

**MASTER THESIS**

**REVOLUTION OF THE FULLY TRANSPARENT LUMINESCENT SOLAR  
CONCENTRATORS  
AND  
ITS IMPACT ON THE WORLD**

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## Abstract

Rapidly increasing demand in energy allows room for constant improvement in renewable energy generation technologies. Solar energy usage is likely to increase even more in the recent years since the sun provides enough energy just in one hour that is sufficient to supply for whole humanity's energy requirement in one year. This study initially explains the history of solar cells as well as how they function by utilizing the sun's wavelengths. Following that, the current and future applications of solar energy is discussed briefly. In the first half of this decade, in 2013, the transparent solar cell technology was invented by MIT professors and since then it is accepted as future's most effective way of producing energy. Considering the fact that the application areas such as integration in the buildings, car windows, greenhouses and other electrical applicants that has a screen to cover with transparent luminescent solar concentrators (TLSC) is extremely crucial in term of world's 2030 and 2050 energy targets. This includes 32% and 100% sustainable energy shares, respectively. This study further examines the comparison of solar cell technologies such as newly emerging Perovskite and Quantum Dots by providing annual developments in efficiency. The quantum dots are used in TLSC in order to reflect the incoming sun's ultraviolet and infrared wavelengths to panel's PV cell where the electricity is generated. This technology is to be implemented through the simulation phase of this work.

Referring to above explanation, this study is related to create a model island by using AutoCAD to demonstrate the city life in every aspect in terms of energy. There are 10 different structures with various window surfaces to be covered with TLSC in order to determine the electricity generation. The solar radiation that comes on vertical positioned panels must be identified to obtain possible electricity production. For that reason, MATLAB is utilized to find exact value of the vertical solar radiation. After obtaining the results, the manual calculations took place in order to approve that the numbers match.

Being such a promising technology, the future prospects as financial point of views is investigated by using the price dropdown of the monocrystalline solar cell from 1975 to 2020. The possible future prices per Watt are effectively calculated by utilizing the trend between these years for 2030 and 2050 energy targets of the European Union. By using this trend, the future price dropdown of transparent luminescent solar concentrators is projected and if the model project were to take place in 2030 and 2050, the plausible budget belonging these years can be found.

As a conclusion, world's population is increasing day by day as the energy demand. Therefore, instead of constructing new renewable technologies in land areas that are limited, using TLSC on buildings and other implementation fields would result in compensating the rising electricity demand.



## **Declaration (§ 18 Para. 4 Nr. 7 APO THI)**

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I hereby declare that the Master thesis submitted with the title,

### **Revolution of the fully transparent luminescent solar concentrators and its impact on the world**

is my own unaided work. All direct or indirect sources used are acknowledged as references.

I agree to the further use of my work and its results (including produced methods and models) for research and education.

This paper was not previously presented to another examination board and has not been published.

Ingolstadt, 24.07.2021

.....

Aydin, Berkan

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Dreaming is the halfway of success.!



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## List of Abbreviations

<b>LCOE</b>	Levelized Cost of Energy
<b>AM</b>	Air Mass
<b>eV</b>	electron Volt
<b>TLSC</b>	Transparent Luminescent Solar Concentrator
<b>LSC</b>	Luminescent Solar Concentrator
<b>CSP</b>	Concentrated Solar Power
<b>BIPV</b>	Building Integrated Photovoltaics
<b>DBR</b>	Distributed Bragg Reflector
<b>BBAR</b>	Broadband Antireflection
<b>c-Si</b>	Crystalline Silicon
<b>MJ</b>	Multijunction
<b>EoT</b>	Equation of Time
<b>R<sub>dif</sub></b>	Corrected Factor of Diffuse Solar Radiation
<b>R<sub>dir</sub></b>	Corrected Factor of Direct Solar Radiation
<b>R<sub>ref</sub></b>	Corrected Factor of Reflected Solar Radiation
<b>LSTM</b>	Local Standard Time Meridian
<b>TC</b>	Time Correction
<b>TL</b>	Local Time
<b>ITO</b>	Indium-tin-oxide
<b>BCP</b>	Bathocuproine
<b>CO<sub>2</sub></b>	Carbon dioxide
<b>DIN</b>	Deutsches Institut für Normung
<b>HVAC</b>	Heating Ventilation and Air Conditioning
<b>ESS</b>	Energy Storage Systems
<b>STC</b>	Standard Test Conditions



## 1. Introduction

The world is changing and enlarging day by day, and there is nothing more significant than energy. Before 18<sup>th</sup> century, it was all about mines, minerals, and quarries. Then petroleum was first discovered in 1859. By the end of the 20<sup>th</sup> century, the means of energy generation remained firm with fossil fuels until solar panels became commercially feasible. Although the fossil fuels have not yet been depleted, the negative impacts on the environment must be replaced with total carbon emission free, in other words, renewable sources.

Scientists have been working hard on increasing the efficiency of the solar panels because the key to surviving from climate change is to enhance solar technology. Solar energy is and will always be more important than other several sustainable energy sources since the solar radiation is everywhere around the solar system. Even in the space, solar energy is the only option to power up the satellites such as ISS (International Space Station). Regarding this, there is only one option to invest in, solar.

Currently, the world's electricity consumption is around 25000 TWh [1] and the earth receives more solar energy in just 1 hour than what humanity uses in entire year considering the solar constant at the top layer of the atmosphere with a value of  $1.7 \times 10^5$  TW [2]. This means, focusing on solar cell technology not only in terms of efficiency, but also in decreasing the manufacturing cost and lowering the material use, are very significant in order to compensate future's increasing energy demand.

In this work, solar trend and technology expectations in the following years will be reviewed. Comparison between 2<sup>nd</sup> and 3<sup>rd</sup> generation solar cell technologies and detailed explanation of transparent luminescent solar concentrators can be found.

A model island is created on AutoCAD to demonstrate the living conditions in city. By using base areas, indoor planning of the buildings is arranged to find out the population. From number of people living in the island, total electricity demand is calculated. Each building's window surface area is calculated to replace with TLSC in order to generate electricity. Since the windows are parallel to the buildings facet, the positioning of the solar panels is vertical, 90 degree. Therefore, the solar radiation must be calculated in vertical position in the given location to project the maximum possible electricity generation, which is done by creating a calculation tool in MATLAB.

In the end, the value of the compensation factor is found by the division of the electricity demand and the generation. In order to illustrate all necessary information with the buildings' 360° views can be seen from the program that is created using Virtual Studio. Of course, the program is not limited with the number of buildings in the model island. A user can enter few variables into the calculation tool which comes with the program in order to see the energy requirement of the desired building structure of own.

Consequently, this work gives precise understanding about the transparent luminescent solar concentrators from invention phase to the implantation and the possible electricity generation, and everything in between.

## 2. Renewable Energy Around the Globe

Each year, billions of dollars are invested into renewable energy systems in order to achieve zero carbon emission targets by 2030 and 2050. Since the industrial revolution in 1760, pollution on the earth began. During these 250 years before the invention of solar cells as the first ever green energy technology, it has been only utilized from fossil fuels to generate electricity. But as burning fossil fuels, they put the Earth in an irreversible path by polluting the environment. For this reason, there are international agreements like Kyoto Protocol and Paris Climate Agreement to avoid consuming world's sources. Therefore, every country in EU and most of the world have their own methods to eliminate CO<sub>2</sub> emission from the Earth. That is why this trend has changed and keep changing as of today. Governments have committed to adding extra 826 GW of non-hydro renewable installed capacity until 2030 which is estimated to cost around \$1 trillion. Compared to 2010-2019 decade, the world has invested total of \$2.7 trillion because of the climate change fact that world's temperature was increased by 2 degrees Celsius [3]. In 2019, total of 184 GW installed renewable capacity was added in a single year and happened to be the highest capacity ever built until the corona pandemic.

This newly added capacity includes 118 GW of solar power and costs roughly \$130 billion. Reason of this was the falling capital costs with decrease expenses in solar cell manufacture. Raising renewable technologies share of global energy generation was increased from 12.4% in 2018 to 13.4% in 2019. Compared to 2009, the share was only 5.9% which is tripled over just 10 years. This can be explained as the decrease in levelized cost of energy (LCOE) leads adding more installed capacity. Despite of COVID-19 pandemic, more than 260 GW of renewable energy installed capacity added globally in 2020 which is the fastest increase trend of all time [4].

### 2.1 Hydropower

Hydropower became an electricity source in the late 19<sup>th</sup> century. Even though, some professionals do not count the hydropower as a renewable energy source because it harms the environment during the construction phase. But subsequently construction is completed with necessary water path for the marine animals to travel through, it is highly efficiency energy generation technique. In 1882, the world's first hydropower power plant started operating in Wisconsin, United States. In 1984, with the completion of the construction of Itapúa Dam which is located on the border between Brazil and Paraguay, was the largest installed capacity dam with 14 GW [5].

Later in 2012, The Three Gorges Dam has been built with 22.5 GW installed capacity in China and since then, it is by far the world's largest hydropower plant [6]. The following figure illustrates the world's total installed capacity and its generation.

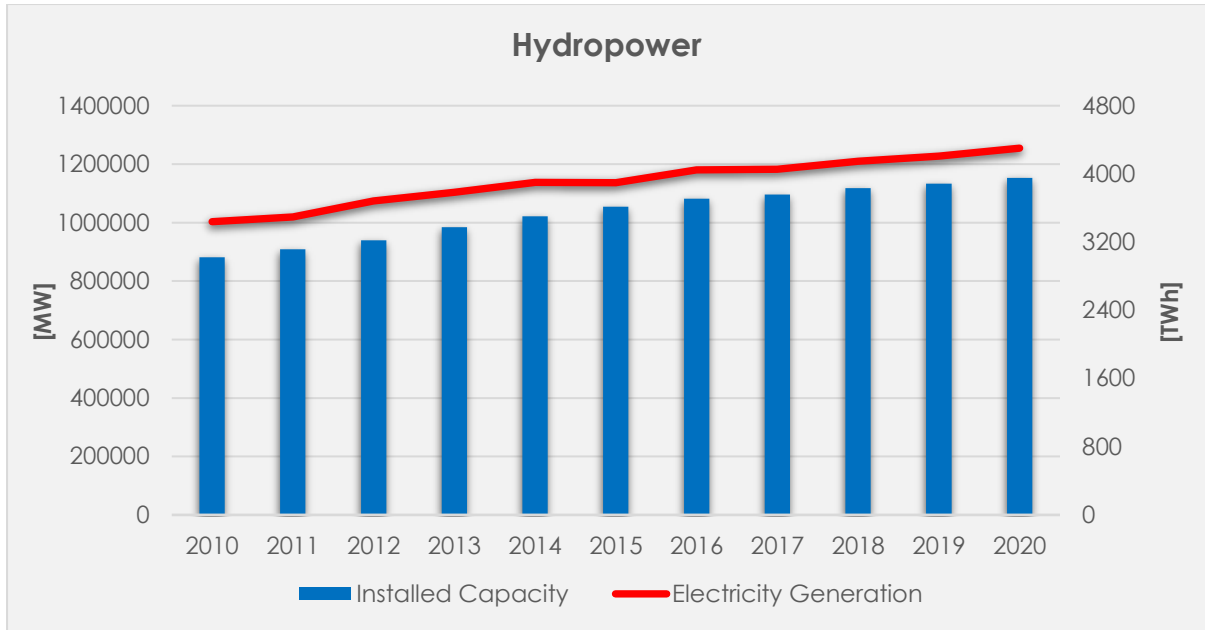


Figure 1: Installed capacity trend of hydropower and its generation [7]

Just alone China has 340 GW of installed capacity from Hydropower. Comparing this, because of lack of water areas, United States have total of 71 GW capacity.

## 2.2 Wind Energy

The major player in wind energy is China. Gansu wind farm is the world's biggest wind farm with 7965 MW currently installed capacity and 20 GW planned will be achieved in the following years [8]. After Gansu farm, Alta Wind Energy Centre comes with 1548 GW installed capacity in California, United States. The third player is involved here as holding the rank of 3<sup>rd</sup> biggest installed capacity wind farm, Muppandal wind farm, is located in Tamil Nadu, India with a 1500 GW installed capacity. [9] As it can be understood, most of the wind capacity around the globe is installed by China, the USA, and India.

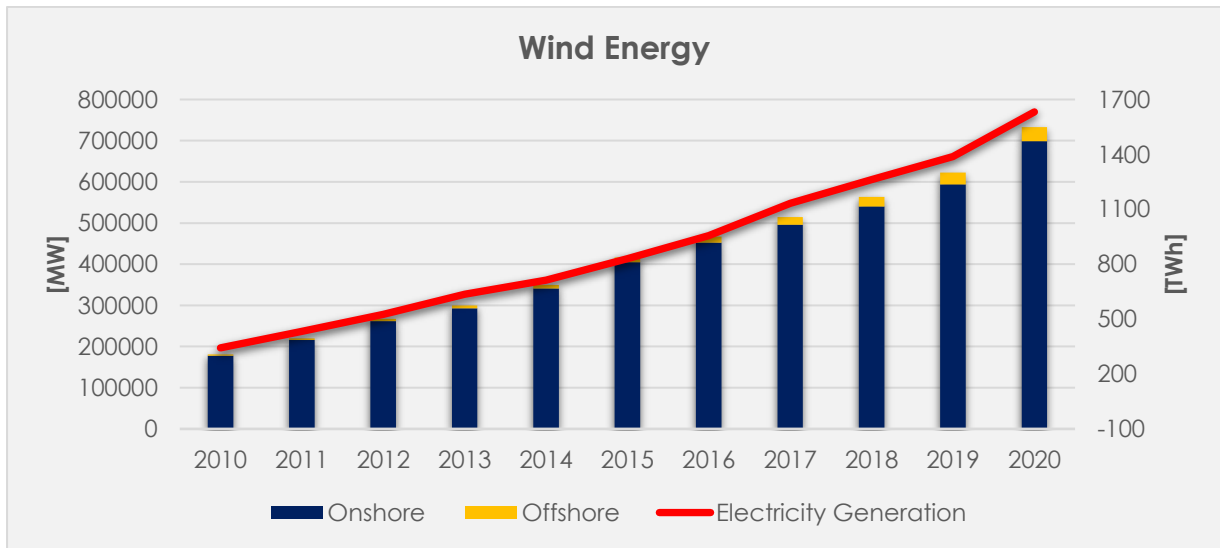


Figure 2: Installed capacity trend of wind power and its generation [10]



Above figure shows the world's total installed capacity is risen to 698 GW in wind power. Just alone United States supported 117 GW while China placed incredible number of wind turbines in the last year also by benefiting from the conditions regarding the pandemic, approximately 71 GW installed capacity has been added and it is totalled to 282 GW. Additionally, Germany is the world's third country in terms of wind energy capacity with 62 GW.

### 2.3 Solar Energy

The biggest contribution into solar energy is made by India. Bhadla Solar Park is located in Rajasthan, and it has an installed capacity of 2245 MW which is constructed on 57 km<sup>2</sup> of area. China built similar plants with similar capacity as 2200 MW in which 7 million panels used [11]. On the other hand, Australia has announced that they are currently constructing what is claimed to be the biggest solar farm to date with approximately 10 GW and its size equals to almost 20000 football fields. Once the construction is completed, it will be visible from the International Space Station and total of \$20 billion AUD will be spent on the project [12].

Following figure demonstrates the world's electricity generation on the right axis while the installed capacity can be visible through the left axis.

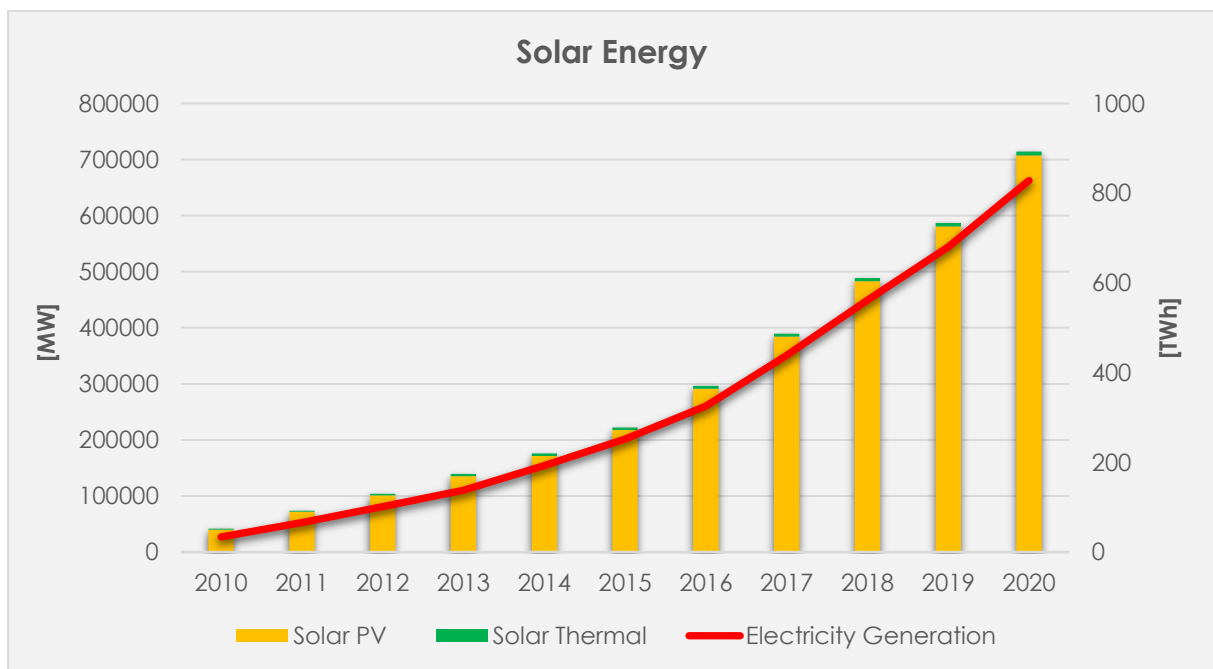


Figure 3: Installed capacity trend of solar energy and its generation [13]

Surely, solar thermal technology is utilized to generate heat in order to warm up the houses or supply hot water demand. But since the data is given as the electricity generation, this is just the conversion between kcal and kWh. Total of 707 GW of solar installed capacity is built around the world.



## 2.4 Bioenergy

Biomass has significant potential in terms of heating or power generation. Additionally, the materials can be converted into oil or gas substitutes which are considered as renewable substitute for gasoline and mostly utilized in transport sector. China has 18 GW of installed capacity in bioenergy where United States has approximately 12 GW capacity. Despite its size, United Kingdom built facilities totalled to 7.1 GW including the world's biggest biomass power plant: The Ironbridge power plant which is located in the Severn Gorge. The total global capacity is around 130 GW [14].

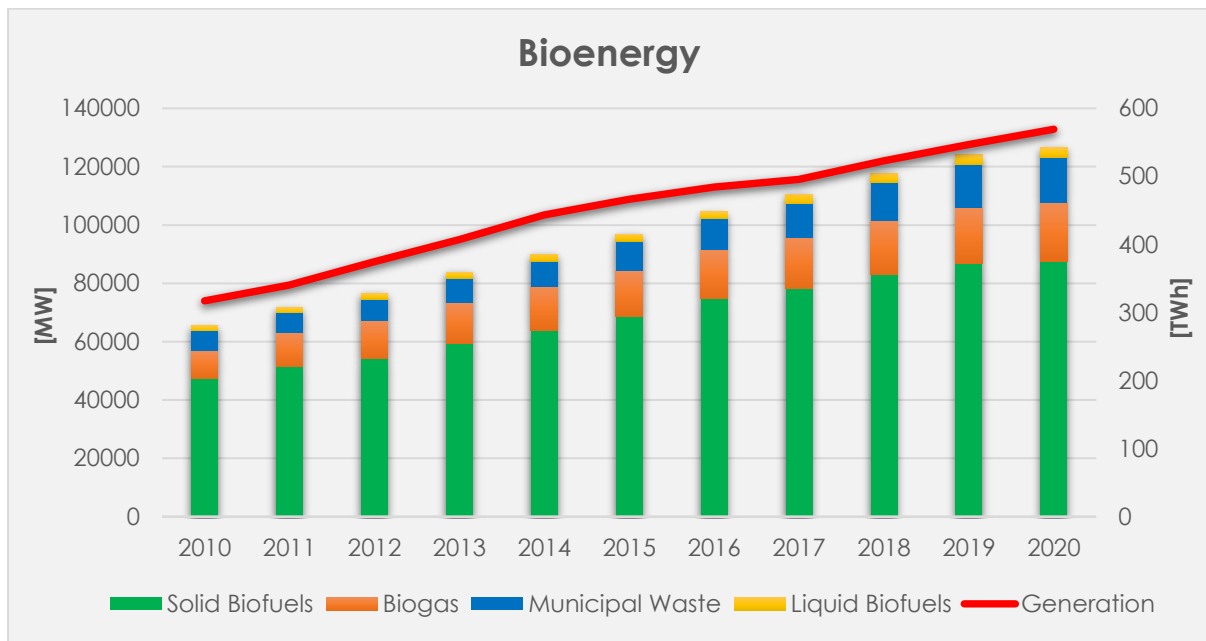


Figure 4: Installed capacity trend of Bioenergy and its generation [14]

## 2.5 Geothermal

The heat that is stored in chemical gas, water or vapor that are found under the various levels of the Earth's surface with different energy levels is called the geothermal energy. Geothermal capacity can only be installed if there is a source in the environment. Therefore, the world's largest installed capacity countries are changed here. Only the United States stays in the first line with approximately 2587 MW installed capacity since the country is home to the world's biggest geothermal complex, known as the Geysers, which comprises 22 geothermal plants at its base in California. Then second and third countries are Indonesia and Philippines with 2130 MW and 1928 MW, respectively. As the fourth country, Turkey has 1613 MW installed capacity. Total world's geothermal installed capacity is around 14 GW, and these four countries hold 8.2 GW which is accounted for 60% of the entire capacity. [15]

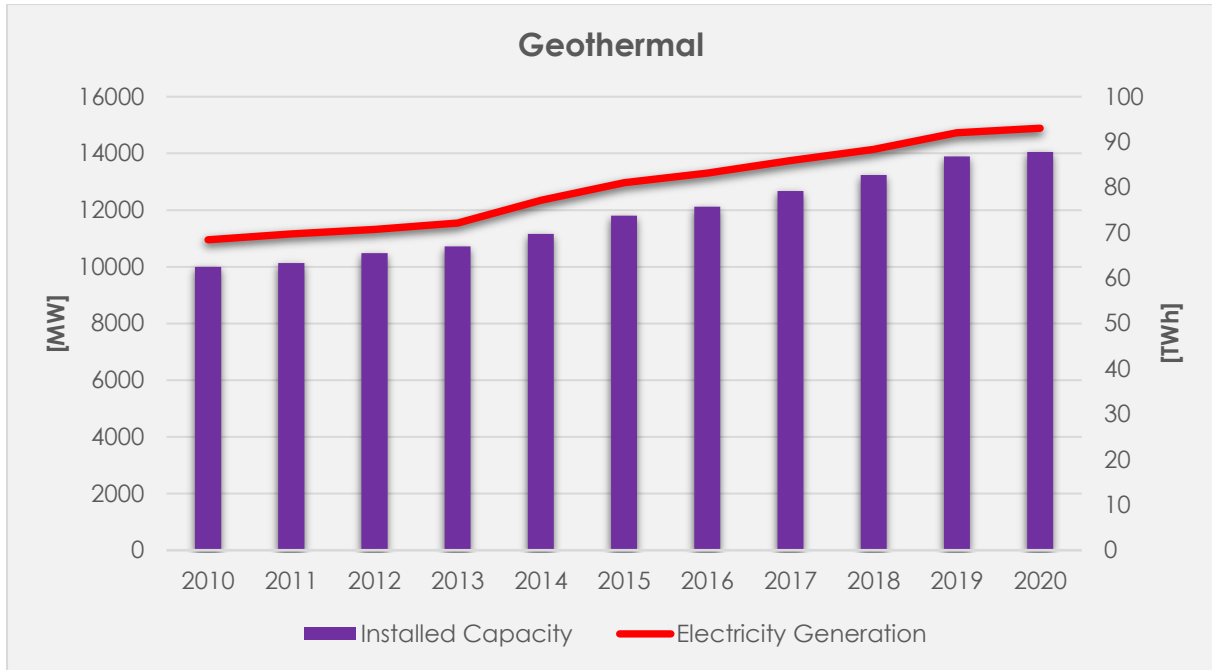


Figure 5: Installed capacity trend of geothermal and its generation [15]

The following figure illustrates the annual growth in percentage for renewable resources. As it can be seen, the fastest increasing trend is solar PV. Especially in 2020, one-fifth of the total deployed renewable installed capacity is formed by individuals and medium size companies that are installing PV panels on their roofs and business sites. [16]

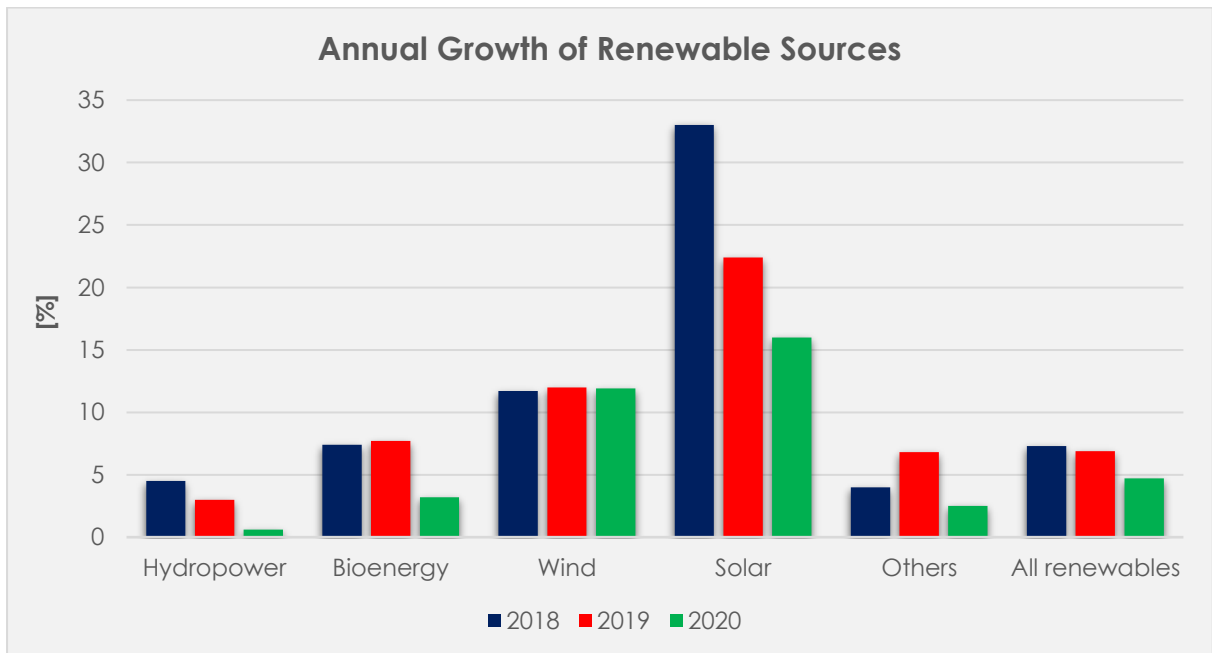


Figure 6: Annual growth for renewable electricity generation by source [16]





## 2.6 Solar Power Progress in the World

Solar power has been an incredibly popular trend over the last 10 years. Development in advancing solar technology leads to reduce cost of materials and production. European Union's 2030 and 2050 energy targets on the other hand, show that carbon emission must be stopped. There will remain no fossil fuel-based energy production facilities by 2050. Because of this trend, investment on solar energy has risen more than any other renewables globally. Most of the PV installed capacity is established by 3 major countries: China, United States, India and also the EU all together. The following figure demonstrates the PV installed capacity over the last 3 years.

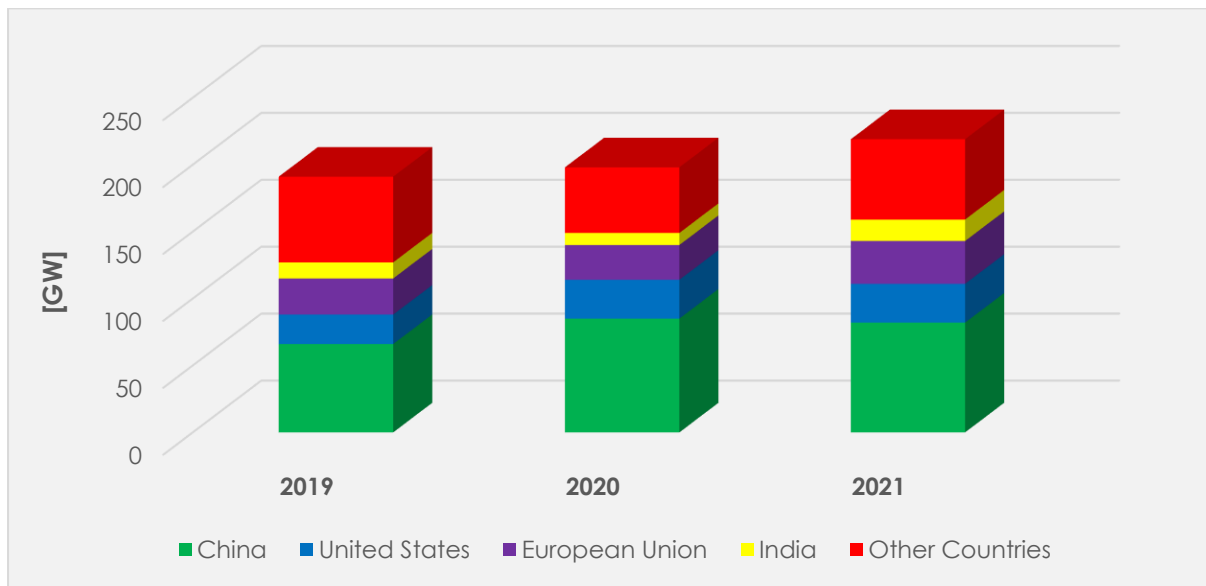


Figure 7: Renewable capacity additions by country/region (own illustration) [66]

Just alone China built 85 GW of PV installed capacity in 2020 and by the end of 2021, another 82 GW capacity is promised to be established. United States and the European Union will add 29 GW and 32 GW respectively in 2021. The world's total cumulative amount of PV installed was 629 GW by the end of 2019. The biggest player in the market: China is the leading country in the world, accounting one third of the whole installed capacity with 208 GW. [17]

## 3. History of the solar cells

Solar cells, also known as photovoltaics, are the tools which convert the energy of the sunlight into electricity. The sunlight consists of 4% ultraviolet, 43% visible light, and 53% infrared [18]. Solar cell focuses on the visible light and also half of the infrared radiation are transformed into electricity. The first practical silicon solar cell with a 6% efficiency was discovered at Bell Labs. But the story of solar cells goes back to 1839, when French scientist Alexandre-Edmond Becquerel investigated the photovoltaic effect.

Several decades later, in 1873, the photoconductivity of selenium was discovered by Willoughby Smith, the British engineer. In 1883, only 6 years of research, the first



selenium solar cells were produced by American inventor Charles Fritt. Before the practical silicon solar cell was found, the major advance in solar technology was made in 1940 by Russell Shoemaker Ohl at Bell Labs. He investigated the silicon samples and one of them had a crack in the middle. He later realized that when the sample was exposed to light, a small current flowed. This crack functioned as the boundary between regions positively and negatively doped. Doping the regions with opposite poles creates an electric field which was later realised as the p-n junction of today's commercial solar cell. This was the first solar cell prototype in history with 1% power to energy conversion efficiency.

13 years later in Bell Labs, by using a silicon sheet containing gallium, a group of scientists including engineers and chemists dipped this sheet into lithium. The real p-n junction solar cell was then created. By placing a light source close to the silicon sheet after connecting to the amperemeter gave a slight jump on the indicator. Though, it was challenging to create a good electrical connection with silicon sheet with early manufacturing techniques. It was later understood that boron-arsenic would form better electrical connections.

On April 25, 1954, Bell Labs illustrated their first ever solar panel application with an 6% efficiency to power up the radio transmitter. This went down on history as the beginning of a new era in terms of sustainable energy generation. [19] The progresses after 1954 can be observed in the figure below.

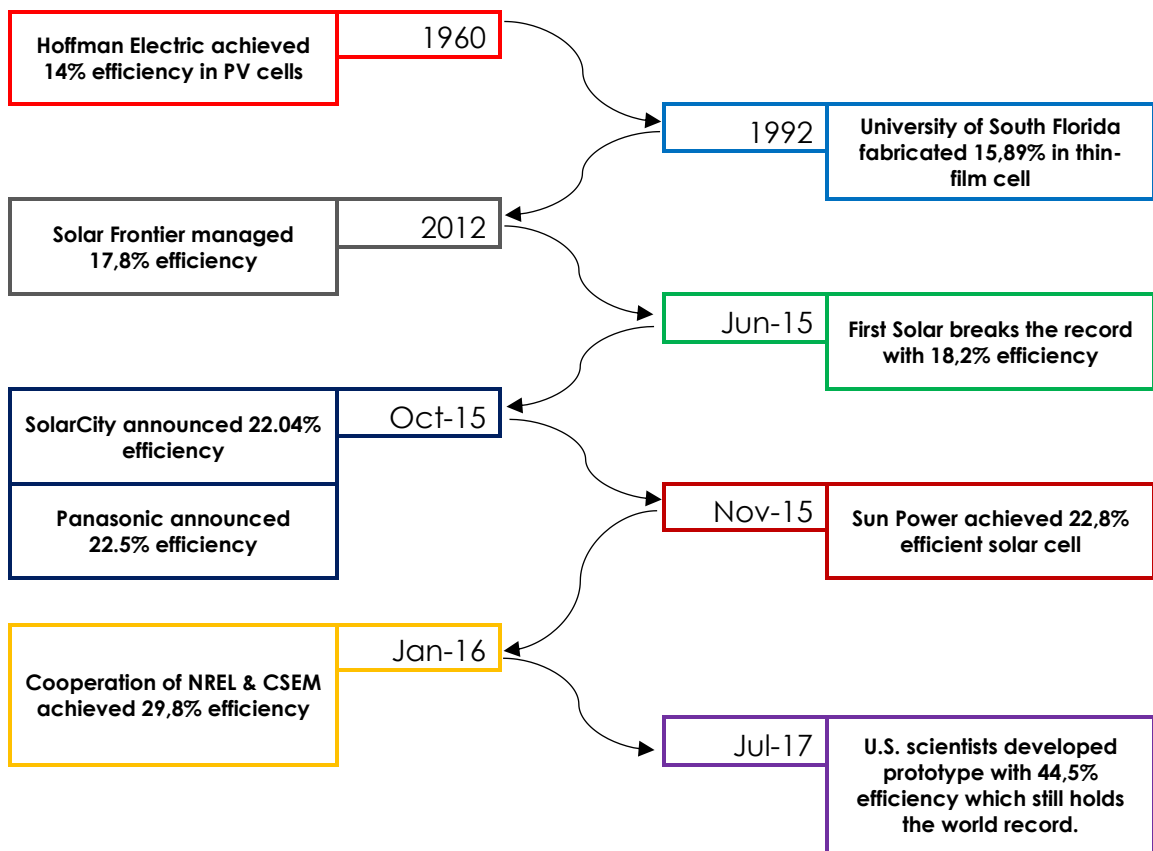


Figure 8: The solar cell development over the last 60 years (own illustration, data from [20])

### 3.1 Working Principle of Solar Cell

Solar cells are made up of two types of semi-conductors, also known as p-type and n-type silicon. P-N junction technology is used in around 90% of all PV panels on the planet. The addition of atoms such as boron or gallium results in p-type silicon, which has one less electron than silicon at its outer level. Boron necessitates the formation of bonds with surrounding silicon atoms having one less electron, resulting in the formation of a hole or electron vacancy.

N-type silicon was made by combining components with one more electron in their outer level than silicon. Phosphorus is the foremost commonly utilized atom in creating solar cells. It has five electrons in its outer level and bonds with neighbouring silicon molecules. Only one electron is involved in bonding and instead moves freely within the silicon structure.

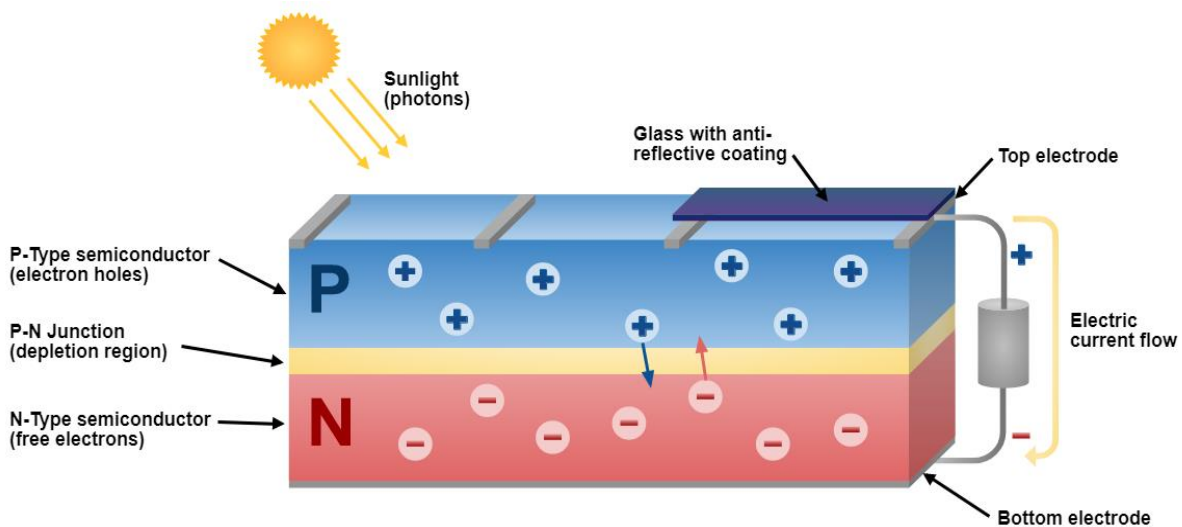


Figure 9: The n-type and p-type layers, internal electric field [21]

Only one electron is not engaged in bonding and instead travels freely inside the silicon structure. All of the holes on the p-type side of the depletion zone must be filled with electrons. After the depletion zone has been filled with electrons, the p-type side of the zone then contains negatively charged ions, while the n-type side now includes positively charged ions. An internal electric field is created as a result of the presence of these oppositely charged ions, preventing electrons in the n-type layer from filling holes in the p-type layer.

When sunlight strikes a solar cell, electrons from the silicon are released. The holes are produced by escaping electrons, and with the assistance of an electric field, the electrons are transported into the n-type layer and the holes to the p-type layer. When two layers are connected by a metallic wire, an inner electric circuit is formed therefore the current can flow. [22]

### 3.2 Shockley-Queisser Limit

Shockley-Queisser limit was named after people who have found it; William Shockley and Hans-Joachim Queisser at Shockley Semiconductor in 1961. It defines the maximum theoretical efficiency of single p-n junction solar cell, giving the maximum efficiency of 30% at 1.1 eV. The limit was set with using 6000K black-body spectrum as an estimation to the solar spectrum. When further calculations were made, it was a great idea to include a rear surface mirror to increase efficiency. With this new method, efficiency is enhanced to its maximum value of 33.7% for a single p-n junction assuming a standard sunlight condition as AM1.5G solar spectrum. That means, under all the power contained in sunlight (1000W/m<sup>2</sup>), falling on an ideal solar cell can maximumly convert 337W/ m<sup>2</sup> into electricity. Still today, most of the high-end solar panels can generate electricity with an efficiency up to 23%. [23]

### 3.3 Solar spectrum and TLSC's absorption

The sun is a major source of radiant energy, and it is 93 million miles away from the Earth. The energy coming from the sun travels in 3 different waves in several wavelengths. This energy is also known as Solar Spectrum, which contains infrared rays (%53), visible light (%44), ultraviolet rays (3%) and their wavelengths are as follows. [24]

- ultraviolet, with wavelengths ranging between 100 – 380 nm
- visible light, with wavelengths ranging between 380 – 780 nm
- infrared, with wavelengths above 780 nm

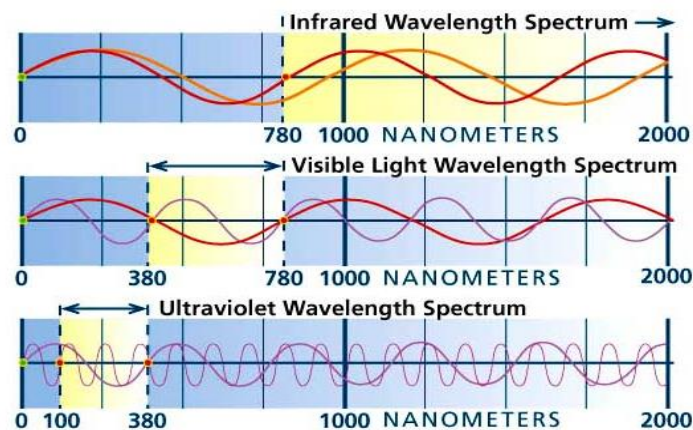


Figure 10: Solar spectrum and wavelength types [24]

Transparent solar concentrators are developed to absorb the invisible rays while letting visible light passes through itself. Infrared (53%) and ultraviolet (3%) are being caught by the quantum dots inside of the TLSC while traditional solar panels can catch only visible lights (44%). As it can be seen from the percentages, traditional solar panels must generate less energy compared to TLSC because it catches higher scale of the spectrum.

However, advancement in the technology over 80 years led the efficiency increase from 6% to 23% in the meanwhile TSLC is still developing to enhance its efficiency.

The visible transmittance is the amount of visible light from the solar spectrum that it passes through a glazing material. A higher transmittance means there is more daylight coming in and it can be calculated with the following formula:

$$T_{vis} = \frac{\sum_{380\text{ nm}}^{780\text{ nm}} T(\lambda) D_{\lambda} V(\lambda)\Delta\lambda}{\sum_{380\text{ nm}}^{780\text{ nm}} D_{\lambda} V(\lambda)\Delta\lambda} \quad (1.1)$$

where:

- $D_{\lambda}$ : Relative spectral features of a D65 illuminant
- $V(\lambda)$ : Spectral luminous efficiency for photopic vision
- $T(\lambda)$ : Monochromatic transmittance of the glass in the visible range
- $\Delta\lambda$ : Wavelength interval

On the other hand, solar transmittance can be calculated with the following formula.

$$T_{sol} = \frac{\sum_{300\text{ nm}}^{2500\text{ nm}} T(\lambda) S_{\lambda} \Delta\lambda}{\sum_{300\text{ nm}}^{2500\text{ nm}} S_{\lambda} \Delta\lambda} \quad (1.2)$$

Where the only difference from the above formula is:

$S_{\lambda}$ : relative spectral distribution of solar radiation

The way TLSC absorbs sunlight is that little quantum dots inside of the concentrator act as a reflector. While visible light passes through to brighten inside, invisible lights are scattered via quantum dots. Lights cannot escape from the solar concentrator and eventually it reaches to the PV cell located in the bottom where the electricity is generated.

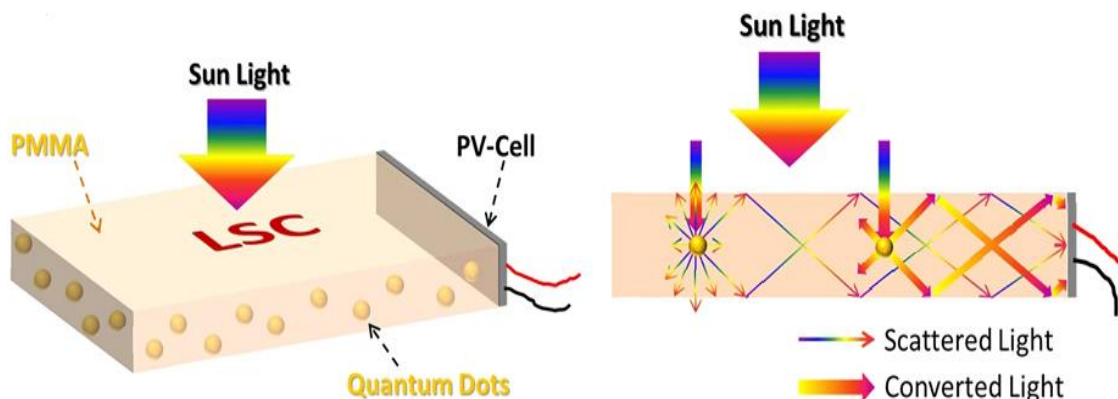


Figure 11: TLSC's light absorption via quantum dots [25]



## 4. Future Prospect of Solar Energy

The Sun emits enough energy into Earth's surface every second to fulfil the entire energy demand of the planet for over an hour. However, less than 2% of the world's energy came from solar in 2018 [26]. In the future, research on solar cells will bring new designs and technologies which will have to absorb more light and convert into power more effectively. Of course, it has to be less costly than the current design. Energy companies are more likely to tackle on solar power if the production of single kWh of energy will be same or lower price than the other sources. Even if the efficiency is not risen dramatically yet, there are some interesting designs that are attached to everyday objects like buildings. Similarly solar fabric technology that can be engaged to any clothing or the floating farms that doesn't cover land area. Some of the futuristic solar technology developments can be seen under this chapter.

### 4.1 Floating Solar Farms

Where land area is not enough or expensive, considering solar panels to be installed on structures that are floating on the water. This is a popular method for some Asian countries, especially for Japan where there is a lack of soil. But, when water areas are covered by solar panels, those areas do not have light permeability which causes destruction on sea life underneath in the long run. Therefore, in the near future, by using transparent solar concentrators that are better in efficiency would solve this issue by letting sun's wavelengths to the deep waters.



Figure 12: Floating solar farm in Asia [27]

## 4.2 Building Integrated Photovoltaics (BIPV)

When covering 4 sides of the building with traditional solar panels, mounting structures are necessary for support. Therefore, thin film photovoltaics are used in this application type because of its thickness that requires no support but sticking onto the windows. Assuming that the efficiency of a transparent luminescent solar concentrators will increase in the near future, it will provide an economically feasible solution for covering all the surface windows with TLSC. While it works as a normal window, it will constantly generate electricity until sunset.

Two different scenarios can be applied here. First, generated electricity is used within the building by a centralized inverter or second, every flat can use the electricity generate by its windows and it can be controlled by small size inverter inside of the apartment as the decentralized generation mechanism. Surplus electricity in both options is feed-in to grid.



Figure 13: Building Integrated Photovoltaics [28]

## 4.3 Solar Cell Fabrics

When solar cells are implemented into the fabrics, it is possible to charge minimal power usage devices such as laptops and smartphones. Besides placing them into clothes, this solar cell fabrics can be very beneficial. It can be tailored on tents and provides the necessary energy to its users. Moreover, just creating a small cylindrical roll allows in the remote areas to charge devices like smartphones. [29]

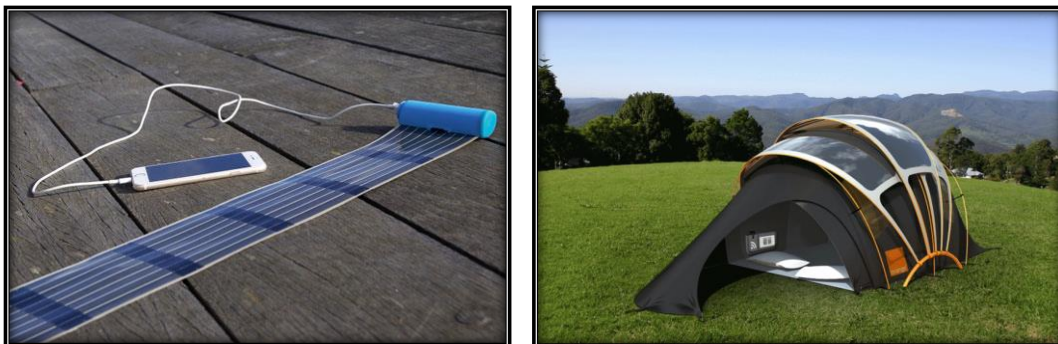


Figure 14: Solar cell fabric usage areas [29,30]

#### 4.4 Photovoltaic Noise Barriers (PVNB)

Noise barriers are commonly used in Europe to reduce noise level between highways and the living spaces. Same way, it is used to separate city from its railways. Approved by the World Health Organisation, traffic noise is recognized to be a serious environmental pollutant which affects the inhabitants adversely living alongside the road infrastructure. Previously, city municipalities were building noise barriers without solar panels integrated but with this application, it will help reduce CO<sub>2</sub> emission which helps the EU's 2050 targets: 100% sustainable energy and zero carbon emission. The application in the below figure has used bifacial solar panels which helps to capture most of the incoming sunlight through different hours of the day.



Figure 15: Photovoltaic Noise Barriers [31]

### 5. Concentrated Solar Power

When it comes to generate energy, there are diverse ways and applications to achieve it. Solar technologies are also divided into two major sub technologies as solar PV, which is the leading solar power technology in the world with a 98% of global solar generation capacity. The rest of the 2% indicates the concentrated solar power (CSP). Solar PV cells directly convert the sunlight into electricity where CSP first collects the sunlight at a line or point which results the heat conversion first then to electricity. But it cannot be used alone as solar PV to generate electricity. [32]

CSP is the fundamental of solar hybrid technology combined with fossil-fuel generators. The sunlight is focalized by the help of mirror field to heat up the fluid. The heated fluid is then utilized to create steam which operates a turbine that generates electricity. These facts help CSP become dispatchable and enhance the annual capacity factor in terms of energy.

But as every technology has its downsides, CSP requires direct sunlight (solar radiation) therefore not possible to use with maximum efficiency in the regions where there are many clouds and hazy skies. Another downside is that CSP system needs to be a big scale system minimum of 10 MW capacity or larger to become economically feasible



and reaching the maximum efficiency. On the other hand, PV systems can be deployed ranging from few kilowatts to hundreds of megawatts. The water resource is very significant for CSP deployment. As mentioned, commercial CSP plant needs a huge capital investment since it has to be large scale, therefore only limited set of investors such as countries themselves are capable of taking on.

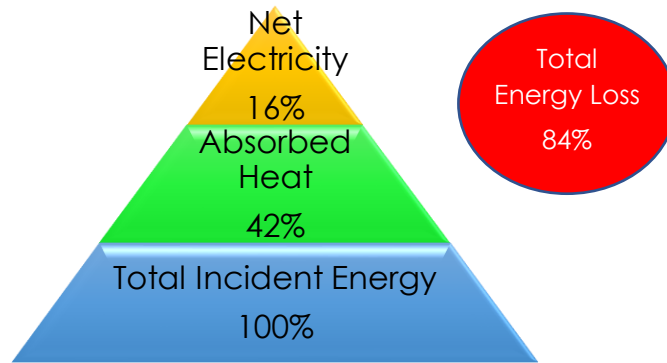


Figure 16: Efficiency of a Typical CSP plant [33]

There are two existing major designs for the CSP system: line focus and point focus.

Based on these two designs, there are currently five primary types of CSP available. Parabolic through, solar tower, linear Fresnel, beam tower and Stirling dish. In the following section, all of these technologies will be briefly investigated.

### 5.1 Parabolic Through

In this special type of application, sunlight is focalized by long parabolic shaped mirrors onto a tube that fluid flows. This fluid is also known as heat transfer fluid, mostly used as synthetic oil. The heated fluid is gathered by the help of receiver tubes. Then it is used to generate steam in a heat exchanger, finally the steam is utilized to generate electricity. All of this process can be easily explained by Rankine cycle.

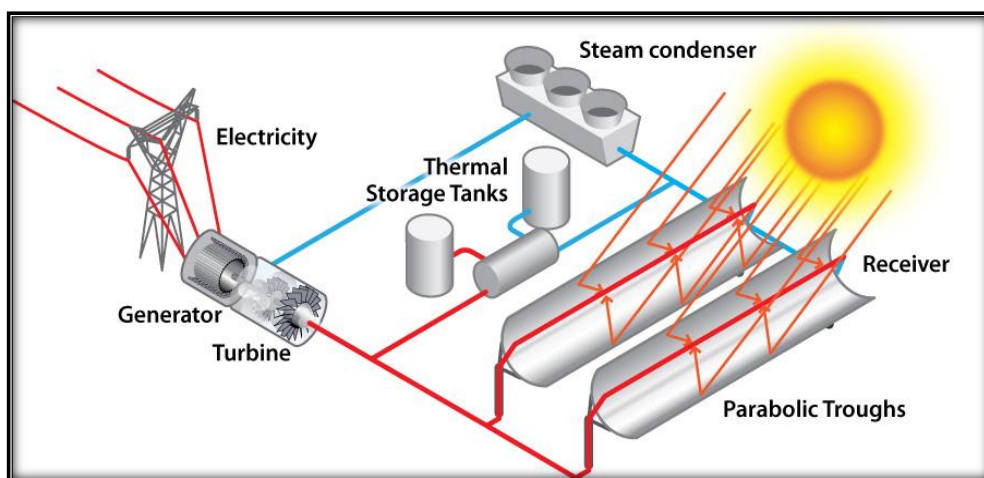


Figure 17: Parabolic Through CSP complete system schema [34]

CSP is now considered as commercial technology. Similar to other solar technologies, parabolic troughs can be equipped with a tracking system that basically rotates the mirrors based on sun's position in order to achieve maximum efficiency. Although, this design is long before found, the main downside is to require high capital investment. Not only the financial part, but also it has problem with technical parts such as heat loss and mechanical issues. As a result, it has a low efficiency value to generate electricity.

## 5.2 Solar Tower

This design includes an array of heliostats/mirrors that are focalized to the top of the solar tower. Since the tower is located in the middle of the array, all of these heliostats need to be equipped with a two-axis tracking system to catch and reflect the maximum amount of sunlight to the tower. The size of the tower is fully dependent on how big the array is. It is correlated as the height of tower equals to the radius of the heliostats area. The benefit of using centralized collector design enables the heating fluid reach higher temperature which means higher efficiency. Solar towers generally use solar salt as the heat transfer fluid and this fluid can exceed from 250 °C to 565 °C [35]. This temperature limit can vary between different heat transfer fluids.

Since solar towers can use hotter fluids because of the system design, they can achieve higher efficiency. The heat transfer surface is minimized in this design, convective heat losses can also be minimized. Additionally, by adding a thermal storage to utilize the heating fluid causes cost reduction which makes the solar towers economically more feasible than parabolic troughs.



Figure 18: CSP- Solar Tower design in United States [35]

### 5.3 Beam Down

The beam down CSP is still developing and yet it is not ready for full plant-size scale. It applies the same working principle as in heliostat mirrors that are located around the solar tower. Instead of collecting the beam radiation directly as solar tower, it utilizes the secondary collector where all the reflected sunlight coming from an array directed into here. This enclosed design may allow very high temperature for fluids which results in high thermodynamic efficiencies. In beam down CSP system, heat transfer and thermal storage fluids are the same therefore better power dispatch is possible. Currently, the biggest barrier here is the manufacturing the high-quality light collectors and some other design issues.

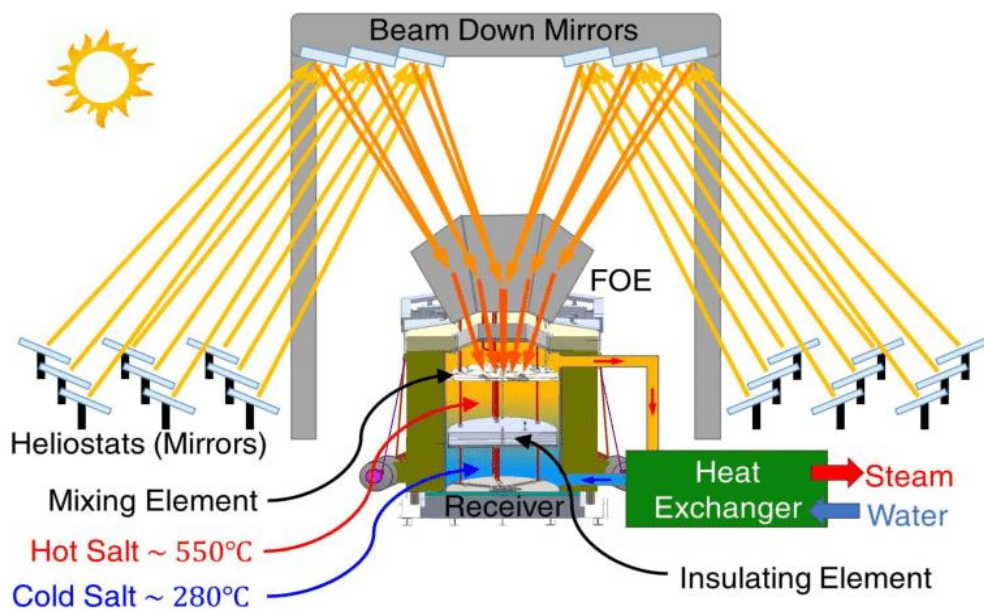


Figure 19: Beam Down CSP system design [36]

### 5.4 Linear Fresnel

The stationary design of Linear Fresnel makes it cheaper, both in capital and operating expenses when compared with parabolic through design. It can provide heat at up to 400°C under maximum of 120 bars of pressure [37]. This design can be operated with water, synthetic oil, or high temperature glycol to generate steam that is needed to spin the turbine. Direct solar radiation is reflected via mirrors which are controlled by single axis tracking system to achieve maximum efficiency. Although it uses a simple design with relatively low temperature fluid, the efficiency of linear Fresnel is lower than other CSP designs.



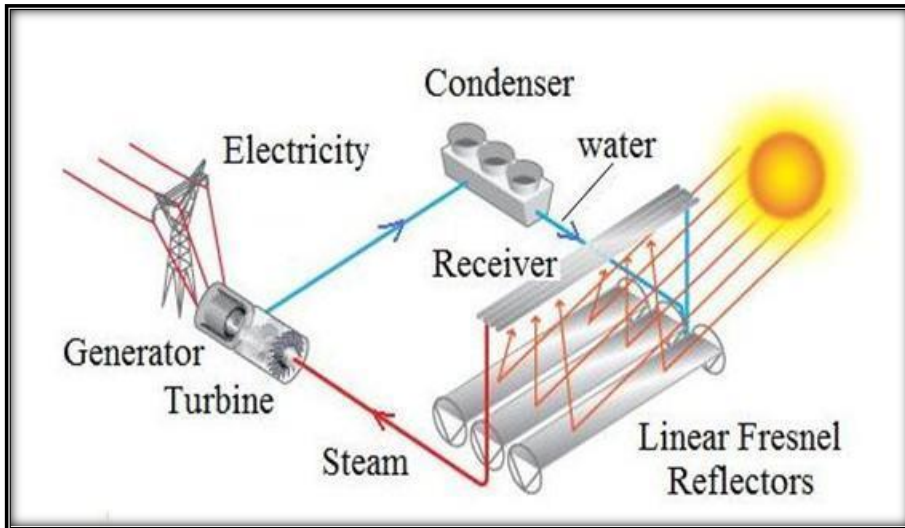


Figure 20: Linear Fresnel CSP system design schematic [37]

### 5.5 Stirling Dish Engine

This CSP technology uses mirror reflectors that focuses all the incoming sunlight into the Stirling engine. The efficiency of this system approaches the maximum thermodynamic efficiency of a heat engine, so called Carnot efficiency. Simply saying that the design has the maximum possible conversion factor within all concentrated solar power technologies.

By using larger units, it is possible to achieve high operating temperatures therefore higher efficiency values. Since each system requires an additional Stirling engine, they are capittally expensive and also high operating and maintenance costs are existed. Furthermore, with the lack of technology, there is currently no energy storage option for Stirling dish engine which is another drawback.



Figure 21: Stirling Dish Engine plant in Dubai [38]

## 6. Invention of the fully Transparent Technology

New solar panel technologies are developing and soon it will transform the global solar energy landscape. Some encouraging technologies like transparent luminescent solar concentrators are in the early stage of development, but with the right investment and researches, it will change the world.

First fully transparent solar concentrator was originally invented in Massachusetts Institute of Technology by Vladimir Bulović, Miles Barr, and Richard Lunt in 2013 [39]. This research was supported by MIT Centre for Excitonic, an Energy Frontier Research Centre funded by the US Department of Energy. Similar studies are carried out by European and Asian universities as well. Today's problem is that the fully transparent solar concentrators have low converting efficiencies. First prototype was aimed to achieve 12% power-conversion although the efficiency after the first laboratory experience was found as 2%. This problem can be solved by simply stacking transparent solar cell sheets together and obtain an efficiency around 10% without disturbing its transparency. Current progress in this field will increase this number but even if it were not developed any further, all the windows around the globe could provide adequate energy with a relatively high cost, which would be decreased in the following years.

Moreover, the lifespan of the materials that are used to create TLSC is another engineering challenge. While manufacturing transparent solar cells includes lots of chemical materials, they also have lifespans that must be preserved long enough to maintain commercially viable service time around 20 years such as monocrystalline cells. Another aspect to be tackled on is that manufacturing of transparent PVs is environmentally friendly and does not require much energy. In fact, the coatings are deposited in near room temperature and there is no need to use glass to protect chemicals like the one in conventional PV cells which results cost reduction in production.

### 6.1 Implementation of the Transparent Solar Cell Technology

The world changes almost every day. Therefore, the current energy generation methods should be also altered. With the help of transparent solar technology, everything will be turned into energy generating devices. Some countries are already in use with it, while other countries are for the far future once the efficiency problem of transparent solar panels is solved. As mentioned before, the efficiency of TLSC is around 10% maximumly. Even this technology with a low efficiency number is being used in building structures, as building integrated photovoltaic also known as BIPV, a new era will begin. Implementing transparent solar panels on all skyscrapers or plazas with a minimum of 90% glass coverage would provide around quarter of the building's energy consumption [39]. This is an undeniable energy generation will lead the world to become CO<sub>2</sub> free. Semi and fully transparent solar materials have started to evolve in the past 5 years. This completely new technology will not only be used in buildings but also electric vehicles. Imagine even when the car is being driven or parked, the transparent solar panels located on the windows will generate energy and continuously feeding the battery packs. The same way, all of the smartphones or



laptop screens can be covered with transparent solar cells to feed their batteries. Another alternative usage can be on agriculture. Greenhouses are important for humanity because with the right climate conditions, anything can be grown in it. Therefore, using TLSC on the roof of the greenhouses will allow sunlight to reach the surface, in the meantime generating energy to any required field. This possible applications will change the entire world because all the energy we require to manufacture products, transportation and living can be easily compensated just with solar power.

## 6.2 Technical Specifications of TLSC

The working principle of luminescent solar concentrators (LSC) are different than normal solar panels. In a dielectric matrix doped with either organic or inorganic elements, LSC wires the incoming light to the silicon cell where the total internal reflection is aimed to be increased. In theory, this concept is charming because concentration factor is possible up to 1000 times. Normally, reaching this high concentration number is only feasible with solar trackers. Unfortunately, practical experiments are way below this factor. Currently the obtained world record per unit surface to catch lights and transform into electric, the power conversion efficiency is calculated as 7.1% [41] The real problem here is the optical path because concentrating the light into solar cell located in the bottom part of the LSC is only possible via optical way, so there is a huge efficiency loss which results the lower efficiency on power to electricity conversion.

Normal solar panels catch the visible light to move the electron and eventually generate electricity. But TLSC is not focused on visible light, in fact it lets the visible light pass through but focuses on ultraviolet and infrared rays coming from the sun that are actually harmful for humans. Infrared rays raise the internal temperature of the eye and causes devastation in a long run. Therefore, covering windows of the residential buildings with transparent solar panels will minimally help protect our eyes and of course avoiding some skin problems.

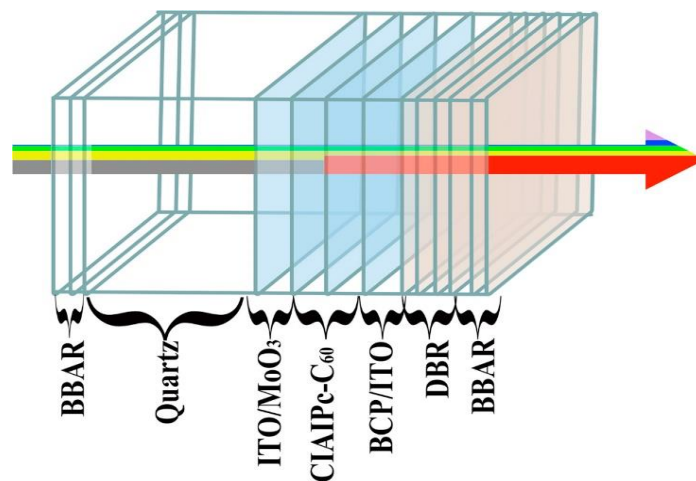


Figure 21: Transparent solar concentrator design structure [42]

The TSC model is basically the process where indium-tin-oxide (ITO), C60, CIAIPc, bathocuproine (BCP) and MoO<sub>3</sub> are coated on to the anode of the cell while the cathode goes under the same coating procedure with Ag through thermal evaporation. A distributed Bragg reflector (DBR) is the near-infrared (NIR) mirror which is transparent and is individually grown on a quartz substrate. In order to provide an 88nm stop band, SiO<sub>2</sub> and TiO<sub>2</sub> layers are sputtered to a chosen thickness while the quartz's' other side is coated with a broadband antireflection (BBAR) layer. This whole procedure and the TSC model aim to catch the ultraviolet and near-infrared wavelengths while letting the visible light pass through [42].

## 7. Comparison of the Solar Panel Technology

Currently developed PV device structures are divided into wafer-based and thin-film technologies. All of the last generation PV cells are belong to the thin-film methodology. As an emerging technology called Perovskite cell is the game changer. Since it was only discovered in 2006, it cannot dominate the market but in near future with the research works invested on this technology, it will be the major energy supply. The initial application was held in 2006 and the publication was made in 2009 with only 3.8% efficiency. Later in 2020, the efficiency was increased to 25.2% by using single-junction structure and 29.15% by using silicon-based tandem [43]. This is the highest value that is occurred within single-junction solar cell. Therefore, Perovskite solar cell is the fastest advancing solar technology in the world.

What makes Perovskite cell very attractive is the low production cost, and most importantly its potential of reaching Shockley-Quiesser limit. There is even the possibility of exceeding the limit in the near future, which is accomplished by the solar technology of gallium antimonide, also known as GaSb cells [73]. Under normal conditions, around 99% of the energy of the sunlight reaching the Earth's surface is between 250 nm – 2500 nm in wavelengths. Previously, the problem was that the multi-junction solar cells were not able to retain the entire incoming spectrum range. Though, this issue is solved with record-breaking photovoltaic cell which has five semiconductor junctions, three of them in a gallium arsenide (GaAs) based section and two in a gallium antimonide, and because of its ability to unlock the energy that lay in the long wavelength photons. Therefore, it can convert more energy than any other developed solar cell [74].

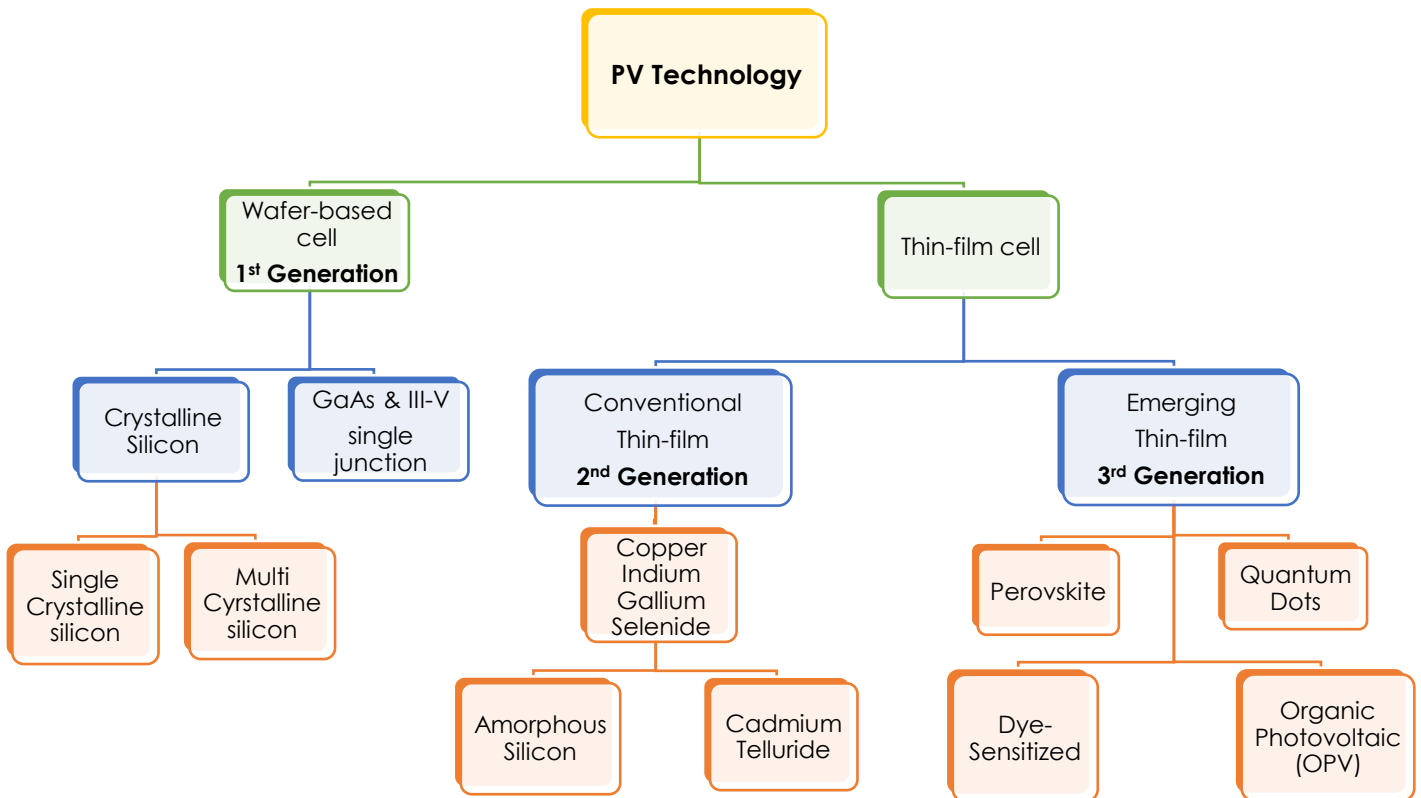


Figure 22: Photovoltaic Technologies in hierarchical order (own illustration, data from [44])

### 7.1 Wafer-based cells

As the name implies, wafer-based silicon cells are manufactured from crystalline silicon sheets that are piled together. Crystalline silicon (c-Si) encompasses single-crystalline and multi-crystalline technologies. Since this is the first commercial photovoltaic cell structure, there are some downsides. Relatively poor ability to absorb lights which leads the manufacturers to use in thick layers of silicon. This causes high capital costs and low power conversion efficiency. They are not flexible as the thin film based solar cells. Despite its limitations, today crystalline silicon dominates PV market and will be the leading PV technology until 2030.

Crystalline silicon (c-Si) cells establish around 90% of the global PV module production in 2014 with 35% market share for single-crystalline and 55% for multi crystalline cells. Recorded efficiencies that were held in laboratory conditions are 25,6% for single and 20,4% for multi crystalline solar cell [45].

Another wafer-based technology is the III-V multijunction (MJ) solar cells. It refers the elements located in group III (Al, Ga, In) and group V (N, P, As, Sb) in the periodical table. They are manufactured from stack of more than two single junction cells that have different level of bandgaps to absorb sunlight. With this method, less sunlight coming to the surface of PV cell will escape therefore the power conversion efficiency becomes higher. Recorded maximum efficiency in test conditions is determined as 46% [45].



## 7.2 Thin Film-based

Thin-film technologies are referred as 2<sup>nd</sup> generation PV cells. They are categorized in two main families; silicon based thin-film and non-silicon based thin-film. These technologies are low-cost to manufacture but they historically had lower efficiency levels as a downside. In non-silicon based thin film family, there is a cell technology called perovskite that is discovered 15 years ago, and it surprises the market with its rapid enhancing efficiency over the last 5 years.

Perovskite is an artificial material consist of a hybrid organic-inorganic lead that is derived from the calcium titanate ( $\text{CaTiO}_3$ ) compound, which is easy to synthesize, and it is considered as the future of solar cells [46]. Perovskite has a high-level light-harvesting active layer that helps to increase its overall efficiency. Having a broad spectrum of light absorption is another advantage. Moreover, it offers high flexibility, semi-transparency, and light weight.

Following figure gives the idea of how thick these solar cells are compared to human hair and the red blood cell. Wafer based demonstrates the thickness of crystalline silicon, while the other two technologies belong to thin film-based technology.

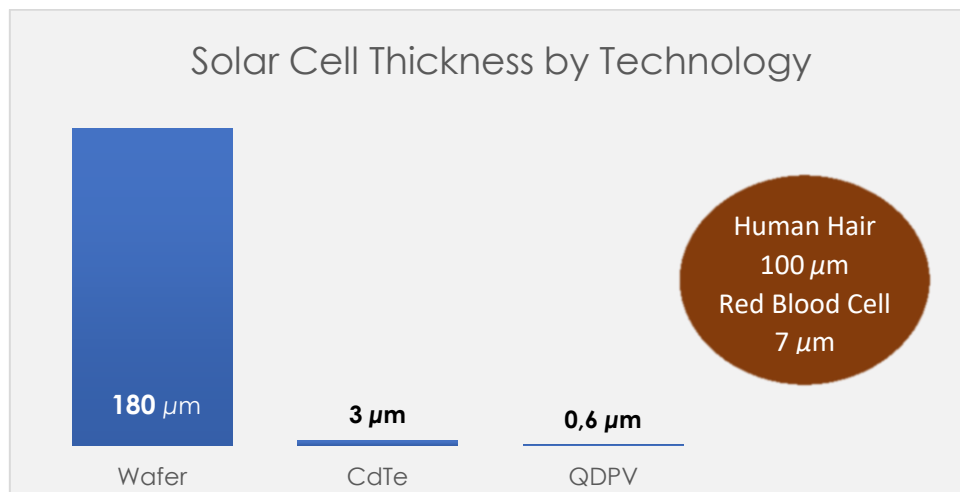


Figure 23: Thickness difference between thin-film and wafer-based (own illustration, data from [45])

Following figure demonstrates the development of all major solar panel technologies between 2000 to 2020. The most promising technologies here are the perovskite and quantum dots since the enhancement has only been realized in the last decade where traditional single crystalline technology has been available in the market for almost 70 years.

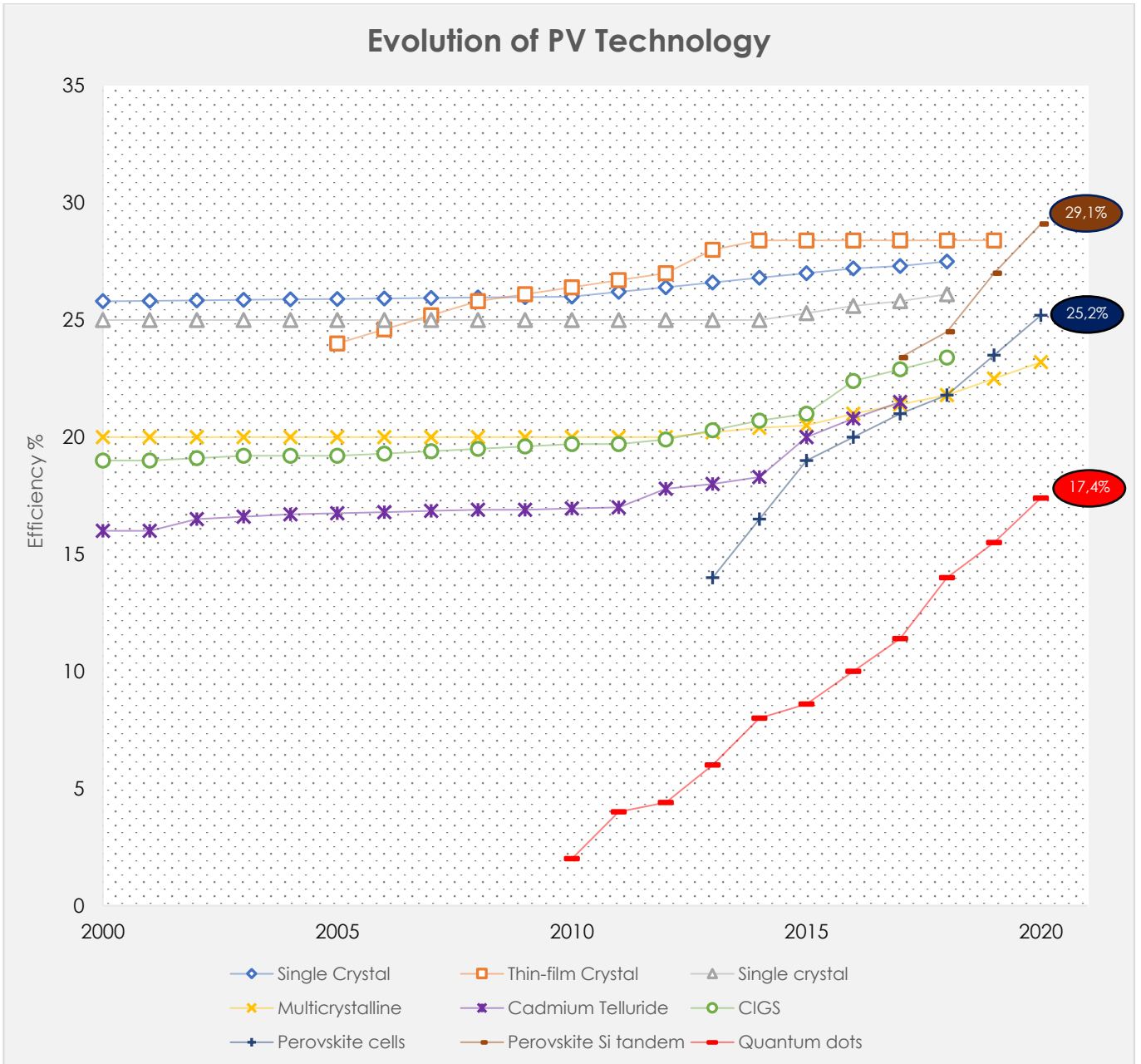


Figure 24: Technological development of PV cells based on efficiency (own illustration, data from [43])

The technological development for perovskite cell tandem structure with silicon just in 4 years increased from 22,4% efficiency to 29,1% which is accepted as the fastest rising trend among solar cells. In the future, newly produced solar cells will be in only 3<sup>rd</sup> generation cells and mostly focus on Perovskite and Quantum Dots technology. Rapid acceleration in efficiency draw attention for perovskite and since the quantum dots technology is used in semi or fully transparent luminescent solar concentrators, it is also considered as the future of solar technologies.

### 7.2.1 Tandem/Hybrid cells

This structure is achieved by stacking individual cells, one on top of another. This serves as that each layer convert a specific light spectrum and leaving the rest of the spectrum to the underlying cell. In this working principle with different layers that is created with various elements allowed to reach the highest efficiency under the test conditions. The world's most efficient solar cell has 46% efficiency but due to the high-cost fabrication process, still cannot break through the market. [47]

### 7.2.2 Quantum Dots

As a third-generation solar cell technology, quantum dots are especially special in terms of future expectations because its optoelectronic properties enable a high efficiency conversion factor of 10%. In the manufacturing process, QDs are cut gently in different sizes to absorb wide spectrum of sunlight which makes them a suitable solution for solar cells' future. Combining this technology with transparent technology creates transparent QD-sensitized solar cells. This special solar cell has the ability of multi excitation generation in which more than one hole-electron pair is excited by single photon. By means of this act, Shockley-Quiesser limit of 33,7% for single-junction solar cells is exceeded. Fluorine-doped Tin Oxide (C) glass is the transparent conductive metal oxide that used in the fabrication of TSC. Later on, titanium dioxide ( $\text{TiO}_2$ ) film is utilized as electron transporting layer (ETL) and another layer is located underneath of ETL, as a hole transporting layer (HTL) is manufactured from Molybdenum trioxide ( $\text{MoO}_3$ ) [48]. After that, Lead (II) sulphide also known as PbS is placed as a light absorber layer that has a band gap of 1.3 eV compared to silicon as a semiconducting material of 1.11 eV [49]. In the end, by using little bit of gold (Au) is thermally evaporated on the QD layer and whole structure is shown in the figure below.

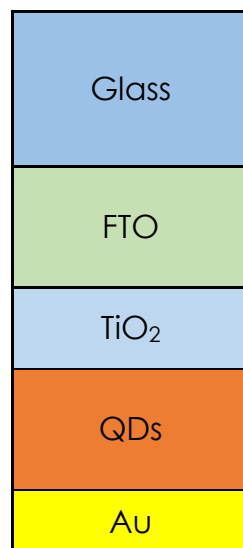


Figure 25: Quantum Dots solar cell structure [48]

## 8. Simulation

An island has been designed to stimulate the living area with a different structural building shapes by using the program AutoCAD. From there, the possible number of people that can fit into these buildings will be calculated. Each structure represents various purposes as commercial and residential. Since each building has distinct energy demands, reference values which belong to the commercial buildings in Frankfurt, Germany were obtained to understand the energy consumptions. With these values, it is easy to obtain the energy consumption of the building structures belong to the model island.

From this point on, all the building measurement must be taken which includes base area of the buildings, number of floors, height of the structure and the window areas are collected. This simulation's purpose is to demonstrate if the new technology solar cell, also known as Transparent Luminescent Solar Concentrator, which uses the quantum dots technology to capture invisible light spectrum are replaced with the windows. With the latest technological developments, it is understood that window glasses can be replaced with TLSC to generate continuous electricity which can be easily used within the apartment itself by using decentralized inverter or as a second option, centralized inverter which has bigger power outputs to supply the whole building.

After capturing all the measurement, a calculation tool must be developed by using MATLAB. There are of course some challenges to illustrate final generated electricity since the TLSC must be positioned vertically to the building's south facet. Until now, none of the solar panels that installed were 90° positioned in the world as a commercial meaning. Considering this angle provides a lower radiation capture factor which results in lower power-energy conversion efficiency. Since TLSC is a new technology, therefore the efficiency is not high as p-n junction solar cells, about only 10% efficiency could be observed by stacking multiple units together. As of today, this is not an issue because the technological development through the solar cells would increase the efficiency in the near future. Assuming in the near future, all the buildings that will be constructed must contain transparent solar cells instead of windows. That will supply a considerable percentage of the consumption and help protect the environment and to become 100% green energy.

This simulation will help researchers understand how much energy can be generated through the given surface areas and how many percent of the consumption can be compensated. By using the calculation tool, it is possible to calculate different applications by only giving the surface area and some other specification. The following screenshot is from AutoCAD to demonstrate the model island. Later on, the dimensions of the building were entered to the MATLAB where the actual calculation occurs.



Figure 26: Model Island

To calculate the energy that TLSC can generate through window surfaces, it is first necessary to understand which factors must be taken into account for solar radiation. However, while collecting monthly or daily basis data of solar radiation is easier than working with hourly solar radiation data involves hard work or mandatorily cost payments for the service provider. But hourly data gives more precise results, therefore let's investigate the parameters for the calculation of hourly solar radiation.

## 8.1 Determination of Solar Radiation

The solar radiation comes from the sun to the atmosphere of the Earth by a value of  $1362 \text{ W/m}^2$  which was measured by satellite. This means, for one hour time from each square meter of area, it can be maximumly obtained 1,36 kWh of energy. This value is also known as solar constant [2]. The solar radiation consists of 3 main elements: direct, diffuse, and reflected solar radiations. Direct radiation indicates the solar radiation comes directly from sun without any disturbance or without facing any obstacle. When the sky has no clouds, completely clear sky gives the maximum value of direct solar radiation. Conversely, diffuse solar radiation is caused by disturbances, e.g., clouds or another preventer in the atmosphere. Lastly, the reflected solar radiation, as the name implies, the radiation which reflects from the surrounding materials such as windows. When merging all these 3 components, the total solar radiation is formed which determines the TLSC energy production.

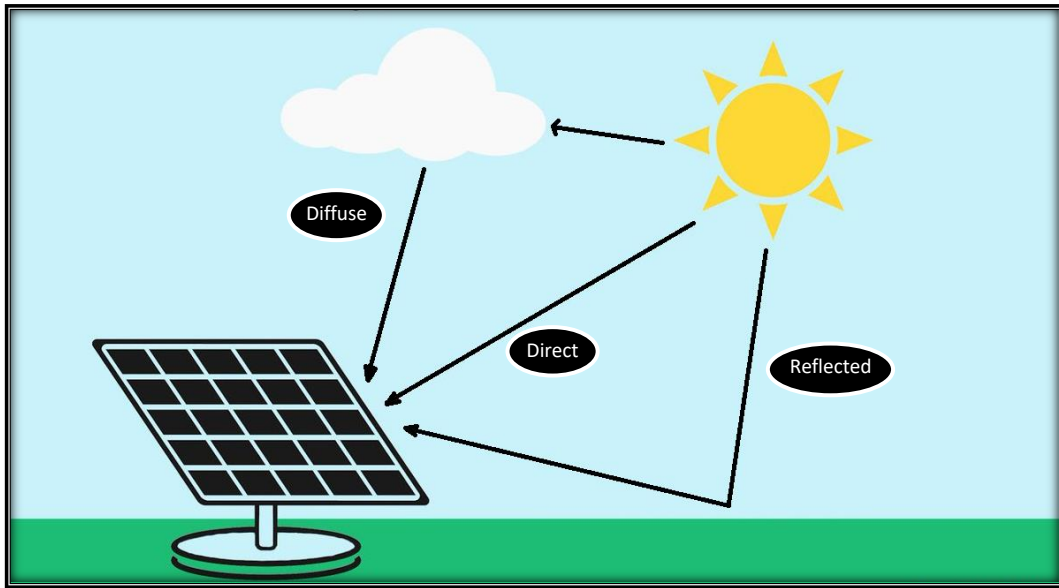


Figure 27: Direct, Diffuse and Reflected radiations (own illustration)

Further equations and definitions show how the solar radiation calculation tool is created and what other important factors should be considered.

As mentioned before, in order to have more precise values, hourly solar radiation data must be utilized. Each location has its special latitude angle ( $\varphi$ ) and longitude angle ( $\lambda$ ) and these must be defined first. The simulation is assumed to be located in Munich area because of high solar radiation value compared to other parts of Germany. Munich's coordinates indicate the latitude and longitude angles; 48.1351° N, 11.5820° E, respectively. Then, declination angle ( $\delta$ ) must be found. It is defined as the tilt of the Earth on its rotating axis and its rotation around the sun. The Earth is tilted 23.45° on its axis but if it weren't, the declination angle would always be 0°. Because of this rotation, the angle changes during the year. [50]

$$\delta = 23.45^\circ \times \sin\left(\frac{2\pi}{365} \times (d + 284)\right) \quad (8.1)$$

After that, solar time must be found. Local Solar Time (LST) is defined as when the sun is at the highest position in given location. Local Time (LT) varies from the local solar time because of Earth's orbit and time zone adjustments. Furthermore, Equation of Time (EoT) has to be defined because LST formula includes it.

$$EoT = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \quad (8.2)$$

$$B = \frac{360}{365} (d - 81) \quad (8.3)$$

LST formula is based on local time (LT) and time correction factor (TC). There is another time factor called Local Standard Time Meridian (LSTM) which is the reference meridian used for a particular time zone. For instant, Munich has UTC+1 between January to March and November to the end of the year. During March until the end of the October, Munich is in UTC+2 time zone which shows that LSTM for Munich is 15° for roughly 5 months and 30° for the rest of the year. [50]

$$LSTM = 15^\circ \Delta T_{UTC} \quad (8.4)$$

$$TC = 4(longitude - LSTM) + EoT \quad (8.5)$$

After obtaining all of these parameters, LST can be finally calculated.

$$LST = LT + \frac{TC}{60} \quad (8.6)$$

Hour angle ( $\omega$ ) converts the LST into the degrees which indicates that the sun moves across the sky. The Earth rotates 15° each hour therefore during 180° movement from East to West, it is accepted as 12 hours, as the half time of the day. During the morning, hour angle has a value of negative and in the afternoon it is positive. Also, the sunset hour ( $\omega_s$ ) can be calculated from the equation below. [50]

$$\omega = 15^\circ (LST - 12) \quad (8.7)$$

$$\omega_s = \cos^{-1}(\tan \phi \cdot \tan \delta) \quad (8.8)$$

Solar zenith angle ( $\theta_z$ ) is the angle between sun's ray and the perpendicular imaginary line to the equator. This angle is closely related to the solar altitude ( $\alpha$ ) angle which is the angle between sunlight and a horizontal plane, both formulas and the schema can be seen below.

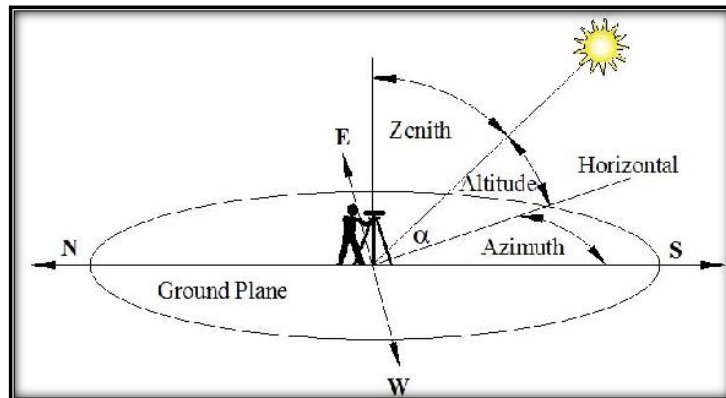


Figure 27: Solar zenith, altitude, and azimuth angle [51]



$$\cos(\theta_z) = \sin(\alpha) = \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \cos(\omega) \quad (8.9)$$

$$\alpha = 90 - \theta_z \quad (8.10)$$

After obtaining these parameters, the slope angle must be defined. Transparent luminescent solar concentrators will be replaced with current windows therefore the slope angle must be  $90^\circ$  as it is parallel to the building structure. As shown in the figure above, azimuth angle has two internal components as surface azimuth ( $\gamma$ ) and solar azimuth angle ( $\gamma_s$ ). When solar panels are located in the Northern hemisphere, they must be facing south and when located in Southern hemisphere, they must be facing north in order to get the maximum benefit from sun. Since Germany is located in Northern part of the world, TLSC will be installed only to the south facet of the buildings. Therefore, azimuth angle is  $0^\circ$ .

The solar incidence angle ( $\theta_i$ ) is the angle between sunlight coming to the surface of the panel and the normal to the horizontal surface. This angle helps to define correction factor of the incoming solar radiation into the tilted surface. In this simulation, panels are located vertically therefore the slope angle ( $\beta$ ) is  $90^\circ$ . Incidence angle can be calculated with the formula below. [52]

$$\cos \theta_i = (\cos \phi \cos \beta + \sin \phi \sin \beta \cos \gamma) \cos \omega \cos \delta + \cos \delta \sin \beta \sin \gamma \sin \omega + \sin \delta (\cos \beta \sin \phi - \sin \beta \sin \phi \cos \gamma) \quad (8.11)$$

After obtaining the incidence angle, following correction factors for diffuse ( $R_{dif}$ ), direct ( $R_{dir}$ ), and the reflected ( $R_{ref}$ ) solar radiations can be calculated.

$$R_{dif} = \frac{1 + \cos \beta}{2} \quad (8.12)$$

$$R_{dir} = \frac{\theta_i}{\theta_z} \quad (8.13)$$

$$R_{ref} = \frac{1 - \cos \beta}{2} \quad (8.14)$$

Eventually, the hourly tilted solar radiation ( $I_t$ ) can be found with the formula below. There is a reflection coefficient ( $\rho$ ) which changes with the object heights but can be accepted as a constant value. This tilted solar radiation value will help calculate the energy generation from TLSC. [53]

$$I_t = I_{dif} R_{dif} + I_{dir} R_{dir} + \rho R_{ref} (I_{dir} + I_{dif}) \quad (8.15)$$





## 8.2 Introducing the Model Island

A model has been created which includes different building shapes with different energy consumptions. Some of the buildings are designed for commercial purposes, some of them are just for residential purpose. Residential buildings' energy consumption is calculated manually by considering all the utility consumers. For commercial buildings, energy demand is found not only in the same way but also confirmed through European Commission's official website to determine energy levels per square meter. The following table shows the names of the structures and their respective base area and height. In the island, there are 4 villas with the same dimensions which will be shown in the following calculation section.

	<b>Structures</b>	<b>Base Area</b>	<b>Height</b>
1-)	Empire State Building	2548 m <sup>2</sup>	140 m
2-)	Radio Tower	1653 m <sup>2</sup>	65 m
3-)	Residential Balcony	1778 m <sup>2</sup>	100 m
4-)	Dark Stylish Building	2393 m <sup>2</sup>	60 m
5-)	Enterprise Tower	1998 m <sup>2</sup>	130 m
6-)	Cylindrical Spradon	2196 m <sup>2</sup>	60 m
7-)	Red Brick Building	1537m <sup>2</sup>	145 m
8-)	Shop Building	446 m <sup>2</sup>	16 m
9-)	Villa (4 pieces)	253 m <sup>2</sup>	10 m
10-)	Governor Building	405 m <sup>2</sup>	12 m

Table 1: Specification of the structures in the model island

Some buildings create shading on the other structures in the island. Instead, not having a complicated calculation tool, shading caused by other buildings has to be ignored. For this reason, it is assumed that TLSC will cover the south facet where the sun is more powerful than other facets. Since the technology of transparent luminescent solar concentrators are not fully developed yet, the efficiency value is very low but as of every technological piece in the early advancement, manufacturing cost can be very high. Therefore, considering the financial point of view from this complete project, shading will be neglected and replacing the windows on the south facet. Let's investigate the building structures one by one to have a clear idea of how the energy that will be generated by TLSC is calculated.

First of all, the main buildings which are either residential or commercial buildings will be analysed. The other 3 structures which are governor building, villas and the shop building will be calculated after the main structures are completed. The following figure is created by the help of render tool in AutoCAD. This allows model to be seen as realistic as possible. One by one, all the window surface areas must be calculated in order to define the exact production from TLSC.

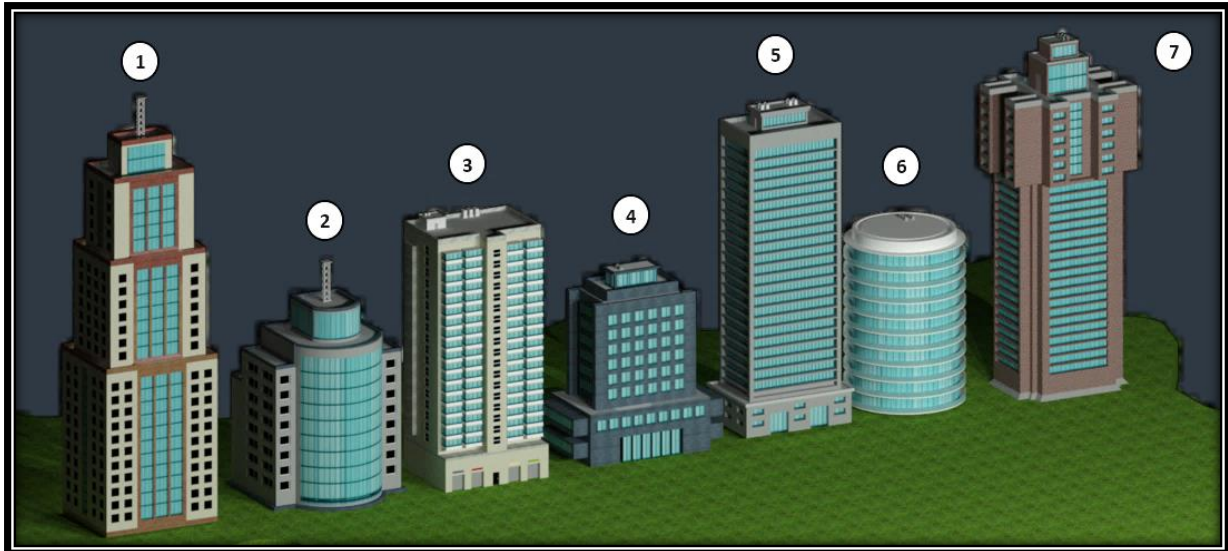


Figure 28: The south view of main buildings

### **1-Empire State Building**

This structure has 3 different size of windows that are ready to replace with TLSC.

Turquoise window dimension: 6,38m\*6,2m, total of 69 pieces.

Black window dimension: 4m\*4,1m, total of 58 pieces.

Window on top: 18,9m\*12,26m, total of 1 piece.

### **2-Radio Tower**

This structure has 3 different size of windows that are ready to replace with TLSC. Since the south facet is cylindrical, the area is calculated based on the angle.

Turquoise window dimension: 34m\*5m, total of 8 pieces.

Black window dimension: 3,5m\*3,06m, total of 16 pieces.

Window on top: 13m\*8m, total of 1 piece.

### **3-Residential Balcony**

This structure has 2 different size of windows that are ready to replace with TLSC.

Turquoise balcony window dimension: 5,48m\*2,11m, total of 72 pieces.

Black middle window dimension: 2,71m\*2,78m, total of 18 pieces.

### **4-Dark Stylish Building**

This structure has 3 different size of windows that are ready to replace with TLSC.

Turquoise window dimension: 3,16m\*3,2m, total of 36 pieces.

Windows on the ground dimension: 2,85m\*8m, total of 6 pieces.

Window on top: 13,12m\*4,09m, total of 1 piece.

**5-Enterprise Tower**

This structure has 4 different size of windows that are ready to replace with TLSC.

Turquoise full floor window dimension: 41,86m\*4m, total of 24 pieces.

Windows on the lower side dimension: 6,1m\*1,6m, total of 6 pieces.

Windows on the ground: 9,28m\*9,78m, total of 2 pieces.

Window on top: 22,07m\*4,5m, total of 1 piece.

**6-Cylindrical Spradon**

This structure has 1 circular form window type that are ready to replace with TLSC. Considering the only south facet, just 120 degree of the total area is calculated.

Turquoise floor window dimension: 34,67\*3,5m, total of 10 pieces.

**7-Red Brick Building**

This structure has 4 different size of windows that are ready to replace with TLSC.

Turquoise floor window dimension: 14,94m\*3,83m, total of 42 pieces.

Above window dimension: 6,41m\*3,51m, total of 12 pieces.

Above mid side window dimension: 6,14m\*4,2m, total of 6 pieces.

Window on top: 20,13m\*13,41m, total of 1 piece.

As main building part is completed, now investigate the small structures in the model island and calculate their window areas.

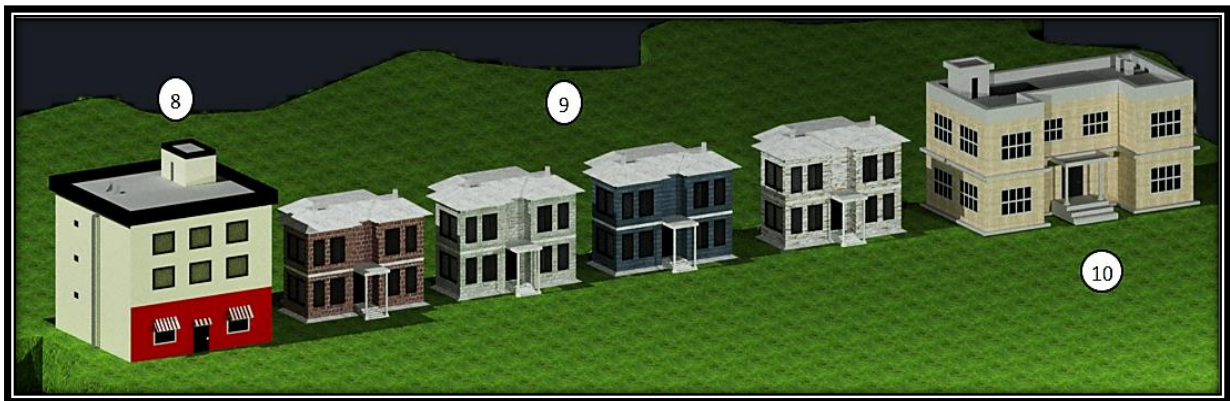


Figure 29: South view of the small structures

**8-Shop Building**

This structure has one size of windows that are ready to replace with TLSC.

Windows dimension: 2,18m\*1,85m, total of 6 pieces.

### 9-Villas

There are 4 pieces of identical structures in the island and has 2 different size of windows that are ready to replace with TLSC.

1<sup>st</sup> Windows dimension: 1,82\*2,8m, total of 4 pieces.

2<sup>nd</sup> Windows dimension: 2,34m\*2,8m, total of 4 pieces.

### 10-Governer Building

This structure has one size of windows that are ready to replace with TLSC.

Black window dimension: 5m\*2,8m, total of 6 pieces.

All window surfaces are calculated, let's see them in the below table as a summary.

WD: Window Dimension

WA: Window Area

#No	Structures		WD	WA	Pieces	Sub Total	Total (m <sup>2</sup> )
1	Empire State Building	1 <sup>st</sup>	6,38 x 6,2	39,55	69	2729,36	3912,28
		2 <sup>nd</sup>	4 x 4,1	16,4	58	951,2	
		3 <sup>rd</sup>	18,9 x 12,26	231,71	1	231,71	
2	Radio Tower	1 <sup>st</sup>	34 x 5	170	8	1360	1635,36
		2 <sup>nd</sup>	3,5 x 3,06	10,71	16	171,36	
		3 <sup>rd</sup>	13 x 8	104	1	104	
3	Residential Balcony	1 <sup>st</sup>	5,48 x 2,11	11,56	72	832,52	968,13
		2 <sup>nd</sup>	2,71 x 2,78	7,53	18	135,60	
4	Dark Stylish	1 <sup>st</sup>	3,16 x 3,2	10,11	36	364,03	554,49
		2 <sup>nd</sup>	2,85 x 8	22,8	6	136,8	
		3 <sup>rd</sup>	13,12 x 4,09	53,66	1	53,66	
5	Enterprise Tower	1 <sup>st</sup>	41,86 x 4	167,44	24	4018,56	4357,95
		2 <sup>nd</sup>	6,1 x 1,6	9,76	6	58,56	
		3 <sup>rd</sup>	9,28 x 9,78	90,75	2	181,51	
		4 <sup>th</sup>	22,07 x 4,5	99,31	1	99,31	
6	Cylindrical Spradon	1 <sup>st</sup>	34,67 x 3,5	121,34	10	1213,45	1213,45
7	Red Brick Building	1 <sup>st</sup>	14,94 x 3,83	57,22	42	2403,24	3097,91
		2 <sup>nd</sup>	6,41 x 3,51	22,49	12	269,98	
		3 <sup>rd</sup>	6,14 x 4,2	25,78	6	154,72	
		4 <sup>th</sup>	20,13 x 13,41	269,94	1	269,94	
8	Shop Building	1 <sup>st</sup>	2,18 x 1,85	4,03	6	24,19	24,20
9	4 Villas	1 <sup>st</sup>	1,82 x 2,8	5,09	4	20,38	186,37
		2 <sup>nd</sup>	2,34 x 2,8	6,55	4	26,21	
10	Governor Building	1 <sup>st</sup>	5 x 2,8	14	6	84	84
						<b>TOTAL:</b>	<b>16034 m<sup>2</sup></b>

Table 2: The summary of all the window surfaces



## 8.3 Defining Electricity Consumption

### 8.3.1 Residential Buildings

There are two approaches to define the electricity consumption of the island. First one is to accept each building as a residential building. In this case, the population can be easily found by just relying on the base area of the structures. In Germany, the apartments that has two residences usually consists of 60 m<sup>2</sup> and a family apartment with 4 people can be accepted as 120 m<sup>2</sup>. But some structures are designed to be assumed as they are residential, therefore going with the second approach will provide more solid results. Moreover, to justify a more realistic result, building number #2 and #5 can be accepted as commercial buildings and the rest of them are the residentials. The energy per square meter is utilized here to determine the consumption of the skyscrapers as commercial buildings. Furthermore, the number of people that use these structures as a workplace can be found using similar approaches. The base areas which can be seen below is calculated through base dimension from the different segments of the building structures as an average.

#No	Buildings	Base dimension (m)	Base Area (m <sup>2</sup> )
1-)	Empire State Building	45,5 x 56	2548
2-)	Radio Tower	36,27 x 45,58	1653,1
3-)	Residential Balcony	52,71 x 33,73	1778
4-)	Dark Stylish	61,36 x 39	2393
5-)	Enterprise Tower	53,84 x 37,11	1998,0
6-)	Cylindrical Spradon	2π.18,7 <sup>2</sup>	2196
7-)	Red Brick Building	41 x 37,5	1537,5
8-)	Shop Building	19,92 x 22,41	446,4
9-)	Villas	13,75 x 18,41	253,13
10-)	Governor Building	13,35 x 30,3	404,5

Table 3: Summary of the buildings' base areas

Except for the building numbers #2 and #5, the population can be directly calculated with the base area. Of course, not all the base area can be directly divided into the apartments because there will be room for elevator, entrance, stairs, and the corridors that are connected to the apartments. The outer wall thicknesses are included in the base area which needs to be excluded. When it comes to the calculation phase, it is crucial to include the Deutsches Institut für Normung (DIN) standards. DIN 277 is used to determine the floor space and room volume of the buildings under construction [54]. The outer wall is created with brick material with a standard thickness of 0.40m including isolation [55].

The area that goes for elevator, stairs, entrance, wall of the flats and the corridors can be assumed as they cover up around 15-20% of the total building base area depending on the application type. However, let's demonstrate this value with an example by using the building #3. The floor plan of the residential balcony building can be seen below. The building has four balconies and one window on the south facet and four large windows are located on the north side. Therefore, it is possible to fit in nine larger flats compared to normal ones.

But even in this case, electricity consumptions are assumed to be equal to more number of people who reside in the flats.

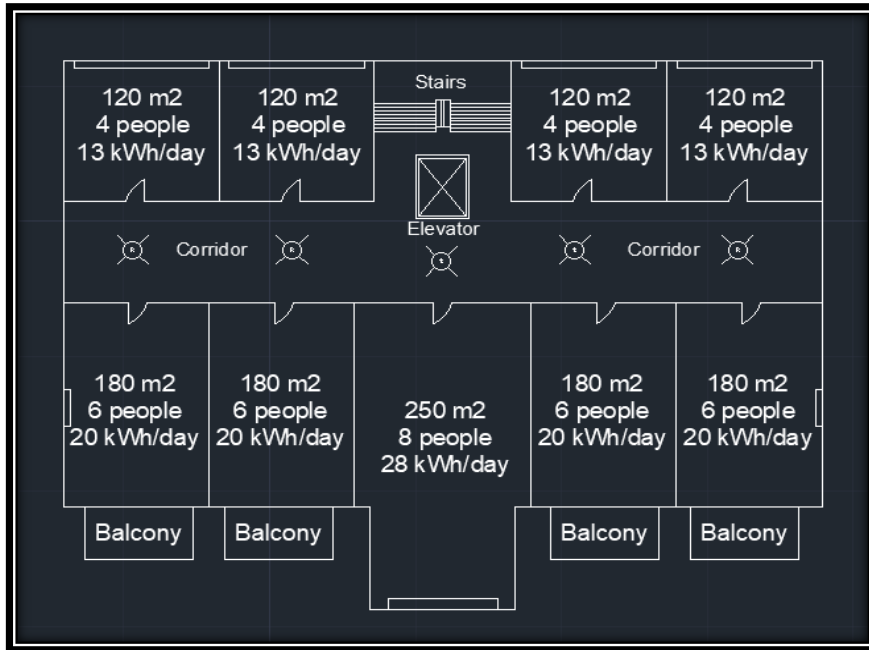


Figure 30: The floor plan of the residential balcony building

As it can be seen from above figure that there are four flats with 120 m<sup>2</sup>, four flats with 180 m<sup>2</sup> and one flat with 250 m<sup>2</sup> of living areas. Total of 1450 m<sup>2</sup> area is occupied by the habitants. The total floor area is 1778 m<sup>2</sup> (Table 3) and after extracting the outer walls of the building, it becomes 1713 m<sup>2</sup> of area. It means, total of 263 m<sup>2</sup> (1713-1450) is left after subtracting the space required for elevator, corridor, stairs, HVAC system and the other necessary parts. So, the percentage that goes for these applications is calculated as 15.63% therefore it is okay to proceed with the factor 0.15 to figure out the useful area.

When these information are taken into account, the renewed buildings' useful living areas can be found to determine electricity consumption through the number of people living in. The following table demonstrates the useful living areas without including the wall thickness into the base area.

#No	Buildings	Floor	Base dimension (m)	Useful Living Area (m <sup>2</sup> )
1-)	Empire State Building	25	45,1 x 55,6	2131
2-)	Radio Tower	12	35,87 x 45,18	1377
3-)	Residential Balcony	20	52,31 x 33,33	1450
4-)	Dark Stylish	10	60,96 x 38,6	2000
5-)	Enterprise Tower	24	53,44 x 36,71	1667
6-)	Cylindrical Spradon	10	2π x (17,9) <sup>2</sup>	1711
7-)	Red Brick Building	26	40,6 x 37,1	1280
8-)	Shop Building	3	19,52 x 22,01	365
9-)	Villas	2	13,35 x 18,01	204
10-)	Governor Building	2	12,95 x 29,9	329

Table 4: Useful living areas





Considering the values that are determined by the building #3, electricity consumption can be found through the number of inhabitants. From the previous Table 4, number of floors can be seen. According to the Stadtwerke München, two people apartment consumes 2500 kWh annually which becomes 6,84 kWh daily [56]. There are 20 floors for the building #3 and each floor has maximum of 48 people which is equal to daily consumption of 160 kWh of electricity. Accordingly, the total building consumption can be found with multiplying the number of floors into the single floor's consumption which is total of 3,2 MWh. Only the villa can be assumed as a constant electricity demand for 4 people which equals to 25 kWh according to German regulations for detached house including utilities. But for the other residential buildings, it has to be considered a factor which indicates the electricity consumption that is consumed by the elevator, indoor lighting, the water pumps, and electricity heating which equals to the normal gas boiler requirements. After adding these consumptions, the total consumption of the buildings can be found.

**Elevator:**

Beginning with elevator, assuming that the elevator travels within 20 floors and making 100 trips a day which should be 8 times more energy consuming than what three story elevator spends a year: 3800 kWh/a [57]. Further, a number must be added for the lighting fixtures to keep the elevator well-lit. This includes 50W of total internal lighting power and assuming it will run 12 hours/day with sensors to maintain sufficient luminous. Since the base area of the building is 1450 m<sup>2</sup>, at least 4 elevator is required to fulfil daily usage demand.

- 3800 kWh/a x 8 times (20 floors) = 30400 kWh/a
- Lighting fixtures = 50W x 12 hours x 365 days = 219 kWh/a
- Using 4 elevators = (30400 + 219) kWh/a x 4 = 122476 kWh/a

**Common area lighting:**

For common areas, lighting can be supplied with bulbs with 10W LED and each floor's corridor has 20 luminaires to provide enough luminaries which is active around 8 hours/day. Energy saving is possible with using sensors.

- 20 luminaires x 10W x 8hours/day x 20 floors x 365 days = 11680 kWh/a

**Pumps (Fire jockey, Hydrophore, Waste):**

The water pump calculation is required for 20 floors and 180 flats, assuming that the pump will run 1700 hours a year [58]. Requirement of the water circulation system of hydrophore, fire jockey pumps and other respective pumps are calculated as 80 kW installed capacity for the entire pumping system.

- 80 kW x 1700 hours = 136000 kWh/a



**Space Heating:**

Normally heating energy is calculated through the unit of kJ by using natural gas in a boiler, but the fossil fuel usage can come to an end. Most of the space electricity heaters are 1500 W and 4 of them are sufficient to provide heat for 120 m<sup>2</sup> flat for 4 people [59]. Also average of 6 hours a day is suitable during 8 months in Germany. Following calculations demonstrate the electricity consumption of the utilities.

- One floor = 48 people \* 1500W \* 6hours/day = 432 kWh/day
- Whole building = 432 kWh/day \* 20 floors = 8640 kWh/day
- Annual Energy Demand = 8640 kWh/day \* 240 days = 2.073.600 kWh/a

The total electricity that goes for utilities is shown below.

Elevator	122476 kWh
Common Lighting Area	11680 kWh
Pumps	136000 kWh
Space Heating	2073600 kWh
<b>Total</b>	<b>2.343.756 kWh</b>

Table 5: Total Electricity demand of utilities in building #3

Total consumption without utilities of the building #3 is yearly of 1168000 kWh. Then utilities including space heating consume around 200% of the resident inhabitants' electricity consumption. By using this factor, other buildings' total energy consumption can be seen at the below table.

#No	Residential Buildings	Without Utilities kWh/day	Without Utilities MWh/a	Total Consumption MWh/a
1-)	Empire State Building	5879	2145,7	6437,1
3-)	Residential Balcony	3200	1168,0	3504,0
4-)	Dark Stylish	2207	805,5	2416,6
6-)	Cylindrical Spradon	1888	689,1	2067,4
7-)	Red Brick Building	3672	1340,4	4021,1
8-)	Shop Building	121	44,1	132,3
9-)	Villa	25	9,1	27,4
10-)	Governor Building	73	26,5	79,5

Table 6: The yearly consumption of the residential buildings

Based on the calculation that is given, the electricity consumption is around 125 kWh per square meter in residential buildings.





### 8.3.2 Commercial Buildings

The approach that is used to calculate the total consumption of the residential buildings were focused on the number of people that live in. But the same approach does not suit for commercial buildings since they are not designed for residential purposes. Therefore, the only approach is to go with the energy requirement per m<sup>2</sup>. Most of the skyscrapers or commercial buildings and have a high consumption rate because of the HVAC system, server rooms and other electrical devices that are not often to see in residential buildings. To comply with the real-world data, some of the European high-rise towers are investigated in order to reach to the value of kWh/m<sup>2</sup>.

The analysis done by Department of Energy (DoE) demonstrates that the electricity consumption per square feet is around 22.5 kWh which is equal to 242 kWh/m<sup>2</sup> [60]. Another aspect came from the European Commission for non-residential buildings including commercial high-rise towers consume around 250 kWh/m<sup>2</sup> [61]. Additionally, simultaneity factor here is very important since the offices are not occupied fully throughout the year because of holidays. Therefore, by adding 0.8 simultaneity factor to the final energy consumption values will make it more realistic. All the detailed energy consumptions can be seen below.

- Lighting = 7 kWh/square foot or 75 kWh/m<sup>2</sup>
- Ventilation = 2 kWh/square foot or 21,5 kWh/m<sup>2</sup>
- Water Heating = 0,5 kWh/square foot or 5,38 kWh/m<sup>2</sup>
- Cooling equipment = 3 kWh/square foot or 32 kWh/m<sup>2</sup>
- Heating equipment = 2 kWh/square foot or 21,5 kWh/m<sup>2</sup>
- Refrigeration & Equipment = 8 kWh/square foot or 86 kWh/m<sup>2</sup> [60]

Based on the European Commission website, residential buildings must consume around 180 kWh per meter square annually but after detailed computation for model island, it is manually found as 125 kWh/m<sup>2</sup> annually therefore this number is taken into account for further calculation of residential buildings.

#No	Commercial Buildings	Useful Area	Floor	Total Consumption MWh/a
2-)	Radio Tower	1378	12	3306,4
5-)	Enterprise Tower	1668	24	8004,7

Table 7: The yearly consumption of the commercial buildings

Final consumptions of all building structures are calculated, and it can be observed at the below table as a summary.



#No	Buildings	Final Consumption MWh/a
1-)	Empire State Building	6437,1
2-)	Radio Tower	3306,0
3-)	Residential Balcony	3504,0
4-)	Dark Stylish	2416,6
5-)	Enterprise Tower	8004,1
6-)	Cylindrical Spradon	2067,4
7-)	Red Brick Building	4021,1
8-)	Shop Building	132,3
9-)	Villas (4 pieces)	27,4
10-)	Governor Building	79,5
	<b>TOTAL:</b>	<b>29995 MWh/a</b>

Table 8: The total consumption of all buildings

Total electricity demand of the model island is 29995 MWh annually and the total glass surfaces that can be replaced with TLSC is total of 16034 m<sup>2</sup>. Since most of the buildings are residential, the glass surface of the buildings is lower than modern day commercial skyscrapers with minimum of 90% glass coverage. In the following chapter, the possible electricity generation through transparent solar panels can be seen.



### 8.4 Defining Electricity Generation

This application type for solar panels is not recommended since the intensity of the sunlight that is reflected on the transparent solar panel surface is very low. Because of the vertical positioning, incoming sunlight is transformed into electricity is expected to be approximately 35% less than the one is placed 22-degree horizontally to catch the maximum amount. Possible outcome as energy generation is anticipated to be low but with enhancements in the near future, the power conversion factor also known as efficiency will be increased to supply more electricity from the same square meter of area. As mentioned before, this model project is assumed to in Munich area. Munich's latitude and longitude angles; 48.1351° N, 11.5820 ° E, respectively [62]. By using these coordinates, the solar radiation being diffuse, direct, and reflected are calculated by using MATLAB. The hourly data has been utilized since it gives more precise results. The solar radiation calculation via MATLAB coding can be seen at the appendix, and the results for solar radiation and generated energy is below.

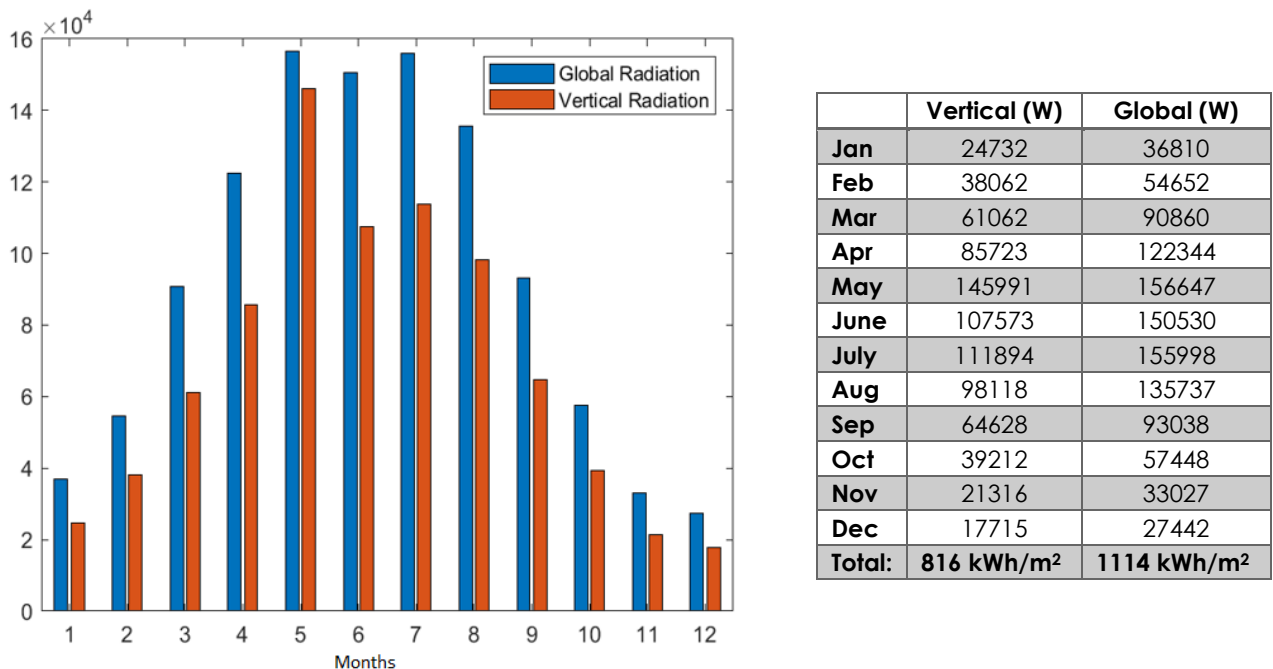


Figure 31: Solar radiation on horizontal surface vs vertical 90° - MATLAB

After reaching the solar radiation of 90-degree vertical positioned TLSC, total electricity generation can be calculated through multiplying the number of meter squared area that transparent solar panels are covered.

From the graph above, the horizontal (global) radiation is totalled to 1114,5 kWh/m<sup>2</sup>.a when the vertical radiation is 816 kWh/ m<sup>2</sup> annually at the given coordinates.

It can be demonstrated that the coding works well with manual computation of the identical outcomes. Electricity generation can be determined with using the multiplication of total area, performance ratio, vertical solar radiation, and the efficiency of the panel.



Performance ratio is assumed as the coefficient for losses by calculating the loss on inverter side, DC and AC cable loss, temperature fluctuations and being dirty on the panel surface. In this application, it is set to 0.8 and efficiency of the panel reaches 10% by stacking the TLSC sheets.

$$E = A * r * H * PR \tag{8.16}$$

**E** = Energy (kWh)

**A** = Total window surface area (m<sup>2</sup>)

**r** = Solar panel efficiency (%)

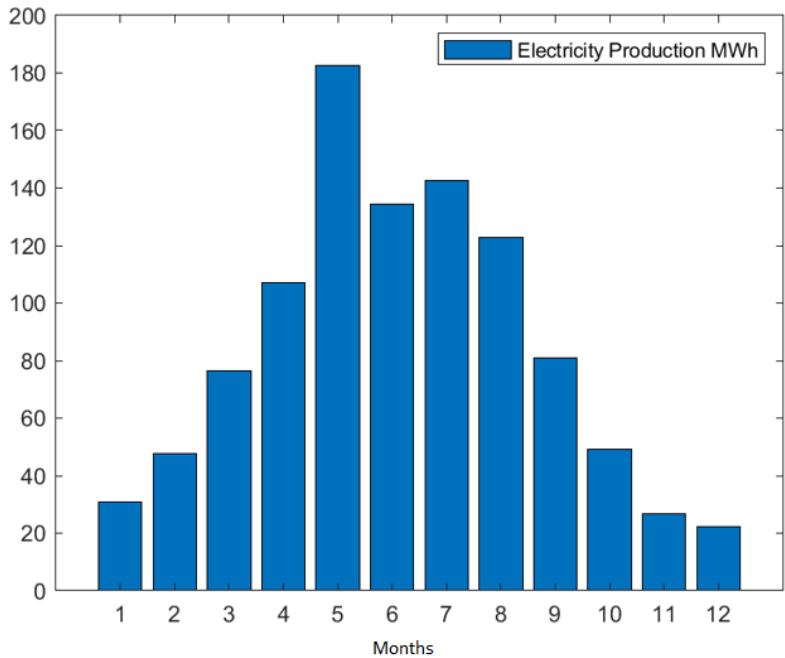
**H** = Annual average solar radiation on vertical surface (kWh/m<sup>2</sup>)

**PR** = Performance ratio, coefficient for losses, 0.8 [63]

Be aware that this nominal ratio is given for standard test conditions (STC): radiation=1000 W/m<sup>2</sup>, cell temperature=25 Celsius, wind speed=1 m/s, AM=1.5.

$$E = 16034 \text{ m}^2 * 10\% * 816 \text{ kWh/m}^2 \cdot a * 0.8 = \mathbf{1046,6 \text{ MWh/a} = 1,046 \text{ GWh/a}}$$

Let's see the MATLAB's result.



Jan	30,9 MWh
Feb	47,6 MWh
Mar	76,3 MWh
Apr	107,2 MWh
May	182,5 MWh
Jun	134,5 MWh
Jul	142,4 MWh
Aug	122,7 MWh
Sep	80,8 MWh
Oct	49,5 MWh
Nov	26,6 MWh
Dec	22,1 MWh

Figure 32: Electricity generation through all the window surfaces - MATLAB

The electricity generation through all the window surfaces in Model Island:

$$= \mathbf{1023,1 \text{ MWh} = 1,02 \text{ GWh}}$$



As it can be seen that both results are really close to each other, therefore calculation is resulted with minimal errors that can be neglected. All consumptions belonging to the buildings can be seen below at the given table along with window areas and the possible electricity generation. The total demand is around 30 GWh and the electricity generation is approximately 1 GWh annually. The compensation factor seems to be around 3.3% by using 10% efficient transparent luminescent solar concentrators that are installed on only south facet with the effect of lowered vertical solar radiation.

That does not apply to all structures when thinking separately. For example, the villas have more window surfaces than other structures, therefore it generates about the half of the consumption.

#No	Buildings	Final Consumption MWh/a	Total Window Area m <sup>2</sup>	Electricity Generation MWh
1-)	Empire State Building	6437,1	3912,28	255,39
2-)	Radio Tower	3306	1635,36	106,76
3-)	Residential Balcony	3504	968,13	63,20
4-)	Dark Stylish	2416,6	554,49	36,20
5-)	Enterprise Tower	8004,1	4357,95	284,49
6-)	Cylindrical Spradon	2067,4	1213,45	79,21
7-)	Red Brick Building	4021,1	3097,91	202,23
8-)	Shop Building	132,3	24,2	1,58
9-)	Villas (4 pieces)	27,4	186,37	12,17
10-)	Governor Building	79,5	84	5,48
	<b>TOTAL:</b>	<b>29995 MWh/a</b>	<b>16034 m<sup>2</sup></b>	<b>1046,71 MWh/a</b>

Table 9: Final overview table of the whole island

As the compensation factor is around 3.3% of the total consumption, only south facet placed TLSC does not make sense. For buildings on the northern hemisphere, panel surfaces must face to south in order to catch the maximum amount of sunlight. That being said, the other two facets as the west and east side of the building's window surfaces can be covered with TLSC as well to increase electricity generation. This will result in higher compensation factor which is crucial to adopt to a new technology by showing it to public that it is sufficient enough.

Based on what Vladimir Bulović (MIT) mentioned about the electricity production that if all of 4 surfaces of the structures are covered with TLSC even with a 5% efficiency, it could fulfil quarter of all electricity needs of the buildings [39]. This includes skyscrapers with 90% glass surface and not referring primary energy. It just emphasizes the electricity without including space heating demand. Certainly, supplying quarter of the total electricity demand is not very realistic in Germany compared to USA where this actual information is found. Because this research was done in California and its annual solar radiation is almost double as the Munich's location [64]. For demonstrating these numbers, the following model has been created in AutoCAD as a skyscraper to cover up all 4 facets to see the electricity generation and its compensation factor for the consumption.

## 9. Simulating 4 Facets TLSC Covered Skyscraper

As mentioned in previous chapter, a skyscraper is created to stimulate what Vladimir Bulović said was correct, assuming 250 kWh/m<sup>2</sup> annual consumption for primary energy demand is ideal as the European Commission stated [61].

In the figure below, the one on the right side is the Enterprise Tower from the model island to compare the size with the new skyscraper named Sapphire Tower. The base area of the Sapphire Tower is 40m into 40m and it has 50 floors, total of 250-meter height.

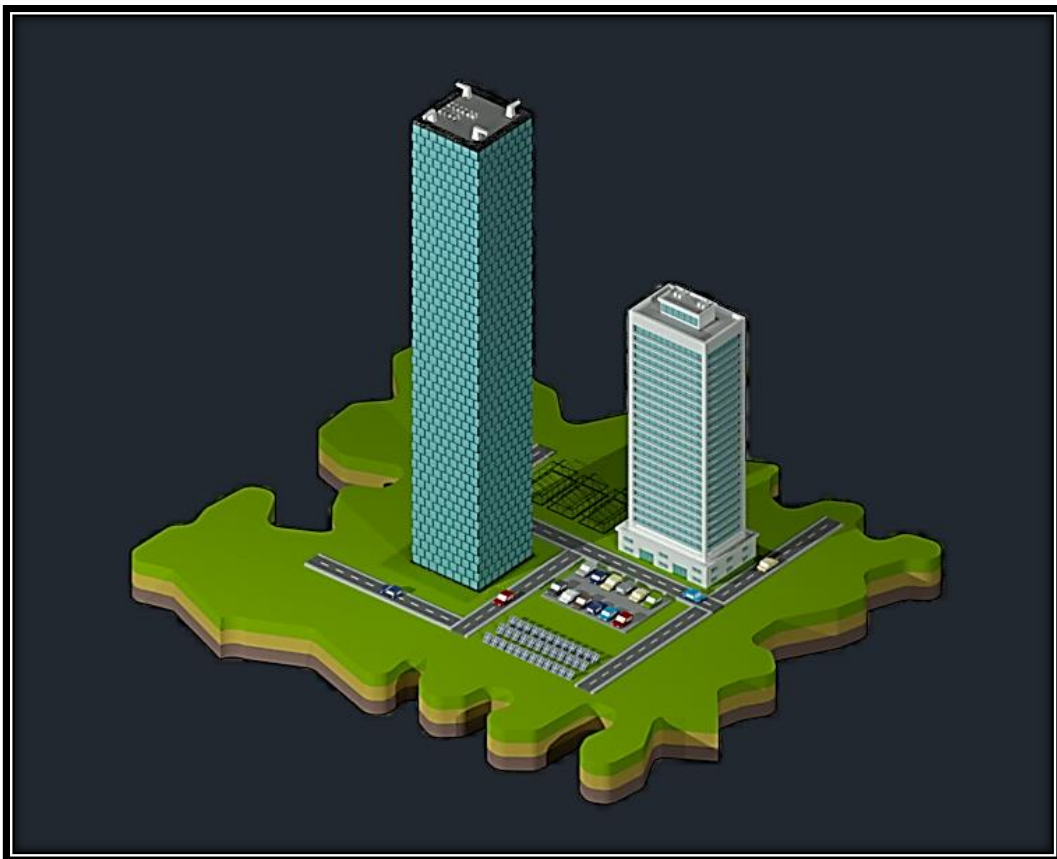


Figure 33: Sapphire and Enterprise Tower

It is assumed that the Sapphire Tower is covered with TLSC for all four surfaces to indicate the maximum possible electricity generation on a skyscraper.

Sapphire Tower	
Single Floor Area	1600 m <sup>2</sup>
Useful Area	1472 m <sup>2</sup>
Number of Floors	50
Architectural Height	250 m
Total Building Area	73600 m <sup>2</sup>
Single facet, one floor window area	162 m <sup>2</sup>
Total Skyscraper window area	32400 m <sup>2</sup>

Table 10: Architectural Specification of the Sapphire Tower



Only electricity consumption can be found from primary energy consumption which is determined as 250 kWh/m<sup>2</sup> annually. But this figure also contains the space heating which has to be subtracted to figure out what the actual electricity demand is. From the previous calculations where the space heating is calculated, it was also found around 50% of the total consumption without utilities. Herewith, primary energy consumption 250 kWh/m<sup>2</sup> can be admissible to 160 kWh/m<sup>2</sup> for only electricity demand.

Electricity consumption of the Sapphire Tower is:

- 50 floors x 1472 m<sup>2</sup> x 160 kWh/m<sup>2</sup>.a = **11776 MWh/a**

But each facet of the tower has various solar radiation throughout the daytime in order to generate electricity. It is assumed that the Sapphire Tower is located in Munich, Germany and since it is in Northern hemisphere, south facet of the building receives the highest radiation, east-west facets have the equal solar radiation amount, and the least is the north facet [71]. The figure below demonstrates the solar radiation changes in different directions as well as the effect of the positioning of the solar panel. Based on this figure, each facets of the tower are calculated with lowered solar radiation levels.

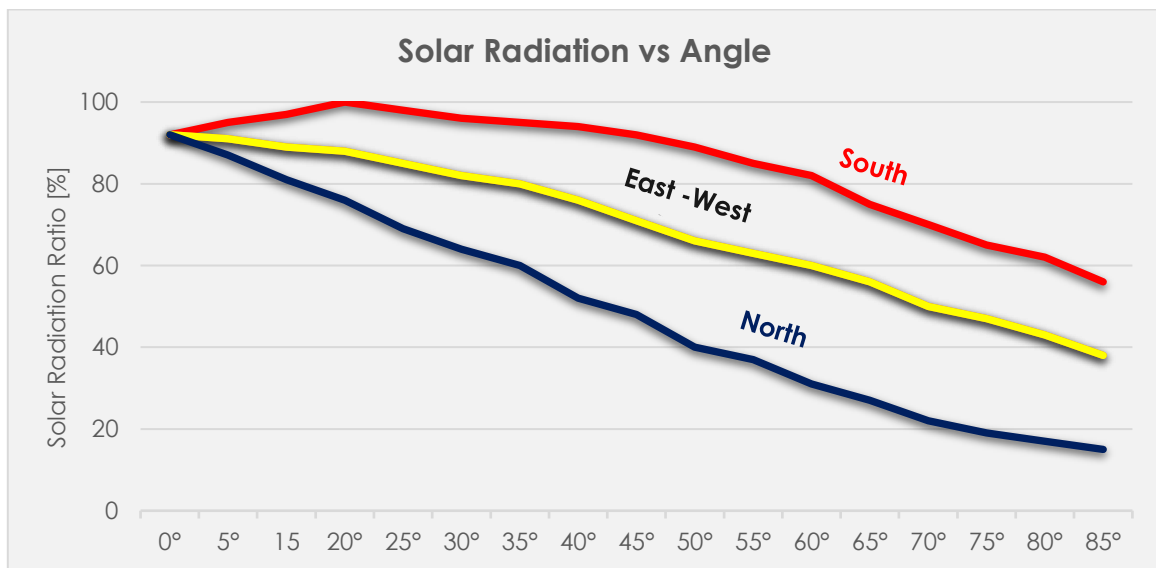


Figure 34: The solar radiation on different directions [own illustration, data from (71)]

The total glass surface of the Sapphire Tower is 32400 m<sup>2</sup>, therefore each facet has total of 8100 m<sup>2</sup> of surface that will be covered with TLSC. The vertical positioning of the panels leads to low generation due the ineffectiveness of the incoming sunlight which is even lower on other facets than south. As it can be seen above, the solar radiation on south facet with 22-degree positioning supplies the highest possible outcome but when it comes to vertical positioning it is only 52% of the total radiation received by the surface. From interpreting the figure, east and west facets are equal as 38% and the lowest radiation is on the north facet in vertical positioning.



The electricity is generated through the formula of  $E = A * r * H * PR$

- South:  $8100 \text{ m}^2 * 816,1 \text{ kWh/m}^2 * 10\% * 0,8 = 528,76 \text{ MWh/a}$
- East:  $8100 \text{ m}^2 * 596,2 \text{ kWh/m}^2 * 10\% * 0,8 = 386,33 \text{ MWh/a}$
- West:  $8100 \text{ m}^2 * 596,2 \text{ kWh/m}^2 * 10\% * 0,8 = 386,33 \text{ MWh/a}$
- North:  $8100 \text{ m}^2 * 235,3 \text{ kWh/m}^2 * 10\% * 0,8 = 152,47 \text{ MWh/a}$

**Total generated electricity: 1453,89 MWh/a**

Seen from above, even with the 10% efficient TLSC with relatively low radiation compared to the USA (%51), it is possible to generate **12,3%** of the total electricity demand. When more time and money is invested in the research and development side of the TLSC, it will hopefully cover more than 50% electricity demand to ensure that the world is on the right path to 100% sustainable energy generation.

Previously, the model island was investigated where only single surface of the building is covered with TLSC. But it is very crucial to demonstrate also all surfaces covered with transparent technology. Relatively more costs are expected in order to cover all four facets as well as generating more energy throughout the years until 2050 will be reviewed.

### 9.1 Comparison between USA and Germany

The Sapphire Tower has total of 32400 m<sup>2</sup> of window area to be replaced with TLSC in order to meet the energy demand. This time, another trendline is utilized to cover all the demand by 2050 and discover the necessary efficiency value to fulfil the energy demand. The Sapphire Tower requires **11776 MWh** of electricity annually. As of today, by reaching maximum 10% efficiency by stacking, it is possible to cover **12,3%** of the total demand in Munich region.

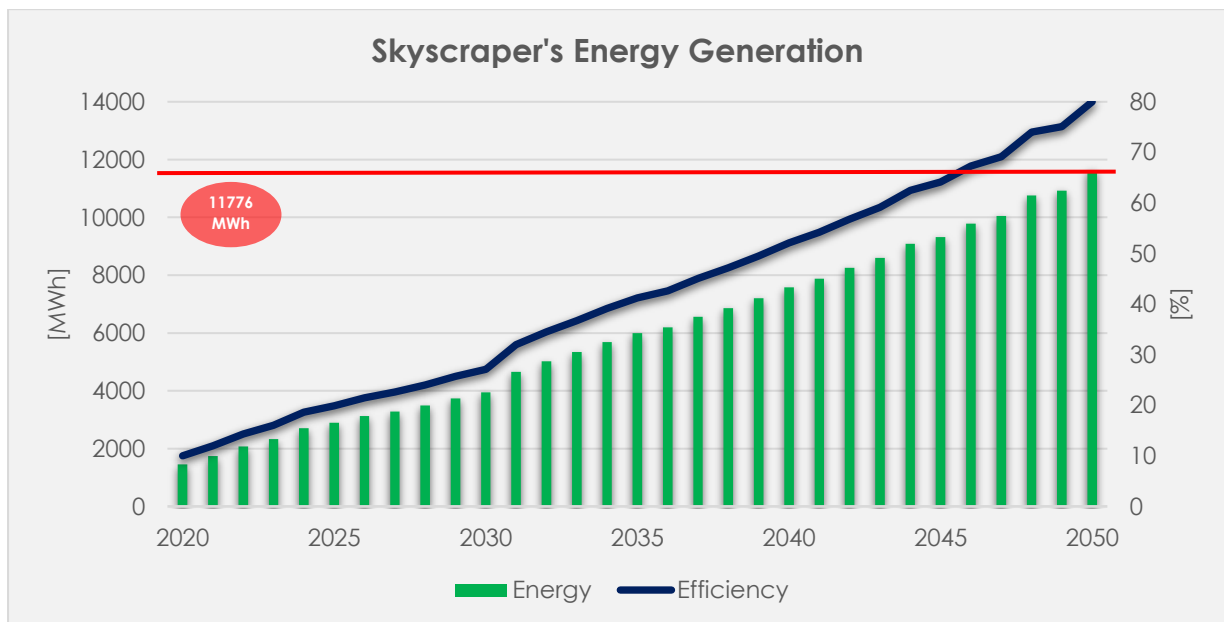


Figure 35: 4 facets TLSC covered Skyscraper's energy generation and its efficiency.



Covering all necessary demand in Munich region is only possible with high efficiency values since the solar radiation is low. The required efficiency value must reach to 80% in 2050 in order to compensate 100% of the consumption. But achieving more than 50% efficiency has never happened in any laboratories therefore it is not practical.

Though, building this skyscraper into somewhere sunnier, such as California, USA is the practical way to follow. Just to demonstrate the difference between the two regions, California has a daily global horizontal irradiation of 5,9 kWh/m<sup>2</sup> which results in 2153 kWh/m<sup>2</sup> annually [70]. The vertical irradiation calculation was done for Munich region and the difference between horizontal and vertical differs around 30%. Following result is for vertical radiation on south facet:

➤  $2153 \text{ kWh/m}^2 \cdot \text{a} \times 0,7 = \mathbf{1507 \text{ kWh/m}^2 \cdot \text{a}}$

Depending on what has been calculated in MATLAB for the vertical radiation in Munich region, it is accepted as the reference value for the vertical radiation in California with a latitude of 36° 46' 41.732" N and a longitude of 119° 25' 4.551" W [72].

Electricity generation through TLSC is calculated with  $E = A \cdot r \cdot H \cdot PR$

- South:  $8100 \text{ m}^2 \cdot 1507,0 \text{ kWh/m}^2 \cdot 10\% \cdot 0,8 = 976,5 \text{ MWh/a}$
- East:  $8100 \text{ m}^2 \cdot 1101,2 \text{ kWh/m}^2 \cdot 10\% \cdot 0,8 = 713,5 \text{ MWh/a}$
- West:  $8100 \text{ m}^2 \cdot 1101,2 \text{ kWh/m}^2 \cdot 10\% \cdot 0,8 = 713,5 \text{ MWh/a}$
- North:  $8100 \text{ m}^2 \cdot 434,71 \text{ kWh/m}^2 \cdot 10\% \cdot 0,8 = 281,6 \text{ MWh/a}$

**Total generated electricity: 2685,1 MWh/a**

Total generated electricity in California is enough to compensate 23% of the Sapphire Tower's consumption, comparing with Munich is only 12,3%. Just because the solar radiation is almost twice as higher than Munich region, the energy generated is almost doubled. Unfortunately, everywhere around the world does not receive the same solar radiation. For that reason, the only possible way to generate more energy from the same square meter is to enhance the power-energy conversion efficiency. For the given California example, if the efficiency of the TLSC is increased to approximately 43,8%, then the full compensation is possible for the entire consumption by using some energy storage systems (ESS) to supply energy even during the nighttime. Since in solar technologies, 44,5% efficiency is achieved in July 2017, therefore it is a credible target.

## 10. Future Scenarios

PV modules has been in the market commercially since 1975. Over the course of 45 years, the PV cell unit prices have dropped down around 5000%. When it was first commercialized, the price per Watt was \$105,7 [67]. All the technological development on the PV cell manufacturing techniques and new concepts for power-energy conversion efficiency led the way to decrease the pricing to only 0,2 \$/Watt on monocrystalline solar panels. This huge dropdown ensured the world meet enough solar power in order to generate totally green energy.

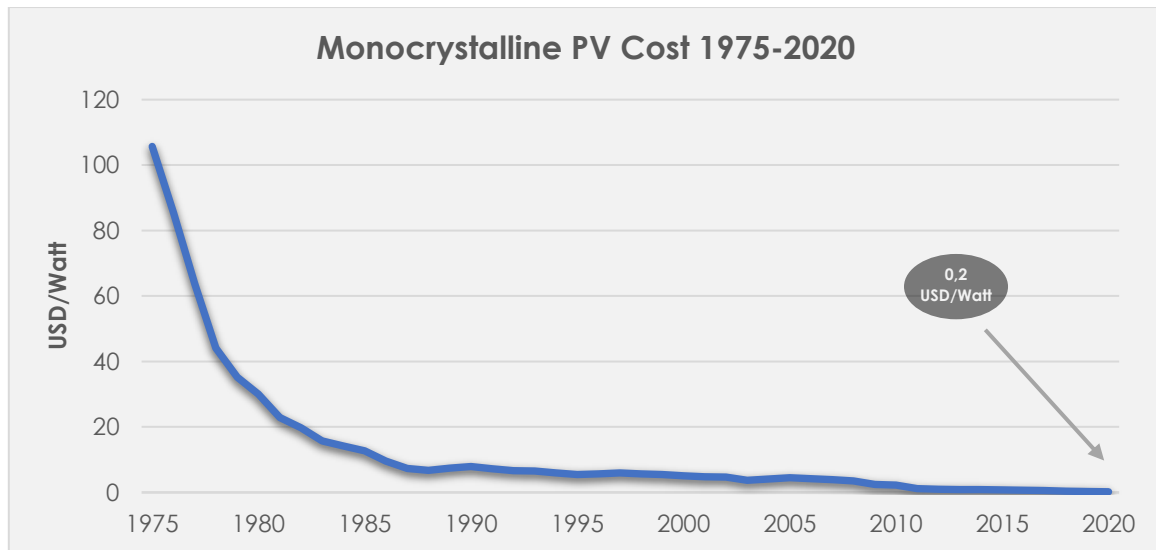


Figure 36: Price dropdown of monocrystalline cells per watt [67]

All the countries have to eliminate the conventional way of generating energy through the fossil fuel-based power plant. The Earth has received enough destruction by humans, and this has to end, therefore the European Union and some other countries have set the energy targets for 2030 and 2050.

### Targets for 2030:

- At least 40% cuts in greenhouse gas emissions. (Compared with 1990 levels)
- At least 32% share for renewable energy.
- At least 32.5% improvement in energy efficiency. [68]

### Targets for 2050:

- 100% sustainable energy by 2050.
- Aiming to achieve CO<sub>2</sub> emission reduction by 95% lower than in 1990. [69]



Since the targets are ambitious, the easiest way to reach is to focus fully on solar energy since the earth receives more solar radiation in an hour compared with the whole year's energy consumption. This gap can be compensated with transparent luminescent solar concentrators by using on every single building window surface areas. To ensure these energy targets are possible, huge technical developments must be on the way. Today, the TLSC technology is expensive in proportion to monocrystalline because it is still at the advancement stage. According to SolarWindow Technologies, one of the earliest commercial companies in the field, the solar window cost around 2000\$ per meter square with a 65 Watts output [65]. This is approximately 30\$/Watt, has the same cost of monocrystalline solar cells in 1980.

By taking the Figure 36 into account, TLSC's future cost in 2030 and 2050 can be presumed. By considering years between 2010 and 2020 on monocrystalline price dropdown, the predicted 2030 and 2050 cost per Watt for TLSC can be seen below.

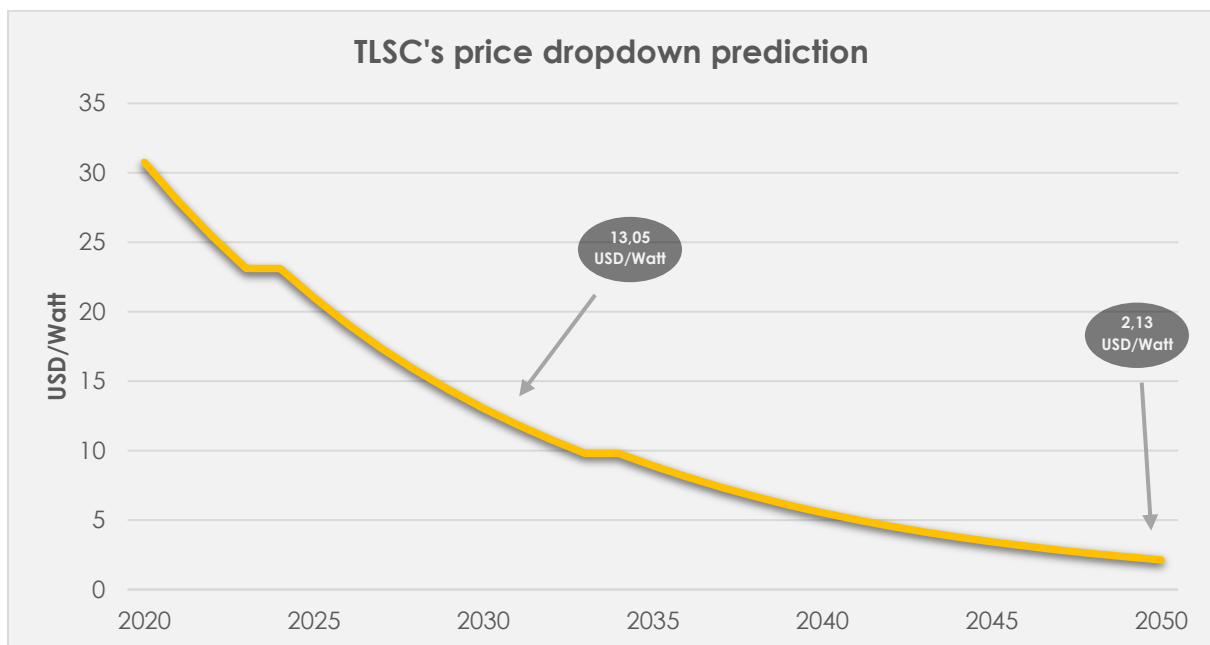


Figure 36: Predicted price dropdown of TLSC per watt

### 10.1 Financial Point of View of the Model Island

In the previous part, predicted price dropdown of transparent luminescent solar concentrators has been shown. Based on these numbers, if the project Model Island plans to be occurred in also in years 2030 and/or 2050, what would be the total project budget in order to generate maximum amount of energy with enhanced efficiency through window surfaces will be reviewed.

- 2020 – 30,76 USD/Watt
- 2030 – 13,05 USD/Watt
- 2050 – 2,13 USD/Watt



As of today, all TLSC windows are very expensive, relatively to low power conversion efficiency and also high manufacturing costs compared to monocrystalline PV panels. But when it comes to efficiency, serious amount of work is ahead although scientists have managed to create a prototype PV cell which has an efficiency of 44,5% which still holds the world highest power conversion ratio. Assuming that the same path is followed by TLSC, then the maximum generated energy through the island and their cost will be shown below for the years of 2030 and 2050.

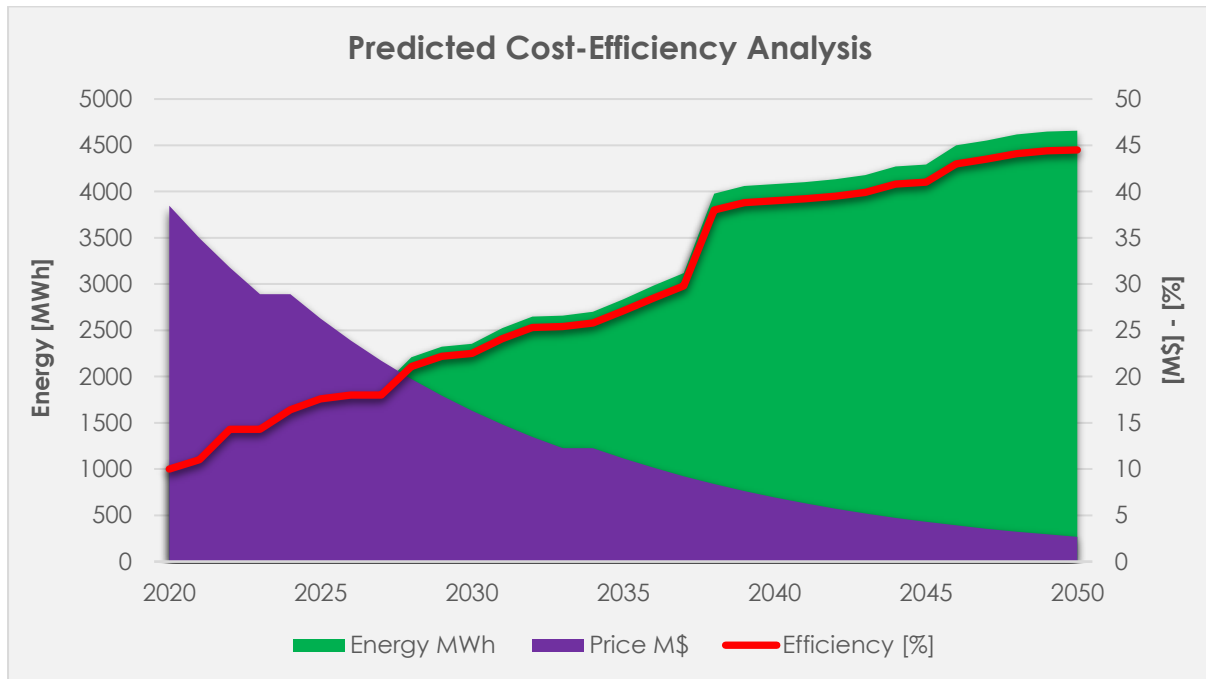


Figure 37: Correlation between cost and efficiency over 30 years

The Model Island was to take place in 2030 and 2050, covering up 1 6034 m<sup>2</sup> of window surfaces results in:

- 2020 – 38,47 million \$
- 2030 – 16,31 million \$
- 2050 – 2,66 million \$

This huge cost dropdowns are realistic, and even more than these drops are expected to be seen in the near future with more research and development activities.

## 10.2 Financial Point of View of Sapphire Tower

The Sapphire Tower has total of 32400 m<sup>2</sup> of glass surface is covered with transparent luminescent solar concentrator in order to compensate the electricity consumption. The same trendline for the future price prediction is utilized to identify the future scenario. The following figure 38 demonstrates the cost descend through 30 years. Moreover, required efficiency levels of the TLSC to supply necessary demand both in Germany and USA have shown below.



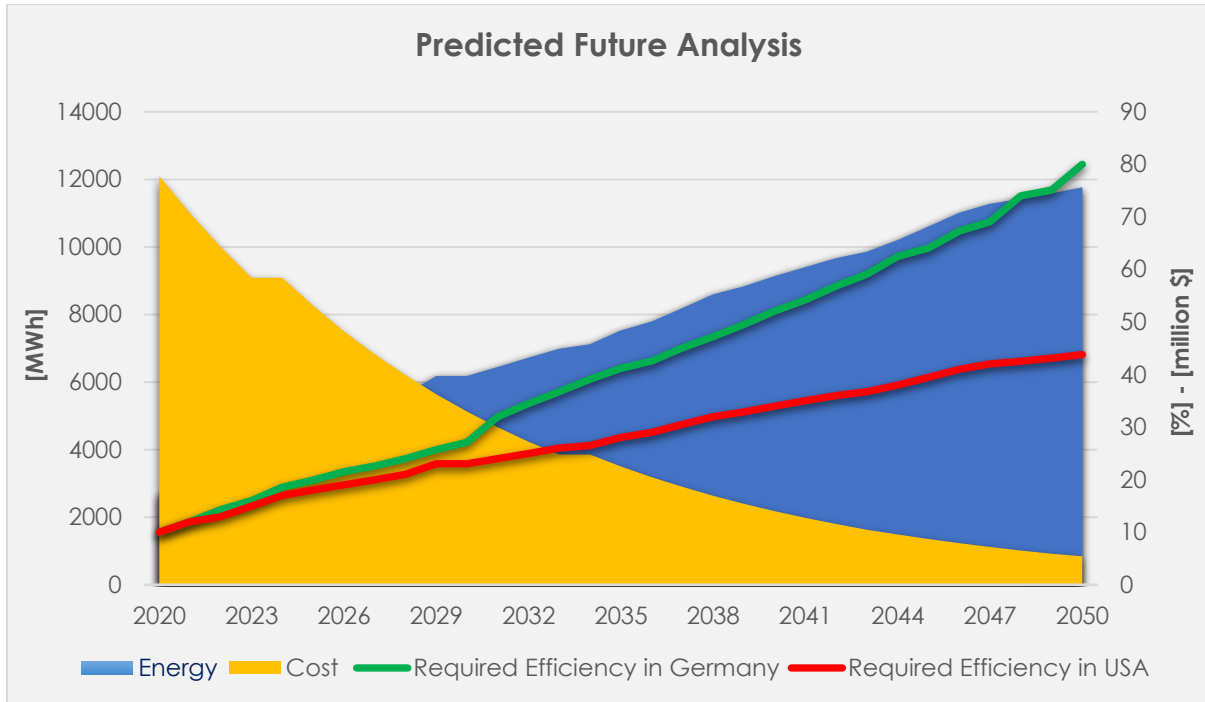


Figure 38: Required energy levels to provide full compensation and cost forecast

The Sapphire Tower was to take place in 2030 and 2050, covering up 32400 m<sup>2</sup> of glass surfaces results in:

- 2020 – 77,73 million \$
- 2030 – 32,96 million \$
- 2050 – 5,39 million \$

As a result, in Munich region where sun is not so powerful as California region, it is not possible to cover up all the demand. But the same purpose can be achieved by implementing into the high solar radiation areas around the globe.

## 11. Overview Program

The program is designed by using Virtual Studio in order to illustrate all the buildings technical specifications along with the possible electricity generation through its windows. The program is not limited only with the model island's buildings but also it gives access to the users who would like to define the electricity generation on own.

There are 10 buildings in display, and it is possible to switch between them by using previous and next buttons. Soon as clicking on the button, all information about the structures is shown at the screen. While seeing the information, the 360° view of the buildings are continuously appeared in the program.



Figure 39: The interface of the overview program

As the second part of the program, calculation of own is possible. By just entering the required 5 data shows the result of generated energy and its compensation factor compared with the consumption. As it is seen, the reference values illustrate the Model Island's numbers and results are shown at the below Figure 40.

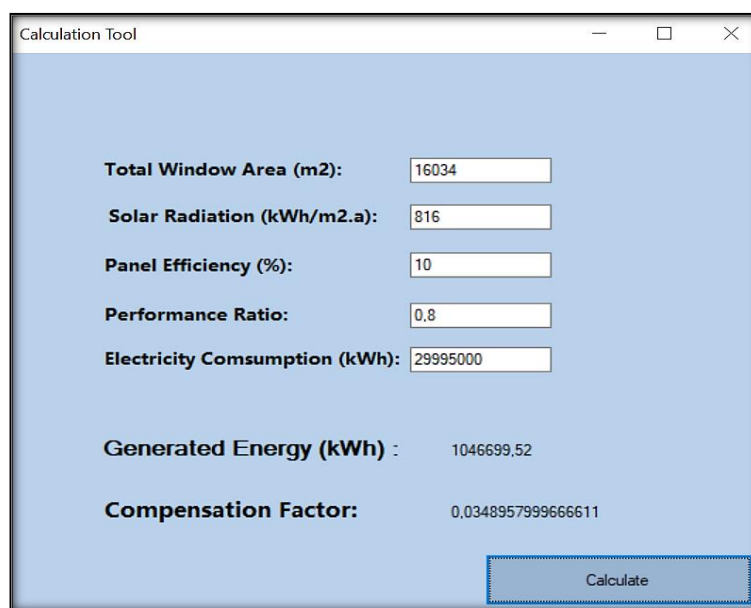


Figure 40: Calculation tool of the overview program

## 12. Conclusion

Throughout mankind's set of experiences, technological advancements bring along more innovative improvements with, therefore there has always been enhancements and will always continue so. Countries over the globe have been investing massive amount of money into renewable technologies, especially in the last two decades. This is mostly because renewables are accepted to form the future since they rely on only natural resources compared to fossil fuels which uses sources that would eventually die out. Among the renewables, the solar power has been the most significant since it has been assured that the solar radiation that travels to Earth is enough to fulfil the whole energy demand of humanity less than an hour. Especially beginning with 2018, solar has been a trend and invested in highly (Figure 6). This high number of investments led researchers focus on inventing further technologies to be implemented in new areas such as BIPV, floating farms as well as CSP. Moreover, increment in the power to energy conversion efficiency has started to be a focus.

Another breath-taking discovery was made in 2013 by MIT academics which is the centre of this thesis study, transparent luminescent solar concentrators. Contrary to consuetudinary solar panels, TLSC catches invisible wavelengths of the sunlight, allowing the light pass through the surface of the panel and illuminate the back of it. Therefore, it is possible to use them in building's window surfaces which would provide an immense amount of area apart from the land areas. Unfortunately, the efficiency is only available up to 10% by stacking solar cell sheets. In order to demonstrate the application of the TLSC, an island consisting of 10 building structures has been created using AutoCAD and it is assumed to be located in Munich region. Since the window surfaces are replaced with TLSC, they would be in vertical positioning which would cause lower radiation. Accordingly, the solar radiation calculation has been done using MATLAB to define exact vertical radiation. After obtaining the required data, total possible generated electricity is calculated with given window surfaces. Since Munich receives relatively lower radiation compared to the most sun-efficient parts of the world, compensation of the energy consumption does not exceed 4% by only placing to the south facet of the buildings.

If this project were implemented in California, USA, covering four facets of skyscrapers which are consisted of 90% glass surfaces, would provide around 23% of the total consumption. To reach full compensation of the electricity consumption in California region, the efficiency of the TLSC must increase to 43,8%. On the other hand, Munich would require 80% efficient panel which is not realistic since even in the STC, maximum of 44,5% efficiency was reached among PV cells in 2017.

Lastly, a program has been formed using Virtual Studio in order to illustrate the island's buildings specifications, as well as its own calculation tool is available for the users to self-calculate their own structures. Consequently, this is the evidence that solar technology is not the sole way but is considered to be the most efficient, beneficial, and futuristic energy supply for our world.

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## APPENDIX

### Coding for solar radiation calculation in MATLAB

#### STEP 1: Days of the year 2020

```
%From Jan 1st to Dec 31st - 365 days
number_of_days=[1:1:365]';
```

#### STEP 2: Finding necessary angle

Latitude, zenith angle, tilt angle (90), hour angle & declination angle must be known to proceed. %

```
latitude_Munich= 48.13;
declination_Munich = 23.45*sin(2*pi/365*(284+number_of_days));
tilt_angle = 90; %Vertical Positioning%
azimuth = 180; %for south facet%
reflection_coefficient = 0.15;
```

#### STEP 3: Hour Angle Calculation

```
LSMT_Munich = 15; % Local Standard Time Meridian %
LL_Munich = 11.34; % Longitude %
LT = [0:1:23]; % Local Time %
global_hourly_Munich = 360*(number_of_days-81)/365;
EoT_Munich = 9.87*sind(2*global_hourly_Munich) - 7.53*cosd(global_hourly_Munich) -
1.5*sind(global_hourly_Munich);
LST_Munich = LT + EoT_Munich/60 + 4*(LL_Munich-LSMT_Munich)/60; % Local Solar Time%
hour_angle_Munich = 15*(LST_Munich-12);
```

#### STEP 4: Cos Zenith

```
cos_zenith_Munich = sin(latitude_Munich).*sin(declination_Munich)+
cosd(latitude_Munich).*cosd(declination_Munich).*cosd(hour_angle_Munich);
zenith_angle_Munich = real(mean(acosd(cos_zenith_Munich)));
altitude_angle_Munich = 90 - zenith_angle_Munich;
% For deleting unnecessary values %
rowstoDelete = altitude_angle_Munich < 0;
altitude_angle_Munich(rowstoDelete) = [0];
```

#### STEP 5: Angle of Incidence

```
azimuth_angle_Munich =
(cosd(declination_Munich).*sind(latitude_Munich).*cosd(hour_angle_Munich)-
sind(declination_Munich).*cosd(latitude_Munich) )./cosd(altitude_angle_Munich);

cos_angle_of_incidence_Munich = ( cosd(latitude_Munich).*cosd(tilt_angle) +
sind(latitude_Munich).*sind(tilt_angle).*cosd(azimuth)
).*cosd(declination_Munich).*cosd(hour_angle_Munich) +
cosd(declination_Munich).*sind(hour_angle_Munich).*sind(tilt_angle).*sind(azimuth)+
sind(declination_Munich).*( sind(latitude_Munich).*cosd(tilt_angle) -
cosd(latitude_Munich).*sind(tilt_angle).*cosd(azimuth));

incidence_angle_Munich = ( acosd (cos_angle_of_incidence_Munich));
```



## STEP 6: Sunset Hour

```
sunset_hour_Munich = acosd (-tand(latitude_Munich).*tand(declination_Munich));
```

## STEP 7: Direct and Diffused hourly horizontal

```
Muc = ((pi/24).*(cosd(hour_angle_Munich) - (cosd(sunset_hour_Munich)))) ./
(sind(sunset_hour_Munich)-
((2*pi.*sunset_hour_Munich./360).*cosd(sunset_hour_Munich)));

global_daily_Munich = dlmread('daily_global_radiation_Munich.m');
global_hourly_Munichx = (Muc.*global_daily_Munich*1000); %Hourly global radiation %
global_hourly_trans_Munich = global_hourly_Munichx';
global_hourly_Munich = reshape(global_hourly_trans_Munich,[8760,1]);
% For deleting unnecessary values %
rowstoDelete = global_hourly_Munich < 0; % Horizontal Radiation %
global_hourly_Munich(rowstoDelete) = [0]; % Global (horizontal) radiation W/m2

diffuse_daily_Munich = dlmread ('daily_diffuse_radiation_Munich.m');
diffuse_hourly_Munichx = (Muc.*diffuse_daily_Munich*1000);
diffuse_hourly_trans_Munich = diffuse_hourly_Munichx';
diffuse_hourly_Munich = reshape (diffuse_hourly_trans_Munich,[8760,1]);
% For deleting unnecessary values %
rowstoDelete = diffuse_hourly_Munich < 0;
diffuse_hourly_Munich(rowstoDelete) = [0]; % Diffuse radiation W/m2

direct_daily_Munich = dlmread ('daily_direct_radiation_Munich.m');
direct_hourly_Munichx = (Muc.*direct_daily_Munich*1000);
direct_radiation_trans_Munich = direct_hourly_Munichx';
direct_hourly_Munich = reshape (direct_radiation_trans_Munich,[8760,1]);
% For deleting unnecessary values %
rowstoDelete = direct_hourly_Munich < 0;
direct_hourly_Munich(rowstoDelete) = [0] ; % Direct Radiation W/m2

global_hourly_irradiance_Munich_Jan = sum(global_hourly_Munich(1:31*24));
global_hourly_irradiance_Munich_Feb = sum(global_hourly_Munich(32*24:59*24));
global_hourly_irradiance_Munich_Mar = sum(global_hourly_Munich(60*24:90*24));
global_hourly_irradiance_Munich_Apr = sum(global_hourly_Munich(91*24:120*24));
global_hourly_irradiance_Munich_May = sum(global_hourly_Munich(121*24:151*24));
global_hourly_irradiance_Munich_Jun = sum(global_hourly_Munich(152*24:181*24));
global_hourly_irradiance_Munich_Jul = sum(global_hourly_Munich(182*24:212*24));
global_hourly_irradiance_Munich_Aug = sum(global_hourly_Munich(213*24:243*24));
global_hourly_irradiance_Munich_Sep = sum(global_hourly_Munich(244*24:273*24));
global_hourly_irradiance_Munich_Oct = sum(global_hourly_Munich(274*24:304*24));
global_hourly_irradiance_Munich_Nov = sum(global_hourly_Munich(305*24:334*24));
global_hourly_irradiance_Munich_Dec = sum(global_hourly_Munich(335*24:365*24));

Monthly_Global_Radiation_Munich = [global_hourly_irradiance_Munich_Jan
global_hourly_irradiance_Munich_Feb global_hourly_irradiance_Munich_Mar
global_hourly_irradiance_Munich_Apr global_hourly_irradiance_Munich_May
global_hourly_irradiance_Munich_Jun global_hourly_irradiance_Munich_Jul
global_hourly_irradiance_Munich_Aug global_hourly_irradiance_Munich_Sep
global_hourly_irradiance_Munich_Oct global_hourly_irradiance_Munich_Nov
global_hourly_irradiance_Munich_Dec];
```



## STEP 8: Vertical Hourly Global Irradiance

```

Rdirect_Munich = incidence_angle_Munich ./ zenith_angle_Munich ;
Rdirect_vector_Munich = reshape (Rdirect_Munich',[8760,1]);
Rdiffused = ( 1 + cosd(tilt_angle) )/2;
Reflected = ( 1 - cosd(tilt_angle) )/2;

vertical_hourly_global_irradiance_Munich =
direct_hourly_Munich.*Rdirect_vector_Munich+ diffuse_hourly_Munich.*mean(Rdiffused)
+ reflection_coefficient.*mean(Reflected).*( direct_hourly_Munich +
diffuse_hourly_Munich );
vertical_hourly_global_irradiance_Munich_Jan =
sum(vertical_hourly_global_irradiance_Munich(1:31*24));
vertical_hourly_global_irradiance_Munich_Feb =
sum(vertical_hourly_global_irradiance_Munich(32*24:59*24));
vertical_hourly_global_irradiance_Munich_Mar =
sum(vertical_hourly_global_irradiance_Munich(60*24:90*24));
vertical_hourly_global_irradiance_Munich_Apr =
sum(vertical_hourly_global_irradiance_Munich(91*24:120*24));
vertical_hourly_global_irradiance_Munich_May =
sum(vertical_hourly_global_irradiance_Munich(121*24:151*24));
vertical_hourly_global_irradiance_Munich_Jun =
sum(vertical_hourly_global_irradiance_Munich(152*24:181*24));
vertical_hourly_global_irradiance_Munich_Jul =
sum(vertical_hourly_global_irradiance_Munich(182*24:212*24));
vertical_hourly_global_irradiance_Munich_Aug =
sum(vertical_hourly_global_irradiance_Munich(213*24:243*24));
vertical_hourly_global_irradiance_Munich_Sep =
sum(vertical_hourly_global_irradiance_Munich(244*24:273*24));
vertical_hourly_global_irradiance_Munich_Oct =
sum(vertical_hourly_global_irradiance_Munich(274*24:304*24));
vertical_hourly_global_irradiance_Munich_Nov =
sum(vertical_hourly_global_irradiance_Munich(305*24:334*24));
vertical_hourly_global_irradiance_Munich_Dec =
sum(vertical_hourly_global_irradiance_Munich(335*24:365*24));

Monthly_Production_Munich = [vertical_hourly_global_irradiance_Munich_Jan
vertical_hourly_global_irradiance_Munich_Feb
vertical_hourly_global_irradiance_Munich_Mar
vertical_hourly_global_irradiance_Munich_Apr
vertical_hourly_global_irradiance_Munich_May
vertical_hourly_global_irradiance_Munich_Jun
vertical_hourly_global_irradiance_Munich_Jul
vertical_hourly_global_irradiance_Munich_Aug
vertical_hourly_global_irradiance_Munich_Sep
vertical_hourly_global_irradiance_Munich_Oct
vertical_hourly_global_irradiance_Munich_Nov
vertical_hourly_global_irradiance_Munich_Dec ];
    
```



## STEP 9: Electricity Production

```

Vertical_Radiation = vertical_hourly_global_irradiance_Munich;

electricity_cost = 29; %cents
feedin_tariff = 8 %cents

Module_Power = 78; %Wp
Total_window_surface = 16034;

Hourly_Peak_Solar_Hour = Vertical_Radiation/1000;
Daily_Peak_Solar_Hour = reshape ( Hourly_Peak_Solar_Hour,24,365);
Daily_Peak_Solar_Hour_Total = sum(Daily_Peak_Solar_Hour);
Hourly_Energy_Production = Hourly_Peak_Solar_Hour * Module_Power *
(Total_window_surface) / 1000000;
Annual_Energy_Production = round (sum (Hourly_Energy_Production)); %MWh

Production_Jan = sum(Hourly_Energy_Production(1:31*24));
Production_Feb = sum(Hourly_Energy_Production(32*24:59*24));
Production_Mar = sum(Hourly_Energy_Production(60*24:90*24));
Production_Apr = sum(Hourly_Energy_Production(91*24:120*24));
Production_May = sum(Hourly_Energy_Production(121*24:151*24));
Production_Jun = sum(Hourly_Energy_Production(152*24:181*24));
Production_Jul = sum(Hourly_Energy_Production(182*24:212*24));
Production_Aug = sum(Hourly_Energy_Production(213*24:243*24));
Production_Sep = sum(Hourly_Energy_Production(244*24:273*24));
Production_Oct = sum(Hourly_Energy_Production(274*24:304*24));
Production_Nov = sum(Hourly_Energy_Production(305*24:334*24));
Production_Dec = sum(Hourly_Energy_Production(335*24:365*24));

Monthly_Production_Munich =
[Production_Jan;Production_Feb;Production_Mar;Production_Apr;Production_May;Product
ion_Jun;Production_Jul;Production_Aug;Production_Sep;Production_Oct;Production_Nov;
Production_Dec]

bar([Monthly_Production_Munich], 'group')
TotalEnergy = sum(Monthly_Production_Munich) %MWh
TotalIncome = (feedin_tariff.*TotalEnergy)/100 %€
    
```

## Coding for Overview Program in Virtual Studio

```

1 //OVERVIEW PROGRAM
2
3 using ClosedXML.Excel;
4 using Microsoft.Office.Interop.Excel;
5 using System;
6 using System.Collections.Generic;
7 using System.ComponentModel;
8 using System.Data;
9 using System.Drawing;
10 using System.Linq;
11 using System.Text;
12 using System.Threading.Tasks;
13 using System.Windows.Forms;
14 using Excel = Microsoft.Office.Interop.Excel;
15 using System.Collections.Generic;
16
17 namespace Berkan_Proje
18 {
19     4 başvuru
20     public partial class Form1 : Form
21     {
22         string[] video_urls = {
23             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Dark Stylish.mp4",
24             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Empire State.mp4",
25             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Enterprise Tower.mp4",
26             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Governor Building.mp4",
27             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Radio Tower.mp4",
28             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Red Brick Building.mp4",
29             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Residential Balcony.mp4",
30             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Shop Building.mp4",
31             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Cylindrical Spradon.mp4",
32             @"C:\Users\Berkanay\Desktop\Project\berkan videolar\Villa.mp4"
33         };
    
```

```

35         string[] video_names = {
36             "Dark Stylish",
37             "Empire State",
38             "Enterprise Tower",
39             "Governor Building",
40             "Radio Tower",
41             "Red Brick Building",
42             "Residential Balcony",
43             "Shop Building",
44             "Cylindrical Spradon",
45             "Villa"
46         };
47
48
49         1 başvuru
50         public Form1()
51         {
52             InitializeComponent();
53         }
54
55         // CREATE EXCEL OBJECTS.
56
57         OpenFileDialog OpenFileDialog1 = new OpenFileDialog();
58
59         int iRow, iCol = 2;
60         int count_for_excel = 0;
61         int count = 0;
62         int video_count = 0;
    
```



```

64 private void readExcel(int count1)
65 {
66     Excel.Application xlApp = new Excel.Application();
67     Excel.Workbook xlWorkbook = xlApp.Workbooks.Open(@"C:\Users\Berkanay\Desktop\Project\Berkan_excel.xlsx");
68     Excel.Worksheet xlWorksheet = xlWorkbook.Sheets[1];
69     Excel.Range xlRange = xlWorksheet.UsedRange;
70     int rowCount = xlRange.Rows.Count;
71     int colCount = xlRange.Columns.Count;
72
73     label7.Text = Convert.ToString(xlRange.Cells[count+2, 2].value);
74     label12.Text = Convert.ToString(xlRange.Cells[count+2, 3].value);
75     label10.Text = Convert.ToString(xlRange.Cells[count + 2, 4].value);
76     label9.Text = Convert.ToString(xlRange.Cells[count + 2, 5].value);
77     label8.Text = Convert.ToString(xlRange.Cells[count + 2, 6].value);
78     label16.Text = Convert.ToString(xlRange.Cells[count + 2, 7].value);
79     label18.Text = Convert.ToString(xlRange.Cells[count + 2, 8].value);
80
81 }
82
83
84
85 1 başvuru
86 private void button3_Click(object sender, EventArgs e)
87 {
88     axWindowsMediaPlayer1.URL = video_urls[video_count];
89     axWindowsMediaPlayer1.Ctlcontrols.play();
90     axWindowsMediaPlayer1.settings.setMode("loop", true);
91     this.textBox1.Text = video_names[video_count];
92     readExcel(count_for__excel);

```

```

94 1 başvuru
95 private void button4_Click(object sender, EventArgs e)
96 {
97     video_count = video_count + 1;
98     axWindowsMediaPlayer1.URL = video_urls[video_count];
99     axWindowsMediaPlayer1.Ctlcontrols.play();
100    axWindowsMediaPlayer1.settings.setMode("loop", true);
101    this.textBox1.Text = video_names[video_count];
102    count = count + 1;
103    readExcel(count_for__excel);
104
105 1 başvuru
106 private void button5_Click(object sender, EventArgs e)
107 {
108     video_count = video_count - 1;
109     axWindowsMediaPlayer1.URL = video_urls[video_count];
110     axWindowsMediaPlayer1.Ctlcontrols.play();
111     axWindowsMediaPlayer1.settings.setMode("loop", true);
112     this.textBox1.Text = video_names[video_count];
113     count = count - 1;
114     readExcel(count_for__excel);

```

## Coding for Calculation Tool in Virtual Studio

```

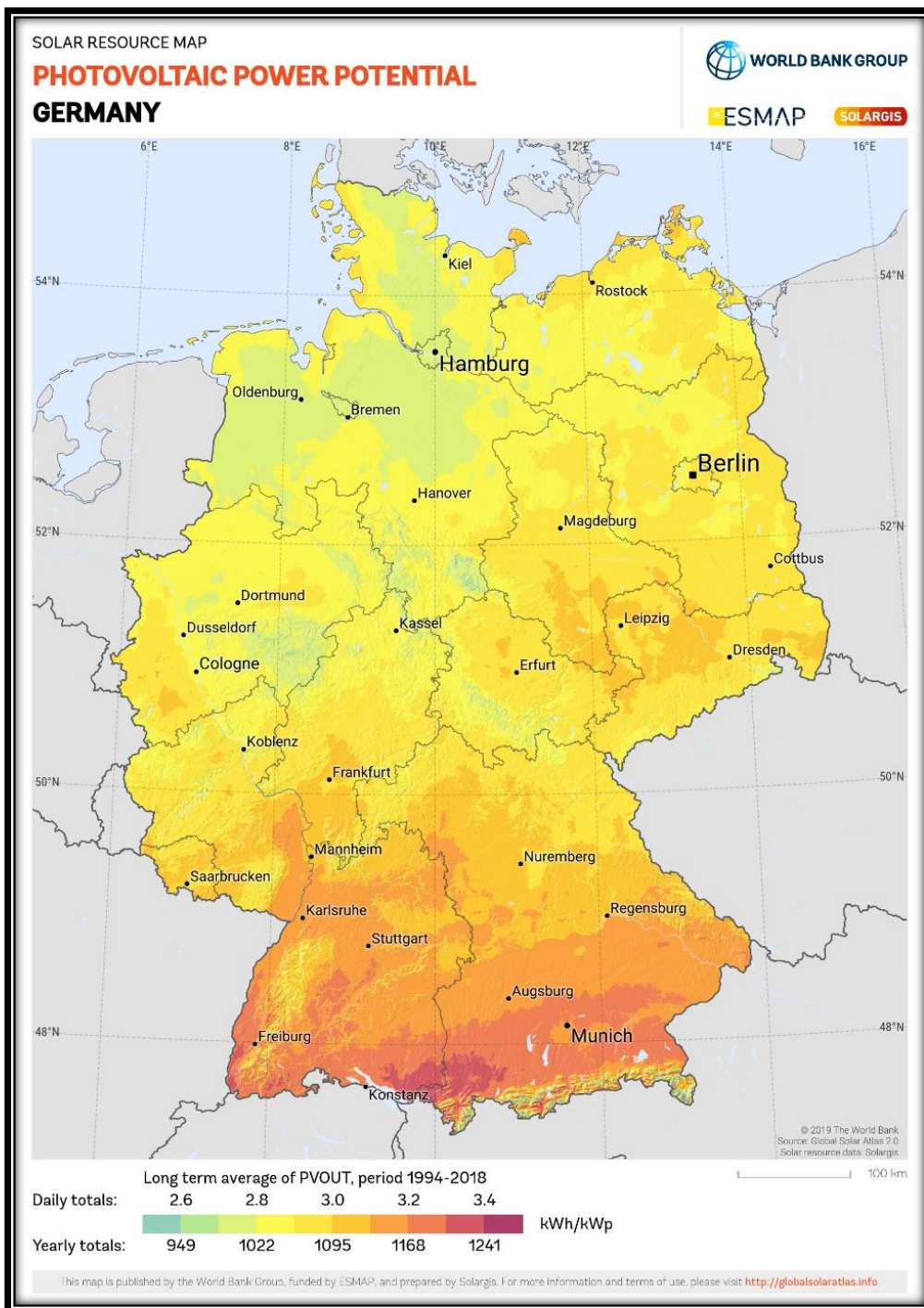
26 1 başvuru
27 private void button1_Click(object sender, EventArgs e)
28 {
29     // E = A * r * H * PR
30     // E --> Energy Generation A --> Window Area r -->
31     // Efficiency of Panel H --> Annual Average of Solar Radiation of Vertical Surface PR --> Performance Ratio
32     double Total_Window_Area = Convert.ToDouble(textBox5.Text);
33     double Solar_Radiation = Convert.ToDouble(textBox4.Text);
34     double Panel_Efficiency = Convert.ToDouble(textBox2.Text);
35     double Performance_Ratio = Convert.ToDouble(textBox1.Text);
36     double Electricity_Consumption = Convert.ToDouble(textBox3.Text);
37
38     double Generated_Energy = (Total_Window_Area * Panel_Efficiency * Solar_Radiation * Performance_Ratio)/100;
39     label8.Text = Convert.ToString(Generated_Energy);
40     double Compensation_factor = Generated_Energy / Electricity_Consumption;
41     label2.Text = Convert.ToString(Compensation_factor);

```





## Solar Radiation Map of Germany





## Solar Radiation Map of United States

