally, heating the wet film removes the solvents and leaves a dry layer of the appropriate thickness material. Many adhesives are now UV-cured. systems for solvent-free ink even while it's not dry (till totally healed). Drying and curing are complicated. that merit a review, but as an example the very hot air drying, UV curing, and for OPVs22 inverted screen-printed silver back electrodes. Comparing power conversion of silver inks efficiency and only UV curable ink tested resulted highest PCE. Later LBIC research measurements showed solvent-based silver inks deteriorated whereas this was not the case for UV curable ink nor for a specifically formulated water-based ink.heat-curing ink (Krebs, F. C., et al. 2011). Thermocleaving with bright lightpolymer side chains in OPV R2R coating processes (Krebs, F. C. and Norrman, K. , 2010).

Thermocleaving a polymer in a 140 °C oven took four hours making this impractically sluggish. On the other hand, employing a custom high-intensity narrow-wavelength light resulted in much quicker webspeeds ranging from 0.2 to 0.4 m/min. Ultra-short lasers were introduced. Pulses ranging from pico- to femto-second. These novel selective methods of laser patterning have promise for R2R processing of solar cells. Short pulses generate less heat which allows carefully removing a thin layer without harming the underside. Early solar reports cells mostly pattern ITO on glass. and PET (Xiao S, 2011). This technology though, has yet to demonstrate functionality. Removing applied substance is usually not a preferred practice in manufacturing if possible. But it may still prove useful in specialized products. Scribing is a major benefit. May help future OPV modules with massive geometric fil-factors matter. Reaching geometric slot die coating and screen-printing fill factors of 45–67%. Although, with high precision It might reach 85%. It is highly unlikely to be taken further than this threshhold (Søndergaard, Roar, et al. 2012).

#### 6.2.2.3. Lamination

The process of lamination as described in Espinosa, Nieves, et al. 2011 "A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions". The adhesive was bonded onto the barrier foil via lamination. The width of the barrier foil that was used for their experiment, was obtained from Amcor Flexibles. It was 305 millimeters, while the width of the lined adhesive that was obtained from 3 M 467 MPF was 298 millimeters. It was selected in order to prevent the accumulation of adhesive on the laminating rubber rollers in the case of the event that there is a little deviation between the adhesive and the foil barrier. It is possible for the barrier material to have a lined adhesive and be trimmed to a width of 250 millimeters on the reverse side in order to accommodate lamination of the operational portions while leaving some of the operational areas exposed (Espinosa, Nieves, et al. 2011). During roll-to-roll processing, silver bus bars are used to make electrical connections, IV-testing.

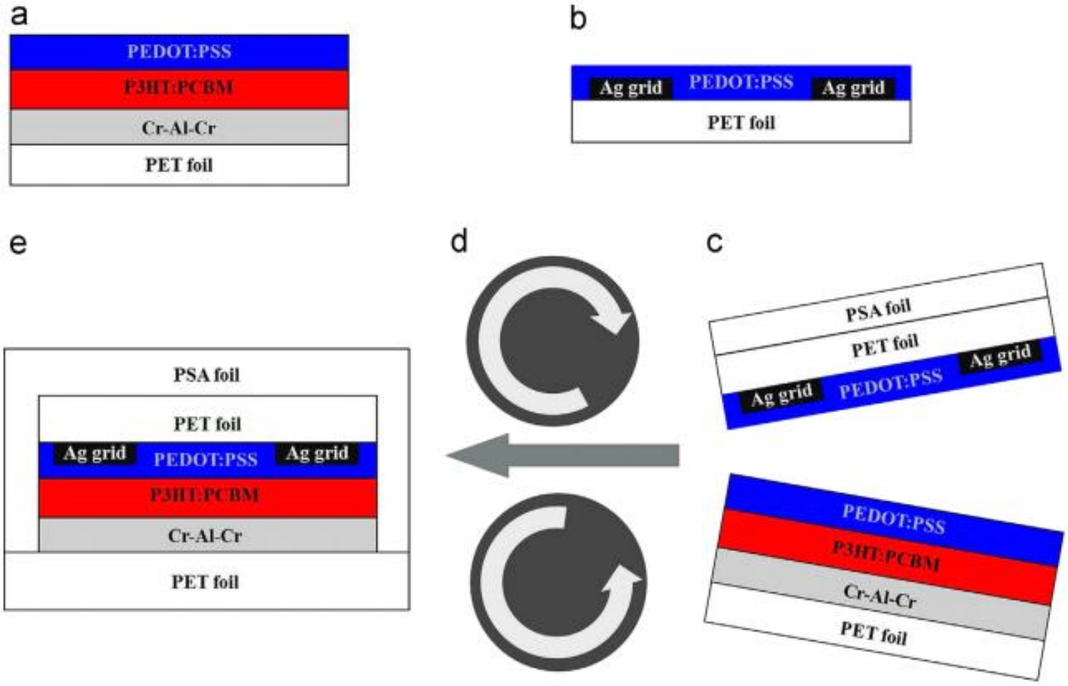


**Figure 16 Adapted from Kaduwal, Deepak, Birger Zimmermann, and Uli Würfel. "ITO-free laminated concept for flexible organic solar cells"**

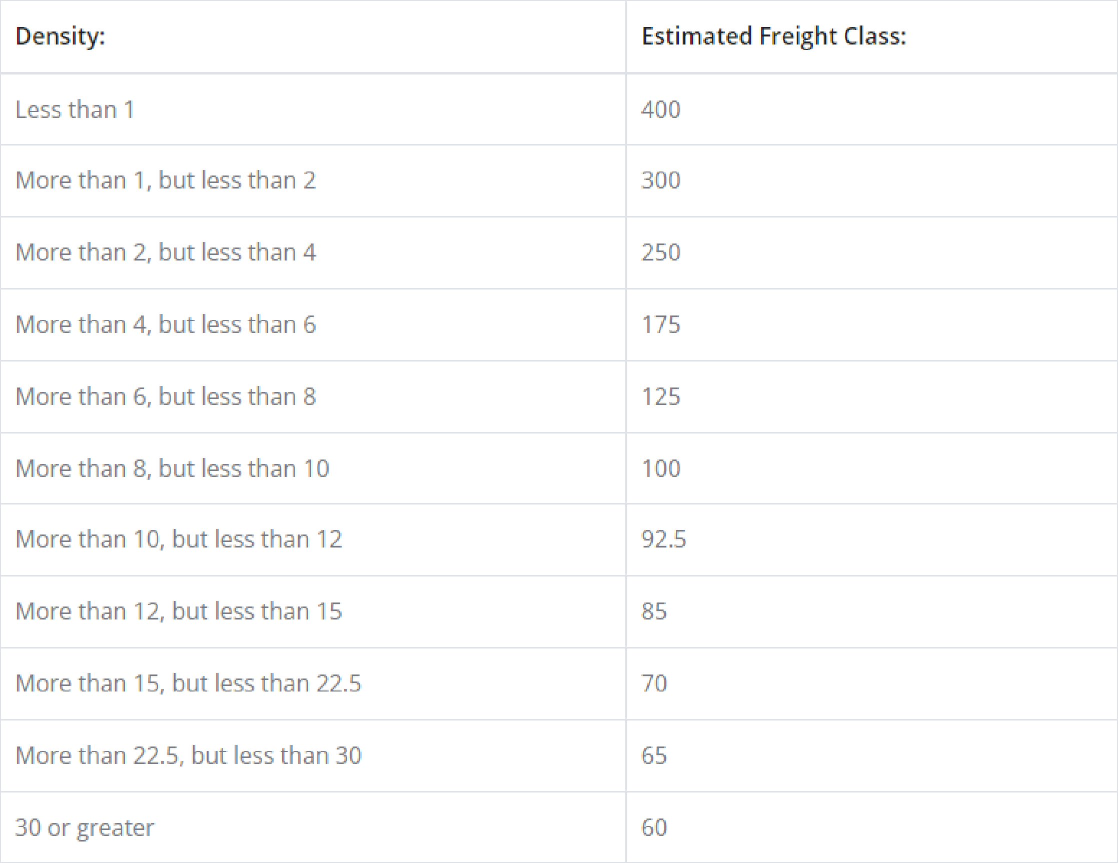
### 5.2.3 Transportation

There are major economic benefits in the logistical organization of OPVs as they tend to be much lighter than their silicon counterparts. Their weight ratio is estimated to be at least 10 to 1 (Riede et al. 2021). The weight disparity as well as the nature of thin-film being much less in thickness and overall, in volume, makes the logistical capacity of the products greater by leaps.

According to the American Bureau of Transportation Statistics, the freight density of a transportable good is the ratio between its volume and weight. Taking this measure into account, transportation companies use this ratio to calculate the dimensional weight of a package, which ultimately determines the billable weight (American Bureau of Transportation Statistics, Accessed 2023). Which is how the carrier calculates the shipping cost. Billable weight varies from carrier to carrier, and service to service. With a tenfold decrease in both volume and weight, organic cells drop the cost of out of house transportation significantly, which also factors in the cost of the final products.

There are specific tiers in the motor freight industry to help standardize costs. Freight classes are designed to help form common standard freight pricing for shipments, which is can be helpful when utilizing many brokers, carriers and warehouses. Freight classes are defined by the National Motor Freight Traffic Association (NMFTA, Accessed 2023) and are based on weight, length, height, density, ease of handling, value and liability from things like theft, damage, breakability, and spoilage. In Table 3 we can see the different ranges that determine the total cost.

**Table 3:**
**“The function between product density and its estimated freight class” Adapted from FCCR, accessed 25/08/2023**



| Density: | Estimated Freight Class: |
|---|---|
| Less than 1 | 400 |
| More than 1, but less than 2 | 300 |
| More than 2, but less than 4 | 250 |
| More than 4, but less than 6 | 175 |
| More than 6, but less than 8 | 125 |
| More than 8, but less than 10 | 100 |
| More than 10, but less than 12 | 92.5 |
| More than 12, but less than 15 | 85 |
| More than 15, but less than 22.5 | 70 |
| More than 22.5, but less than 30 | 65 |
| 30 or greater | 60 |

The costs also are helped even if the business chooses to keep the transportation in-house. The weight to value ratio of the products help dramatically, as more product can be transported per fuel and storage space unit of the truck. The same holds true for the shipping industry and air transport (Prentice,Prokop, 2015).

### 5.2.4 Usage and retail

Organic solar cells are meant to be mass produced in rolls. Cheap, in massive quantity and homogenous active layer material that can be used in a variety of applications. Each design described in this paper will need a few modifications in its production and different types of materials to be produced. For example, the active sun shade could benefit from the production of a few different light spectrum absorbers, which means that multiple layers of different color will need to be produced (Xu, Yu, 2014).

The specific usage and retail may be determined by the business. For example, the usage of the organic portable solar panel is pretty straight forward. It is meant to be used for camping and outdoor activities, by its nature though it can be leveraged even as an off-grid system to shave off electricity costs for houses, if the design permits it. Another example is the retail of the active sun shade. It can range from electronic stores, to large hardware stores, even supermarkets that have a section for home and car hardware. The channels for all three retailers are valid and its up to the market's specific conditions to determine the most suitable choice. Not to mention that these kinds of decision also affect the marketing aspect of the product.

The flow of materials which is depicted in Figure 18, shows the different branches that result from the applications, while the original materials remain the same. This removes the bottleneck effect that some consumer products have in the manufacturing phase of their life-cycle, due to their specialized process demand.

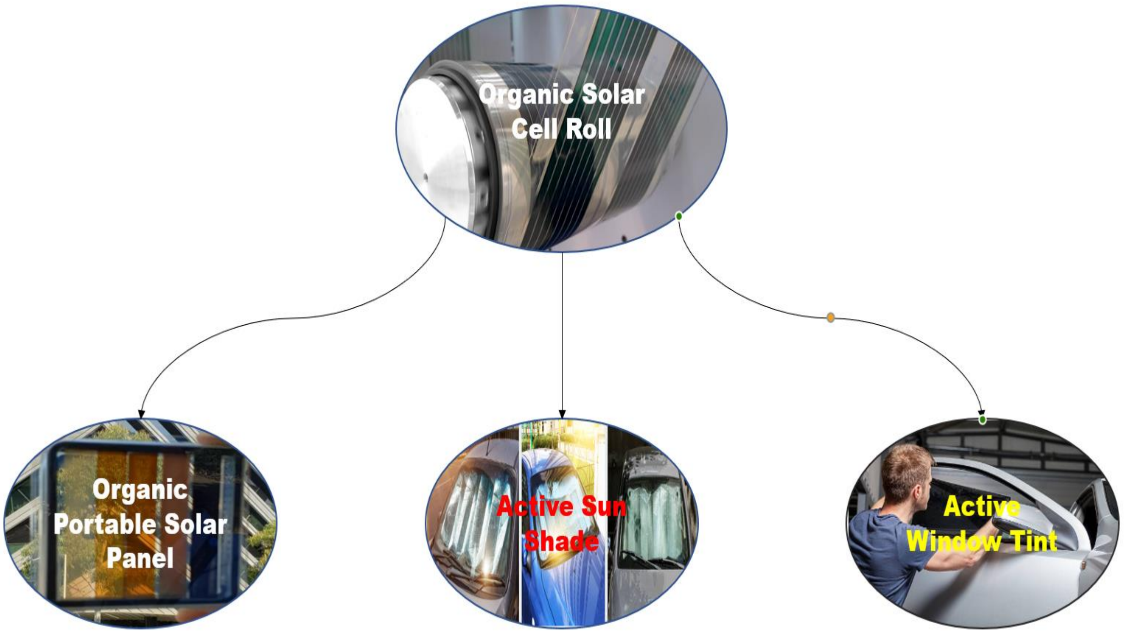


**Figure 17 "The flowchart of the solar cells towards their different applications"**

### 5.2.5 Waste disposal

One of the main focus for the panel is to be 100% recyclable. Unlike silicon solar cells, organic solar cells are not laminated with adhesives making re-melting and re-use of recovered materials not suitable for new plastic products (Ha, 2020). When panels are manufactured with silicon cells, back sheets, and glass glued together using encapsulating materials (plastic), which employ the same laminating concept, the same principle is applied. The aluminum frames may be taken apart by hand, and the glass can either be fractured and re-melted, or it can be retrieved whole if it was not damaged. Polymeric encapsulants and back sheets are often not recyclable due to their composition. Due to contaminants such as lead, plastic, and/or cadmium in the case of thin-film panels , the glass used in solar panels cannot be recycled as float glass (Shellenberger, 2018). Which is fortunate as OSC's don't use lead and cadmium and rigid glass is avoided in the production of flexible solar products.

### 5.2.6 Conclusion

After the life-cycle analysis, the conclusion is that the technology has the potential of being sustainable long-term, if proper materials and processes are used or developed. With the designs and research anchored at the sustainability pillar, the technology may have the opportunity of moving the solar market towards a low barrier of entry for passive power production. More products will have the option to integrate solar systems to their design and function, either to boost productivity or mitigate power consumption. All of the above, without having the catastrophic environmental effects that unchecked mass-production can create. With the right infrastructure and waste management, this economic sector can be transformed from a niche, to a standard.

Considering the previous assessment of organic solar cells, the following sections explore three products that make use of the technology's biggest advantages. The choice of products was made based on the idea of maximizing the exploitation of the characteristics of the organic solar cells. Existing products were chosen as to make realistic assumptions and accurate estimates. The specific products were chosen as their use makes the most out of the organic cell technology. The first two products provide a new perspective for existing products. Instead of using silicon cells as an energy producer, they make use of organic solar systems in order to achieve comparable results, cheaper and sustainably. The third product uses a concept that has been already tested practically, in building design and applies it to vehicle design, making use of every surface that is exposed to the sun.

## 5.3 The transportable solar panel

### 5.3.1 Introduction

The first concept we are going to be looking at is an alternative to transportable crystalline and amorphous silicon solar panels. In an attempt to bring further down the initial costs of installation, this concept uses the working principle of a solar panel but with a twist. The twist being that instead of a factory encased semi-conductor, the semi-conductor is organic and applied to flexible substrates.

**Figure 18 A portable commercially available solar panel system**

The solar panels use organic cells to optimize for cost and transportability. The positioning of the product is to significantly undercut the initial cost of buying a transportable solar system, while also providing a comparable power production. It is known that silicon solar cells are more efficient than polymer cells. So instead of depending on the progress of scientific research, the product can just leverage its advantage of weight and low cost to provide the same wattage, by just being wider.

A brief comparison of existing transportable solar systems is in place. According to the Research and Markets 2022 report "Portable Solar Panel Industry Outlook - Forecast (2022-2027)", the global Portable Solar Panel market size is forecast to reach US$1,296.3 Million by 2027, growing at a CAGR of 17.5% from 2022 to 2027. In addition, the expansion of the industry has been helped along over time by steps taken by governments to provide access to off-grid energy sources, the increasing prevalence of portable and wireless energy-efficient gadgets, and growing worries over the diminishing availability of traditional energy sources such as fossil fuels. The market demand for portable solar panels is expected to be fuelled in the long term by a number of factors, including an increase in spending on solar-powered consumer electronic items, a rise in demand for flexible and thin-film electronic devices, a move toward electric or hybrid automobiles, and a number of other factors.

The increasing need for electronic devices that are flexible or thin film acts as a primary factor that is propelling the market expansion towards foldable solar panels. Because of the tremendous advancements being made in flexible electronics or thin film devices, there has been a considerable increase in the demand for foldable panels. These panels can be conveniently stored in large quantities and ensure integration into a variety of appliances, in contrast to rigid ones. Foldable solar panels are becoming increasingly popular for usage in a broad variety of end use applications. These applications include powering camping gear, field communication radios, GPS systems, and many others. Foldable solar panels lightweight designs, portability, and ease of setup are all contributing factors to their rising popularity. As a consequence of this, the market demand for portable foldable solar panels has been growing steadily over time. An international research team from Pusan National University in South Korea announced in February 2021 that they had developed a prototype for a solar cell that could be folded over 10,000 times while still maintaining an adequate level of power conversion efficiency. Because of this change or expanding demand for ultra-thin flexible electronics, such elements are projected to help in the market expansion of portable solar panels in the long term.

### 5.3.2 Working principle and applications

The working principle of the aforementioned solar panel is identical to the traditional silicon panels, with a few modifications to maximize the desired features. Namely, the design needs to be resistant enough to withstand all weather conditions of low intensity. The consumer expects that in mild weather conditions the device can be left out in the open, as the hassle of uninstalling the whole system according to small frequent changes in climate conditions is not sustainable.

The previous mean that its working condition should be suitable for a liveable temperature range between -10C° and 50C°, like its silicon counterpart (Chander et al. 2015). Also, the product must be resistant to rain and light hail, while maintaining its flexiblity and light weight. It should also be designed to be heat resistant, which polymer cells are. Furthermore, the light degradation problem of the technology that the product is based, must be improved upon significantly, in order to provide a comparable lifespan to its competitors (Riede et al. 2021).

The baseline of the viability of the product is its mathematical point in which it stops being economically viable to buy a new one every X years. Every major producer of portable panels claims that the lifespan of their products is 25 years (Bluetti, Anker, Rocksolar). Which means that for half the price, the conceptual product would need half the lifespan at least.

The applications that can be derived from a flexible panel are limitless, in the sense that freedom of shape and its light weight may enable it to be applied to surfaces that conventional panels couldn’t cover (Liu et al 2021). For the purposes of this paper there is one derivative product that needs to be considered. The product is a solar cover for tents. The flexible panel by itself cannot be crumpled extensively, as folding cells damage their structure which leads to efficiency loss and faster degradation (Li, X. *et al.* 2021). So, a tent cover that harnesses solar power may be desirable. Such a design could also enable summer campers to use the tent during the day, or at least provide a charging station for small electronic devices.

### 5.2.3 Design specifics

The idea of cheap and replaceable products is made to combat thermal, light, chemical and mechanical degradation of the organic cell.  Crystalline silicon is a resistant material in of itself, as opposed to organic ones. A simple example of the OSC’s cost effectiveness is that the manufacturing process of such a design doesn’t need components such as an ITO (Kaduwal et al. 2014). The ITO is one of the major costly components in panel manufacturing and the idea of a panel that is designed without it, drives down the cost significantly. Its feasibility and its properties allow the idea to be integrated naturally in our own design, taking advantage of the designs cost reduction (Angmo et al. 2013).

For this particular product, only plastic and metal substrates are considered, in order to maintain the flexibility. Flexible solar cells are often fabricated using thin metal foils with a thickness of less than 125 micrometers, which are themselves flexible (Wong, William S., and Alberto Salleo, 2009). The great ductility of metals contributes to the foil‘s remarkable degree of flexibility. Stainless steel foil is the most common type of flexible metal substrate because of its low cost, great thermal stability and excellent chemical stability. Commonly used plastic substrates are polyethylene terephthalate (PET), PEN, polycarbonate (PC) and polyimide (PI) (Li, X. *et al.* 2021). PET is by far the best candidate because of its flexibility and its infinite recycle potential.

### 5.2.4 Cost analysis

The cost of the organic portable cells in order to be competitive needs to be at least half of a silicon one. The available systems cost between 0,75$-2,5$ per watt (solarportablepanel.com, www.thinkepic.com, Accessed 24/08/2023). This means that in order to be economically logical for a consumer to choose portable polymer cells they need to range between 0,37$-1,25$ per watt. With the assumption that this is feasible we are going to calculate the watt per price relationships of the two competitors.

Efficiency will be included in this section as opposed to the design analysis. Cost in solar cells is always measured as a function of efficiency/currency as the energy input is considered the same for each application. The efficiency achieved by OSC’s ranges around 15-20% as opposed to silicon ones that hover between 20-25%. Assuming an average for both at the center of their range, OSC’s at 17,5% and silicon at 22,5%. We can calculate that for tha same cost. The calculation is clear that an organic system that achieves half the price, the efficiency is over double than that of silicon. In theory, the system’s efficiency is higher than half, so for double the size, the OSC would produce an equivalent of a 35% efficiency silicon solar cell.

### 5.2.5 Market positioning

The main angle of this product is to lower the entry cost of a portable power generating system. The democratization of products leads to profit in every product until now, portable power generating systems in principle follow the same, as it was proven by the solar panel cost reduction during the 2010-2022 period. The market experienced exponential growth (Madsen et al. 2019) which is directly linked both to a solar systems upfront cost and its cost effectiveness.

The design factors can also play a big role in the sale of systems as campers and outdoor activities hobbyists, consider weight and storage capacity as main factors of their equipment. Both of these features are the main competitive edge of OSCs that allows them to dominate in this particular niche of the outdoor equipment market.

## 5.3 The solar sun shade/ solar umbrella

### 5.3.1 Introduction

The second concept is also simple enough. The product is an internal car membrane that connects to a port feeding it energy, or running the cars conditioning system to keep the cabin cool in hot summer months or warm during winter. It is a combination of sun shades and OPV’s. A technology that is already in the market and an application already tested makes the concept promising ().

There are two designs considered for this idea. The first is a regular, low cost sun shade as seen in figure 20, only with an organic thin film integrated in its design.

**Figure 19 A traditional car sun shade**

The simplest of the two ideas, it is a sun shade that generates electricity. The idea speaks for itself. The product can come with a small coverter built in, for charging electronic devices, or make use of a car port designed specifically. The automotive industry is rapidly integrating electronic systems in their designs so the addition of such a port could be fairly simple. The full analysis of such a port is in section 6.3.3 as it is essential for the future possibility of such a system charging an electric vehicle.

The second idea is a solar car internal umbrella. The interior based umbrellas as seen in figure 21, can also be improved, by adding two foldable extensions that also shade and make use of the front seat windows. The connection to the car is the same as before, as is the idea of a converter and cable to charge electronic devices. The product was elected to be internal as the car protects the device from wind and moisture.

External car umbrellas were not considered as the weather conditions accelerate the degradation of cells. Which holds true even for current textile umbrellas. Even with light snow or tree foliage, the efficiency would significantly drop.

Figure 20 An interior sun shade umbrella for cars and a concept foldable umbrella

### 5.3.2 Working principle and applications

The working principle is identical to an OPV solar cell. The twist is the application. Polymer solar cells are non-toxic which makes them very good fits for any application that is in human environments or even prosthetics. The placement of the membranes is inside the vehicle, to prevent weather hazards from degrading the cells.

The sun shade performs two functions. The first is shading the inside of the vehicle, as a traditional sun shade would. The second one is where the product has an edge over the competition. By converting sunlight into electricity, the device can charge anything plugged into it. This includes any electronic devices like phones, powerbanks etc. More importantly though, it can be taken a step further by looking further into the future. Electric cars are notorious for their range problems. A product that helps ease that problem could be very desirable for electric car owners. Combined with the electric car market growing, the market for solar sun shades would follow. Additionally, the insufficient power grid capacity, is predicted to be a catalyst in the economic growth of developed countries (Harrison Fell, Dr James Glynn, et al. 2022). An insufficient grid is sure to accelerate the growth of all markets that focus on power production independent from it. The independency from the grid is also attractive to the consumer, which will aid the marketing effort of the production company.

In the applications front, the product can also be used outside of vehicles. As long as there is light exposure, the umbrella could work as a power production resource, provided that the design with the integrated inverter is followed. The specific use remains open as the product design could implement a vehicle specific design, or a generalist approach by integrating an inverter that feeds electrical ports.

### 5.3.3 Design specifics

The design of the sun shade is optimized to use the advantages of the technology and eliminate the challenges that it faces. One of the biggest challenges, not only for the product, but for PSC's in general, is thermal stability. A recent study by Qi et al. 2022 showed that was by incorporating a moderate amount of random copolymer PY into the active layers, the thermal stability improved, while maintaining the initial photovoltaic performance (Qi et al. 2022). The results of their characterization demonstrated that PY had an influence on the crystalline, morphological, and optical characteristics of the blends. The amorphous random copolymer that was spread in the polymer domain caused disruption in the aggregation of photovoltaic polymer chains, while simultaneously improving the order of acceptors, which resulted in a more pronounced phase separation. Because of the inclusion of PY, the crystallinity of the donor and acceptor was suppressed, and the mobility of the polymer chains was reduced when they were subjected to thermal stress (Qi, Qingchun, et al. 2022). These two factors contributed to the more stable active layer shape and better thermal stability. As a consequence of this, a device based on P3HT:O-IDTBR that had a 10% PY obtained photovoltaic performance that was equivalent to that of the control device. Over seventy percent of the improved P3HT:O-IDBTR:PY device's original efficiency was preserved during eight days of continuous heating at 150 degrees Celsius (Qi, Qingchun, et al. 2022). This is ideal for the realisation of the product as the sun shade during summer, may be very well exposed to temperatures of about 50 degrees celsius for hours.

The flexibility of PSC's allows a certain degree of freedom as for the storage of the product, the application and use. The aim of organic solar cells manufacturers is to produce in mass with R2R methods. This means that the products may very well be stored like traditional foil products and in other cases folded. Although, thin films are flexible they relinquish some efficiency when crumpled or compressed (Dauzon, E. et al. 2021). This limits the design of the products as it needs to be folded and unfolded in specific manners. Consumers don’t always adhere to such rules, which can lead to wear and tear of the product. Alas, there are geometries like the ones used for portable solar panels that use lines of material without printed material and compartmentalise the panels si that they can be stored and folded at these specific points.

### 5.3.4 Cost analysis

In this section the cost per unit was calculated. In the cases that the components are still in the research phase, estimates were used. Either by the components maker or by combining research information for the purposes of this paper.

There a few assumptions and concessions to be made for the concept to be true to the cost calculated. Starting with, the door window and windshield size. The numbers in table X represent the industry average for various car types.

**Table 4 “Average Window Sizes for Consumer Cars“**

| | Windshield | Door windows |
|---|---|---|
| Smaller Cars | 150cm×80cm=1,2m^2 | 36cm×61cm=0,2m^2 |
| Bigger cars | 206cm×166cm=3,4m^2 | 40cm×66cm=0,26m^2 |

According to Table 4 there are four sizes of thin films that need to be produced. The estimated cost for an organic solar cell ranges from 48$ to 138,90$ per m^2 (Kalowekamo, Joseph, and Erin Baker, 2009). The 2010-2020 decade saw a steep decline of solar cell cost (Green M.A 2019). That is why the calculations are going to be made with its lowest estimate, 48$/m^2. This estimate is older than the 2010-2022 solar boom so the reality might be quite lower. For the efficiency of the cells, we are going to assume a rough 15%. The highest recorded efficiency recorded in a lab is 19.2% (The Hong Kong Polytechnic University. "Record 19.31% efficiency with organic solar cells." Article in ScienceDaily, published 1 June 2023 and accessed 04/08/2023).

As stated before, the product needs to be able to charge electronics and car batteries. That is why an analysis of how much energy it can convert into electricity is essential to understand the feasibility of such an endeavor.

Smaller cars have a total of 1,4m^2 available on their windows. The solar constant ranges from 1358-1364 watts per squared meter (Australian Space Weather Forecasting Service https://www.sws.bom.gov.au/Educational/2/1/12, Accessed 04/08/2023). Using STC (Standard Testing Conditions) the system which is 1,4m^2 is exposed to 1000 watts of sunlight.

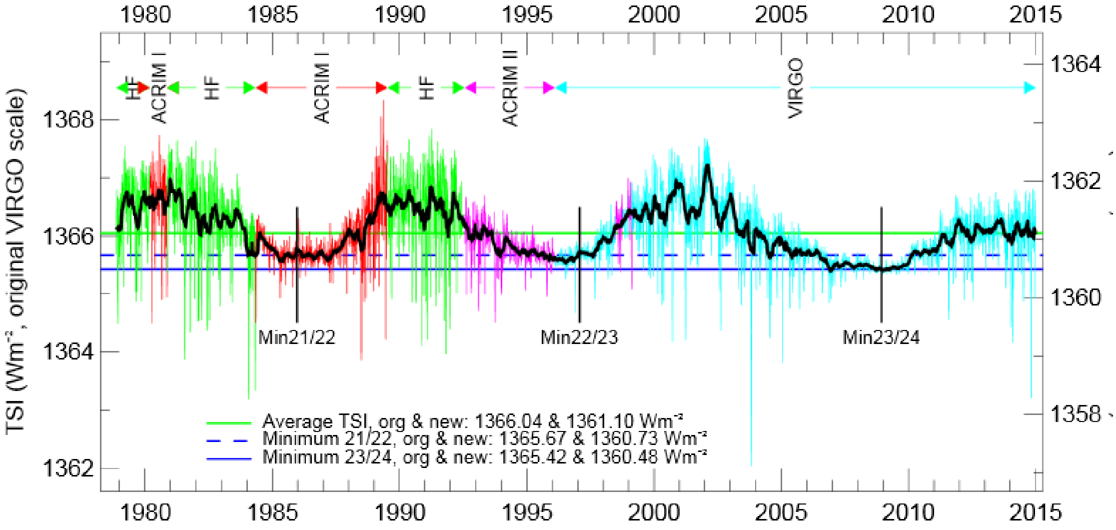


**Figure 21 adapted from Australian Space Weather Forecasting Service https://www.sws.bom.gov.au/Educational/2/1/12**

With a 15% efficiency this translates to a 200W system approximately. So the system is able to produce 200W/h. The average electric car in 2023 has about 60kwh battery capacity and a kilometer consumes about 0,198kwh. This means that an hour of exposure translates to a kilometer of range. Considering that the average range according to capacity is 60kwh÷0,198kwh/km=300km. In a month, with 5 hours of exposure a day, the sun shade could produce 150 kilometers.

Bigger cars, with only the surface area changing, ceteris paribus, they are 540W systems. They produce 540w per hour, but accounting for their size we could assume that the kilometers gained are about the same as smaller cars for the sake of simplicity.

### 5.3.5 Market and positioning

The market that these two concepts belong, is the automotive window power sunshade market. According to Technavio the market is projected to expand at a compound annual growth rate (CAGR, year) of 15.74% between the years 2022 and 2027. It is anticipated that there would be a growth in market size of 1,396.61 million USD. The expansion of the market is dependent on a number of different reasons, including the fact that window-power sunshades maximize the effectiveness of HVAC (Heating Ventilation, Air-conditioning) systems, the fact that more time is spent inside vehicles, which pushes demand for window-power sunshades, and the increasing demand for luxury automobiles.

Even if we take into account the much smaller market of solar shading systems, which these products don’t exactly fit in, in 2019 the worldwide market for solar shading systems was valued at $17,550.0 million. This figure is expected to increase to $21,348.2 million by 2027, representing a compound annual growth rate (CAGR) of 3.9% from 2020 to 2027 (www.alliedmarketresearch.com , Accessed 28/08/2023).

The competitors of these products are tradition sunshades and umbrellas which provide the similar service of blocking sunlight but without the added feature of producing electrical power. That is the competitive edge that the marketing of this product will be based on. Furthermore, the technology combines well with EVs and Hybrid vehicles.

## 5.4 Window tint for electric vehicles

### 5.4.1 Introduction

The main idea of this product, is to apply the practice of printing OSCs on glass, on vehicle glass. Organic solar cells are already gaining traction in the role of window membranes or complete semi-transparent glass systems as well as Building Integrated Photovoltaic systems (Shukla et al. 2017). Office buildings and generally structures with large glass surface areas with a lot of sun exposure, provide the possibility to produce energy by installing thin-film technologies on these surfaces. Companies like Onyx solar or Heliotek have already applied the technology with an efficiency just shy of 10%. In figure 23 the semi-transparent cell is shown printed on glass (Sarojwal et al. 2021).

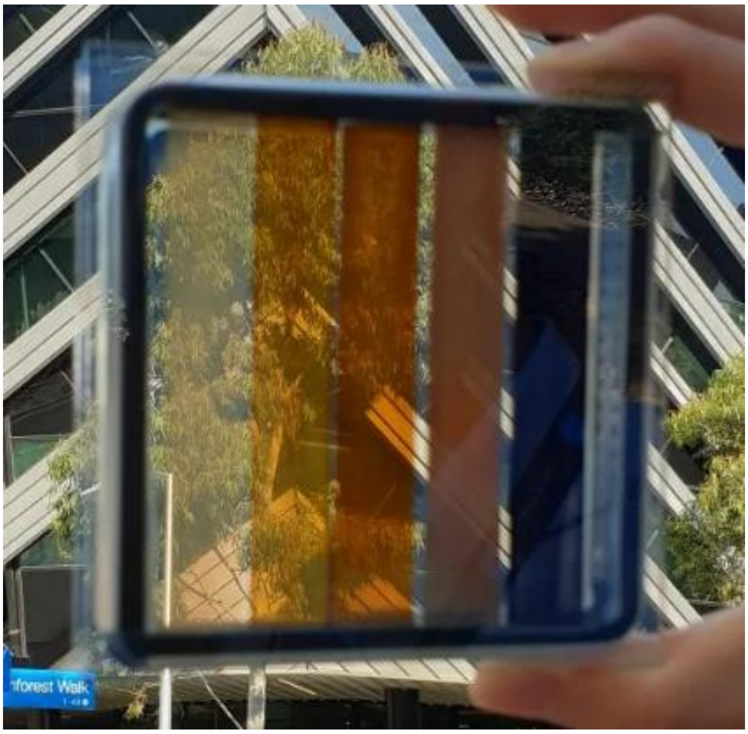


**Figure 22 A semi-transparent perovskite solar cell with different levels of transparency, credits to Dr Jae Choul Yu**

The concept functions exactly like an organic solar cell printed on a glass substrate. The semi-transparent cell functions like a tint, to keep the car shaded and to produce electricity while doing it.

The biggest challenges the technology faces are the method of connection and the implementation. Much like conventional films, OSCs foils can be applied directly to car glass like stickers (Riede et al. 2021), assuming that they are designed with this intention.

The alternative would be to print directly on car glass, which will add steps, albeit short ones in the automotive manufacturing process. Either way, the connection of a foil, or a directly printed cell poses a challenge, as the power conversion system would need to be integrated directly to the dashboard and doors.

**Figure 23 A vehicle glass film, credits to Cars Insider, Accessed 11/09/2023**

### 5.4.2 Working principle and applications

The working principle is that of a solar panel, with the only distinction being the surface utilized. The applications of such a specialized product are fairly limited, as the whole concept tackles a very specific niche in the shading and vehicle glass industry. The idea follows the philosophy of utilising untaped surfaces for PV production, which makes every structure more energy efficient and actively gives back, cutting down cost by producing instead of just enduring.

The main point of friction is the membrane application method, aftermarket foil or integrated printing by the vehicle manufacturer. Both methods are pre-existing and both methods have proven to be economically viable for both manufacturers and indepenedent professionals. The first possibility is to produce vehicle glass directly with the tint as many manufacturers already do. The distinction would be that in order to produce the glass with a photovoltaic tint, the manufacturer would need an OPV printer. The benefit of this method is that practically, printing the cell on the window is an identical process of printing the cell on a glass substrate. A lot of research has been focused on capitalising on the flexibility of OPVs, but with a glass substrate, the stability aspects of the cells are optimized (Li, X. *et al.* 2021). The second one would be a foil from a roll, produced by a company that makes aftermarket tints and distributed to window tint professionals to apply.

### 5.4.3 Design specifics

The integration to the car is the biggest challenge that the product faces. It needs to be enough incentive for car manufacturers to include such a system and this technology to be widespread. In theory, the organic solar cell printed on the inside of the vehicle window, connects through its anode an cathode to an electrical circuit that travels through the vehicle and at its end, an inverter is connected to convert the current.

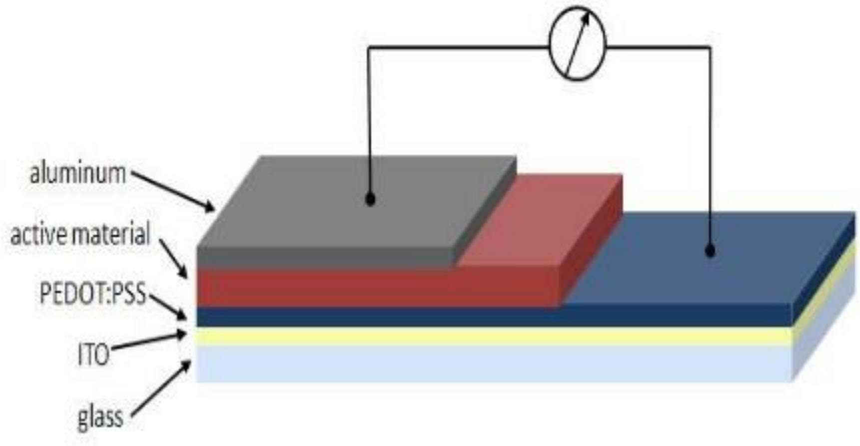


**Figure 24 "The schematic of the concept of Organic Solar cells printed on glass" (Adapted from NTUA Physics Department website, June 2010) http://www.physics.ntua.gr/biolift/research/solar_cells, Accessed 11/08/2023**

The last but not least, the aspect that also plays a big role in the products success is the lifespan, end of life and replacement. The lifespan is a major metric that a lot of research and commercial R&D has been dedicated to its improvement. In Li, Y., Huang, X., Ding, K. et al. it is extrapolated that a lifetime of 30 years could be achieved. With the natural gap between theoretical values and conditions, even if the data is disproven by a value of 33% and the real value is closer to 20 years, the product still is well within the average lifespan of a vehicle. Which means that the glass membranes will never need to be replaced.

For the sake of the argument, we will also use data from the 2023 study by Li, Y., Huang, B. et al. 2023 which claims 10000 hours of organic solar cell potential function, it translates to 1.14 years of life. Assuming that the consumer will need to change the membranes every year, which could be coupled with a yearly maintenance service, the cost of the membranes would need to be affordable on a yearly budget range for the consumer.

For each hypothesis, the importance of cost effectiveness cannot be overstated. Even if the membranes need replacement every year, if they produce enough current to balance out the cost, they become either a zero-cost purchase, or better yet an investment that saves money for the consumer.

### 5.4.4 Cost analysis

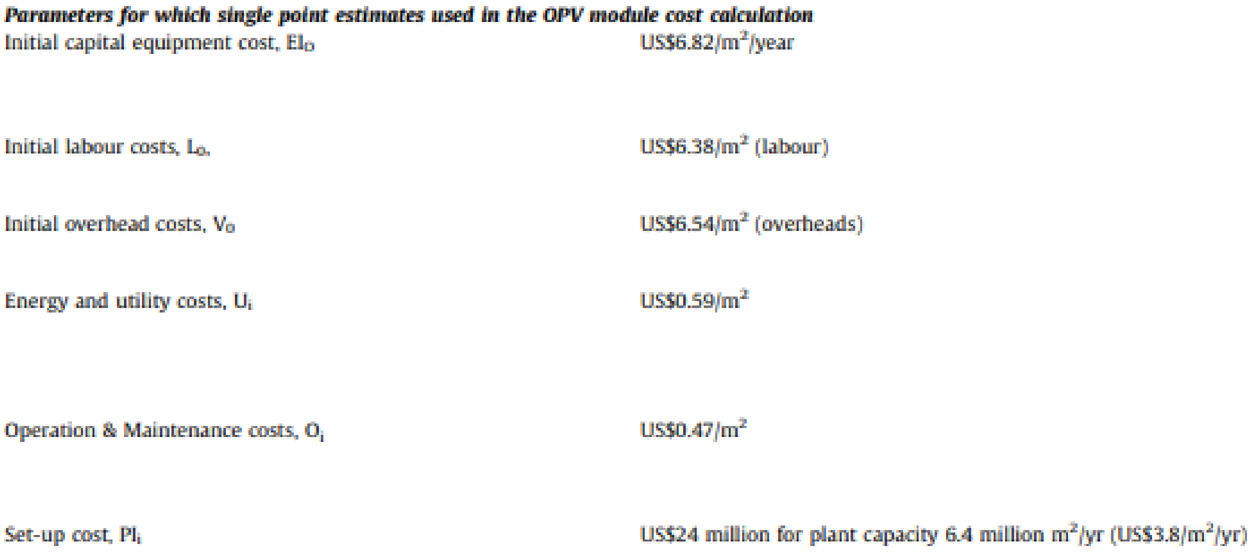
The average price per square meter of organic solar cell will be the same as in section 6.3 for consistency. The average rear side window of a car is comparable with the front ones, 0.2 meters squared, as are rear windows. This means that there is a total available of 2,2 square meters available for smaller cars and 4,7 square meters for bigger cars (VEHQ.com). So that means that under full sun and the right direction the energy potential assuming a 15% efficiency is 330W for smaller cars and $4.7 \times 1000 \times 15\% =$ 705W (Van der Roest, et al. 2023).

These numbers are assuming full illumination and perfect conditions. The reality though is that depending on the suns position, practically half of the side windows will be light, so a safe assumption would be to calculate using 1,6 square meters for smaller cars and 3.9 square meters for bigger ones. This still leaves 240W for small cars and 585W for big ones.

The cost of buying a membrane of $2.2 \times 48\$$ square meters costs 96$ without the cost of installation which is varies highly. For bigger vehicles the figure is $4.7 \times 48\$=225.6\$$. These figures represent the manufacturing cost of the average foil membranes.

There is also the possibility of vehicle manufacturers to adopt the process in house. In Ajay Gambhir et al. (2016), , the projected costs of a full production system is analysed. In Figure 25,, each cost per meter squared is analysed, and according to scale and production capacity, a company could elect to buy foil or create an in-house production of it.

**Table 5 “An excerpt of Parameters and ranges explored in sensitivity analysis“ Adapted from Gambhir et al. 2016**



| ***Parameters for which single point estimates used in the OPV module cost calculation*** | |
|---|---|
| Initial capital equipment cost, $EI_O$ | US$6.82/m$^2$/year |
| Initial labour costs, $L_O$, | US$6.38/m$^2$ (labour) |
| Initial overhead costs, $V_O$ | US$6.54/m$^2$ (overheads) |
| Energy and utility costs, $U_i$ | US$0.59/m$^2$ |
| Operation & Maintenance costs, $O_i$ | US$0.47/m$^2$ |
| Set-up cost, $PI_i$ | US$24 million for plant capacity 6.4 million m$^2$/yr (US$3.8/m$^2$/yr) |

## 5.4.5 Market and positioning

These solar tint membranes provide an alternative for vehicle window tints. They compete for their share in the window shading market but they cannot be compared further than that. The solar tint, provides energy production from car windows which is a whole new approach to car manufacturing design. And all of this without compromising safety as the materials used in foils are also polymers, specifically, PET in most commercial applications.

This is the positioning of the product as well. The organic tint is a both a product and an investment that the consumer makes to integrate a passive power production system for his EV (Electric Vehicles).

# Chapter 6 Conclusion and Future Work

## 6.1 Summary

In summary, the panorama of solar cell technologies paints a vivid portrait of human ingenuity in the face of pressing energy challenges. The journey embarked upon in this discourse spans the expanse of photovoltaic principles to the frontiers of emergent solar technologies. This trajectory underscores the paramount importance of renewable energy sources in shaping the global energy landscape (Güney, 2019).

Silicon-based solar cells, stalwarts of the solar domain, epitomize reliability and efficiency. Decades of refinement have elevated them to pinnacles of performance, contributing significantly to renewable energy adoption. However, diversification has emerged as a linchpin in overcoming limitations and broadening applicability (Ramanujam, et al. 2020).

Thin-film solar cells, heralded by CdTe, CIGS, and perovskites, unfurl new possibilities. Their flexibility, potential for cost-effective manufacturing, and adaptability to unconventional surfaces mark a paradigm shift . Through innovation in materials and processes, these contenders stand to democratize solar energy access and facilitate integration into urban landscapes (Ramanujam et al. 2020) .

The organic solar cells captivate the imagination due to their ability to be lightweight and semi-transparent. Although there are still challenges to overcome in terms of efficiency and stability, these technologies hold promise for applications in wearable technology, architecture, and other fields (Sampaio et al. 2022). Their technology permits the application and exploitation of surface areas inaccessible to traditional heavy installations of solar panels. Their transparency also makes possible their application to glass surfaces with untapped solar potential . The advancement of this field is contingent on improvements in material engineering and device optimization.

Yet, the journey is not without obstacles. Energy storage, an indispensable counterpart to intermittent solar generation, engages researchers and industries. The symbiotic evolution of storage solutions and solar technologies is indispensable to an energy-abundant future (Amrouche et al. 2016). Concurrently, the environmental toll of production mandates a sustainable approach, necessitating reduced resource consumption and heightened circularity.

As the world steers towards sustainable energy futures, the role of solar cell technologies is unassailable. They epitomize the synergy between scientific innovation, economic progress, and environmental sustainability (Duan, Uddin, 2020). Societies poised on the precipice of change recognize the urgency of embracing renewable energy options, and solar cells stand as one of the vanguard technologies.

In the following sections, the takeaways and future work are laid out, in order to make organic solar cells commercially viable for the applications of the concept products and new innovative applications far beyond the scope of this paper.

## 6.2 Portable organic PVs takeaways and future work

The first concept, portable organic PVs, according to their use, make clear the need of OPVs to be resistant to various types of degradation.

The thermal and light stability of organic solar cells (OSCs) occupies a pivotal role in determining their long-term performance and practical viability. Thermal stability refers to the ability of OSCs to withstand elevated temperatures without experiencing significant degradation in efficiency or structural integrity (Duan, Uddin 2020). In the context of OSCs, the photoactive layer and charge transport materials are susceptible to thermal-induced morphological changes that can impede charge generation and transport. Therefore, thorough investigation of the thermal stability of materials within OSCs is imperative. This analysis necessitates not only the assessment of individual components but also the investigation of the interactions between them in response to temperature fluctuations (Riede et al. 2021).

Additionally, light stability, often referred to as photostability, encompasses the capacity of OSCs to endure prolonged exposure to sunlight without suffering from photochemical degradation. The diverse materials used in OSCs may exhibit variable photochemical behaviors under irradiation, affecting not only the power conversion efficiency but also the operational lifespan of the device (Riede et al. 2021). Thus, the analysis of thermal and light stability remains an indispensable aspect of OSC research, influencing the development of robust and commercially viable organic photovoltaics.

The chemical stability of organic solar cells (OSCs) emerges as a critical determinant of their reliability and long-term performance. Chemical stability refers to the resistance of the constituent materials and interfaces within OSCs to chemical reactions, which can lead to undesirable morphological changes, degradation of energy levels, and impaired charge transport. The organic materials employed in OSCs often exhibit susceptibility to oxidative, hydrolytic, or photochemical reactions, which can compromise the device's efficiency and operational lifespan (Duan, Uddin 2020). Investigating the chemical stability of OSCs requires a comprehensive assessment of not only the individual organic molecules but also their interfaces and interactions with adjacent layers, electrode materials, and ambient conditions. Moreover, the identification and design of stable materials demand a rigorous understanding of the underlying degradation mechanisms, facilitating the formulation of strategies to enhance chemical stability (Duan, Uddin, 2020). In the pursuit of commercially viable and durable OSCs, the analysis of chemical stability stands as a pivotal focal point, guiding material selection, encapsulation techniques, and operational protocols.

The physical or structural stability of organic solar cells (OSCs) constitutes an essential facet in ensuring their viability for practical applications. Physical stability encompasses the capacity of OSCs to maintain their mechanical integrity and functional properties under mechanical stresses, temperature fluctuations, and other environmental factors. OSCs often consist of multilayer architectures, with diverse materials stacked in intricate arrangements (Savagatrup et al. 2015). These materials may undergo mechanical stress-induced changes, such as cracking, delamination, or morphological alterations, which can adversely affect charge transport pathways and energy harvesting efficiency. Therefore, understanding the mechanical behavior of each layer, their interactions, and potential failure modes is integral to designing OSCs that endure operational conditions (Savagatrup et al. 2015). Structural stability also extends to the stability of interfaces, where phenomena like interdiffusion or layer detachment can impede performance. As OSCs move towards integration in flexible and wearable devices, considerations of physical stability become even more pertinent. Thus, the analysis of physical/structural stability remains a cornerstone of OSC research, guiding material engineering and device design to yield robust and enduring organic photovoltaic technologies.

## 6.3 Organic solar shades takeaways and future work

The idea of organic solar shades isn’t a far reach. It is not even something novel per say. Solar umbrellas have existed as a concept for many years, due to the invention of thin films. It’s the electronics industry growth though that brings such ideas closer to economic feasibility.

In the current context of renewable energy, organic solar cells emerge as viable contenders for the production of sustainable power, the enhancement of efficiency in organic solar cells has emerged as a crucial goal. Within the several complex aspects of this endeavor, the emphasis on cost-efficiency arises as a pivotal factor (Kabir et al. 2018). This discussion explores the complex relationship between efficiency and cost in OSCs, providing a clear explanation for the compelling reasons behind the need to enhance efficiency while also minimizing manufacturing costs (Sampaio, 2022). The convergence of scientific advancements, careful material selection, the capacity to scale processes, and the broader societal implications all underscore the need of improving cost-effective efficiency in organic photovoltaics (Sampaio, 2022).

Resource optimization underpins polymer solar cell efficiency-cost relationships. Increased efficiency boosts energy output from sunlight, making organic solar cells (OSCs) more productive and cost-effective over time (Dhilipan et al. 2022). When trying to balance rising energy demand and scarce resources globally, these components' interactions are crucial. Scientific activities that boost efficiency depend on material science and device engineering advances. Engineering materials with tailored energy levels and better charge transport improves photon absorption and use efficiency (Tong et al. 2020). Innovative acceptor-donor pairs and advanced molecular architectures have helped reduce energy dissipation, improving technological efficiency.

The selection of materials plays a crucial part in the ongoing discussion about cost-efficiency in organic solar cells (OSCs). The integration of high-performance materials into cost-effective device designs is of utmost importance, notwithstanding the potential for significant efficiency benefits that these materials may bring (Li et al. 2021). This requires a thorough assessment of the trade-offs between the performance of materials and the costs associated with their manufacturing. Organic materials possess an inherent advantage due to their ability to be processed using solution-based processes, hence presenting the opportunity for cost-effective manufacture on a wide scale. Nevertheless, it is crucial to carefully balance material stability, scalability, and compatibility with cost-effective manufacturing processes in order to attain economically feasible organic solar cells (Aziz, Ismail, 2015). Therefore, the field of material engineering involves a complex balance between maximizing efficiency and guaranteeing economic viability (Tong et al. 2020).

The importance of scalability in manufacturing processes becomes a critical factor in determining cost-efficiency. Methods that are focused on finding solutions, such as inkjet printing, roll-to-roll coating, and spray deposition, are in line with the concepts of scalability since they enable quick and cost-efficient deposition of materials (Aziz, Ismail, 2015). These processes facilitate the production of organic solar cells (OSCs) on a large scale, while maintaining cost-effectiveness per unit area. Nevertheless, there are still obstacles that need to be overcome in order to provide consistent performance across a large number of manufactured devices and to reduce the occurrence of defects. Efforts in research focused on optimizing processes, controlling quality, and enhancing yield play a crucial role in achieving the cost-effective potential of scalable organic solar cell (OSC) manufacturing (Espinosa et al. 2014).

The worldwide implications of cost-effective efficiency improvements in organic solar cells have far-reaching consequences for all economic activity. The imperative to confront climate change necessitates the expeditious implementation of renewable energy technology, and organic solar cells has the capacity to significantly impact this shift (Sampaio, 2022). Cost-effective organic solar cells not only have the potential for sustainable energy generation but also expand the advantages of clean energy solutions to a wider range of applications. As the cost of OSCs decreases, the obstacles preventing individual customers and communities from participating in renewable energy disappear, hence promoting inclusiveness and democratizing the availability of such energy sources.

In summary, the need to optimize the efficiency of organic solar cells while simultaneously prioritizing cost-effectiveness is a complex undertaking that encompasses several aspects, including scientific advancements, selection of suitable materials, scalability of production processes, and socioeconomic factors. By leveraging the synergistic relationship between enhanced efficiency and optimized manufacturing costs, organic solar cells have the potential to extend beyond the confines of the laboratory and be used in varied real-world applications not necessarily confined within the renewable energy sector (Riede, 2021). The convergence of scientific efforts and industrial advancements has led to the development of cost-effective and highly efficient organic solar cells (OSCs), which hold promise in guiding mankind towards a future that is both sustainable and robust in terms of energy.

## 6.4 Organic solar tint takeaways and future work

The solar tint is a natural extension of the properties and production methods of OPVs as their semi-transparency permits a lot of applications in the fenestration industry. With the rise of EV technology and the developed economies turning to the electrification of transportation, any system that can provide extra electricity, beyond the grids capabilities, is a candidate for economic success (Kabir et al. 2018). The decentralisation of electricity production is a principle that can benefit the consumer by investing in products that alleviate utility costs and gives them more indepenency. It also serves well utility companies as the grids stress will continue to increase during the electrification era that is approaching rapidly (Toshov, Saitov 2019).

This discourse delved into the multifaceted rationale underlying the need to make OSC production as economically viable as possible, encompassing factors spanning material selection, manufacturing techniques, scalability, and the broader societal implications (Li et al. 2021).

Central to the call for cost-efficiency in OSC production is the vision of democratizing access to clean energy solutions. Photovoltaic technologies have historically been associated with high capital investments, impeding their widespread deployment, particularly in regions with limited financial resources. By prioritizing cost-effectiveness, solar cells transcended this barrier, paving the way for increased adoption across diverse socioeconomic strata (Kannan, Vakeesan 2016). The utilization of organic materials, with their potential for roll-to-roll printing and solution-based processing, offers a departure from the resource-intensive fabrication methods of traditional inorganic solar cells . This innovation holds the promise of reducing production costs, enhancing accessibility to clean energy, and fostering energy independence for communities worldwide (Kannan, Vakeesan, 2016).

Material selection plays an instrumental role in steering OSC production towards cost-efficiency. Organic materials, characterized by their abundance and potential for synthetic scalability, offer a cost advantage compared to their inorganic counterparts. However, the intricate balance between material performance, stability, and cost-effectiveness underscores the complexity of this choice. Engaging in a meticulous evaluation of the cost-performance trade-off is paramount to achieving optimal material selections for OSCs. Additionally, the pursuit of advanced material engineering, wherein synthetic routes are optimized for scalability, is indispensable. This involves streamlining synthetic pathways, minimizing waste generation, and ensuring reproducibility across large-scale manufacturing (Rathore,Panwar, 2022)

Manufacturing techniques wield a profound influence on the cost profile of OSCs. Solution-based processing methods, such as inkjet printing, slot-die coating, and spray deposition, stand as cornerstones of cost-effective production. The ability to apply materials in a controlled, additive manner facilitates reduced material waste and enhanced throughput (Aziz, Ismail, 2015). Integrating these techniques with roll-to-roll processes further augments their potential for mass production. However, challenges remain in ensuring consistent quality, minimizing defects, and maintaining high throughput rates. Research efforts directed towards refining these techniques, optimizing process parameters, and addressing scalability bottlenecks are pivotal to realizing cost-efficient OSC production (Riede et al. 2021).

The economic viability of OSCs extends beyond immediate production costs, encapsulating considerations of device longevity, energy yield, and environmental impact. Durability, a paramount concern, hinges on the stability of organic materials under operational conditions (Riede et al. 2021). A delicate balance must be struck between cost-effective materials and those capable of withstanding extended exposure to sunlight, temperature variations, and humidity (Duan,Uddin, 2020). Enhancing stability translates to prolonged operational lifetimes and lower maintenance costs, thereby fortifying the economic proposition of OSCs over their life cycle.

In conclusion, the imperative of cost-efficiency in organic solar cell production is underpinned by multifaceted motivations ranging from equitable energy access to sustainable deployment strategies. Material selection, manufacturing techniques, and stability considerations intertwine to shape the trajectory of OSCs in the renewable energy landscape (Li et al. 2021). Embracing cost-effective solutions bolsters the potential for widespread adoption, enabling OSCs to fulfill their promise as a transformative force in the transition towards a sustainable energy future. As research advances and innovation thrives, the realization of cost-efficient OSC production stands as a beacon of potential, illuminating a path to greener horizons.

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