

# **Technische Hochschule Ingolstadt**

## **Faculty of Mechanical Engineering**

### **MSc. Renewable Energy Systems**

#### **Master's Thesis**

**Subject:** Review of Agricultural Photovoltaic Systems and Simulation on MATLAB of Tomato Production under Agricultural Photovoltaic System with Double-Glass Monofacial and Bifacial PV Modules

**Name and Surname:** Sercan Yalçın

**Issued on:**

**Submitted on:**

**First examiner:** Prof. Dr.-Ing. Daniel Navarro Gevers

**Second examiner:** Prof. Dr.-Ing. Wilfried Zörner

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I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, \_\_\_\_\_

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Sercan Yalçın

# Table of Content

Acknowledgements .....	1
Abstract .....	2
1. Introduction.....	3
2. Renewable Energy Systems.....	6
2.1. Wind Energy .....	9
2.2. Hydro-Power Energy.....	11
2.3. Bioenergy.....	12
2.4 Geothermal Energy.....	12
2.5. Solar Energy.....	13
2.5.1 Photovoltaic Technology: .....	14
3. The Plant Kingdom.....	19
3.1. Photosynthesis .....	21
3.2. Plant Development:.....	23
3.2.1. Water .....	24
3.2.2 Temperature.....	25
3.2.3. Light .....	25
3.2.4 Humidity .....	27
3.2.6. Others .....	27
3.3. Effects of Climate Change on Agriculture.....	27
3.3. Mathematical Models on Plant Growth .....	28
4. Agricultural Photovoltaic Systems.....	31
4.1. Literature Review .....	34
4.2. Summary.....	41
5. Agricultural Photovoltaic Systems Simulation.....	42
5.1 Determination of Solar Radiation in the Simulation: .....	43
5.2. Determination of Tomato Production in the Simulation: .....	47
5.3. PV Installation Layout on the Field and Energy Production from PV Modules in the Simulation:.....	50
5.4. Economical Approach of APV Systems in the Simulation.....	52
5.5. Summary.....	52

6. Case Study: Application of APV System Tomato Production Simulation in Almeria (Spain), Ingolstadt (Germany) and Mersin (Turkey) .....	54
6.1. APV Simulation in Almeria .....	55
6.2. APV Simulation in Ingolstadt .....	58
6.3. APV Simulation in Mersin .....	62
6.4. Discussion of APV Simulation Results:.....	65
7. Conclusion .....	68
Reference list .....	70
APPENDIX A .....	78

## List of Figures

Figure 1: Installed APV System in Egypt by GridParity AG	3
Figure 2: Petroleum usage for electricity production between 1973-2015 (IEA Statistics, 2015)	6
Figure 3: CO2 Induced by human distribution by years (2° Institute, 2020)	7
Figure 4: Primary energy production Distribution by Energy resources in 2018 (BP, 2019)	9
Figure 5: Wind Mill and Wind Turbines-Netherlands (Lagerwey, 2017)	10
Figure 6: Wind Turbine Types (Wagner, 2017)	10
Figure 7: Installed renewable energy systems shares (IRENA, 2019b)	11
Figure 8: The structure of Semi-conductors	14
Figure 9: Energy gap- Efficiency Relations of different semiconductors (Ozturk, 2017)	15
Figure 10: Monocrystalline, thin film And Polycrystalline PV modules respectively	16
Figure 11: Standard & Double Glass PV Module	17
Figure 12: Transparent Pv modules on Terrace	18
Figure 13: The Plant Kingdom Classification	19
Figure 14: Plant Classification Examples (French, 2015)	21
Figure 15: Equation of Photosynthesis	21
Figure 16: Photosynthetic Active Radiation Gap (Wollaeger and Runkle, 2014)	22
Figure 17: Life Cycle of a Seed Plant (Tomato) (TomatoSphere, 2016)	23
Figure 18: Tomato Flower (Rost, 1996)	24
Figure 19: The germinated plants under lightened and lightless conditions (Quizlet, 2015)	26
Figure 20: Droughtiness (Onedio, 2015)	28
Figure 21: Tailor-Made Crop Growth Model for Tomato Production Inputs and Outputs (Gil, Bojaca and Schrevens, 2017)	30
Figure 22: Utility-Scale PV System (Hil, 2019)	31
Figure 23: Floating PV Systems for Aquafarming (CleanFuture, 2018)	33
Figure 24: APV System [15]	34
Figure 25: First AgriPV Sketch [13]	35
Figure 26: Matsue City Greenhouse PV configurations - a: inline, b: crossed (Yano et al., 2010)	36
Figure 27: Montpellier APV System- Left: The sketch of half density and full density settlement. Right: The picture of the field. (Morrou and Guilioni et al., 2013)	37
Figure 28: Lettuce Growth under PV Modules in Japan. - A: Uppside of the greenhouse, B: Inner side of the greenhouse, C: Inner Side of greenhouse under PV and diffusing film (Tani et al., 2014)	39
Figure 29: Heggelbach APV System (Schindele et al., 2020)	40
Figure 30: Representative display of direct, diffuse and reflected radiation (ArcGIS)	43
Figure 31: Solar Angles (Ronoh, 2017)	45
Figure 32: PV Installation	50
Figure 33: Layout of the PV Modules	51
Figure 34: Identified PV Modules in APV Simulation	52
Figure 35: The Output View of the APV Simulation	54
Figure 36: Map of Spain and Marked Location of Almeria (Google, 2020)	55
Figure 37: The Global Solar Radiation Distribution by Months in Almeria	55
Figure 38: Change of the Air Temperature and Humidity in Almeria during the Year (Meteoblue, 2020)	56
Figure 39: The General Overview of the APV Installation with M50 Modules in Almeria	58
Figure 40: Map of Germany and Marked Location of Ingolstadt (Google, 2020)	58
Figure 41: The Global Solar Radiation Distribution by Months in Ingolstadt (Meteoblue, 2020)	59
Figure 42: Change of the Air Temperature and Humidity in Ingolstadt during the Year	60
Figure 43: Map of Turkey and Marked Location of Mersin (Google, 2020)	62

*Figure 44: The Global Solar Radiation Distribution by Months in Mersin* \_\_\_\_\_ 63  
*Figure 45: Change of the Air Temperature and Humidity in Mersin during the Year (Meteoblue, 2020)*\_\_\_\_\_ 64

## List of Tables

<i>Table 1: Tilted (25°) Solar Radiation in Almeria</i>	56
<i>Table 2: The Results Overview of the Simulation with a Different Kind of PV Modules in Almeria</i>	57
<i>Table 3: Tilted (25°) Solar Radiation in Ingolstadt</i>	60
<i>Table 4: The Results Overview of the Simulation in Ingolstadt with PV Modules with Different Transparency</i>	60
<i>Table 5: Return of Invest for 30% Self Consumption in Ingolstadt</i>	61
<i>Table 6: Tilted (25°) Solar Radiation in Mersin</i>	64
<i>Table 7: The Results Overview of the Simulation in Ingolstadt with PV Modules with Different Transparency</i>	65

## List of Abbreviations

$CO_2$	Carbon dioxide
$(\omega_s)$	Sunset Angle
$\theta_i$	Incidence Angle
$GP_d$	Daily Gross Photosynthesis
$GP_h$	Hourly gross photosynthesis
$I_{dif}$	Diffuse solar radiation
$I_{dir}$	Direct solar radiation
$I_h$	Global hourly horizontal solar radiation
$I_d$	Global daily horizontal solar radiation
$I_{ref}$	Reflected solar radiation
$I_t$	Hourly tilted solar radiation
$L_l$	Longitude angle
$L_s$	Local Meridian
$M_{res}$	Respiration
$P_{max}$	Photosynthesis Rate
$RF_h$	Harvested Ripe Tomato
$R_{dif}$	Corrected Factor of Diffuse Solar Radiation
$R_{dir}$	Corrected Factor of Direct Solar Radiation
$R_{ref}$	Corrected Factor of Reflected Solar Radiation
$TMP_{daily}$	Daily Average Temperature
$T_b$	Base Temperature
$T_{ef}$	Effective Temperature
$\theta_z$	Solar Zenith Angle
$\gamma_s$	Solar Azimuth Angle
<b>APV</b>	Agricultural Photovoltaic
<b>ATT</b>	Accumulated Thermal Time
<b>CK</b>	Effects of VPD on Photosynthesis
<b>CO</b>	Carbon Monoxide
<b>DMf</b>	Dry Matter of Fruits
<b>DML</b>	Dry Matter of Leaves
<b>DMp</b>	Dry Matter of Tomato Crop
<b>DMS</b>	Dry Matter of Stems
<b>E</b>	Electrical Energy
<b>EoT</b>	Equation of Time
<b>GHG</b>	Greenhouse Gasses
<b>hd</b>	Harvesting Day
<b>IC</b>	Investment Cost
<b>IRENA</b>	International Renewable Energy Agency
<b>i</b>	Insurance Cost
<b>kg</b>	Kilogram
<b>kWh</b>	Kilowatt hour
<b>LAI</b>	Leaf Area Index
<b>LST</b>	Local Solar Time
<b>MTOE</b>	Tonne of Oil Equivalent
<b>n</b>	Number of Days
<b>NM</b>	Number of Modules
<b>PAR</b>	Photosynthetic Active Radiation
<b>pd</b>	Planting Day
<b>PGRED</b>	Photosynthesis Rate Depending on the Hourly Temperature
<b>PLM2</b>	Plant Density

<b>PPFD</b>	Photosynthetic Photon Flux Density
<b>PSH</b>	Peak Solar Hour
<b>PV</b>	Photovoltaic
<b>PVPD</b>	Correction Factor for Photosynthesis Rate
<b>Q10</b>	Sensitivity to temperature
<b>QE</b>	Quantum Efficiency
<b>RMRF</b>	Respiration Rate for Fruits
<b>RMRL</b>	Respiration Rate for Leaves and Stems
<b>ROI</b>	Return of Invest
<b>ST</b>	Solar Time
<b>TMP</b>	Hourly Temperature
<b>TOMOGRO</b>	
<b>TWh</b>	Terawatt hour
<b>VPD</b>	Vapor Pressure Deficit
<b>VPDL</b>	Vapor Pressure Deficit on Photosynthesis
<b>Wp</b>	Watt Peak
<b>XK</b>	Light Extinction Coefficient
<b>XM</b>	Leaf Transmission Coefficient
<b>YEGM</b>	Yenilenebilir Enerji Genel Müdürlüğü (Turkey)
<b><math>\beta</math></b>	Slope Angle
<b><math>\gamma</math></b>	Surface Azimuth
<b><math>\delta</math></b>	Declination Angle

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*Never stop dreaming...*

## Abstract

Increasing number of populations in the world day by day will be expected to cause growing agricultural land demand to produce enough food and energy demand. At the present time, the electric energy production by photovoltaic cells have an increasing popularity all around world and they play big role among all the renewable energy systems on meeting increasing energy demand. Towards obtaining high energy from PV systems, ground-mounted PV installations on huge fields is needed. Accordingly, it obstructs to make agricultural production on that field. To prevent this, Agricultural Photovoltaic (APV) Systems have been developed to get double-yield – food and energy – on the same land. The idea of the APV Systems is to install PV modules to a specific height with long construction materials, hence, the crop production can be made underneath of PV modules. One of the biggest problems of APV systems is that they cause decrement on crop production because of shading by PV modules. In this study, the review of the APV Systems have been performed. Afterwards, it is realized that there is no compact simulation program, which simulates the crop production, the energy production from PV, and economy of the project at the same time. Therewith, APV Systems simulation program has been developed on MATLAB. The developed program can analyze the tomato production in the selected location under glass-glass transparent monofacial and bifacial PV modules, which have been selected from the catalogue of the company GridParity AG and their names, power and transparency are M72-330 Wp (12%), B72-370 Wp (12%), M50-250 Wp (40%), B32-165 Wp (53%), respectively. The identified locations in the simulation program are Almeria (Spain), Ingolstadt (Germany) and Mersin (Turkey), respectively. In this way, the tomato production under different transparent modules and on different climates have been simulated. As it is expected, the tomato production was the highest amount under B32-165 Wp (53%) modules, because of its having the most transparent surface. On the other side, the most convenient climate for tomato production among these 3 cities has been stated as in city of Mersin. Lastly, the return of invest in the simulation result differed in different cities because of having different electricity cost and bifacial PV module B72-370 Wp was the most successful one on the matter of economic analyses.

## 1. Introduction

The significant increase of the human population year by year causes increased demand on what the human requires to realize their vital activities such as more houses, more food, more energy, etc. At the beginning of the industrial revolution, the required energy has been started producing from fossil-fuels without thinking about its harm to the environment. After international agreements and going green policy of the countries on energy production, the importance of renewable energy systems have been noticed. Solar energy systems are one of the most important renewable energy systems, however huge areas are needed to obtain enough energy output to feed the energy demand. If the solar energy systems mounted on the ground in a huge field, they prevent the area to make agricultural activities. It means, by installing huge PV farms, instead of producing crops for food demand of the populations, only energy will be produced by PV Systems. Therefore, Agricultural Photovoltaic Systems have been developed and it is aimed to get double yield with producing crops and energy from PV in the same field.



**Figure 1: Installed APV System in Egypt by GridParity AG**

Goetzerberger and Zastrow brought up APV Systems' idea the first time in their research in 1981. The idea was to install the PV modules with long construction materials on the crop plantation areas. Hence, not only food will be produced, but also electrical energy from PV modules will be produced. However, the idea has been waited some decades to be realized and the first installation of APV System has been made in Montpellier in 2010. In the following years, the application of APV Systems has been increased and the PV Modules are started using on the rooftop of the greenhouses.

The aim of most of the research papers on APV Systems is to find out how the shading will affect the growth and output of the plants. Additionally, the energy output of the PV modules has been simulated by using different simulation programs. However, any of the researches was about developing a compact simulation program for only APV Systems. In this study, a simulation program for tomato production under APV Systems with transparent modules has been developed on MATLAB by using a tomato production model called 'Tailor-made Crop Growth Model'. The results have been obtained for 3 different cities, which are Almeria (Spain), Ingolstadt (Germany) and Mersin (Turkey) and 4 different glass-glass mono facial and bifacial modules have been simulated with the name, power, and transparency of M72-330 Wp (12%), B72-370 Wp (12%), M50-250 Wp and B32-165 Wp (53%), respectively. Hence, the effect of transparency of the modules on the tomato plant may be observed. On the other side, the impact of climate on tomato production in open field areas can be also researched by using the APV Simulation program.

When the simulation runs, the user must answer 4 questions in below to get the results;

- Please select the country, where you want to install the APV System. (Spain, Germany or Turkey)
- Please select the city, where you want to install the APV System. (Almeria, Ingolstadt, and Mersin)
- Please select the PV Module. (M72-B72-M50-B32)
- Please enter the size of the planting area. (in  $m^2$ )

As a result of the simulation program, the user will have an idea about the articles as below;

- The weight of produced ripe tomato
- The produced electrical energy from PV Modules
- The Investment Cost
- Return of Invest

In the second chapter, the importance of renewable energy will be discussed, and different kinds of renewable energy systems will be reviewed. PV Technology will be explained in detail and as a new technology, glass-glass bifacial PV modules will be introduced.

In the third part of the study, the general information about plants will be explained. The lifecycle of the plants will be discussed and the optimum requirements for the plants, especially for tomato, will be discussed.

In the fourth part, as a combination of the second and third chapters, the Agricultural Photovoltaic Systems technology will be explained. All the researches from the beginning of its history until today will be reviewed as a literature review.

In the fifth part, all the mathematical equations, which have been used in the APV Simulation program, will be explained in detail. This part includes tomato production calculations, energy from PV modules calculation, and economical assessment.

In the sixth and the last part, the simulation program will be run for the cities of Almeria, Ingolstadt, and Mersin for different kinds of PV Modules and the results will be discussed at the end.

Consequently, the developed APV Simulation, of course, is open to be developed professionally. By using this program, the farmers and investors can easily inform themselves about the benefits of APV systems on their land and the idea of APV systems can spread easily around the farmers and investors.

## 2. Renewable Energy Systems

From the beginning of the industrial revolution, energy requirement becomes one of the main issues for the development of the countries. The countries, which have already energy resources like coal or natural gas in their homeland, have become strategically significant locations. Accordingly, these countries have got an advantage to grow economically by selling their resources to energy-demanding countries. In this sense, several bilateral agreements and even wars made between countries to get global energy supremacy. Hence, it can be said that having energy resources would allow the countries or cause to have occurred new problems with other countries.

Energy usage is a must for humans to continue their vital actions. The importance of energy has been noticed by society after the first petrol crisis in October 1973. (Karagol and Kavaz, 2017) During the War 'Yom Kippur' between Arab Countries and Israel, the support of the US to Israel got a reaction by the Organization of Arab Petroleum Exporting Countries (OAPEC) and an embargo was placed by OAPEC firstly on the US and following on European countries. (Orki, 2019) As a result, the crisis affected the socioeconomics of energy importing countries negatively. On the other hand, in a good manner, the crisis made the countries try to find solutions against petrol usage efficiency and provide themselves more energy security of supply. (Orki, 2019) While in the crisis time the production of electricity was made 24% by petrol (IEA Statistics, 2015), that rate decreased dramatically in the further years and utilization of renewable energy on electricity production has been increased by energy-demanding countries to be influenced slightly against any energy crisis and decrease foreign-source dependency. Hence, awareness dominated the researches and the development of renewable energy systems.

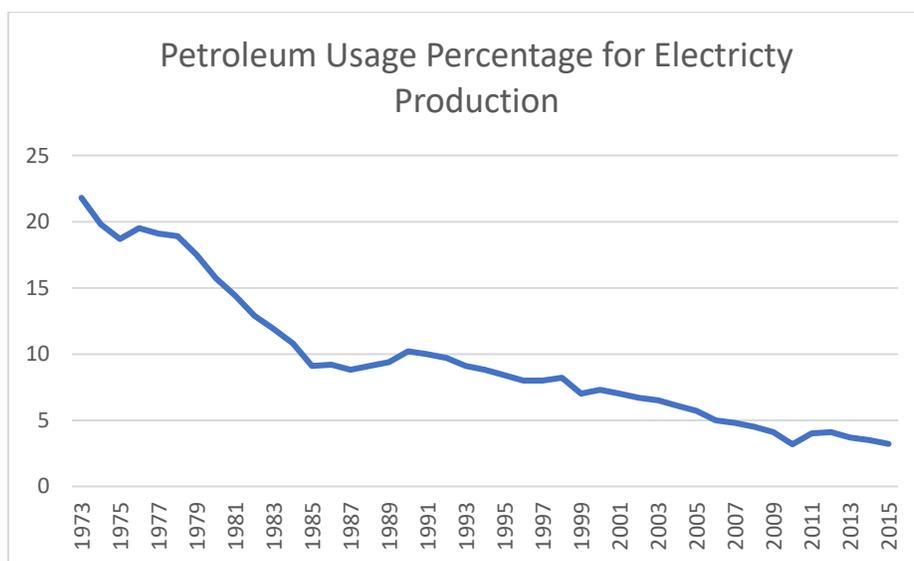


Figure 2: Petroleum usage for electricity production between 1973-2015 (IEA Statistics, 2015)

On the other hand, there is no doubt that energy resources on earth are not unlimited and usage of fossil fuels on energy production influences the environment in a bad way. Global energy demand increases year by year, and it's expected to be 50% more in 2050. (Kahan, 2019) By the year 2018, 13.864,9 MTOE primary energy was required and 83% of the global primary energy was consumed by fossil fuels with 33% from oil, 23% from natural gas, and 27% from coal. (BP, 2019) It indicates that energy production is highly dependent on fossil fuels and it will not be an easy process to leave consuming fossil fuels. However, when taking into attention environmental issues, the fossil fuel requirement in the world must be terminated in further decades for having a cleaner future. Figure 3 demonstrates the increase of  $CO_2$  level with humanity's activities and the dramatic increasing after the industrial revolution can be also noticed. On the graph, the  $CO_2$  level at present is at its highest level with 413 ppm. (2° Institute, 2020) Needless to say, combusting fossil fuels is the biggest reason for that situation and different fuels have different  $CO_2$  emissions. For instance, hard coal releases 0,34 kg  $CO_2$  to produce 1 kWh while natural gas releases 0,20 kg  $CO_2$  for producing the same amount of energy. (Erneubare Energien und Klimaschutz, 2020)



**Figure 3: CO2 Induced by human distribution by years (2° Institute, 2020)**

The greenhouse gasses (GHG) such as  $CO_2$ ,  $CO$ , etc. (Ma, 1998) provide a convenient environment to living creatures on earth by keeping sunlight inside the atmosphere and it's called the greenhouse effect (Ozmen, 2011). In the absence of GHG, the temperature of the air expected to be  $-18\text{ }^{\circ}\text{C}$  according to NASA. (Ma, 1998) Beyond being just advantages of GHG for living creatures, the unregulated increase of GHG as in the last century brings along various troubles on earth such as climate change.

Temperature increasing with global warming will cause to decrease raining, increase drought and desertification. (Ozmen, 2011) Correspondingly, global warming will be expected to affect countries economically with changing agricultural products, geographically with increasing sea levels and in energy manner with increasing cooling system utilization because of warmer weather. (Mann and Selin, 2020) Additionally, as of the date of the first quarter of 2020, the virus COVID-19, as known as Coronavirus, affected significantly the social life in many countries so far and brought along panic on humanity. When this situation taking into consideration, according to the research paper, the melting glaciers in Siberia's cattle graves because of global warming might bring back the 'Anthrax Virus' which ensues harm and death among humans and animals. (Revich and Podolnaya, 2011) Consequently, global warming will be not affected only the environment, but also it is expected to originate more diseases. Hence, the scientists and the governments concentrated on finding solutions with many pieces of research and decisions in global conferences to prevent advanced climate change. When considering fossil fuels' being limited and harmful effects on the environment, made raised the investments on Renewable Energy Systems instead of traditional fossil fuel plants.

Renewable energy is produced by renewable resources which can renew themselves before consuming it all unlike fossil fuels for energy production. (YEGM, 2015) Solar energy, wind energy, bioenergy, and hydro energy can be given as an example of renewable energy resources. Renewable energy has been always taking place in civilizations and social life since the antique age. For instance, solar energy played a big role in the formation of fossil fuels and humans used oil for lighting time 9000 years ago and some civilizations used solar energy with mirrors to burn a fire. (Sorensen, 1991) Apart from solar energy, the wind power used for transportation by Egyptians in 3100 BC. (*Encyclopedia of Energy*, no date) On the other side, bioenergy sources have been using throughout human history. For instance, woods (Guo, Song and Buhain, 2015) have been using for on the purpose of heating and cooking and organic fertilizers have been taken place on plant production for 12500 years. (Larramendy and Soloneski, 2019)

It's already mentioned that renewable resources have been using for heating purposes for long ages. On the other side, in the first period of the invention of electricity, producing electricity with renewable resources like solar and wind was far too expensive than fossil fuels. (Sorensen, 1991) Even though renewable energy sources have been occupying a place in our life for a long time, utilization of these sources more efficiently with technological developments is one of the most important topics in our present century against the impact of climate change by fossil fuel resources. It can be seen in Figure 4 the contribution of renewable energies to primary energy production in 2018. Regarding electricity

production, 9% of the total electricity production was generated by solar and wind energy (Enerdata, 2019). It is expected to increase in further decades. In further subchapters, it's going to be discussed about the major renewable energy technologies.

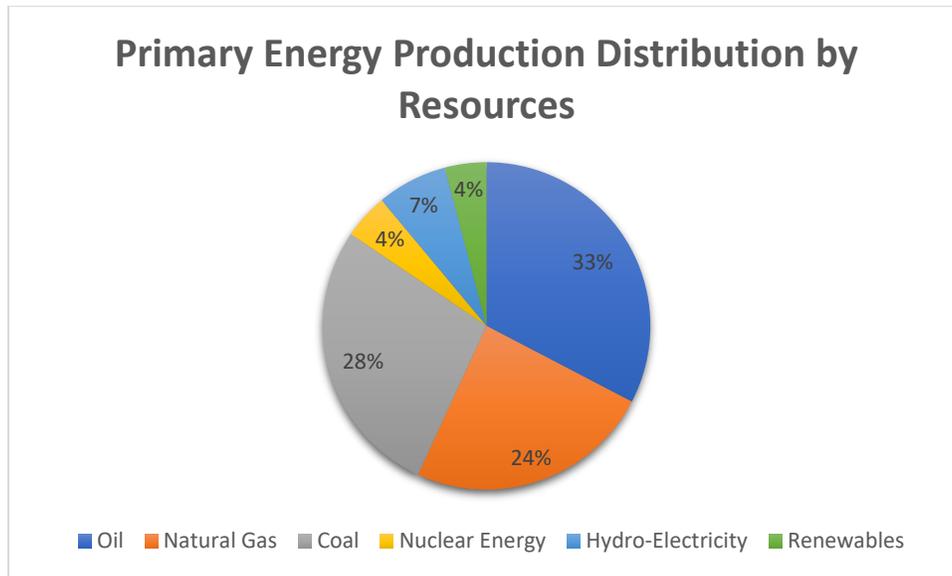


Figure 4: Primary energy production Distribution by Energy resources in 2018 (BP, 2019)

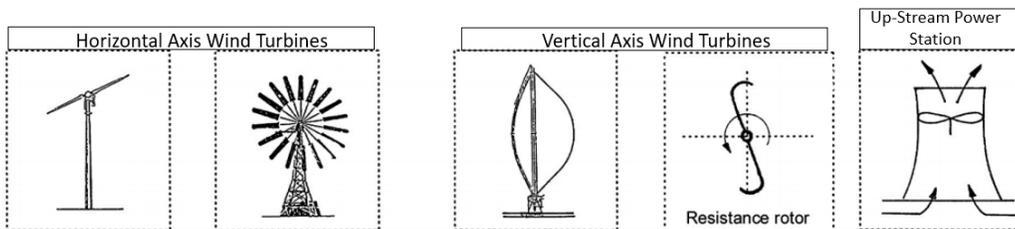
## 2.1. Wind Energy

The wind is the air movement which is occurred by temperature and pressure differences on a different part of the earth and it flows from high pressure to low pressure. As a renewable energy resource, wind energy, has been getting used for centuries by civilizations for pumping waters, grain milling, and generating mechanical power by using windmills (Behçet *et al.*, 2014). When the design of the wind technologies is considered, the modern version of the windmills is called wind turbines which have been invented in the late 19<sup>th</sup> century. (Elibuyuk and Ucgul, 2014)



**Figure 5: Wind Mill and Wind Turbines-Netherlands (Lagerwey, 2017)**

Wind turbines are huge devices that convert kinetic energy of the wind to electrical energy by the various parts contain. In the history of wind turbine technology, different designs have been experienced depending on their turning direction such as horizontal axis, vertical axis, or up-stream power stations. (Wagner, 2017). The vertical axis wind turbines don't need to have a tower since they can be placed on the ground, therefore the investment cost gets lower. However, it's known that the wind speed goes up undoubtedly the high-level increases, therefore this kind of wind turbines cannot produce a high capacity of electricity because of their being not very tall and their efficiency are not high enough (Elibuyuk and Ucgul, 2014). On the other side, even though their complexity and having long parts, the horizontal wind turbines have popularity in the 21st century. The modern high power capacity wind turbines have been produced with 3 blades owing to have a constant moment of inertia (Elibuyuk and Ucgul, 2014). Depending on the height of the 3 blade wind turbines, the power production capacity of them can scale up to MWs. However, higher power capacity means higher tower and blades and it brings along transportation problems. One of the biggest wind turbines that are in operation for off-shore is produced by General Electric with 12 MW power capacity and 260-meter height. (GE Renewable Energy, 2020)



**Figure 6: Wind Turbine Types (Wagner, 2017)**

The annual electricity energy potential out of the wind up to speed 5,1 m/s inconvenient landscapes has been 53.000 TWh. In this manner, in the present century, the utilization of wind energy to electricity production keeps on increasing. The global total installed power of wind turbines by the year 2019 is 597 GW, while it was 21 GW in 2001 with 50 GW contribution only in 2018 (Wind Energy International, 2019) (Statista, 2019) and the energy production out of the covers 6% of the total electricity production. (Enerdata, 2019) It's expected that in the future, wind energy will take more place in energy production contributions.

## 2.2. Hydro-Power Energy

Even though hydropower plants don't count as renewable energy systems by some authorities because of its harm to the environment on the progress of building them, it is the most used renewable energy system among the hydro-energy potential owner countries. The logic behind the hydropower plants is to save potential energy by using water in established height. The stored water is flowed down to get kinetic energy and by using turbines the kinetic energy is converted into electrical energy.

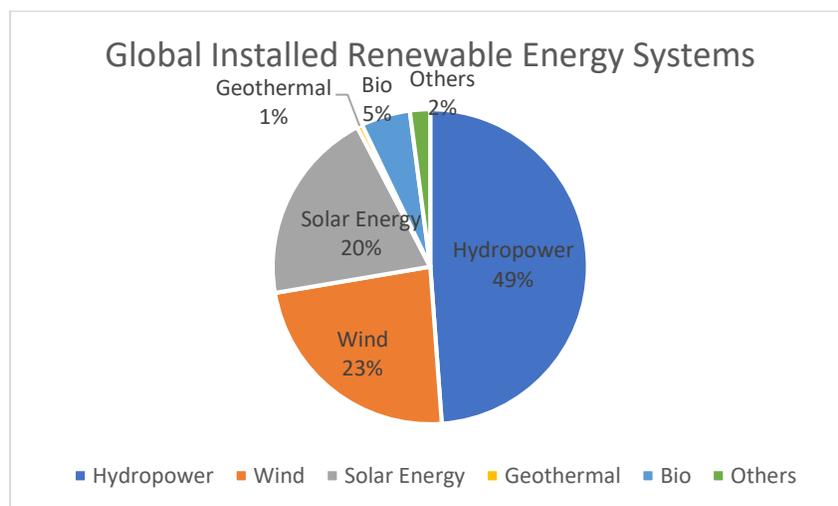


Figure 7: Installed renewable energy systems shares (IRENA, 2019b)

Although the investments on hydropower plants decreased by the year 2018, it still has the biggest installed power share among renewable energy systems as can be seen in Figure 7. The total installed power of renewable energy systems is 2351 GW, while only the hydropower plants are 1172 GW. (IRENA, 2019b) China, Brazil, and Canada are the countries that produce the most electrical energy out of hydropower plants. (Dincer *et al.*, 2017)

### **2.3. Bioenergy**

Biological waste is the product that all residual outputs which are generated by living creatures such as agricultural residues, biological municipal wastes, and animal manure. For many centuries, biowaste has been using for heating or cooking purposes and as fertilizer. However, direct combustion of biowaste or utilizing it directly as fertilizer is not an efficient way to reach the maximum energy capacity of biowaste. Therefore, biofuel technologies gain importance to get electricity and heat energy out of biowastes.

As a biofuel, biogas is the output of biomass after several processes. There are several ways to produce biogas out of biomass and one of the most popular ways, which is called Anaerobic Digestion, is to leave biomass in a special construction on convenient conditions such as warm temperature, good PH value without oxygen. At the end of the process, the biogas is gathered on the top of the special construction and the solid material on the bottom can be used as a high-quality fertilizer which is decontaminated from its heavy odor. (Seadi *et al.*, 2008) Thereafter, biogas can be converted to electrical and heat energy by using Combined Heat Power plants and among all the other renewable energy resources, biogas is the only renewable resource that can be converted to heat and electrical energy at the same time.

Bioenergy covers the biggest direct heating demand with 96% among renewable energy resources, while solar energy is 3% and geothermal energy is 1%. (World Bioenergy Association, 2019) Regarding the global installed power of the biogas plant is over 18 MW by the year 2018 which is doubled itself in 10 years. (Wang, 2019) When considered the non-stop biowaste production during the living creature's existence, using them for the benefits of society is very crucial for our environment positively.

### **2.4 Geothermal Energy**

The geothermal energy is the heat energy accumulated in chemical gas, water, or vapor under the different levels of the ground. It has been using by humanity for ages, in the beginning, it's has been used only in the sense of human health as in thermal baths. With the development of the civilizations, geothermal energy was started using for cooking, heating purposes, and lately for electrical energy production. (YEGM, 2020)

The interior surface of the area should be known perfectly before installing a geothermal plant for electricity production because the temperature of the water stream must be hot enough to produce electrical energy effectively. The operating logic of these plants is the same as Organic Rankin Cycle. The injected steam (water) from the well is transferred to the steam generator, condenser, and heat

exchanger respectively and the energy of steam is transformed into electrical energy. (Taylor, Water and Krumdieck, 2013)

The power generation with geothermal energy was 90 TWh in 2018 regarding the historical data. Although when the growth rate of the geothermal energy production is not that high when compared with the other renewable energy resources, the energy production in 2030 with geothermal energy is expected to be 282 TWh.

Thus far the main renewable energy resources have been introduced mainly. Since the main topic of this research is solar energy, solar energy, and its technology will be discussed in detail in the further step.

## **2.5. Solar Energy**

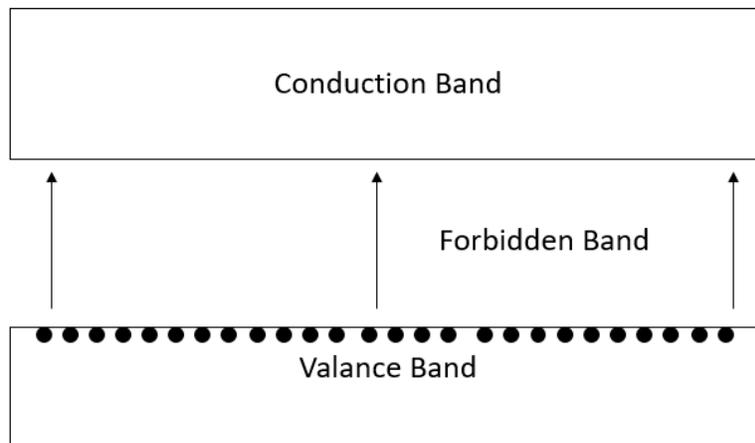
The sun is situated in the center of the solar system which consists of earth, 7 other planets, and several satellites. Although the extraterrestrial life could not be discovered in space up to now, our planet, the earth, is the most convenient one for living creatures with having an atmosphere and its ability to keep different gases and energy of sun such as heat. With this aspect, the solar energy is a must from the beginning of life on earth.

Almost all the energy types were reformed by solar energy, for instance, the fossil fuels arise from solar energy in million years, as an example the bio-wastes from the plants occur with photosynthesis by using the energy of the sun and as it's already discussed in wind energy part, the wind energy occurs by temperature differences. In that sense, solar energy is the main energy resource that triggers to be the other energy resources created. (Szabo, 2017)

Although solar energy has been used for centuries by different societies, Leonardo da Vinci, who is a polymath who lived in Renaissance (Bayav, 2019), invented the concave mirrors to collect sunlight in one point to obtain hot water. This was the first application of a solar concentrator. (Szabo, 2017) Further, after the industrial revolution, solar energy technologies started developing, however in the beginning the electricity production with solar energy only has been utilized to water to obtain steam and the electricity has been produced by steam turbines. (Breeze *et al.*, 2007) However, electricity production directly without using any transition element like steam has been getting possible with the development of Photovoltaic Modules Technologies. Since the topic of this research mainly about PV systems, it is going to be discussed in detail on the next subchapter.

### 2.5.1 Photovoltaic Technology:

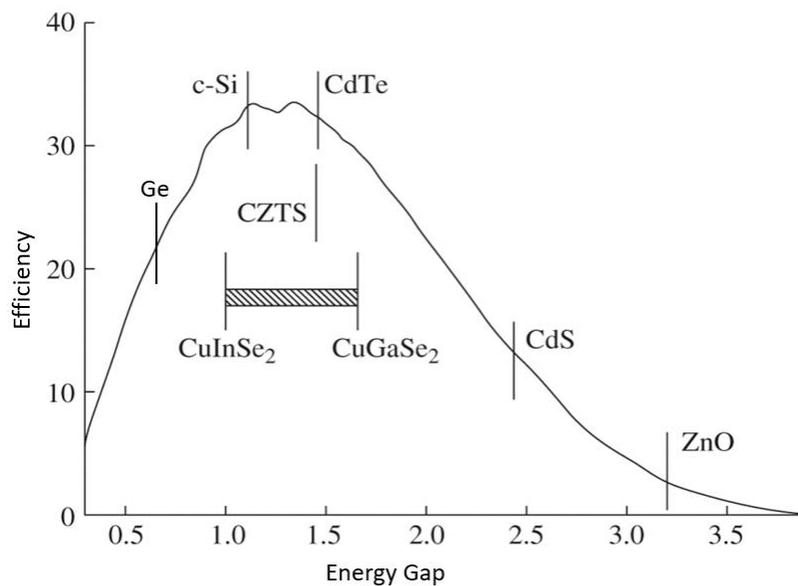
PV systems are the devices that convert the solar light of beam to direct electrical energy without using any intermediate element such as steam turbine-like discussed in the previous chapter. Everything has been started in 1839 with the discovery of Edmond Becquerel – French scientist – on the relationship between electricity production and light of beam while the light impingement on anode and cathode electrodes which are inside an electrolytic solution. (US Department of Energy) The discovery of the photovoltaic effect of selenium element has been discovered by Prof. Richard Evans Day and William Grylls Adams in 1876 (Adams and Day, 1876), thereafter the first solar cell from selenium with 1% efficiency has been represented by Charles Fritts in 1883. (Fraas, 2014) However, the selenium cells are not the technology that is used for PV cells in our century. The modern PV cells that are produced in the era of the 21<sup>st</sup> century can be described silicon solar cells and the invention of silicon solar cells with 6% efficiency has been made by the company 'Bell Labs' in the US for space field mission purposes. (Fraas, 2014) Different elements have been tested as PV cells such as germanium (Ge), Gallium Antimonide (GaSb), Gallium Arsenide (GaAs), Cadmium Telluride (CdTe) and Silicon (Si), however, silicon cells are the most cost-effective cells that can be produced so far. (Weitz, 2018)



**Figure 8: The structure of Semi-conductors**

Regarding the structure of PV cells, they are semiconductors like diodes, transistors which are non-conductors in standard conditions, while they are conductors if the required conditions are provided for them and the required condition can be explained like in further. The semiconductors have 3 parts in their structure as it can be in Figure 8. That is called 'valance band' which consists of all the electrons, 'forbidden band' in which electrons cannot be placed, and 'the conductive band' which is the place, to where the electrons jump in after the energy absorption from outside and the element gets conductivity.

Different elements need different energy band gaps to jump their electrons from the valance band to the conductive band. Regarding the required condition of the PV cells, it can be provided by implementing light on the cells between convenient wavelength bands. (Weitz, 2018) The different energy gap values of the different semi-conductors can be seen in Figure 9. As an example, the energy gap of Germanium (Ge) and Silicon (Si) are 0,66 and 1,12 eV, respectively. (Haddara, Ashburn and Bagnall, 2017) (Weitz, 2018) Therefore it can be explained that, if 2 eV energy applied on Ge and Si, the former will use 0,66 eV for jumping conduction band and the rest will be converted to heat; however, the letter will use 1,12 eV for jumping and the rest will be converted to heat. Hence, the heat energy will be got out less in the Silicon element and that's one more reason to use the Silicon element for PV cell production instead of other elements. (Weitz, 2018)



**Figure 9: Energy gap- Efficiency Relations of different semiconductors (Ozturk, 2017)**

As a semiconductor, PV cells have to be doped with different elements to increase their conductivity. As an example, Si element has 4 electrons in its last orbit and when 4 times Si is doped with Phosphorus (P) element, which has 5 electrons on its last orbit, 1 electron of P will be free, and it's called N junction or conductive. On the other hand, when the Si element doped with Boron (B) element, which has 3 electrons on its last orbit, 1 electron will be a deficit and it's called P junction or acceptor. When the combination of P-N junction is formed as a solar cell, the positive charges accumulate in N-junction and negative charges accumulate in P junction, therefore it causes a voltage generation. When light is put on the solar cell and the P-N junction is connected with a cable, the movement of the positive and negative charges will generate electricity. (Weitz, 2018)

Connecting serial or parallel several solar cells each other compose one PV module. PV modules diverge to different categories in itself; these are mainly thin-film, polycrystalline, and monocrystalline PV modules.



**Figure 10: Monocrystalline, thin film And Polycrystalline PV modules respectively**

The thin-film PV cells are produced by implementing different semiconductors on different materials such as glass, steel, or plastic. The thin-film PV cells are known for their flexibility; therefore, thin-film PV applications are very easy. However, the disadvantage of the thin-film PV cells is to have low efficiency of around 5-8%. (Oguz, Karakan and Uslu, 2015)

The other type of solar cell is polycrystalline solar cells that are produced from melted silicon which cools inside a graphite mold. (Sharma and Jain, K., Sharma, A., 2015) At the end of the process the solar cells are made perfect square shape by cutting it. Generally, this kind of solar cell has 15-17% efficiency. Additionally, as an advantage polycrystalline solar cells are cheaper than monocrystalline which will be explained in the next lines.

When the purity of the silicon is increased, the efficiency of the solar cell will increase proportionally. Monocrystalline solar cells are the most efficient solar cells among the all solar cell types with 24% efficiency in laboratory conditions (Dobrzanski and Macek, 2012) The monocrystalline solar cells have to be produced with Czochralski process, therefore at the end of the process, the shape of the monocrystalline solar cells will be circular. The connecting circular solar cells together on a surface would be ineffective, that's the reason the circular monocrystalline solar cells are shaped like circular squares by cutting. As two disadvantages, the removed materials cause a loss of silicon, and increment purity of silicon made monocrystalline more expensive than the other cells.



**Figure 11: Standard & Double Glass PV Module**

By the year 2020, one solar cell has around 5 W power capacity. Accordingly, for instance, to obtain a 300 Wp PV module, 60 solar cells must be connected. On the standard PV modules, the PV cells are placed between a glass and a metal back sheet which protects the module while transportation against damages. These kinds of solar modules are the most utilized ones with its metal frame and mostly 25 years of warranty. On the other side, with the development of PV technology impacted the frame and back sheet material of the solar energy to increase not only the warranty of the solar modules but also its properties. In today's technology, glass-glass PV modules started taking the stage. Glass-glass PV modules can be described as 'solar cell sandwich inside double glass structure'. Glass-glass PV technology increases the warranty of PV modules to 30 years. On the other hand, the double glass technology brings along the transparency on the module surface which can provide several advantages to a PV module. The biggest opportunity is that PV modules can be produced like bifacial by placing the solar cells to facing both sides of the glasses. (Kreinin *et al.*, 2010) Hence, the PV module will produce energy not only from the direct solar lights but also from the reflection of the solar lights from the materials around the installation. The reflected solar radiation of the bifacial module can increase the annual production around 30% depending on the reflection characteristics of the ground. (Sun *et al.*, 2018) Additionally, the double-glass PV modules made a way for installing transparent PV modules aesthetically i.e. in the terrace of the houses. On the other hand, transparent PV modules have been using for Agricultural purposes to produce electricity and the agricultural material at the same time. In further chapters, the relation between Agriculture and PV modules will be discussed in detail.

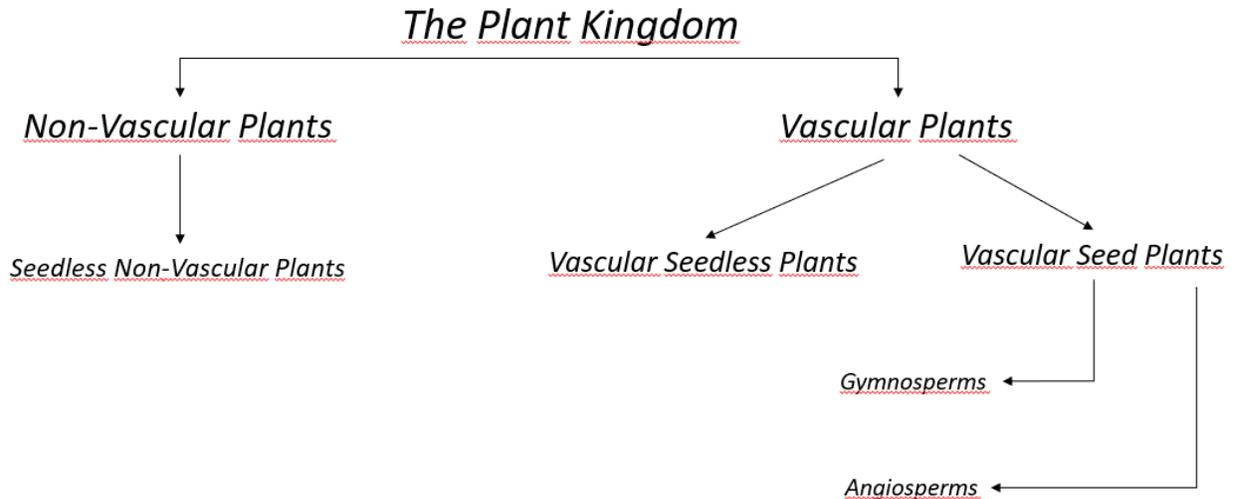


**Figure 12: Transparent Pv modules on Terrace**

Lastly, about solar energy, the installed capacity of PV solar energy reached to more than 518 GW globally. (Jäger-Waldau, 2019) The installed power capacity is expected to increase in the further years because of the government's zero-emission policies.

### 3. The Plant Kingdom

The plant kingdom consists the living creatures like trees, flowers, seaweed, etc. with almost 390.000 species. All the other living creatures including humans have required the existence of the plants. The exploitation of the plants can be in different ways for different species. For instance, the plants provide accommodation to some livings; a big amount of livings are nourished with vegetables and fruits; and last but not least, the plants release oxygen to the atmosphere and produce their nutrition to inhabit with making photosynthesis by using sunshine, carbon dioxide, and water. In short, the plants convert the energy of the sun to oxygen and the nutritious fruits or vegetables. (Y.Serin, 2010) Therefore, the plants are called 'autotroph livings', since they can produce their complex organic nutrition by using simple organic materials. As the importance of the sun energy discussed in the previous chapter, the sun has the biggest impact on the plant kingdom.



**Figure 13: The Plant Kingdom Classification**

For centuries, researches on different living benefits from Taxonomy Science, which makes classification to study different genres easily among all the living creatures. Hence, the huge amount of the plant kingdom diverges to different classification regarding their various characteristics. Primarily, the plants as a basis can be examined in different features as further information. The first regarding having vessels in two different groups which are called vascular plants and non-vascular plants. The second, regarding how they breed themselves, for example with spores or seeds. (Haider, 2018) Mainly, the classification can be seen in Figure 13.

Non-vascular seedless plants do not have a transmission element specialized for water or food transportation. Instead, they absorb the water, therefore they are situated in humid regions. Oppositely to roots on the ground, the non-vascular plants do have rhizoids to hold the ground and absorption of their requirements. Additionally, nonvascular seedless plants reproduce themselves with spores which means they do not originate flowers at all. The most-known non-vascular seedless plant type can be said mosses, liverworts, hornworts. (Haider, 2018) (Dianne, 2018)

Vascular plants, on the other hand, have functional structures to transmit water and nutrients to the required parts of the plant. That transportation system consists of different parts such as, from the ground to top; roots, xylem & phloem, leaves. The mission of the roots is to connect and fix the plant on the ground and absorbing required water and minerals for photosynthesis in the plant and transfer them to the xylem & phloem. Regarding xylem and phloem, they are responsible to convey the materials. There are several differences between xylem and phloem. While the xylem is a lifeless element that transports only water and minerals one way from the roots to the leaves, the phloem is an alive element that transports two-way nutrition obtained from photosynthesis. The leaves which have mostly green color are responsible for photosynthesis, respiration, and transpiration. The type of leaves differs depending on the climate of the settled area of the plant. (Fiore, 2018) Regarding the reproduction of the vascular plants, two different reproduction types can be examined. The most-known vascular seedless plants are the ferns. They reproduce themselves with spores. The vascular seed plants, differently, reproduce themselves with female and male organs. At the end of the reproduction process, the fruits are formed. The seed plants are named regarding the openness of the seed. The gymnosperm plants like pine, spruce are the plants that have open seeds, while angiosperms are known as flowering plants and they have closed seed. (Taiz and Zeiger, 2002) Tomatoes can be given as an example of an angiosperm vascular plant and in this thesis tomato plant growth model under PV Systems will be examined by using MATLAB. In further subchapters, the plants will be discussed some more detail to understand how they live and grow. Hence, a fundamental ground will be established for further chapters.

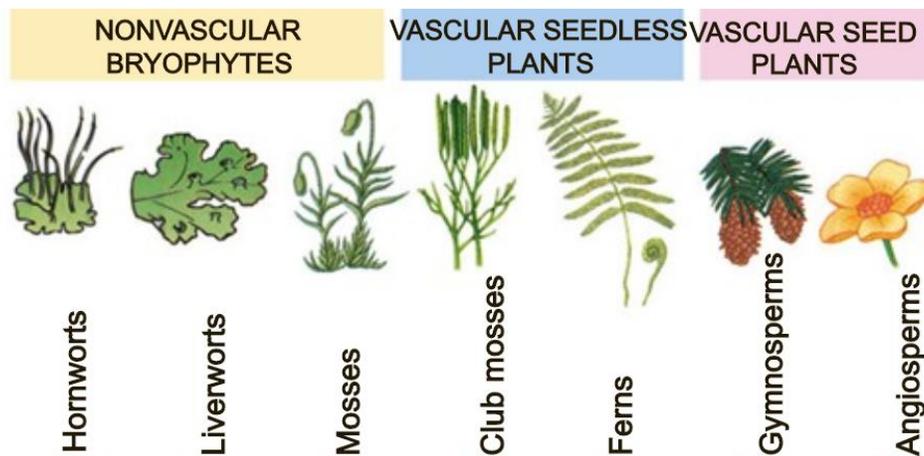


Figure 14: Plant Classification Examples (French, 2015)

### 3.1. Photosynthesis

Photosynthesis is a chemical reaction in the leaves that the plants produce oxygen and its nutrition - sugar- under the favor of the light, carbon dioxide, water, and minerals. (Taiz and Zeiger, 2002) The energy from the respiration must be used to get the required articles inside the plant.

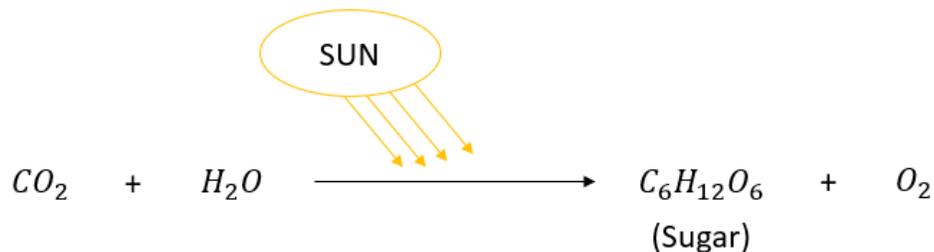
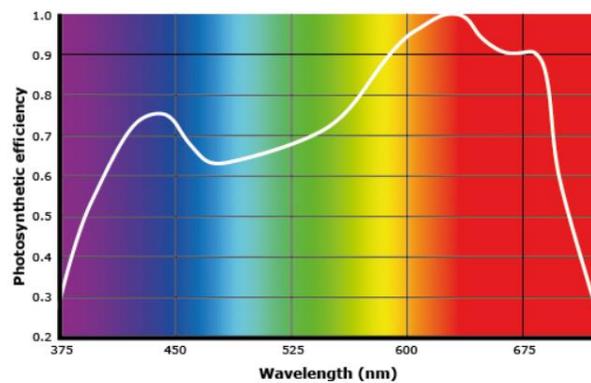


Figure 15: Equation of Photosynthesis

Like all the other living creature cells, the cell of the plants can be likened to a small municipal. In other words, there are several organelles inside the cell's cytoplasm which make vital activities happen. For instance, mitochondrion generates energy (ATP) from nutrition and oxygen by respiration (KOÇ, 2003); vacuole makes the temporal storage of the protein and arranges the waste management of the cell. (Shimada *et al.*, 2018) Regarding responsible organelle for photosynthesis, that organelle in the cell

named 'Chloroplast'. Besides, Chloroplast turns out the amino-acid synthesis, fatty acids, and chlorophyll. (Jensen and Leister, 2014) The pigment, chlorophyll, is the part to give the leaves green color by reflecting the green color wavelength of sunlight and absorbing the red and blue. The importance of light wavelengths on photosynthesis will be discussed further. The long and the short of it, the absorbed sunlight helps to water and carbon dioxide molecules get into reaction by activation of some enzymes and at the end of the process, oxygen and sugar are generated. (Alberts, Johnson and Lewis, 2002)

The photosynthesis brings along several advantages to the existence of life on earth. As a product of photosynthesis, oxygen, is a significant element for almost all living creatures. It provides to realize carbon cycle in nature. That means photosynthesis takes an important place in fossil fuel generation through the centuries. (Cook, 2013) On the other hand, the photosynthesis is directly related to plant development, raising photosynthesis level increases the biomass productivity of the plant (National Research Council (US) Committee on Research Opportunities in Biology, 1989). Surely, the plant development and fruit generation have an outstanding place for life on earth.



**Figure 16: Photosynthetic Active Radiation Gap (Wollaeger and Runkle, 2014)**

Solar radiation can be described as power per square meter from the sun and wavelength of the solar radiation is specified as between 0,3 and 2,8  $\mu\text{m}$ . Although solar radiation is one of the most crucial inputs for a plant to realize photosynthesis, only the wavelength of solar radiation between 0,4 and 0,7  $\mu\text{m}$  can be used for photosynthesis. That band of solar radiation is called 'Photosynthetic Active Radiation' (PAR). In further chapters, the simulation of tomato development and production will be modeled. Therefore, the determination of the PAR amount inside the solar radiation will make the production modeling more precise. According to the reference, the ratio between PAR and solar radiation has been specified between 0,45 and 0,5. In this respect, in this project, the PAR value will be practiced as 47% of the solar radiation. (Tsubo, M., Walker, S., 2005) Some researchers brought forward

the idea of increasing the gap in the wavelength of PAR. Accordingly, they placed nanomaterials in the chloroplast of the plant, which can absorb the light over PAR, and they achieved to get 30% more photosynthetic reaction than normal. (Giraldo *et al.*, 2014)

### 3.2. Plant Development:

In the manner of all the living creatures having a life cycle, plants have their life cycle as well. In each phase of the plant, the requirement and the released hormones vary. In this part, each stage of a plant face during its life cycle will be discussed. Since the tomato plant growth will be simulated in the further chapters, the growth stages of the tomato plant in this subchapter. In this regard, it is better to give scope for the specification of the tomato plant.

*Solanum Lycopersicum*, as known as tomato, is one of the most popular agricultural products among humanity. Consuming tomato has so many benefits on the human body with its being the source of various vitamins such as vitamin A, vitamin C, etc. (Nicola, Tibaldi and Fontana, 2009) While the native land of the tomato is South America, nowadays the production of the tomato plant has spread all around the world. According to the reference, annual global tomato production is over 180 million tons. China leads the tomato production with almost 60 million tons, which is the one-third of the whole global tomato production. Turkey and Spain are on top ten of tomato producers in the world with 3<sup>th</sup> and 8<sup>th</sup> place respectively. On the other side, Germany is in 80<sup>th</sup> place. As expected, the climate conditions affect growth efficiency. (FAOSTAT, 2017)

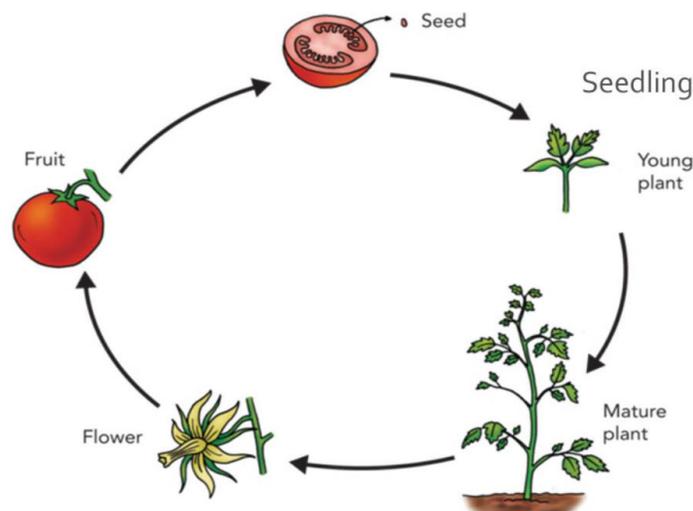
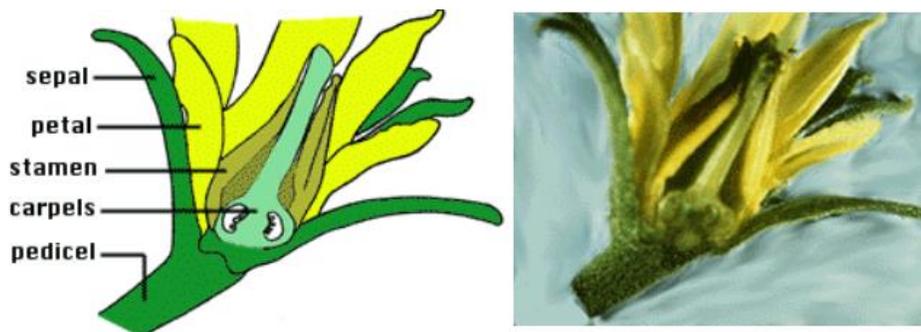


Figure 17: Life Cycle of a Seed Plant (Tomato) (TomatoSphere, 2016)

Mainly the development process of the seed plants is almost the same. Regarding the development stages of a vascular seed plant – tomato is also in this group – everything starts with planting the seed in the soil. The seed is the covered embryo, which is the output of the pollination of the flower and has all the characteristics of the plant. That cover helps the overcome embryo from hard conditions such as the cold or lack of water until the seed finds convenient conditions for itself such as optimum temperature, water, etc. Until finding suitable conditions, that stage of seed is called ‘dormancy period’. When the convenient conditions are met for plant and the growth potential of the embryo is bigger than mechanical limitations of the seed cover, officially the germination begins. (Karakurt, Aslantaş and Eşitken, 2010) The following stages of germination (Meier, 2018) in plant development are leaf development, hence the plant produces its food by photosynthesis. Thereafter, the vegetative stage takes place, in which the number of leaves increases apparently, and the stems become thicker. Then, the seed plant generates buds and flowers respectively. The flower is the most colorful and attractive part of a plant and it involves mainly the sepal, the petal, the carpels or pistil, and the stamen. (Rost, 1996) The sepal – green part - protects the buds before they become flowers. Petal can be various colors and there is the part which spread the nice smell to attract the insects on the flower. Hence, the generated pollens by stamen – male organ – can be transported to carpels by that animals or in some cases wind for reproduction. At the end of the reproduction process, the pistil transforms into the fruit and it is in charge to protect seed. (Rost, 1996)



**Figure 18: Tomato Flower (Rost, 1996)**

As already specified in the previous paragraph, the plant needs convenient conditions to germinate, grow, and develop. The critical requirements can be seen in the following subchapters.

### **3.2.1. Water**

Water is an essential requirement for all living creatures. The water has a place in the first step of plant growth, germination. (Relf and Ball, 2009) Enough water must be taken by the seed to begin the vital activities. Lack of water affects dramatically the photosynthesis; correspondingly growth, and

productivity. (Zlatev and Lidon, 2005) On the other impact of the water is to fill some specific cells called turgor, hence water-filled cells keep the body upright. It can be observed that a dehydrated faded plant will become upright again in a short time after watering it.

### **3.2.2 Temperature**

Considering there is almost no life between the temperatures below 0 °C and above 50 °C apart from exceptions, the importance of temperature on living creatures is understandable. Regarding the plant kingdom, different classified plants can have different optimum temperature values to be germinated and grown-up. For example, the optimum temperature for the woody plants has been determined as between 20 and 30°C. While the extra high temperatures than the optimum temperature of the plants might stop the photosynthesis and death of the cells in the plants, extra cold temperatures might freeze the water between the cells and in turgor; hence it may cause the death of the plant. (Peskiroglu *et al.*, 2016)

Like all the other plants, tomato plants have also optimum conditions to grow healthfully. The temperature of the environment of planted tomato is of vital essential. Tomato plant needs a minimum of 10°C. (Relf and Ball, 2009) Even though the optimum temperature is specified as between 20 and 27 °C, they can be planted in the climate temperature range 10 to 37 °C. However, out of this range affects growth and reproduction dramatically. (Giraldo *et al.*, 2014) Therefore, temperate climates with less temperature difference between day and night should be chosen for better-quality tomato production.

In the further chapter, the effect of the climate and temperature on tomato production can be seen in general with the simulation on MATLAB.

### **3.2.3. Light**

The light plays the biggest role in photosynthesis, in parallel with the physical metamorphosis of the plant. After the germination period, the light becomes one of the most important parameters for the plants. Because the plant must produce nutrition to use it in respiration.



**Figure 19: The germinated plants under lightened and lightless conditions (Quizlet, 2015)**

The spreading light signals into the plant cannot be understood by the scientist yet. But regarding that discovered so far, the plants have 16 different photosensors, which are consisting of proteins. The most important photosensor, which affects the plant growth in the first place, is called phytochrome. (Dalkılıç, 2018) The phytochromes were first discovered in research on germination of lettuce plant with its sensitivity on red/far-red light of the sun. Phytochromes have two way of work, which depends on their being activated by changing the light from red to far-red. It is observed that the activated phytochromes by red light provide the plant to realize all the vital actions under convenient conditions including photosynthesis; while under far-red light, the plant cannot make photosynthesis. The amount of the far-red light increases in the sunset time or when the plant is shaded by building or any other plant, hence the phytochrome gets deactivated and photosynthesis stops. In the experiments, it was seen that the germination of lettuce increased to 100% under red light and decreased to 0% under far-red light. (Dalkılıç, 2018) Figure 19, it can be seen the growth of the plants on the normal cycle of activated photochrome and inactivated photochrome. The ratio of activation and deactivation time determines the photoperiodism of the plant. (Dalkılıç, 2018) The photoperiodism separates the vital routine of the plant today and night. If the plants need light more than 12 hours, they are called 'long day plants'. On the other side, if they need light less than 12 hours a day, they are called 'short-day plants'. (Demirsoy, L., Ozturk, A. and Serce, 2017) That means, long day plants need more activated phytochrome than deactivated phytochrome to be grown healthfully and the short-day plants are the other way around. Therefore, the plants have to be planted in the daylight conditions of the environment to get better production.

### **3.2.4 Humidity**

Another climate factor that affects plant development is humidity. The increasing temperature increases the holding water capacity of air. The relative humidity is the ratio of current water inside air and the maximum water that air can keep in the current temperature. (Wollaeger and Runkle, 2016) The biggest impact of the humidity can be seen in the transpiration of the plant. (Tibbitts, 1979) Regarding the transpiration of the plant, vapor pressure deficit (VPD) takes more importance than relative humidity. VPD refers to subtraction between air moisture and the maximum water capacity that air can hold when it is saturated. (Wollaeger and Runkle, 2016) (Tibbitts, 1979) Hence, it can be said that decreasing air moisture increases VPD value. Correspondingly to increased VPD makes the plant saturation increased. There are different positive effects of transpiration on plants. For instance, it keeps the plant cooler in high temperatures and provides a water cycle in the environment. On the other side, the transpiration makes the stomata of the plants closed and it badly affects the photosynthesis. Therefore, increasing VPD impacts photosynthesis and vegetative growth of the plant dramatically. (Zhen *et al.*, 2019)

### **3.2.6. Others**

All living creatures have specific requirements to grow and live healthfully. The factors which influence plant growth are countless. For instance, the plant growth can be increased, of course, with the quality of the soil, using fertilizers and strengthening by the various hormones. However, the simulation that you will be seen in the further chapters will be performed according to the climate factors. In the simulation, the soil quality and fertilizer utilization will be ignored.

## **3.3. Effects of Climate Change on Agriculture**

Climate change and the probable effects have already been discussed in Chapter 2. Due to this thesis being about both solar energy as renewable energy and agriculture, it is important to know the impacts of global warming on plants.

Climate change will bring along increasing temperature, correspondingly the drought, unexpected weather events, and irregular rains. Consequently, climate change is expecting to influence the plants considerably on various sides. According to the reference, the climate change will affect life through agriculture in 3 different sections. (Srivastava, 2013) The first one is the direct effects on plants. In this part, because of the inordinate high temperatures will affect the photosynthesis, thus the efficiency on plant growth will fluctuate. On the other hand, climate change causes postponements for planting, flowering, and harvesting schedules. (Kadioglu *et al.*, 2020) The second effect on plants is indirect

effects. Climate change will cause drought in some agricultural lands because of the temperature and lack of precipitation or cause floods because of the high amount raining. As a matter of course, the quality of the soil will impact badly. (Srivastava, 2013) In consequence of former statements, thirdly socioeconomics of society will be troubled. The accelerating amount in population will increase the food demand. (Srivastava, 2013) However, decreasing the number of agricultural lands because of climate change, will cause less food production and boosted food prices, respectively. Mentioned prospects demonstrate how climate change might affect agriculture.



**Figure 20: Droughtiness (Onedio, 2015)**

### ***3.3. Mathematical Models on Plant Growth***

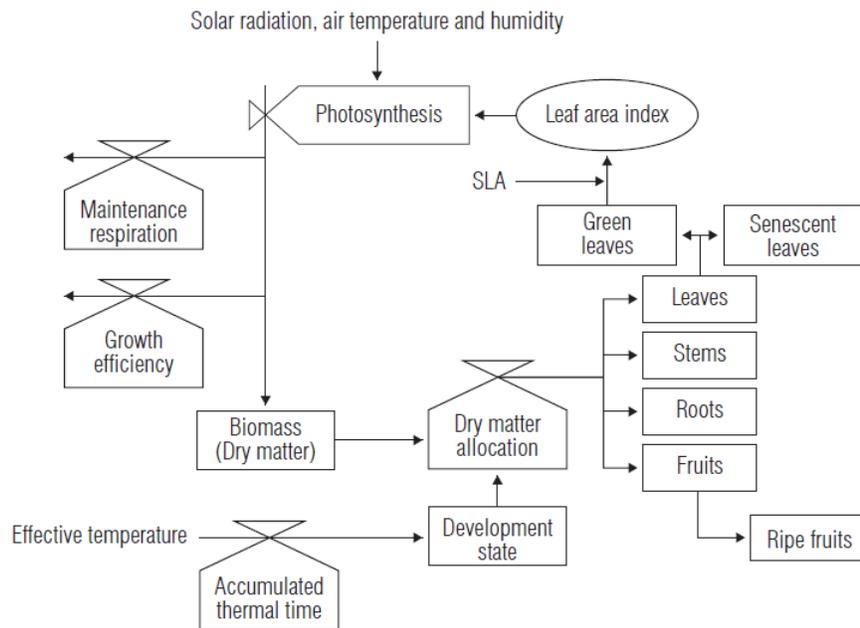
Various plants especially medical and aromatic ones have been using for nutritive, wellness, cosmetic, and seasoning purposes over the centuries. (Acibuca and Budak, 2018) As one discipline in science, botany, involves all the researches regarding plant kingdom. Botany gardens have been existing for centuries and it is known that the first botany gardens established by Aristoteles. However, the first botany garden on education purposes constituted in 1545 in Italy and the botany science has been improved until today. (Muminoglu, Tahta and Aslan, 2018) With the help of the researches on plants and developed technology provide the scientist to perform mathematical models on plant growth.

The mathematical models of the plants can be described as the identified mathematical equations for the specified plant. Those equations can involve both variables regarding the climate and soil conditions and constants. When the climate and the soil characteristics of the intended planting land, such as

annual temperature, humidity, solar radiation, etc., entered as inputs in the simulation, which is constituted with mathematical equations, the rate of estimated plant growth and the ripe fruit can be estimated. This model can provide several opportunities for agriculturalists. Primary advantages of the plant growth models are their decreasing the cost and consumed time on plant researches because experimenting on plants while they grow takes a lot of time and it is costly. Hence, it is possible to see if the plant can grow efficiently in the land without planting it. (Pamuk and Ozgurel, 2005)

This study aims to examine the behavior of the plants under PV systems. Various mathematical plant growth model has been constituted so far for different kind of plants. In this study, because of the popularity of tomato, tomato plant growth has been decided to be researched in different locations under PV modules. In this direction, tomato growth models have been analyzed and represented as follows.

Over the last decades, several tomato growth models have been performed. A photosynthesis model on the tomato plant by using light and  $CO_2$  inputs has been performed by (Acock *et al.*, 1978) The prediction of optimal harvest date for tomato is modeled by (Machado *et al.*, 2004) and the maximum and minimum temperature values of the planted are utilized to define that. The other growth model is TOMOGRO, which specifies a dynamic tomato growth model depending on solar radiation, temperature, and  $CO_2$  in a greenhouse by (Jones *et al.*, 1991). These references were just some examples to remark that there are many in numbering researches on tomato plant growth models. In this study, '*A tailor-made crop growth model for the tomato production systems*' (Gil, Bojaca and Schrevens, 2017) will be performed on MATLAB and simulation will be made under PV modules with different transparencies in different locations, which have different climate conditions.



**Figure 21: Tailor-Made Crop Growth Model for Tomato Production Inputs and Outputs (Gil, Bojaca and Schrevens, 2017)**

The selected growth model works daily by using the hourly information of solar radiation, photosynthetic active radiation, which explained former, temperature, and humidity values. At the end of the modeling, the amount of the ripe tomato can be calculated for an open farm or a greenhouse. In the simulation, the characteristic of the soil has been ignored. Therefore, the soil specifications of simulated lands in Germany, Spain, and Turkey have been accepted as they are the same quality of the soil. The related diagram regarding the tomato growth model can be seen in Figure 21. The equations will be explained in the Methodology phase of the study with the PV module production and economic analysis.

Up till now in the study, the PV modules as a renewable energy system and the general definition of plant kingdom have been reviewed as supportive knowledge to be understood the main topic, 'Agricultural Photovoltaic Systems'. In the next chapter, the review of the Agricultural Photovoltaic Systems will be performed and then the following chapter the simulation of Agricultural PV systems will be completed by using the Tailor-Made Crop Growth Model for Tomato Production.

## 4. Agricultural Photovoltaic Systems

Photovoltaic systems are one of the dominating and increasing electrical energy supplies in tandem with wind energy among all the renewable energy systems. The reason why the requirements for energy production increase every year is the increasing energy demand day by day. Developments on industry and population growth are the main factor in this increment. As it is well known, the main necessities of humans are energy and food. Accordingly, the increasing population around the world gives rise not only to energy demand but also to food demand.



**Figure 22: Utility-Scale PV System (Hil, 2019)**

The production of PV systems differs regarding the solar energy potential of the installed area. For instance, a PV system needs 1.5 m<sup>2</sup> to produce annually 1 MWh in northern parts, while completing the same system requires one-third of the area to produce the same energy in the area close to the equator. (Fritsche *et al.*, 2017) When it is considered that for each MW PV system installation, a 2-hectare area is needed (Satnra *et al.*, 2017); it can be understood that the required area for utility-scale PV systems is huge. Regarding the expectations of solar growth until 2050, it is expected that installed solar power in the world will be 8500 GW. (IRENA, 2019a) That means, assuming all the PV installations as utility-scale systems, the 17-million-hectare area would be needed to reach that aim globally in 2050. Correspondingly, increasing food demand will bring along the more requirement for agricultural areas than before. (Satnra *et al.*, 2017) Hence, the land-use efficiency term has been getting important to use rural areas more efficiently. The idea behind increasing the efficiency of agricultural lands is to use one

on the top of the other. That means, instead of using the land only for agriculture or only for PV systems, using the area for both will increase the land efficiency. As an output, not only food but also energy will be produced.

Agriculture is the fullest extent of planting plants and growing animals to produce food, what humans require. Agriculture is the major sector of a country in many aspects such as providing food safety, increasing national income, producing raw material for other industries, etc. (Dogan, Arslan and Berkman, 2015) The history of agriculture starts almost 11.500 years ago. (Preuschen *et al.*, 2019) However only over a hundred years ago, technological developments and researches on the raising of agricultural productions have been started increasing. (Preuschen *et al.*, 2019) Correspondingly, the modern agricultural concept came insight and in contrast to traditional agriculture, the needed human labor gave place to machinery. (Ozturk, Yasar and Eren) The modern agricultural devices require an energy supply such as fossil fuels for driving tractors or electricity – produced from fossil fuel - for pumping water and irrigation. (Ozturk, Yasar and Eren) The effort on decreasing fossil fuel utilization globally has been affected by the agricultural sector in the direction of boosting renewable energy applications. Regarding the usage of solar energy, it has been performed for different aims and places as follows. So, in the beginning, the various grounds of solar energy usage in agricultural systems will be explained and then the main topic, which is about Agricultural Photovoltaic Systems on plants, will be discussed.

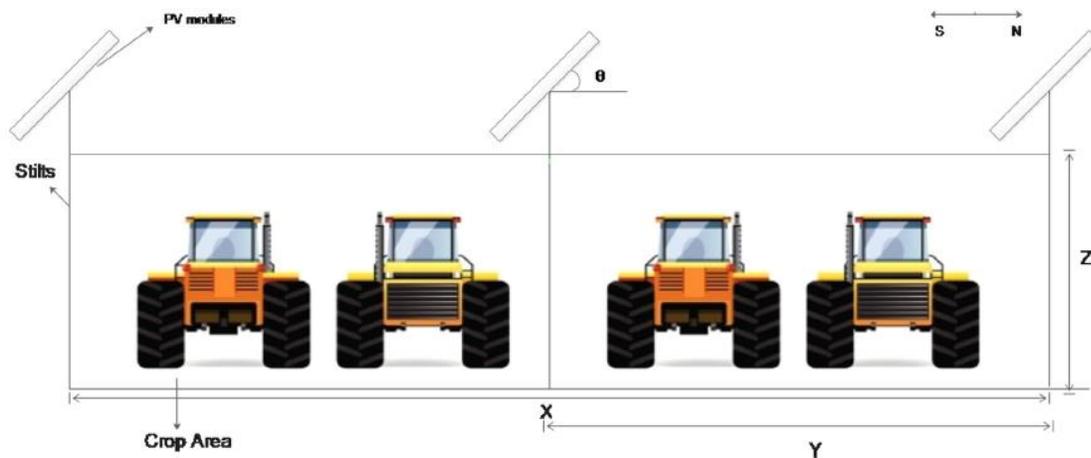
Aquafarming is one of the agriculture branches which focuses on breeding on marina animals. Similar to all the other facilities, also aquafarming establishments required electrical energy. Generally, those establishments are found outside of the urban where the grid does not reach. (Campen, Guidi and Best, 2000) Even in the case of the existence of a grid, the utilization of renewable energy is a critical solution to contribute to green energy production by meeting their self-consumption. The energy can be supplied by PV systems on this kind of establishments to ventilating the water by pumps to increase the productivity of breeding, to be used to electrify ice-makers before transportation of the marine animals, or to provide light to increase the safety of the establishment and divers. (Campen, Guidi and Best, 2000)



**Figure 23: Floating PV Systems for Aquafarming (CleanFuture, 2018)**

The other utilization of PV in rural areas is the wastewater purification. All the living creatures influence on bad water quality; therefore, the dirty water must be decontaminated by using electrical devices. That energy can be supplied by PV systems and there are already so many examples in the world such as in China with 60 MW. (Xue, 2017)

APV Systems are the implementation of plant growing and electrical energy production from PV - also called Agrivoltaics -, which is the essential topic of this study. This technology aims to get double yield with the production of crops and energy at the same time. That double yield provides many benefits to the farmers with regards to increasing plant safety and socio-economic view such as decreased energy cost for watering plants etc. (Younas *et al.*, 2019) The combination of PV and crops might be beneficial for the plant itself as well. The shading caused by PV provides to decreased water loss and drought in the soil; the research shows that optimized shading can save the water in the soil between 14 and 29%, so it helps to the plant not to be exposed to drought in hot climates and of course, decreases the respiration costs. (Dinesh and Pearce, 2016) (Younas *et al.*, 2019) Basically, the system consists of PV modules, which are placed in an array to keep the shading at an acceptable level on the top of the agricultural land. In this sense, the utilization of transparent double-glass PV modules instead of standard PV modules with metal back sheet increases the illumination on the land. That system can be applied to the top of the greenhouses and free lands by using a long construction profile. The reason for using long profile constructions for a PV system is to ensure easiness to the bulky vehicles when they work on planting, harvesting, etc.



**Figure 24: APV System [15]**

To understand the topic, the literature review on APV will be performed in the next subchapter, which consists of the history, challenges, installed countries. In light of this information, in the further chapter, the effect of different transparent modules in APV systems on the tomato plant will be simulated on MATLAB.

#### **4.1. Literature Review**

The utilization idea of a successive combination of crops and PV systems have been found only some decades ago. *Goetzerberger and Zatsrow* are the founding fathers of the idea of APV systems. (Goetzeberg and Zatsrow, 1982) In the paper, it is specified that mounting PV modules up to 2 meters long instead of directly to the ground will bring along some advantages. However, several arrangements have been specified regarding increasing the productivity from both sides. It is mentioned that the PV modules should be south orientated and tilted to increase energy production, on the other hand, settlements of the PV modules should be up from the ground level and the space between PV modules should be enough to homogenous solar radiation convention. In the article, 2 different PV module configurations with 2 different spacing between modules and tilt angles have been mentioned and, in both configurations, enough solar radiation could go on the ground. The first sketch can be seen in Figure 25. (Goetzeberg and Zatsrow, 1982)

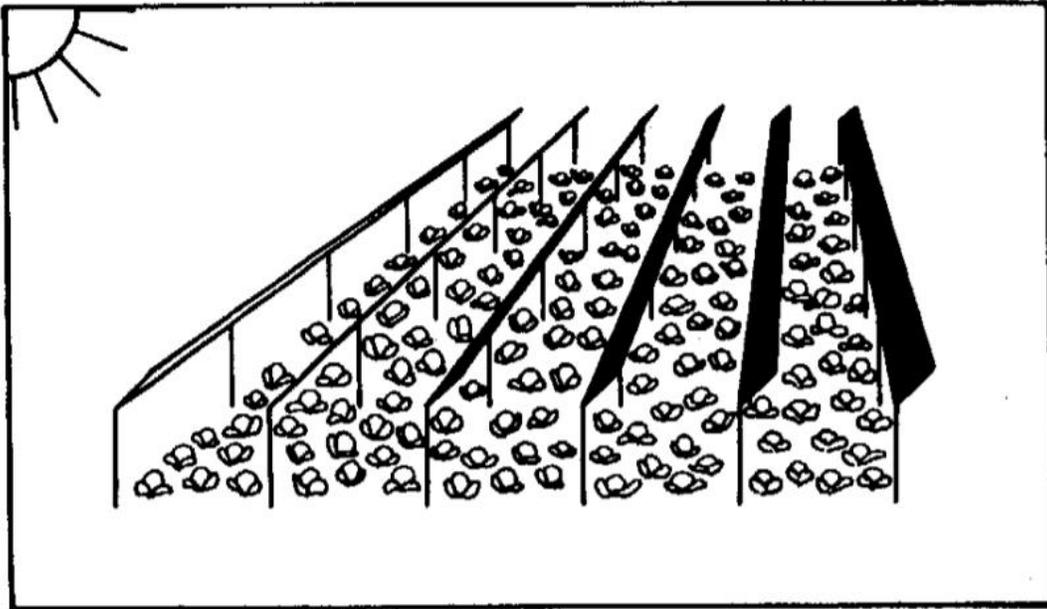
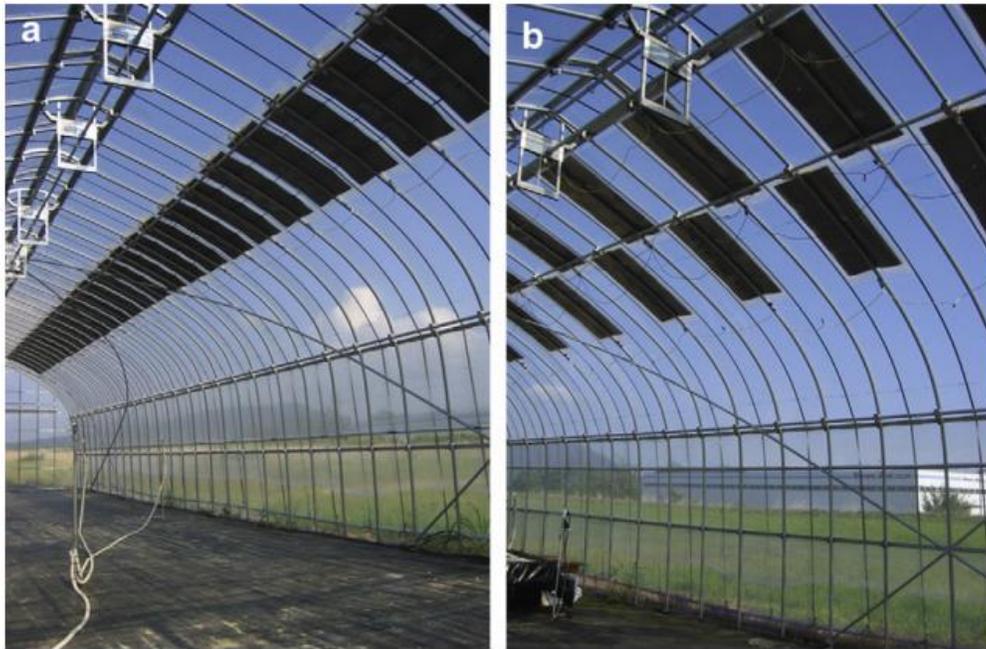


Figure 25: First AgriPV Sketch [13]

(Kozai and He, 1999) researches on the effect of PV modules on the greenhouses. In the research, the PV modules have been placed with different spacing in between to see the effect of shading on PV modules on plant growth. It is mentioned that if the PV modules cover less than 60-80% in the winter and 30-50% in the summer of the roof of the greenhouse, it will not affect the solar radiation on the ground for plant growth.

Yano *et al.* (2010) reported the shading rate and electricity production of 30 PV modules, which cover 13% of the roof of the greenhouse, in Matsue City, Japan with 2 different The PV modules were placed as it can be seen in Figure 26 in a line and crossed, respectively. It is observed that the crossed PV configuration had a better solar light distribution in the greenhouse and since the electrical production of both settlements is almost the same, crossed configuration has been decided more convenient one. (Yano *et al.*, 2010)



**Figure 26: Matsue City Greenhouse PV configurations - a: inline, b: crossed (Yano *et al.*, 2010)**

Although the first published research about APV by *Goetzerberger et. al. in 1981*, the first installation of the APV system has been made on 820 m<sup>2</sup> area in Montpellier, France in 2010. The research on the installed system has been reported by (*Dupraz et al., 2011*). In the project, the researches have been attached importance to the settlement of the PV modules. Therefore, two different module settlement densities have experimented as full density and half density. The modules have been placed with a 25° tilt angle and 1,64 m spacing between modules, which is called optimal placement with full density. And 3,2 m spacing between modules called half density. It is reported that APV systems might increase the productivity of the land up to 60-70%. The research on this field continued with the same researches with the following article. (*Morrou and Wery et al., 2013*) reported the effect of the shading on the lettuce plant under PV panels in the APV system in Montpellier. It was clarified that the lettuce production differs under different densities of PV modules. In half density, the lettuce production is not influenced so much, however, under full density PV modules, the lettuce production decreased 48%. Correspondingly, the researches advise to let at least 70% of the radiation spread under the PV modules for better plant production. To get 70% radiation on plants, the researchers suggest two variations. The first is to make settlement of the PV modules with low densities and the second is to monitor radiation level under PV modules and in case of the low level of radiation, electronically adjustable PV slope should step in and provide increasing the radiation level by changing the slope. Furthermore, again some researches have been performed by some researches in Montpellier APV Field and reported. *Marrou et Al. (2013)*

reported that besides the temperature, solar radiation is crucial for lettuce and cucumber plant growth. However, under the APV system, the temperature of the plants did not show a huge alteration to affect plant growth.



**Figure 27: Montpellier APV System- Left: The sketch of half density and full density settlement. Right: The picture of the field. (Morrou and Guilioni *et al.*, 2013)**

(*Campiotti et al.*, 2011) reported a closed greenhouse system with tomato production under PV modules on the roof. The scope of this research was to discover the energy requirements of the tomato plants and to meet the demand by using PV modules. The energy demand of the 21 tomato plants in 120 cultivation days specified as 19.48 kWh, while the 1,1 kWp PV system produced 333.6 kWh energy between September and December.

(*Urena-Sanchez et al.*, 2012) made experiments in a greenhouse with tomatoes. The experiment has been performed in the city of Almeria and the roof of the greenhouse has been 9,8% covered by PV modules. It is mentioned that the tomato quality and the amount of production did not affect by shading at all. However, there are also different researches, which shows the decrement on tomato production under shading.

(*Kadowaki et al.*, 2012) made research on Welsh onion cultivation under PV modules in a greenhouse. The PV modules placed in 2 different configurations as in Figure 26. Regarding the straight line, it is reported that the electrical energy production was as expected, however, the production of onions has

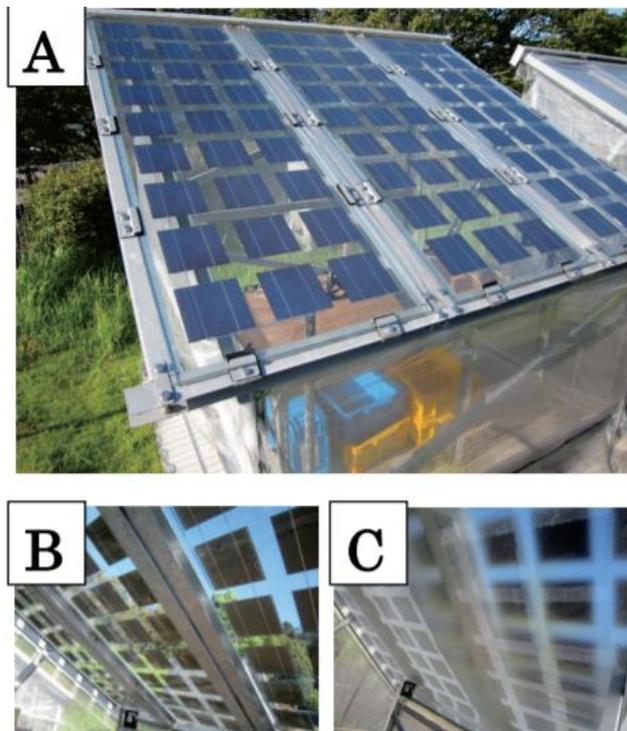
been decreased because of shading significantly. On the other side, it is specified that both for electrical energy and crop, production, the crossed PV installation gave better results.

(*Carlini, Honorati and Castellucci, 2012*) simulated 1456 high-efficiency PV modules on the roof of a developed greenhouse system by a drawing. The scope was to provide enough heating and cooling to the tomato plant by producing energy from PV modules. In the article, the reduction of solar radiation inside the greenhouse because of the PV modules remarked. It is enough to affect the photosynthesis of the plants.

(*Marucci et al., 2012*) specified the importance of covering the material of a greenhouse. In the article, it was remarked that mostly opaque materials have been using for covering and the covering material does affect not only the solar radiation but also the temperature inside the greenhouse. Therefore, the article suggests that the usage of transparent modules may bring along some advantages. In the further chapter, the simulation tomato production under Agrivoltaics will be performed on MATLAB and the effect of transparent modules will be examined.

(*Cossu et al., 2014*) reported a greenhouse with a 50% covered roof with PV modules. Tomato production and electricity production has been examined. The PV system caused a 64% reduction in solar radiation inside the greenhouse when compared with the normally covered greenhouse. Accordingly, tomato production decreased by 18%. However, when the economic analyses have been performed, it is stated that the energy production by PV modules compensate for the drop in crop production and it provides a better economic advantage to the greenhouse with a double yield with crops and energy.

(*Tani et al., 2014*) specified that although some plants influence dramatically by decreasing solar radiation, some plants like lettuce can continue its growth with on the high level of shading. The experiment has been performed with 81 pieces of 50% transparent glass-glass PV modules. Under one part of the PV modules, the transparent light-diffusing film was placed and in the other part, the light diffused directly from the transparent PV module. On one side the lettuce production decreased under only PV modules, however on the other side the lettuce production improved under diffusing film. Therefore, the researches advise the diffusing film as an applicable method. The model can be seen in Figure 28.



**Figure 28: Lettuce Growth under PV Modules in Japan. - A: Upperside of the greenhouse, B: Inner side of the greenhouse, C: Inner Side of greenhouse under PV and diffusing film (Tani *et al.*, 2014)**

(Yano, Oneo and Nakata, 2014) made a research on 39% covered of greenhouse roof with two different kinds of transparent bifacial PV modules. The first PV module was consisting of 30 solar cells, while the second kind of solar module had 10 solar cells. Hence, shading and electricity production was 3 times more in the first party PV modules. However, in both modules, crop production did not affect and is convenient for agricultural usage on the roof of the greenhouses. In the farther simulation in MATLAB, the bifacial modules will be tested, too.

(Bulgari *et al.*, 2015) made research on tomato plant cultivation under glass and PV modules in two different greenhouses. The roof was 50% covered by PV modules in the first greenhouse, and the second one was the traditional greenhouse. The tomato yield in different greenhouses in the months between May and September has been compared with each other. The tomato production was the same in traditional and PV greenhouse only in July, while in the other months the tomato yield was always more in a traditional greenhouse. It explains tomato production has been affected by shading. Moreover, it is specified in the article that not only the tomato production reduced but also there was also some

deficit of hormones and sugar in the tomatoes under the PV module greenhouse. However, the quality may increase by using more transparent modules.

(Valle *et al.*, 2017) made research on the APV system, which was installed in Montpellier in 2010, the same as in Figure 6. However, this time instead of fixed PV modules, the experiments have been made on PV modules with the solar tracker. It is specified that using solar trackers increase solar radiation on the ground, therefore it affects plant growth positively. On the other side, electricity production from PV modules increases.

(Schindele and Scheider, 2019) reported by Fraunhofer Institute that the APV System which is installed in Heggelbach. The system has PV power of 198 kWp and under PV modules, the researchers examined the growth of 4 different plants, which are wheat, potatoes, clover, and celery. They specified that the land-use efficiency is increased up to 186% with potato growth. Furthermore, Schindele, S. *et al.* (2020) explained the economic aspects of APV systems. It is indicated that not all the crops are convenient for APV systems to get a sufficient price-performance ratio. (Schindele *et al.*, 2020)



**Figure 29: Heggelbach APV System (Schindele *et al.*, 2020)**

The aim of PV module utilization in agricultural lands is to increase land efficiency. Hence, the Land Equivalent Ratio (LER) is defined. LER can be calculated as Equation 1 below. It is basically, the

productivity ratio of the land with mixed land usage with PV and crops to the usage of the land for only crops or only PV. For example, if an APV System has 1.5 LER, it means from 100-hectare land will make production as 150-hectare land. Therefore, if the LER of the APV System is bigger than 1, it can be said that the system is convenient. (Dupraz *et al.*, 2011)

$$LER = \frac{Crop\ Yield_{AgriPV}}{Crop\ Yield_{only\ crop}} + \frac{PV\ Yield_{AgriPV}}{PV\ Yield_{only\ PV}} \quad (3.1)$$

#### **4.2. Summary**

The increasing population in the world brought along the idea of using the same land for double yield with energy production and crop growth. In response, Agricultural Photovoltaic Systems have been developed. APV system is a newly emerging technology around the world owing to increasing demand for food, energy, and fertile land; it provides to produce electricity from PV modules and plant growth under PV modules. Although the shading occasioned by PV modules is something needed for plant growth to decrease temperature and water loss (Araco-Delgado *et al.*, 2018), that shading has to be optimized not to influence the crop badly. Otherwise, that system would bring along harm to the farmer's agricultural goals instead of benefits. However, if the system optimized for both crop growth and energy production by PV, various opportunities will become along for the farmers.

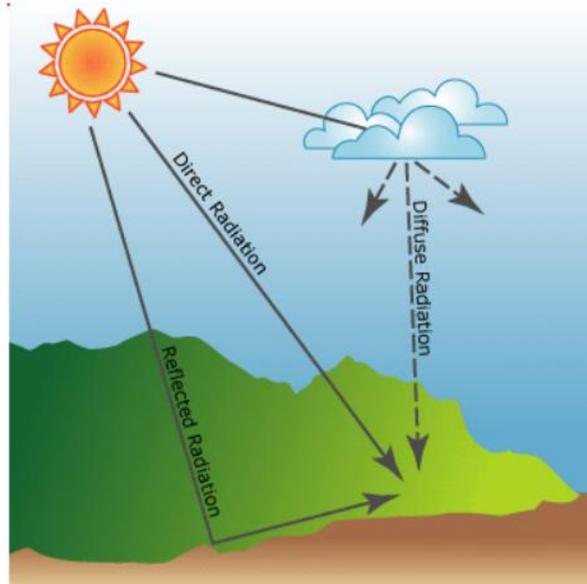
Regarding the advantages of APV systems, it prevents the drought of the land with shading up to 29%. Therefore, the usage of APV might be convenient in high-temperature climates. Some reduction in the production of crops is acceptable when electrical energy production contributes to production. Hence, the farmer will be made self-consumption and have benefited economically. It will not only bring advantages to the farmers but also the country by using the land for double yield. According to the researches, land efficiency is increased by up to 170% with APV applications. Therefore, it is expected that the APV systems will be so crucial for the next generations for double yield because of the increasing demand for fertilize lands. (GreenID, 2018)

## **5. Agricultural Photovoltaic Systems Simulation**

In the study so far, solar energy systems as a renewable energy system and plant kingdom have been discussed and explained as a basis. Further, as a combination of solar systems and plant growth, APV Systems have been explained and the researches on APV have been revealed. It is noticed after the literature review that there are several simulations have been performed to discover how the APV system affects the plants and how much energy the PV system produces. However, all the performed simulations have been made by using two different simulation programs, the former is to investigate plant growth and the latter is to check PV production. There is no simple and combined simulation program, which gives a prime idea to the potential APV installers to their farms. Therefore, in this study, a basic simulation has been made for the potential APV customers on MATLAB. They only need to enter required inputs to the simulation program and as an output, the user will get how many kilogram rape fruits will be produced and the energy production from PV. In the simulation, tomato production will be performed as already mentioned in previous chapters by using the Tailor-made Crop Growth Model. The steps of the simulation will be explained further.

As already explained in the previous chapters, the solar radiation is crucial for both energy production by PV modules and crop growth. However, while collecting data of solar radiation on a monthly or daily basis is kind of easy, getting hourly solar radiation data for different locations involves hard work or obligatory costly payment to the data services. Therefore, in the first part of the simulation, the way of obtaining approximate hourly solar radiation will be explained. Thereafter, in the further chapter, the solar radiation of Almeria (Spain), Ingolstadt (Germany), and Mersin (Turkey) will be evaluated and correspondingly the tomato production under different PV modules will be simulated and the results will be compared.

## 5.1 Determination of Solar Radiation in the Simulation:



**Figure 30: Representative display of direct, diffuse and reflected radiation (ArcGIS)**

Electromagnetic radiation comes from the sun, which provides the necessities for living creatures such as heat, light, etc., called solar radiation. It is measured by pyranometers and the unit of the solar radiation is  $W/m^2$ .  $1367 W/m^2$  solar radiation reaches in the outer of the atmosphere and the value of reached solar radiation on earth decreases depending on the instant climate of the area. The solar radiation part company with direct, diffuse, and reflected solar radiation. Direct solar radiation is the solar radiation that comes from the sun which does not face the obstacle. The direct solar radiation value is on its maximum level in a clear sky day. The opposite way around, the diffuse solar radiation arises from the obstacles through the atmosphere, for instance, the clouds or any preventer. The reflected solar radiation is, as the name implies, the solar radiation which reflects from the surrounding materials such as buildings, glass, etc. When all these radiation types are considered, the total solar radiation is formed, and it will determine the PV production and crop growth generally. Further definitions and equations represent the steps, which have been followed in the simulation, to clarify the process.

The determination of hourly solar radiation is a specific location is required a lot of information and data regarding the location. In the development of the simulation program on MATLAB, the first step is to define the latitude angle ( $\phi$ ), longitude angle ( $L_l$ ) and local meridian ( $L_s$ ) of the field. The latitude angle is accepted  $0^\circ$  on the equator, and through the southern and northern, any locations get one latitude angle between  $90$  and  $-90$ . Then the declination angle ( $\delta$ ) is defined and can be calculated as in Equation

5.1 and  $n$  is defined as the number of the days. The declination angle happens because of the 23.45° tilt angle of the world against the sun. Because the rotation of the earth itself and around the sun makes that angle change during the year.

$$\delta = 23.45 \cdot \sin\left(\frac{2\pi \cdot (284 + n)}{365}\right) \quad (5.1)$$

Further, the local solar time (LST) and equation of the time (EoT) have to be defined to calculate the solar angles. Then by using the solar angles, the hourly solar radiation of the field will be calculated by using the average monthly data. The local solar time is the evaluates the location of the sun. Time local solar time can be calculated as in Equation 5.2 by using longitude and meridian angle, besides EoT, where can be calculated as in Equation 5.3. (PV Education, 2019)

$$LST = LC + \frac{4 \cdot (L_l - L_s) + EoT}{60} \quad (5.2)$$

$$E = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \cos(B) \quad (5.3)$$

$$B = 360 \times \left(\frac{n - 81}{365}\right) \quad (5.4)$$

Hour angle ( $\omega$ ) can be defined as the angular measurement of the time. The hour angle is 0 in the noontime and it is considered negative before noon and positive afternoon. Equation 5.5 represents the calculation of the hour angle. Additionally, the sunset angle ( $\omega_s$ ) also can be defined as in Equation 5.6, and it depends on latitude and declination angles.

$$\omega = 15 \times (ST - 12) \quad (5.5)$$

$$\omega_s = \cos^{-1}(-\tan \phi \cdot \tan \delta) \quad (5.6)$$

The solar zenith angle ( $\theta_z$ ) is the angle between Sunlight and the perpendicular imaginary line to the equator. The calculation of the solar zenith angle can be seen in Equation 5.7. The altitude angle ( $\alpha$ ) is the complementary angle of the solar zenith angle and the related formula of the altitude angle can be seen in Equation 5.8.

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (5.7)$$

$$\alpha = 90 - \theta_z \quad (5.8)$$

The slope angle ( $\beta$ ) is an important factor in PV module placement.  $0^\circ$  slope means the PV modules placed on the ground horizontally, and  $90^\circ$  slope means they placed on the ground vertically. The suggested slope of the PV modules is between  $10^\circ$  and  $40^\circ$  to avoid dust and snow on the PV modules. In our project, the slope has been determined as  $25^\circ$ . At the end of the calculations, horizontal solar radiation and  $25^\circ$  tilted solar radiation values will be obtained.

Regarding the azimuth angle, there are 2 different azimuth angles, surface azimuth ( $\gamma$ ) and solar azimuth angle ( $\gamma_s$ ). The solar modules needed to be placed facing to the south in the northern hemisphere and north in the southern hemisphere to have more production. The azimuth angle is  $0^\circ$  facing to the north, while it is  $180^\circ$  facing to the south.

Lastly, regarding the solar angles, the incidence angle ( $\theta_i$ ) is the angle between solar rays and the normal to the tilted surface. It can be calculated as in Equation 5.9. Almost all the angles calculated before was a preparation to define incidence angle. Incidence angle will help to define correction factors to transform the horizontal solar radiation data to chosen tilted angle solar radiation, which is important for PV production.

$$\cos \theta_i = (\cos \phi \cos \beta + \sin \phi \sin \beta \cos \gamma) \cos \delta \cos \omega + \cos \delta \sin \omega \sin \beta \sin \gamma + \sin \delta (\sin \phi \cos \beta - \sin \phi \sin \beta \cos \gamma) \quad (5.9)$$

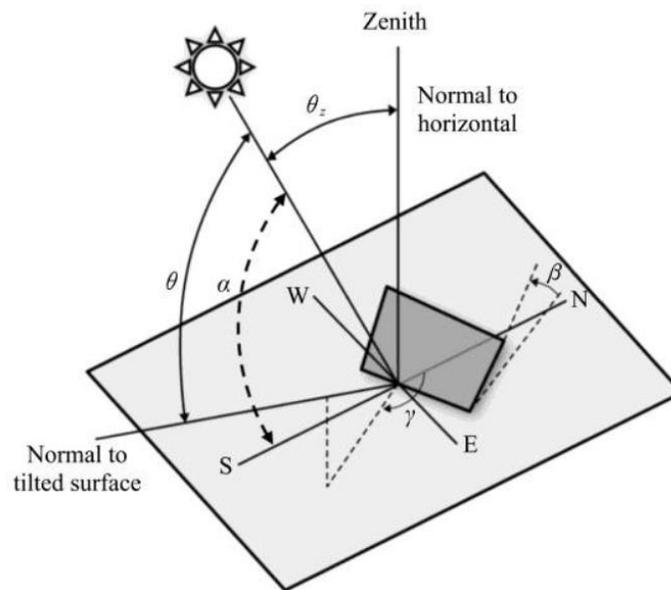


Figure 31: Solar Angles (Ronoh, 2017)

As already explained before, the horizontal solar radiation data affects crop production, while the tilted solar radiation data is crucial for PV production. Therefore, both horizontal and tilted solar radiation has to be calculated in the simulation. But firstly, the global hourly horizontal solar radiation ( $I_h$ ) data has to be defined, and then by using correction factors, tilted solar radiation will be calculated, too! By using Equation 5.10 below, the horizontal daily solar radiation ( $I_d$ ) data of a location can be transformed into hourly solar radiation data. This equation has to be used for each horizontal direct ( $I_{dir}$ ), diffuse ( $I_{dif}$ ) and reflected ( $I_{ref}$ ) This equation is extremely important, because reaching hourly solar radiation data for a very specific location may be very hard. In the study, the obtained monthly solar radiation for Almeria, Ingolstadt, and Mersin will be given in the further subchapter, calculated hourly solar radiation for each location will be shared and the results of the APV system in each city, while tomato growth will be discussed there.

$$\frac{I_h}{I_d} = \frac{\frac{\pi}{24} \cdot (\cos \omega - \cos \omega_s)}{\sin \omega_s - \left(\frac{2\pi\omega_s}{360}\right) \cdot \cos \omega_s} \quad (5.10)$$

Owing to obtain hourly horizontal solar radiation data, the tilted solar radiation data can be also calculated. The further 3 Equations are the corrected factors for each direct ( $R_{dir}$ ), diffuse ( $R_{dif}$ ), and reflected ( $R_{ref}$ ), solar radiation. Earlier, they have been explained as 3 parameters in total solar radiation.

$$R_{dir} = \frac{\theta_i}{\theta_z} \quad (5.11)$$

$$R_{dif} = \frac{1 + \cos \beta}{2} \quad (5.12)$$

$$R_{ref} = \frac{1 - \cos \beta}{2} \quad (5.13)$$

Finally, the hourly tilted solar radiation can be calculated as in Equation 5.14. In the equation, solar radiation is defined as  $I$  and reflection coefficient ( $\rho$ ) will be 0.15 in the whole study. Further, the obtained horizontal solar radiation and tilted solar radiation will be used for crop and PV production, respectively.

$$I_t = I_{dir}R_{dir} + I_{dif}R_{dif} + \rho I_{ref}(I_{dif} + I_{dir}) \quad (5.14)$$

## 5.2. Determination of Tomato Production in the Simulation:

In this part of the study, the steps during the simulation for the ripe tomato production will be explained by using the reference 'Tailor-Made Crop Growth Model for Tomato Production'. (Gil, Bojaca and Schrevens, 2017) The calculation of the tomato growth rate by using equations in the reference is to subtract from the daily photosynthesis rate of the tomato crop to daily respiration.

As already mentioned, the global hourly horizontal solar radiation ( $I_h$ ;  $W/m^2$ ) will be used in the tomato production simulation. The calculated  $I_h$  in the previous chapter have to be transformed into Photosynthetic Active Radiation (PAR), which is explained in chapter 3 and then to the Photosynthetic Photon Flux Density (PPFD;  $\mu mol m^{-2} s^{-1}$ ). It is known that PAR takes place in 47% of the total solar radiation. The calculation of PPFD from  $I_h$  can be seen in Equation 5.15. PPFD gives an idea about how many mols sunlight the crop will get per second, which affects crop production significantly. (Langhans and Tibbitts, 1997)

$$PPFD = (I_h \cdot 0,47) \cdot 4,57 \quad (5.15)$$

Besides hourly solar radiation data, the hourly temperature (TMP) and the hourly humidity data must be defined for each location. In this study, the hourly historical temperature and humidity data have been found from the weather data company, *Meteoblue*, and the data will be mentioned in the case study part for each location. The importance of the temperature and humidity have been already discussed in the previous chapters because they affect the photosynthesis rate of the crop. Equation 5.16,  $P_{max}$  refers to the maximum leaf photosynthetic rate and it depends on  $CO_2$  use efficiency ( $\tau$ ;  $\mu mol CO_2 m^2 s^{-1} ppm^{-1}$ ),  $CO_2$  amount of the air ( $ppm$ ), humidity and temperature.  $CO_2$  the concentration of the air has been selected as 360 ppm in this study. In Equation 5.16, PGRED is a correction factor for photosynthesis rate depending on the hourly temperature of the location. Equation 5.17 shows the calculation of the PGRED and the optimum temperature gap for tomato growth can be understood. On the other hand, the other factor, which affects photosynthesis rate ( $P_{max}$ ) is PVPD and Equation 5.18 shows how to calculate PVPD. As it can be seen in the Equation 5.18, PVPD is contingent upon Vapor Pressure Deficit (kPa), the effect of Vapor Pressure Deficit on Photosynthesis (VPDL; kPa) and a constant factor about the effects of VPD on photosynthesis (CK,  $kPa^{-1}$ ). In this study, CK has been selected as  $-0,8 kPa^{-1}$ . The importance of VPD has been discussed in the previous chapters.

$$P_{max} = \tau \cdot CO_2 \cdot PVPD \cdot PGRED \quad (5.16)$$

$$PGRED = \begin{cases} 0, & \text{if } TMP < 9^\circ C \\ TMP - 9, & \text{if } 9 \leq TMP < 10^\circ C \\ 1, & \text{if } 10 \leq TMP < 28^\circ C \end{cases} \quad (5.17)$$

$$\begin{aligned} & -0,083.TMP + 3,33, & \text{if} & & 28 \leq TMP < 40^{\circ}\text{C} \\ & 0, & \text{if} & & TMP \geq 40^{\circ}\text{C} \end{aligned}$$

$$PVPD = e^{(CK.(VPD-VPDL))} \quad (5.18)$$

By using the outputs in the 4 equations below, the hourly gross photosynthesis ( $GP_h$ ;  $CH_2O h^{-1}$ ) of the tomato plants can be calculated. Equation 5.19 demonstrates how to calculate  $GP_h$ . In the equation, as can be seen, there are different parameters. The value of the parameters has been selected according to the reference and accordingly, the light extinction coefficient (XK) is 0.58; the leaf light transmission coefficient (XM) is 0.091; leaf quantum efficiency (QE) is  $0.0645 \mu mol CO_2 \mu mol^{-1} photon$ . Leaf area index (LAI) is a parameter, which affects the photosynthesis in the leaf directly, selected as 3.0 according to the reference. (Heuvelink *et al.*, 2014)

$$GP_h = \frac{P_{max}}{XK} \cdot \ln \left( \frac{(1 - XM) + QE.XK.PPFD}{(1 - XM).QE.XK.PPFD.e^{-XK.LAI}} \right) \quad (5.19)$$

By making use of the  $GP_h$  daily gross photosynthesis ( $GP_d$ ;  $CH_2O d^{-1}$ ) of the tomato plant can be calculated as in Equation 5.20. The plant density (PLM2;  $plants/m^2$ ) on the field effects the  $GP_d$  and the fruit yield significantly. Tuan, N. made a research on plant density of the tomato and the effects, correspondingly, the PLM2 selected as  $2,5974 plants/m^2$ . (Tuan and Mao, 2015)

$$GP_d = \sum_{h=1}^{24} (GP_h \cdot 3600) \cdot \frac{30 \cdot 10^{-6}}{PLM2} \quad (5.20)$$

The produced energy to grow by the plant with photosynthesis is already calculated with the previous equations. However, the living creatures must spend energy for respiration ( $M_{res}$ ;  $gCH_2O d^{-1}$ ) to realize the vital actions. Consequently, the spent energy decelerates the plant growth. The respiration of a plant directly depends on the air temperature. Different constant parameters are defined to calculate respiration. Sensitivity to temperature ( $Q_{10}$ ) is determined as 1.4; the respiration rate for leaves and stems ( $RMRL$ ;  $gCH_2O g^{-1} DMd^{-1}$ ) is specified as 0.015; the respiration rate for the fruits is determined as 0.01 ( $RMRF$ ;  $gCH_2O g^{-1} DMd^{-1}$ ). The  $TMP_{daily}$  is the daily average temperature data, which is constituted from TMP. Average dry matter of leaves (DML; g), dry matter of stems (DMs; g), and dry matter of fruits (DMf; g) is specified respectively as 19.9, 16, and 20.9 according to the reference.

$$M_{res} = Q_{10}^{0.1(TMP_{daily}-20)} \cdot (RMRL.(DML + DMs) + RMRF.DMf) \quad (5.21)$$

Finally, the daily crop growth can be calculated as in Equation 5.22. The growth efficiency coefficient (GREF;  $gDMg^{-1}CH_2O$ ) is selected as 75% in this study.

$$DM_p = (GP_d - M_{res}) \cdot GREF \quad (5.22)$$

The obtained  $DM_p$  is the measure of the total tomato crop, which covers leaf, stem, and fruit. However, the study aims to obtain the amount of harvested ripe tomato out of one tomato crop. Therefore, Equation 5.23 has to be applied to define the number of fruits in one tomato crop. Accumulated Thermal Time ( $^{\circ}Cd$ ) is the accumulation of the daily effective temperature ( $T_{ef}$ ). The calculation  $T_{ef}$  is a comparison of them  $TMP_{daily}$  with the base temperature ( $T_b$ ), which is  $10^{\circ}C$  and as it is discussed  $10^{\circ}C$  is the lowest temperature for tomato crop growth. In Equation 5.25, the pd and hd refer to planting day and harvesting day of the year, respectively. The most effective tomato plantation date is between April and May and 70 days should pass until the tomatoes have to be harvested, according to the farmers' experiences. Therefore, in this study for the pd has been chosen as 90 and 120, respectively. The former is the day of beginning of the April and the latter is the day of the beginning of May. In the case study part of the study, the difference in the yield will be observed.  $a_f$ ,  $b_f$ ,  $c_f$  refer to the constant parameters and the values are 51.34, 0.006, and 0.521, respectively.

$$DM_f = DM_p \cdot \left( \frac{c_f}{1 + a_f \cdot e^{-b_f \cdot ATT}} \right) \quad (5.23)$$

$$T_{ef} = \begin{cases} 0, & \text{if } TMP_{daily} \leq T_b \\ TMP_{daily} - T_b, & \text{if } TMP_{daily} > T_b \end{cases} \quad (5.24)$$

$$ATT = \sum_{d=pd}^{hd} T_{ef} \quad (5.25)$$

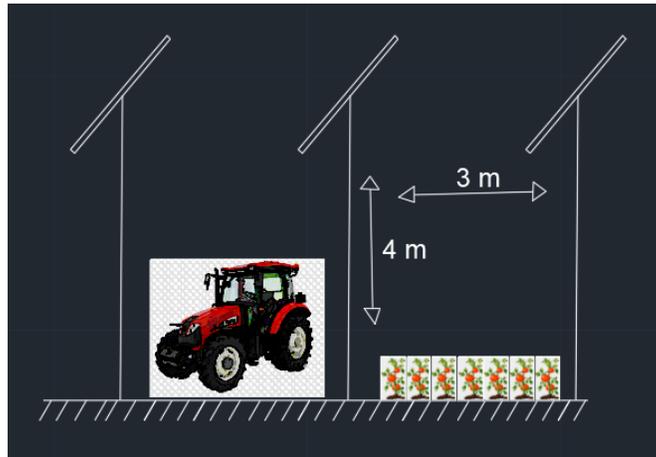
Finally, the harvested ripe tomato ( $RF_h$ ) production from one tomato crop can be calculated as in Equation 5.26.  $TDM_f$  refers to the total  $DM_f$  during the plantation period in 70 days.  $a_{rf}$ ,  $b_{rf}$ ,  $c_{rf}$  are constant parameters, which are 10830, 0.009, and 0.668, respectively.

$$RF_h = TDM_f \cdot \left( \frac{c_{rf}}{1 + a_{rf} \cdot e^{-b_{rf} \cdot ATT}} \right) \quad (5.26)$$

In the simulation so far, obtaining solar radiation and tomato production has been explained. In the next subchapter, the settlement of the PV modules over the tomatoes will be explained.

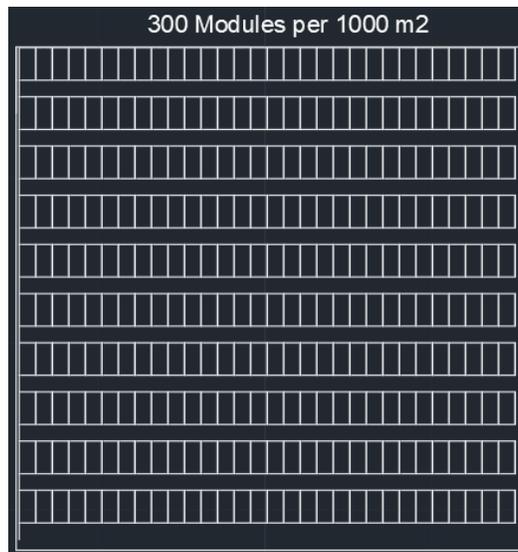
### **5.3. PV Installation Layout on the Field and Energy Production from PV Modules in the Simulation:**

In the previous 2 subchapters, the determination of solar radiation and tomato production background aimed at the simulation have been explained in detail. Besides these, the layout of the PV modules on the agricultural estate and the type of the PV modules are big matters in terms of transmitting the solar radiation on the tomatoes as much as possible. To have a better idea about the installation of the modules, the basic drawing of the installation has been made in AUTOCAD and it can be seen in *Figure 32*. The PV modules will be installed in 4 meters high to give feasibility to the heavy construction equipment and the space between the modules will be 3 meters. Additionally, the tilt angle of the modules has been determined as 25°.



**Figure 32: PV Installation**

In the simulation, the glass-glass transparent modules supplied by the company, GridParity AG, which supports me endlessly for this study, will be simulated. The name of the modules with their output power and light transparency respectively are M72 (330 Wp; 12%), M50 (250 Wp; 40%), B72 (330 Wp; 12%) and B32 (165 Wp; 53%). The M and B letters in the PV module names refer to the 'Mono facial PV Module' and 'Bifacial PV Module'. The PV Modules can be seen in As already explained, in the bifacial module the production will in the double side. The layout of the PV modules can be seen in Figure 33. It is designed to be 300 PV modules per 1000 m<sup>2</sup>.



**Figure 33: Layout of the PV Modules**

The energy production out of the PV modules will be made by using Equation 5.27. The hourly peak solar hour (PSH) gives information about solar radiation of the location. The maximum solar radiation reaching on the ground of the earth can be  $1000 \text{ W/m}^2$ . PSH can be calculated as the total daily tilted solar radiation divided by  $1000 \text{ W/m}^2$ . Hence, the total hours of maximum solar radiation reached on the ground can be calculated. The  $W_p$  refers to the output power of the selected module and  $NM$  refers to the number of installed modules on the field. In the simulation, the program will ask the user the type of the module and the size of the area. According to the answers of the users, the program on MATLAB will be calculated the produced tomato and electrical energy ( $E$ ) respectively.

$$E = PSH.W_p.NM \quad (5.27)$$



**Figure 34: Identified PV Modules in APV Simulation**

#### **5.4. Economical Approach of APV Systems in the Simulation**

In the simulation, a basic economical approach has been performed just to give some ideas about how sensible to build an APV system in the selected location. The simulation of economical approach gives a result of the return of invest (ROI) by using investment cost (IC), cost of electrical energy in the installed location (c), annual electrical energy production from PV (E), insurance (i) and maintenance cost (m) of the APV system. The investment cost of the project differs regarding the selected modules. The total investment cost including construction aluminum material will be calculated 2,15 €/Wp for M50 Modules, 1,48 €/Wp for B72 Modules, 1,57 €/Wp for M72 Modules and 3,02 €/Wp for B32-165 Wp, according to the offer from GridParity AG. The lifetime of the project has been selected as 30 years. The annual Insurance cost is determined as 0.2% of the investment cost and the annual maintenance cost is determined as 14 €/kWp. In Equation 5.28, the ROI calculation can be seen.

$$ROI = \frac{IC}{E \cdot c - (i + m)} \quad (5.28)$$

The economic analyses have been made independently of tomato production. However, in the results of the simulation, the deficient tomato production, because of the shading of the PV system and inconvenient temperature values, will be seen in weight and prices. By definition of the APV systems, although the plant production will be decreased a little bit, the solar energy production will balance the total production at the end.

#### **5.5. Summary**

In this part of the study, all the equations and steps, which have been used in the design of the simulation, have been introduced. All the steps of coding in MATLAB Editor can be seen in Appendix A. In the beginning, the hourly

solar radiation has been constituted by using solar angles and daily average solar radiation data. The calculated hourly horizontal solar radiation has been used to calculate tomato production and hourly tilted solar radiation data has been used to find energy production from PV modules. Tailor-made Crop Growth Model has been used for tomato production and all the equations in this model have been introduced step by step. In the end, economic analyses for the APV system has been explained.

It is known that feasibility assessments are very crucial for most of the engineering installations. The simulation aims to provide results without installing the system in the area for future APV customers. Once the simulation in MATLAB runs, the program needs some user inputs for making the calculations for a specific area and the program asks the questions as follow;

- *Please select the country (Germany, Spain, or Turkey?)*
- *Please select the city (Ingolstadt, Almeria or Mersin?)*
- *Please enter the selected PV Module (M50, M72, B72, B32)*
- *Please enter the size of the area (in  $m^2$ )*

In this study, the weather data has been collected for only 3 different cities in 3 different countries. Therefore, the simulation will be performed for the stated 3 cities. After entering all the needed inputs correctly in the simulation; as a result, the screen as in *Figure 35* appears and the feasibility of the APV installation can be discussed. As can be seen, the output of the simulation will be giving information about the total production of ripe tomato, energy production out of PV modules, and the economic background of the project. In the further chapter, the simulation will be applied for Almeria, Ingolstadt, and Mersin and the feasibility of the APV system will be compared and the results will be discussed.

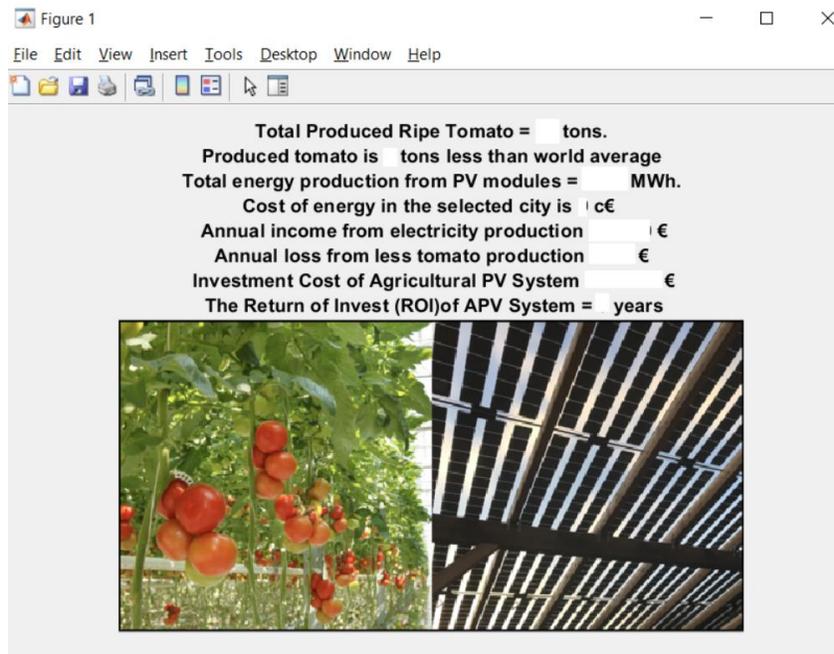


Figure 35: The Output View of the APV Simulation

## 6. Case Study: Application of APV System Tomato Production Simulation in Almeria (Spain), Ingolstadt (Germany) and Mersin (Turkey)

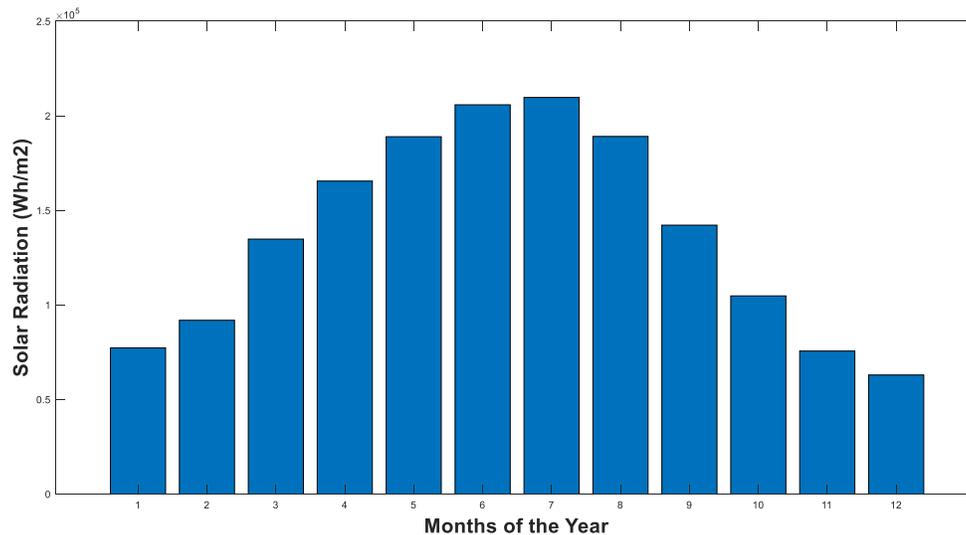
In this part of the study, the programmed APV simulation for tomato production will be performed in the city of Almeria, Ingolstadt, and Mersin, which are the southern cities of Spain, Germany, and Turkey, respectively. In the end, the sensibility of APV system installation in each city will be discussed and the results in the different cities and the influence of different transparencies of the PV modules on tomato production will be observed. In further subchapters, geographical characteristics of the cities will be introduced, and the simulation results will be noticed. It is determined that all the simulations will be performed in a 1-hectare area to ease the comparisons. In the simulation, the land productivity and type of land in the different cities have been estimated completely the same and the utilization of fertilizer has been ignored in all the cities. Exactly, accounting the soil productivity would make this simulation more precise. However, studied simulation will be enough to get the first ideas about the APV system for related customers.

## 6.1. APV Simulation in Almeria



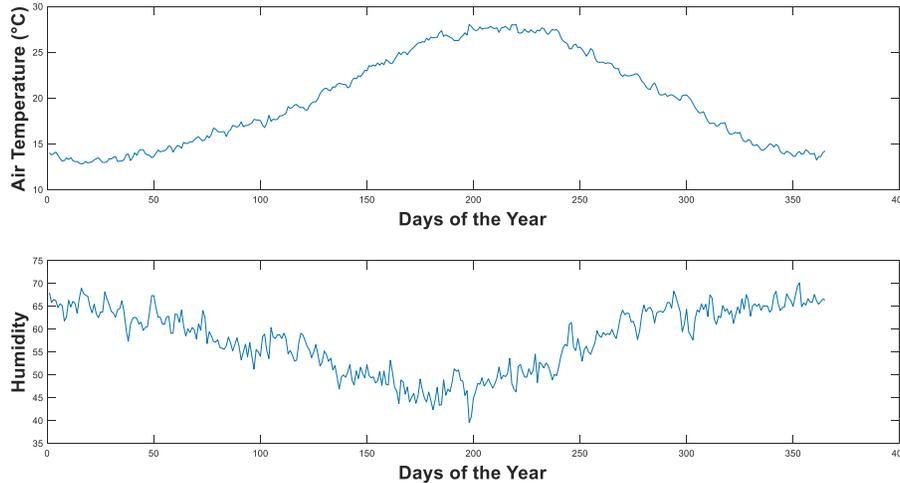
**Figure 36: Map of Spain and Marked Location of Almeria (Google, 2020)**

Almeria is a city in the region of Andalusia in Spain, with the coordinates of  $36^{\circ} 50' 17.3004''$  N and  $2^{\circ} 27' 35.0640''$  W. The city is well-known with its agricultural potential and using a different kind of agricultural techniques. On the other side, the huge size of greenhouses covered with plastic turns some part of the city into a 'sea of plastic'. (DeutscheWelle, 2019) Since, the city located in the south part of Spain, it is expected that the solar energy potential of the city is also very high.



**Figure 37: The Global Solar Radiation Distribution by Months in Almeria**

In Figure 37, the monthly global solar radiation distribution in the city of Almeria, which is constituted by the simulation on MATLAB, can be seen. It can be observed that the solar radiation value is relatively high especially between April and September. On this matter, it is an influential advantage for energy production by PV and tomato growth. However, solar radiation value is not the only factor, which affects productivity.



**Figure 38: Change of the Air Temperature and Humidity in Almeria during the Year (Meteoblue, 2020)**

The other two factors, which affect productivity, are shown in Figure 38. That temperature and humidity values are constituted from 30 years of historical weather data, which is supplied by Meteoblue. It can be seen in the figures that, the value of temperature during the year hardly goes under 10 °C, which is a perfect condition for tomato production and the humidity level is acceptably high, which does not influence the respiration badly. By looking at the graphs so far, it can be commented that the weather conditions are good enough for tomato production.

**Table 1: Tilted (25°) Solar Radiation in Almeria**

Month	January	February	March	April	May	June	July	August	September	October	November	December
25° Tilted Radiation (MWh/m <sup>2</sup> )	0,14	0,14	0,15	0,16	0,18	0,20	0,21	0,18	0,15	0,14	0,13	0,13

The tilted solar radiation will be used in the equations to define solar energy production by PV modules in Almeria. All the values above have been constituted from the APV system simulation program on MATLAB. After obtaining all the radiation, temperature, and humidity data for the city of Almeria, the last step is to run the simulation and see the results. In the first simulation, it is accepted that the tomato crop has been planted on the 1<sup>st</sup> of May with 70 days growth period and as a PV module, M50-250 Wp modules with 40% transparency have been simulated.

The result screen can be seen in Figure 39. In the case of installing an APV system over the 1-hectare area with M50-250 Wp modules in Almeria, 24 tons of ripe tomato will be harvested, which is 14 tons less than the general average. Of course, less tomato production will bring along less profit on tomato production, however, on the other side, producing electrical energy from the PV modules will bring a big profit to the farmer and balance the income positively. The economical assessment, which has been done for the city of Almeria, has been done by taking into consideration the existence of net metering in Spain. Therefore, there will be no difference on the money side when the producer makes self-consumption and feed-in to the grid. The simulation has been run for the other module types as well, and all the results for each type of PV module can be seen in Table 2. All the results will be evaluated together in the discussion part in the further subchapter.

**Table 2: The Results Overview of the Simulation with a Different Kind of PV Modules in Almeria**

<b>PV Module</b>	<b>Transparency</b>	<b>Harvested Tomato (tons)</b>	<b>Produced Energy – PV (MWh)</b>	<b>Energy Cost (c€/kWh)</b>	<b>Annual Income by PV Energy (€)</b>	<b>Investment Cost (€)</b>	<b>Return of Invest</b>
M72-330W	12%	19	4015	23,84	957.176	3.108.600	3.36 years
B72-370W	12%	19	5317	23,84	1.267.572	3.374.400	2.75 years
M50-250W	40%	22	3042	23,84	725.212	3.225.000	4,62 years

B32- 165W	53%	22	2312	23,84	551.180	2.993.739	5,65 y.
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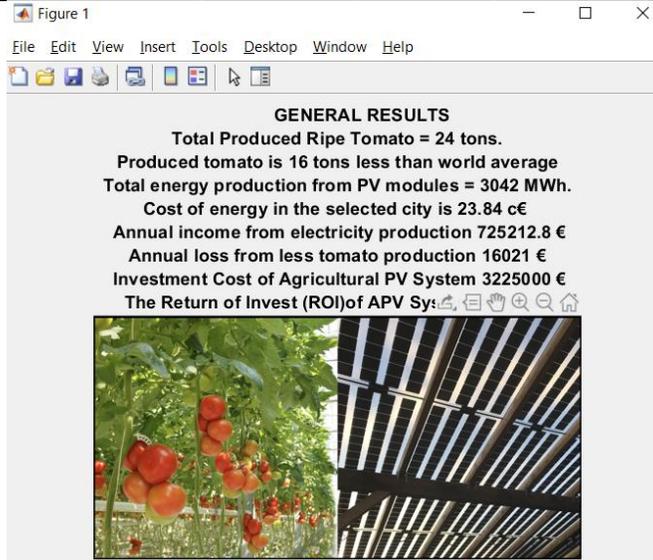


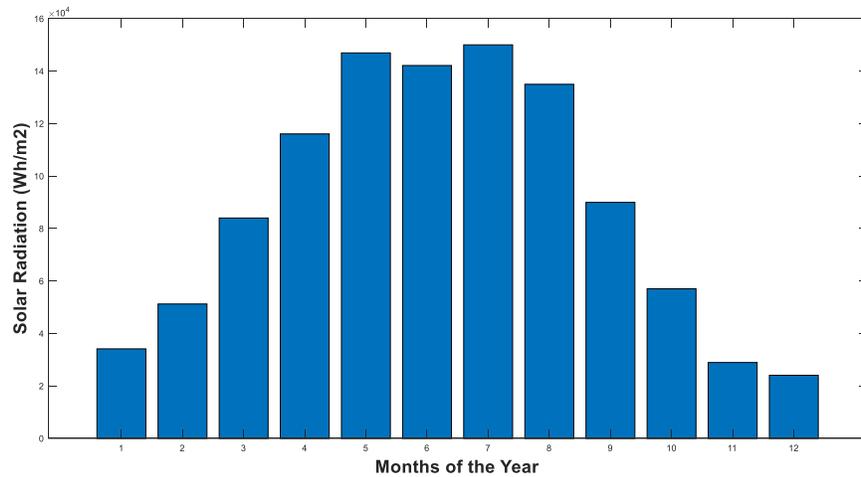
Figure 39: The General Overview of the APV Installation with M50 Modules in Almeria

## 6.2. APV Simulation in Ingolstadt



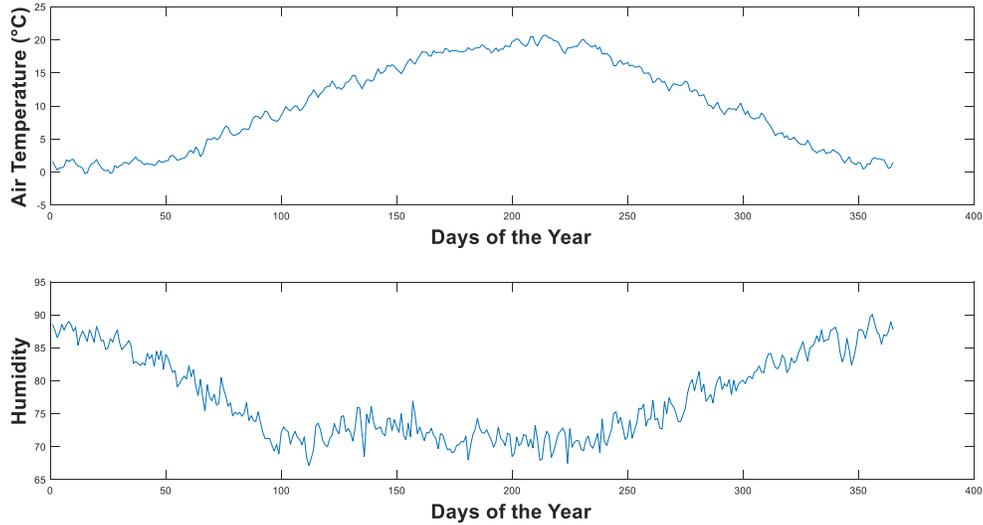
Figure 40: Map of Germany and Marked Location of Ingolstadt (Google, 2020)

Ingolstadt is a small city in the Bavaria region of Germany, which is situated in the very south part of Germany with the coordinates of 48° 46' N and 11° 26' W. In the region, farming of the hops and strawberries are very popular. Since the proximity of the region in the south, the temperature of the air during the year is relatively higher, when it is compared with the north parts of the country. Nevertheless, even that mentioned high-temperature values are not enough for tomatoes, therefore the tomato crops have been producing in the greenhouses to obtain optimum temperature for the tomatoes.



**Figure 41: The Global Solar Radiation Distribution by Months in Ingolstadt (Meteoblue, 2020)**

In Figure 41, the global solar radiation by months in Ingolstadt can be seen. Although the transmitted solar radiation on the city of Ingolstadt is very low in winter months, it increases significantly between April and August. That increment will affect positively electrical energy production by PV modules, but for the tomato growth, the other factors are of capital importance.



**Figure 42: Change of the Air Temperature and Humidity in Ingolstadt during the Year**

In Figure 42, the 30 years of average historical weather data, which is constituted by using supplied data from the company Meteoblue. As already explained, the tomato crop starts its life-cycle over 10 °C and the optimum temperature is between 20 and 30 °C. On the other side, up to 70% humidity is acceptable for tomato growth. The temperature values of the city of Ingolstadt is very low for efficient tomato production. Therefore, the tomato production in Germany has been doing mostly inside greenhouses. The simulation results further will show what happens if the tomato is produced in an open field under the APV system in Ingolstadt.

**Table 3: Tilted (25°) Solar Radiation in Ingolstadt**

Month	January	February	March	April	May	June	July	August	September	October	November	December
25° Tilted Radiation (MWh/m <sup>2</sup> )	0,069	0,082	0,106	0,123	0,146	0,139	0,144	0,139	0,103	0,083	0,055	0,051

The values given in Table 3 show the tilted solar radiation at 25°, which is useful for the PV modules when they face the sun at 25°. As is expected, the electricity production by solar modules will be higher during the Spring and Summer months. By using all the inputs above, the simulation has been run for Ingolstadt and the evaluation of the APV system for tomato production in Ingolstadt can be made easily. The plantation of the tomatoes has been estimated as the 1<sup>st</sup> of May and 70 days have been accepted as growth period.

**Table 4: The Results Overview of the Simulation in Ingolstadt with PV Modules with Different Transparency**

PV Module	Transparency	Harvested Tomato (tons)	Produced Energy – PV (MWh)	Energy Cost (c€/kWh)	Annual Income by PV Energy (€) (100% self-cons.)	Investment Cost (€)	Return of Invest
M72-330W	12%	0,077	2549	30,43	775.660	3.108.600	4,2
B72-370W	12%	0,077	3376	30,43	1.027.316	3.374.400	3,5
M50-250W	40%	0,091	1931	30,43	587.603	3.225.000	5,8
B32-165W	53%	0,093	1468	30,43	446.712	2.993.739	7

As already expected, the tomato production in Ingolstadt has been affected dramatically because of air temperature during the plantation period. The production is very low for the 1-hectare area with between 77 kgs and 93 kgs, depending on the transparency of the modules. In Germany, there is no net-metering. Therefore, the selling price of produced energy to the grid is not the same as the purchased price from the grid. The cost of energy in Germany with all taxes is 30,43 c€, however, the feed-in tariff is 7 c€ by at the beginning of 2020. In Table 4, the economic analyses have been performed for 100% self-consumption and the return of investment is fair enough. However, fully self-consumption is not mostly possible for such an agricultural area. Therefore, in the Table 5, the ROI for 30% of self-consumption can be also seen.

**Table 5: Return of Invest for 30% Self Consumption in Ingolstadt**

PV Module	Investment Cost (€)	Income from Energy Production by PV (30% Self-Consumption) (€)	ROI

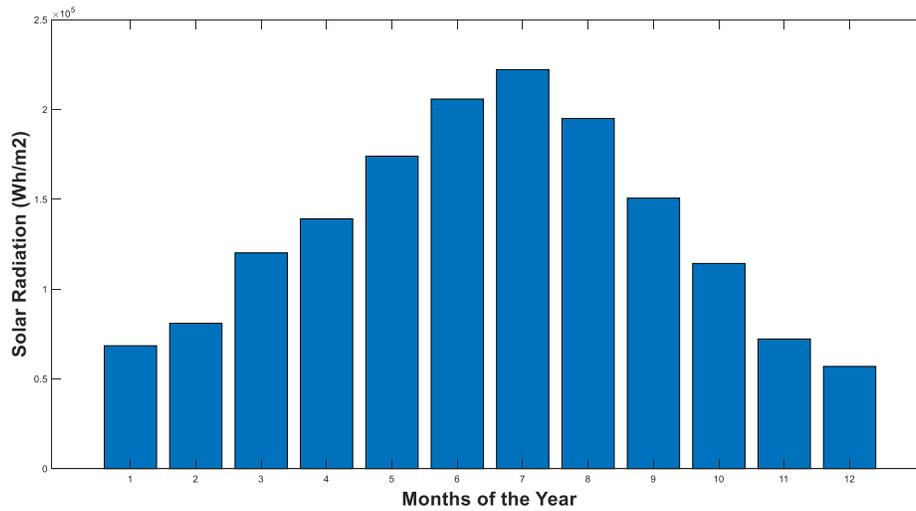
M72-330W	3.108.600	357.599	10
B72-370W	3.374.400	473.619	8
M50-250W	3.225.000	270.899	13
B32-165W	2.993.739	205.945	16

### 6.3. APV Simulation in Mersin



**Figure 43: Map of Turkey and Marked Location of Mersin (Google, 2020)**

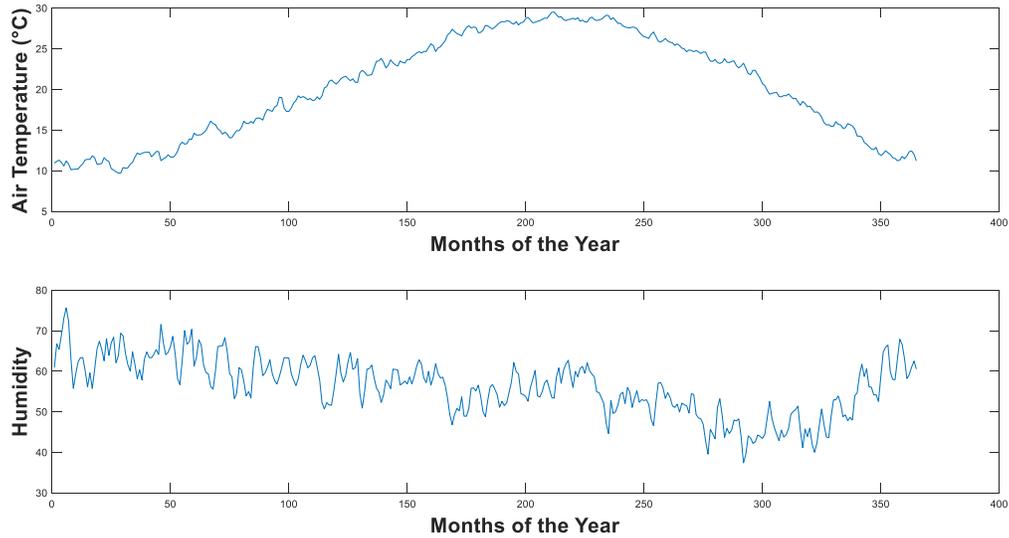
Mersin is a city, which settles on the southern part of Turkey with the location of 36° 48' 43.5708" N and 34° 38' 29.3244" E. The city is well-known with its sunny and hot weather – almost 300 days in a year is sunny -. There can be seen the biggest port in Turkey and the other source of income of the city is tourism and agricultural production. Citrus trees (lemon, orange, etc.) and banana production in Mersin place a premium on agricultural production in Turkey. 60% of the lemon production in Turkey is produced in Mersin.



**Figure 44: The Global Solar Radiation Distribution by Months in Mersin**

The respective monthly solar radiation values, which is constituted from the APV Simulation on Matlab, can be seen in Figure 44. From winter to summer, solar radiation values increase significantly, and it reaches its maximum value in July. In this sense, the climate of the city is very convenient for electrical energy production from PV modules. However, on the other side, the temperature and humidity values have to be analyzed to see the convenience of the area for tomato production.

The temperature and humidity values can be seen in Figure 45. That values are constituted by using 30 years of average data and have been collected from the climate data company 'Meteoblue'. As can be seen from the graphs, the climate looks very convenient for tomato production in an open field. On the plantation day, when is the 1<sup>st</sup> of May, the average air temperature value is 20 °C with 60% humidity. Further, the simulation will be run and the result for the tomato production in Mersin will be observed.



**Figure 45: Change of the Air Temperature and Humidity in Mersin during the Year (Meteoblue, 2020)**

The electricity production by PV modules will be calculated by using tilted solar radiation values. In the APV simulation, the monthly total tilted radiation values for 25° is calculated and the values can be seen in

Table 6. It is highly expected that electricity production from PV modules will be always high, especially in the summer months. However, Turkey uses one of the cheapest electricity all around Europe, when compared with the other European countries. (Even so because of the bad economic situation in Turkey, it is relatively expensive for the Turkish public) Therefore, the ROI expected to be high. The simulation will be run for Turkey and results for each PV module can be seen as in further.

**Table 6: Tilted (25°) Solar Radiation in Mersin**

Month	January	February	March	April	May	June	July	August	September	October	November	December
25° Tilted Radiation (MWh/m <sup>2</sup> )	0,132	0,123	0,144	0,140	0,176	0,210	0,227	0,196	0,171	0,166	0,128	0,119

The APV simulation result for different transparency of PV modules in Mersin can be seen in *Table 7*. It can be seen that tomato production is not affected by the shading of PV in favor of convenient climate conditions. As it is expected, increasing transparency of the module increases the tomato production, too. Regarding the economical approach, Turkey has net-metering for electricity production with PV modules, which means the buying and selling cost of the electricity is the same. Although electricity production from PV modules is very high, the ROI is over 8 years for each type of module because of the low cost of electricity. For the Turkish APV System Model, it would

be better to develop the system in the Turkish market to decrease the investment cost. Then the investment might be more sensible.

**Table 7: The Results Overview of the Simulation in Ingolstadt with PV Modules with Different Transparency**

PV Module	Transparency	Harvested Tomato (tons)	Produced Energy – PV (MWh)	Energy Cost (c€/kWh)	Annual Income by PV Energy (€)	Investment Cost (€)	Return of Invest
M72-330W	12%	30	3956	9	356.040	3.108.600	10
B72-370W	12%	30	5239	9	471.510	3.374.400	8
M50-250W	40%	34	2997	9	268.730	3.225.000	13
B32-165W	53%	35	2278	9	205020	2.993.739	16

The APV Simulation for each type of module has been run in 3 different cities. Further, the results and the comparison between the cities will be discussed.

#### **6.4. Discussion of APV Simulation Results:**

Generally, the simulations are one of the most important materials in engineering disciplines to see the sensibility of any constructions and developments before investing and installing it. Accordingly, in this study, the simulation of tomato production under APV systems has been constituted on MATLAB to give some ideas before investing in APV Systems to future users.

In the previous subchapters, the APV Simulation has been performed in the cities of Almeria, Ingolstadt, and Mersin, respectively. Since the difficulty of reaching weather data of more cities, the simulation has been limited with only that 3 cities. However, the obtained results from the simulation for these 3 cities are fair enough to make comparisons between them. The plantation date of the tomatoes has been selected as the 1<sup>st</sup> of May and the plantation duration has been accepted as 70 days. 4 different Glass-glass transparent mono facial and bifacial PV modules have been utilized with the transparency of 12%, 12%, 40%, and 53%, respectively. Hence, the importance of the transmitted solar radiation on tomato growth has been evaluated. In light of this information, the

APV Simulation for tomato production has been performed for 3 cities under different transparency of PV Modules and the results have been obtained.

From the perspective of different PV modules, the ripe tomato production under M72-330W (12%) and B72-330W (12%) is completely the same in all the cities because they have the same transparency. As it is already expected, however, the energy production of M72 and B72 are different. Although the output power of B72-370W is 1,12 times bigger than M72-330W, the energy production of B72-370W is 1,32 times bigger than M72-330W. The reason for that difference is that B72 modules are bifacial modules and they can produce energy from the back-sheet as well. On the other side, it can be observed in all cities that the tomato production increases under high transparent M50-250W (40%) and B32-165W (53%) PV modules. The tomato production increments with increasing transparency in Almeria, Ingolstadt, and Mersin are 3 tons, 14 kg, and 4 tons, respectively, with M50 modules; 3 tons, 16 kg, and 5 tons with B32 modules. However, increasing transparency will decrease the output power of the module. Therefore, the energy production with M50-250W and B32-165W will be lower than M72-330W and B72-370 W. Correspondingly, the decrement on energy production will affect the economy of the project. By using the price list of GridParity AG, the complete system prices have been constituted for each module and the total price of the system for the 1-hectare area has been calculated in the APV simulation program. Thereafter, the investment cost of the systems with M72-330W, B72-370W, M50-250W, and B32-165W have been calculated as 3.108.600€, 3.374.400€, 3.225.000€, 2.993.739€, respectively. Hence, ROI has been calculated regarding the energy production and selling cost of energy in different cities.

The climate factor plays the biggest role in tomato production and energy production from PV modules. All the information about climate data for the selected cities has been introduced by graphs in the previous subchapters. When compared the ripe tomato production, the most tomato will be produced in Mersin, according to the simulation results. Almeria follows Mersin and the least ripe tomato production will be in Ingolstadt. The biggest reason for that is temperature differences between the cities. The air temperature in Ingolstadt on 1<sup>st</sup> of May is 12 °C and it reaches maximum 18 °C during plantation duration, while the air temperature in Mersin on 1<sup>st</sup> of May is 20 °C and it increases until 28 °C during the plantation period. Additionally, it is expected that high humidity values in Ingolstadt might increase respiration and it might affect the growth negatively. When the optimum climate factors of the tomato kept in mind, it can be seen that the climate of Mersin is more convenient to grow a tomato in open-air fields. On the other side, the tomato production difference between Almeria and Mersin occurred because of humidity differences, even the temperature values are so close to each other.

For an investment, producing a lot means nothing, if that production would not bring money to the investor. The energy policy controls the renewable energy market and supplemented subsidies provide to give reliability to the investors. In the simulation results, the difference in electricity production income between the cities occurred because of the different cost of energy.

When ROI of all the simulation results has been analyzed, it can be seen that investing in APV Systems in the city of Almeria will bring more benefit economically, although the tomato production is decreased to half compared to world tomato production. The reason for that is the energy act of Spain on renewable energy systems by using net-metering. Hence, the energy supplier can sell his produced electricity with its purchased price. Turkey uses also net-metering; however, the energy cost is very low compared to Spain. Therefore, income from energy production in Turkey is significantly lower than in Spain, even though the annual energy production is not very different. On the other hand, there is no net-metering in Germany, therefore the purchasing price and selling price of electricity is 30,43 c€ and 7 c€, respectively. For this reason, 100% self-consumption in Germany will bring along the best income to the investor. In the first simulation result of Ingolstadt, 100% self-consumption in the agricultural area is accepted and in the second simulation, it is accepted that the agricultural area makes 25% self-consumption and 75% of feeding grid. As can be seen in the results, there is a huge difference in income between self-consumption and selling the energy into the grid.

Consequently, APV Simulation provides to the future investors to see the sensibility of installing APV System in their fields. The transparency of the modules affects the tomato production, surely, however, the air temperature of the installed area impacts the production more. Even the investment cost of bifacial modules is higher than the others, the produced energy will balance the economy of the project quickly. Lastly, it is observed that APV simulation is a simulation program, which is open to be developed and made more professional. However, It gives some ideas as to interested people on APV Systems.

## 7. Conclusion

Throughout human history, technological innovations bring along more technological developments with, as a result of the curiosity of humans and always wishing to have better. For instance, at the beginning of the industrial revolution, obtaining energy from fossil fuels was a sensible idea -still it is until some points-, however, the impact of the fossil fuels on the environment and it is being limited quantity made humans develop other technologies to produce energy. Hence, the importance of renewable energy systems has come into the forefront. After all, renewable energy systems, especially wind turbines and PV modules, have been started installing.

The installed power of PV systems covers 20% of all the renewable energy systems in the world with 518 GW. Obtaining huge energy outputs by PV modules is the required installation on huge areas; it can be estimated like 1 MW ground-mounted PV installations needs a 1.5-hectare area. However, the increasing population in the world brings along an increasing demand for food and correspondingly, increasing demand for agricultural areas. Therefore, Agricultural Photovoltaic Systems technology has been developed for double yield by producing both food and energy on the same land.

The idea of APV Systems is to install PV Modules on a long construction, which does not prevent the working of heavy machines on the field. However, that technology, of course, brings along some problems, too. The shading that occurred from the PV modules affects crop production and many types of research have been made on shading. On one side, some plants, like lettuce, have positive behavior on its growth while shading; on the other side some plants show a negative reaction. So, before installing any energy systems, it is important to make simulations to estimate the results of the system. All the researches on APV Systems so far have been simulated by using 2-3 different simulation programs to define crop production, PV production, and economic analyses, respectively. In this study, a simulation program for tomato production under APV Systems by using different glass-glass transparent modules have been developed on MATLAB.

The simulation of APV Systems in the cities of Almeria, Ingolstadt, and Mersin has been performed in the study. The selected glass-glass transparent PV modules were chosen in the stock of the company GridParity AG, with their name, power, and transparency; M72-330 Wp (12%), B72-370 Wp (12%), M50-250 Wp (40%), B32-165 Wp (53%), respectively.

All the weather data values of the cities have been discussed in the previous chapter. Regarding the solar radiation values, it is calculated in the APV Simulation on MATLAB that the most electricity production has been made with B72 modules in every city, since its being bifacial module. With the advantage of high solar radiation during the year, Almeria is the city, which is expected to make more energy production by PV modules, regarding the results on APV Simulation. Although the B72 shows the best performance on energy production, B72 is the PV module with M72, which impacts the tomato production the most. In this aspect, tomatoes under B32 modules with 53% transparency will be affected at least from the APV System. Furthermore, regarding the results on APV System simulation for tomato production, the city of Mersin is expected to grow most tomatoes under APV System.

Concerning the economical outputs from the simulation, the cost of electricity, and the policies of the countries on renewable energy systems affect the return of investment a lot. For instance, even the energy production by PV modules in Mersin is very high, regarding simulation results, because of the low energy costs in Turkey, the investment will not pay back in a short time. However, on the other side, the economic perspective of the system in Almeria seems very positive. The APV System in Almeria will pay back itself in at least 5 years. Regarding the economical results in Ingolstadt, it depends on completely the self-consumption rate of the agricultural field. Since there is no net-metering in Germany, the selling and buying price of the electricity is very different. Therefore, it is observed in the project that increasing self-consumption will bring to investors more income.

Consequently, APV Systems are expected to increase in further years to increase the efficiency of land with double-yield. However, it is important to show the benefits of this system to the producers of the agricultural goods by supporting with some simulation results. In this study, a usable simulation program has been developed for tomato production under APV Systems. This simulation program is just the beginning of an idea and it can be improved and made professional with more professional hands.

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# APPENDIX A

## Contents

- [SOLAR RADIATION CALCULATIONS %%](#)
- [Hourly Solar Irradiation i Almeria %%](#)
- [STEP 1: %%](#)
- [STEP 2: %%](#)
- [STEP 3: %](#)
- [STEP 4: %](#)
- [STEP 5: %](#)
- [STEP 7: %](#)
- [STEP 9: %](#)
- [SOLAR RADIATION CALCULATIONS MERSIN %%](#)
- [Hourly Solar Irradiation i Mersin %%](#)
- [STEP 1: %%](#)
- [STEP 2: %%](#)
- [STEP 3: %](#)
- [STEP 4: %](#)
- [STEP 5: %](#)
- [STEP 7: %](#)
- [STEP 9: %](#)
- [SOLAR RADIATION CALCULATIONS INGOLSTADT %%](#)
- [Hourly Solar Irradiation i Ingolstadt %%](#)
- [STEP 1: %%](#)
- [STEP 2: %%](#)
- [STEP 3: %](#)
- [STEP 4: %](#)
- [STEP 5: %](#)
- [STEP 7: %](#)
- [STEP 9: %](#)
- [Tomato Production](#)

%%%%%%%%%

Technische Hochschule Ingolstadt

%%%%%%%%%

%%%%%%%%%

MSc Renewable Energy Systems

%%%%%%%%%

%%%%%%%%%

Master Thesis

%%%%%%%%%

Tomato Production underAgriPV Simulation Different Transparency of PV Modules  
%%%%%%%%%

```
clc
clear all
```

## **SOLAR RADIATION CALCULATIONS %%**

### **Hourly Solar Irradiation i Almeria %%**

#### **STEP 1: %%**

```
%From 1st of January to 31st of December - 365 days
number_of_days=[1:1:365]';
```

#### **STEP 2: %%**

Latitude, zenith angle, tilt angle, reflection coefficient, hour angle %% and declination angle should be known.%

```
latitude_Almeria= 36.51; %% Changes for different cities
declination_Almeria = 23.45*sin(2*pi/365*(284+number_of_days));
tilt_angle = 25;
azimuth = 0;
reflection_coefficient = 0.15;
```

#### **STEP 3:%**

Hour angle Calculation %%

```
Ls_Almeria = 15; %Local standart meridian - Changes for different cities %
LL_Almeria = -2.23; %Longitude - Changes for different cities%
LT = [0:1:23]; %Local Time%
```

```

global_hourly_Almeria = 360*(number_of_days-81)/365;
ET_Almeria = 9.87*sind(2*global_hourly_Almeria) - 7.53*cosd(global_hourly_Almeria) -
1.5*cosd(global_hourly_Almeria); %Equation of Time%
ST_Almeria = LT + ET_Almeria/60 + 4*(Ls_Almeria-LL_Almeria)/60; %Solar Time%
hour_angle_Almeria = 15*(ST_Almeria-12);

```

#### **STEP 4:%**

```

%Cos zenith%
cos_zenith_Almeria =
cosd(latitude_Almeria).*cosd(declination_Almeria).*cosd(hour_angle_Almeria)+sin(latitude_A
lmeria).*sin(declination_Almeria);
zenith_angle_Almeria = real (mean (acosd( cos_zenith_Almeria)));
altitude_angle_Almeria = 90 - zenith_angle_Almeria;
rowstoDelete = altitude_angle_Almeria < 0;
altitude_angle_Almeria(rowstoDelete) = [0];

```

#### **STEP 5:%**

```

%angle of incidence%
azimuth_angle_Almeria=
(cosd(declination_Almeria).*sind(latitude_Almeria).*cosd(hour_angle_Almeria)-
sind(declination_Almeria).*cosd(latitude_Almeria) )./cosd(altitude_angle_Almeria);
cos_angle_of_incidence_Almeria = ( cosd(latitude_Almeria).*cosd(tilt_angle) +
sind(latitude_Almeria).*sind(tilt_angle).*cosd(azimuth)
).*cosd(declination_Almeria).*cosd(hour_angle_Almeria) +
cosd(declination_Almeria).*sind(hour_angle_Almeria).*sind(tilt_angle).*sind(azimuth)+sind(
declination_Almeria).*( sind(latitude_Almeria).*cosd(tilt_angle) -
cosd(latitude_Almeria).*sind(tilt_angle).*cosd(azimuth));
incidence_angle_Almeria = ( acosd (cos_angle_of_incidence_Almeria));

```

#### **STEP 7:%**

```

%sunset hour%
sunset_hour_Almeria = acosd (-tand(latitude_Almeria).*tand(declination_Almeria));

```

```

% STEP 8: %
% Hourly horizontal Direct and Diffused %

```

```

A = ((pi/24).*(cosd(hour_angle_Almeria) - (cosd(sunset_hour_Almeria)))) ./
(sind(sunset_hour_Almeria)-((2*pi.*sunset_hour_Almeria./360).*cosd(sunset_hour_Almeria)));

global_daily_Almeria = dlmread('daily_global_radiation_Almeria.m'); %Daily global
average%
global_hourly_Almeria1 = ( A.*global_daily_Almeria*1000); %Hourly global radiation %
global_hourly_trans_Almeria = global_hourly_Almeria1';
global_hourly_Almeria = reshape(global_hourly_trans_Almeria,[8760,1]);
rowstoDelete = global_hourly_Almeria < 0; % Horizontal Radiation %
global_hourly_Almeria(rowstoDelete) = [0]; % B is Global (horizontal) radiation w/m2

diffuse_daily_Almeria = dlmread ('daily_diffuse_radiation_Almeria.m');
diffuse_hourly_Almeria1 = (A.*diffuse_daily_Almeria*1000);
diffuse_hourly_trans_Almeria = diffuse_hourly_Almeria1';
diffuse_hourly_Almeria = reshape (diffuse_hourly_trans_Almeria,[8760,1]);
rowstoDelete = diffuse_hourly_Almeria < 0;
diffuse_hourly_Almeria(rowstoDelete) = [0]; % is diffuse radiation w/m2

direct_daily_Almeria = dlmread ('daily_direct_radiation_Almeria.m');
direct_hourly_Almeria1 = (A.*direct_daily_Almeria*1000);
direct_radiation_trans_Almeria = direct_hourly_Almeria1';
direct_hourly_Almeria = reshape (direct_radiation_trans_Almeria,[8760,1]);
rowstoDelete = direct_hourly_Almeria < 0;
direct_hourly_Almeria(rowstoDelete) = [0] ; % Direct Radiation w/m2

global_hourly_irradiance_Almeria_Jan = sum(global_hourly_Almeria(1:31*24));
global_hourly_irradiance_Almeria_Feb = sum(global_hourly_Almeria(32*24:59*24));
global_hourly_irradiance_Almeria_Mar = sum(global_hourly_Almeria(60*24:90*24));
global_hourly_irradiance_Almeria_Apr = sum(global_hourly_Almeria(91*24:120*24));
global_hourly_irradiance_Almeria_May = sum(global_hourly_Almeria(121*24:151*24));
global_hourly_irradiance_Almeria_Jun = sum(global_hourly_Almeria(152*24:181*24));
global_hourly_irradiance_Almeria_Jul = sum(global_hourly_Almeria(182*24:212*24));
global_hourly_irradiance_Almeria_Aug = sum(global_hourly_Almeria(213*24:243*24));
global_hourly_irradiance_Almeria_Sep = sum(global_hourly_Almeria(244*24:273*24));
global_hourly_irradiance_Almeria_Oct = sum(global_hourly_Almeria(274*24:304*24));
global_hourly_irradiance_Almeria_Nov = sum(global_hourly_Almeria(305*24:334*24));
global_hourly_irradiance_Almeria_Dec = sum(global_hourly_Almeria(335*24:365*24));

```

```

%Monthly Global HORIZONTAL Radiation Almeria -- For PAR this information will be used
Monthly_Global_Radiation_Almeria = [global_hourly_irradiance_Almeria_Jan
global_hourly_irradiance_Almeria_Feb global_hourly_irradiance_Almeria_Mar
global_hourly_irradiance_Almeria_Apr global_hourly_irradiance_Almeria_May
global_hourly_irradiance_Almeria_Jun global_hourly_irradiance_Almeria_Jul
global_hourly_irradiance_Almeria_Aug global_hourly_irradiance_Almeria_Sep
global_hourly_irradiance_Almeria_Oct global_hourly_irradiance_Almeria_Nov
global_hourly_irradiance_Almeria_Dec]; % Monthly Horizontal Radiation

```

### **STEP 9:%**

```

Rb_Almeria = incidence_angle_Almeria ./ zenith_angle_Almeria ;
Rb_vector_Almeria = reshape (Rb_Almeria',[8760,1]);
Rd = ( 1 + cosd(tilt_angle) )/2;
Rr = ( 1 - cosd(tilt_angle) )/2;

tilted_hourly_global_irradiance_Almeria = direct_hourly_Almeria.*Rb_vector_Almeria+
diffuse_hourly_Almeria.*mean(Rd) + reflection_coefficient.*mean(Rr).*(
direct_hourly_Almeria + diffuse_hourly_Almeria );

tilted_hourly_global_irradiance_Almeria_Jan =
sum(tilted_hourly_global_irradiance_Almeria(1:31*24));
tilted_hourly_global_irradiance_Almeria_Feb =
sum(tilted_hourly_global_irradiance_Almeria(32*24:59*24));
tilted_hourly_global_irradiance_Almeria_Mar =
sum(tilted_hourly_global_irradiance_Almeria(60*24:90*24));
tilted_hourly_global_irradiance_Almeria_Apr =
sum(tilted_hourly_global_irradiance_Almeria(91*24:120*24));
tilted_hourly_global_irradiance_Almeria_May =
sum(tilted_hourly_global_irradiance_Almeria(121*24:151*24));
tilted_hourly_global_irradiance_Almeria_Jun =
sum(tilted_hourly_global_irradiance_Almeria(152*24:181*24));
tilted_hourly_global_irradiance_Almeria_Jul =
sum(tilted_hourly_global_irradiance_Almeria(182*24:212*24));
tilted_hourly_global_irradiance_Almeria_Aug =
sum(tilted_hourly_global_irradiance_Almeria(213*24:243*24));
tilted_hourly_global_irradiance_Almeria_Sep =
sum(tilted_hourly_global_irradiance_Almeria(244*24:273*24));

```

```

tilted_hourly_global_irradiance_Almeria_Oct =
sum(tilted_hourly_global_irradiance_Almeria(274*24:304*24));
tilted_hourly_global_irradiance_Almeria_Nov =
sum(tilted_hourly_global_irradiance_Almeria(305*24:334*24));
tilted_hourly_global_irradiance_Almeria_Dec =
sum(tilted_hourly_global_irradiance_Almeria(335*24:365*24));

```

```

Monthly_Tilted_Radiation_Almeria = [tilted_hourly_global_irradiance_Almeria_Jan
tilted_hourly_global_irradiance_Almeria_Feb tilted_hourly_global_irradiance_Almeria_Mar
tilted_hourly_global_irradiance_Almeria_Apr tilted_hourly_global_irradiance_Almeria_May
tilted_hourly_global_irradiance_Almeria_Jun tilted_hourly_global_irradiance_Almeria_Jul
tilted_hourly_global_irradiance_Almeria_Aug tilted_hourly_global_irradiance_Almeria_Sep
tilted_hourly_global_irradiance_Almeria_Oct tilted_hourly_global_irradiance_Almeria_Nov
tilted_hourly_global_irradiance_Almeria_Dec ];

```

## **SOLAR RADIATION CALCULATIONS MERSİN %%**

### **Hourly Solar Irradiation i Mersin %%**

#### **STEP 1: %%**

```

%From 1st of January to 31st of December - 365 days
number_of_days=[1:1:365]';

```

#### **STEP 2: %%**

Latitude, zenith angle, tilt angle, reflection coefficient, hour angle %% and declination angle should be known.%%

```

latitude_Mersin= 36.81;    %%% Changes for different citiesp %%
declination_Mersin = 23.45*sin(2*pi/365*(284+number_of_days));
tilt_angle = 25;
azimuth = 0;
reflection_coefficient = 0.15;

```

#### **STEP 3:%**

Hour angle Calculation %%

```

Ls_Mersin = 30; %Local standart meridian - Changes for different cities %
LL_Mersin = 34.64; %Longitude - Changes for different cities%

```

```

LT = [0:1:23]; %Local Time%
global_hourly_Mersin = 360*(number_of_days-81)/365;
ET_Mersin = 9.87*sind(2*global_hourly_Mersin) - 7.53*cosd(global_hourly_Mersin) -
1.5*cosd(global_hourly_Mersin); %Equation of Time%
ST_Mersin = LT + ET_Mersin/60 + 4*(Ls_Mersin-LL_Mersin)/60; %Solar Time%
hour_angle_Mersin = 15*(ST_Mersin-12);

```

#### **STEP 4:%**

```

%Cos zenith%
cos_zenith_Mersin =
cosd(latitude_Mersin).*cosd(declination_Mersin).*cosd(hour_angle_Mersin)+sin(latitude_Mersin).
*sin(declination_Mersin);
zenith_angle_Mersin = real (mean (acosd( cos_zenith_Mersin)));
altitude_angle_Mersin = 90 - zenith_angle_Mersin;
rowstoDelete = altitude_angle_Mersin < 0;
altitude_angle_Mersin(rowstoDelete) = [0];

```

#### **STEP 5:%**

```

%angle of incidence%
azimuth_angle_Mersin=
(cosd(declination_Mersin).*sind(latitude_Mersin).*cosd(hour_angle_Mersin)-
sind(declination_Mersin).*cosd(latitude_Mersin) )./cosd(altitude_angle_Mersin);
cos_angle_of_incidence_Mersin = ( cosd(latitude_Mersin).*cosd(tilt_angle) +
sind(latitude_Mersin).*sind(tilt_angle).*cosd(azimuth)
).*cosd(declination_Mersin).*cosd(hour_angle_Mersin) +
cosd(declination_Mersin).*sind(hour_angle_Mersin).*sind(tilt_angle).*sind(azimuth)+sind(declination_Mersin).*(
sind(latitude_Mersin).*cosd(tilt_angle) -
cosd(latitude_Mersin).*sind(tilt_angle).*cosd(azimuth));
incidence_angle_Mersin = ( acosd (cos_angle_of_incidence_Mersin));

```

#### **STEP 7:%**

```

%sunset hour%
sunset_hour_Mersin = acosd (-tand(latitude_Mersin).*tand(declination_Mersin));

```

**% STEP 8: %**

**% Hourly horizontal Direct and Diffused %**

```

Mer = ((pi/24).*(cosd(hour_angle_Mersin) - (cosd(sunset_hour_Mersin)))) ./
(sind(sunset_hour_Mersin)-((2*pi.*sunset_hour_Mersin./360).*cosd(sunset_hour_Mersin)));

global_daily_Mersin = dlmread('daily_global_radiation_Mersin.m'); %Daily global average%
global_hourly_Mersin1 = ( Mer.*global_daily_Mersin*1000); %Hourly global radiation %
global_hourly_trans_Mersin = global_hourly_Mersin1';
global_hourly_Mersin = reshape(global_hourly_trans_Mersin,[8760,1]);
rowstoDelete = global_hourly_Mersin < 0; % Horizontal Radiation %
global_hourly_Mersin(rowstoDelete) = [0]; % B is Global (horizontal) radiation w/m2

diffuse_daily_Mersin = dlmread ('daily_diffuse_radiation_Mersin.m');
diffuse_hourly_Mersin1 = (Mer.*diffuse_daily_Mersin*1000);
diffuse_hourly_trans_Mersin = diffuse_hourly_Mersin1';
diffuse_hourly_Mersin = reshape (diffuse_hourly_trans_Mersin,[8760,1]);
rowstoDelete = diffuse_hourly_Mersin < 0;
diffuse_hourly_Mersin(rowstoDelete) = [0]; % is diffuse radiation w/m2

direct_daily_Mersin = dlmread ('daily_direct_radiation_Mersin.m');
direct_hourly_Mersin1 = (Mer.*direct_daily_Mersin*1000);
direct_radiation_trans_Mersin = direct_hourly_Mersin1';
direct_hourly_Mersin = reshape (direct_radiation_trans_Mersin,[8760,1]);
rowstoDelete = direct_hourly_Mersin < 0;
direct_hourly_Mersin(rowstoDelete) = [0] ; % Direct Radiation w/m2

global_hourly_irradiance_Mersin_Jan = sum(global_hourly_Mersin(1:31*24));
global_hourly_irradiance_Mersin_Feb = sum(global_hourly_Mersin(32*24:59*24));
global_hourly_irradiance_Mersin_Mar = sum(global_hourly_Mersin(60*24:90*24));
global_hourly_irradiance_Mersin_Apr = sum(global_hourly_Mersin(91*24:120*24));
global_hourly_irradiance_Mersin_May = sum(global_hourly_Mersin(121*24:151*24));
global_hourly_irradiance_Mersin_Jun = sum(global_hourly_Mersin(152*24:181*24));
global_hourly_irradiance_Mersin_Jul = sum(global_hourly_Mersin(182*24:212*24));
global_hourly_irradiance_Mersin_Aug = sum(global_hourly_Mersin(213*24:243*24));
global_hourly_irradiance_Mersin_Sep = sum(global_hourly_Mersin(244*24:273*24));
global_hourly_irradiance_Mersin_Oct = sum(global_hourly_Mersin(274*24:304*24));
global_hourly_irradiance_Mersin_Nov = sum(global_hourly_Mersin(305*24:334*24));
global_hourly_irradiance_Mersin_Dec = sum(global_hourly_Mersin(335*24:365*24));

```

```

%Monthly Global HORIZONTAL Radiation Almeria -- For PAR this information will be used
Monthly_Global_Radiation_Mersin = [global_hourly_irradiance_Mersin_Jan
global_hourly_irradiance_Mersin_Feb global_hourly_irradiance_Mersin_Mar
global_hourly_irradiance_Mersin_Apr global_hourly_irradiance_Mersin_May
global_hourly_irradiance_Mersin_Jun global_hourly_irradiance_Mersin_Jul
global_hourly_irradiance_Mersin_Aug global_hourly_irradiance_Mersin_Sep
global_hourly_irradiance_Mersin_Oct global_hourly_irradiance_Mersin_Nov
global_hourly_irradiance_Mersin_Dec]; % Monthly Horizontal Radiation

```

### **STEP 9:%**

```

Rb_Mersin = incidence_angle_Mersin ./ zenith_angle_Mersin ;
Rb_vector_Mersin = reshape (Rb_Mersin',[8760,1]);
Rd = ( 1 + cosd(tilt_angle) )/2;
Rr = ( 1 - cosd(tilt_angle) )/2;

tilted_hourly_global_irradiance_Mersin = direct_hourly_Mersin.*Rb_vector_Mersin+
diffuse_hourly_Mersin.*mean(Rd) + reflection_coefficient.*mean(Rr).*( direct_hourly_Mersin
+ diffuse_hourly_Mersin );

tilted_hourly_global_irradiance_Mersin_Jan =
sum(tilted_hourly_global_irradiance_Mersin(1:31*24));
tilted_hourly_global_irradiance_Mersin_Feb =
sum(tilted_hourly_global_irradiance_Mersin(32*24:59*24));
tilted_hourly_global_irradiance_Mersin_Mar =
sum(tilted_hourly_global_irradiance_Mersin(60*24:90*24));
tilted_hourly_global_irradiance_Mersin_Apr =
sum(tilted_hourly_global_irradiance_Mersin(91*24:120*24));
tilted_hourly_global_irradiance_Mersin_May =
sum(tilted_hourly_global_irradiance_Mersin(121*24:151*24));
tilted_hourly_global_irradiance_Mersin_Jun =
sum(tilted_hourly_global_irradiance_Mersin(152*24:181*24));
tilted_hourly_global_irradiance_Mersin_Jul =
sum(tilted_hourly_global_irradiance_Mersin(182*24:212*24));
tilted_hourly_global_irradiance_Mersin_Aug =
sum(tilted_hourly_global_irradiance_Mersin(213*24:243*24));
tilted_hourly_global_irradiance_Mersin_Sep =
sum(tilted_hourly_global_irradiance_Mersin(244*24:273*24));

```

```

tilted_hourly_global_irradiance_Mersin_Oct =
sum(tilted_hourly_global_irradiance_Mersin(274*24:304*24));
tilted_hourly_global_irradiance_Mersin_Nov =
sum(tilted_hourly_global_irradiance_Mersin(305*24:334*24));
tilted_hourly_global_irradiance_Mersin_Dec =
sum(tilted_hourly_global_irradiance_Mersin(335*24:365*24));

```

```

Monthly_Tilted_Radiation_Mersin = [tilted_hourly_global_irradiance_Mersin_Jan
tilted_hourly_global_irradiance_Mersin_Feb tilted_hourly_global_irradiance_Mersin_Mar
tilted_hourly_global_irradiance_Mersin_Apr tilted_hourly_global_irradiance_Mersin_May
tilted_hourly_global_irradiance_Mersin_Jun tilted_hourly_global_irradiance_Mersin_Jul
tilted_hourly_global_irradiance_Mersin_Aug tilted_hourly_global_irradiance_Mersin_Sep
tilted_hourly_global_irradiance_Mersin_Oct tilted_hourly_global_irradiance_Mersin_Nov
tilted_hourly_global_irradiance_Mersin_Dec ];

```

## **SOLAR RADIATION CALCULATIONS INGOLSTADT %%**

### **Hourly Solar Irradiation i Ingolstadt %%**

#### **STEP 1: %%**

```

%From 1st of January to 31st of December - 365 days
number_of_days=[1:1:365]';

```

#### **STEP 2: %%**

Latitude, zenith angle, tilt angle, reflection coefficient, hour angle %% and declination angle should be known.%%

```

latitude_Ingolstadt= 48.76;    %% Changes for different citiesp %%
declination_Ingolstadt = 23.45*sin(2*pi/365*(284+number_of_days));
tilt_angle = 25;
azimuth = 0;
reflection_coefficient = 0.15;

```

#### **STEP 3:%**

Hour angle Calculation %%

```

Ls_Ingolstadt = 15; %Local standart meridian - Changes for different cities %
LL_Ingolstadt = 11.42; %Longitude - Changes for different cities%

```

```

LT = [0:1:23]; %Local Time%
global_hourly_Ingolstadt = 360*(number_of_days-81)/365;
ET_Ingolstadt = 9.87*sind(2*global_hourly_Ingolstadt) -
7.53*cosd(global_hourly_Ingolstadt) - 1.5*cosd(global_hourly_Ingolstadt); %Equation of
Time%
ST_Ingolstadt = LT + ET_Ingolstadt/60 + 4*(Ls_Ingolstadt-LL_Ingolstadt)/60; %Solar Time%
hour_angle_Ingolstadt = 15*(ST_Ingolstadt-12);

```

#### **STEP 4:%**

```

%Cos zenith%
cos_zenith_Ingolstadt =
cosd(latitude_Ingolstadt).*cosd(declination_Ingolstadt).*cosd(hour_angle_Ingolstadt)+sin(l
atitude_Ingolstadt).*sin(declination_Ingolstadt);
zenith_angle_Ingolstadt = real(mean(acosd(cos_zenith_Ingolstadt)));
altitude_angle_Ingolstadt = 90 - zenith_angle_Ingolstadt;
rowstoDelete = altitude_angle_Ingolstadt < 0;
altitude_angle_Ingolstadt(rowstoDelete) = [0];

```

#### **STEP 5:%**

```

%angle of incidence%
azimuth_angle_Ingolstadt =
(cosd(declination_Ingolstadt).*sind(latitude_Ingolstadt).*cosd(hour_angle_Ingolstadt)-
sind(declination_Ingolstadt).*cosd(latitude_Ingolstadt)
)./cosd(altitude_angle_Ingolstadt);
cos_angle_of_incidence_Ingolstadt = (cosd(latitude_Ingolstadt).*cosd(tilt_angle) +
sind(latitude_Ingolstadt).*sind(altitude_angle_Ingolstadt).*cosd(azimuth)
).*cosd(declination_Ingolstadt).*cosd(hour_angle_Ingolstadt) +
cosd(declination_Ingolstadt).*sind(hour_angle_Ingolstadt).*sind(altitude_angle_Ingolstadt).*sind(azimuth)
+sind(declination_Ingolstadt).*(sind(latitude_Ingolstadt).*cosd(altitude_angle_Ingolstadt) -
cosd(latitude_Ingolstadt).*sind(altitude_angle_Ingolstadt).*cosd(azimuth));
incidence_angle_Ingolstadt = (acosd(cos_angle_of_incidence_Ingolstadt));

```

#### **STEP 7:%**

```

%sunset hour%
sunset_hour_Ingolstadt = acosd(-tand(latitude_Ingolstadt).*tand(declination_Ingolstadt));

```

```

% STEP 8: %
% Hourly horizontal Direct and Diffused %

Ing = ((pi/24).*(cosd(hour_angle_Ingolstadt) - (cosd(sunset_hour_Ingolstadt)))) ./
(sind(sunset_hour_Ingolstadt)-
((2*pi.*sunset_hour_Ingolstadt./360).*cosd(sunset_hour_Ingolstadt)));

global_daily_Ingolstadt = dlmread('daily_global_radiation_Ingolstadt.m'); %Daily global
average%
global_hourly_Ingolstadt1 = ( Ing.*global_daily_Ingolstadt*1000); %Hourly global radiation
%
global_hourly_trans_Ingolstadt = global_hourly_Ingolstadt1';
global_hourly_Ingolstadt = reshape(global_hourly_trans_Ingolstadt,[8760,1]);
rowstoDelete = global_hourly_Ingolstadt < 0;          % Horizontal Radiation %
global_hourly_Ingolstadt(rowstoDelete) = [0];        % B is Global (horizontal) radiation
w/m2

diffuse_daily_Ingolstadt = dlmread ('daily_diffuse_radiation_Ingolstadt.m');
diffuse_hourly_Ingolstadt1 = (Ing.*diffuse_daily_Ingolstadt*1000);
diffuse_hourly_trans_Ingolstadt = diffuse_hourly_Ingolstadt1';
diffuse_hourly_Ingolstadt = reshape (diffuse_hourly_trans_Ingolstadt,[8760,1]);
rowstoDelete = diffuse_hourly_Ingolstadt < 0;
diffuse_hourly_Ingolstadt(rowstoDelete) = [0];        % is diffuse radiation w/m2

direct_daily_Ingolstadt = dlmread ('daily_direct_radiation_Ingolstadt.m');
direct_hourly_Ingolstadt1 = (Ing.*direct_daily_Ingolstadt*1000);
direct_radiation_trans_Ingolstadt = direct_hourly_Ingolstadt1';
direct_hourly_Ingolstadt = reshape (direct_radiation_trans_Ingolstadt,[8760,1]);
rowstoDelete = direct_hourly_Ingolstadt < 0;
direct_hourly_Ingolstadt(rowstoDelete) = [0] ;        % Direct Radiation w/m2

global_hourly_irradiance_Ingolstadt_Jan = sum(global_hourly_Ingolstadt(1:31*24));
global_hourly_irradiance_Ingolstadt_Feb = sum(global_hourly_Ingolstadt(32*24:59*24));
global_hourly_irradiance_Ingolstadt_Mar = sum(global_hourly_Ingolstadt(60*24:90*24));
global_hourly_irradiance_Ingolstadt_Apr = sum(global_hourly_Ingolstadt(91*24:120*24));
global_hourly_irradiance_Ingolstadt_May = sum(global_hourly_Ingolstadt(121*24:151*24));
global_hourly_irradiance_Ingolstadt_Jun = sum(global_hourly_Ingolstadt(152*24:181*24));
global_hourly_irradiance_Ingolstadt_Jul = sum(global_hourly_Ingolstadt(182*24:212*24));

```

```

global_hourly_irradiance_Ingolstadt_Aug = sum(global_hourly_Ingolstadt(213*24:243*24));
global_hourly_irradiance_Ingolstadt_Sep = sum(global_hourly_Ingolstadt(244*24:273*24));
global_hourly_irradiance_Ingolstadt_Oct = sum(global_hourly_Ingolstadt(274*24:304*24));
global_hourly_irradiance_Ingolstadt_Nov = sum(global_hourly_Ingolstadt(305*24:334*24));
global_hourly_irradiance_Ingolstadt_Dec = sum(global_hourly_Ingolstadt(335*24:365*24));

%Monthly Global HORIZONTAL Radiation Almeria -- For PAR this information will be used
Monthly_Global_Radiation_Ingolstadt = [global_hourly_irradiance_Ingolstadt_Jan
global_hourly_irradiance_Ingolstadt_Feb global_hourly_irradiance_Ingolstadt_Mar
global_hourly_irradiance_Ingolstadt_Apr global_hourly_irradiance_Ingolstadt_May
global_hourly_irradiance_Ingolstadt_Jun global_hourly_irradiance_Ingolstadt_Jul
global_hourly_irradiance_Ingolstadt_Aug global_hourly_irradiance_Ingolstadt_Sep
global_hourly_irradiance_Ingolstadt_Oct global_hourly_irradiance_Ingolstadt_Nov
global_hourly_irradiance_Ingolstadt_Dec]; % Monthly Horizontal Radiation

```

### STEP 9:%

```

Rb_Ingolstadt = incidence_angle_Ingolstadt ./ zenith_angle_Ingolstadt ;
Rb_vector_Ingolstadt = reshape (Rb_Ingolstadt',[8760,1]);
Rd = ( 1 + cosd(tilt_angle) )/2;
Rr = ( 1 - cosd(tilt_angle) )/2;

tilted_hourly_global_irradiance_Ingolstadt =
direct_hourly_Ingolstadt.*Rb_vector_Ingolstadt + diffuse_hourly_Ingolstadt.*mean(Rd) +
reflection_coefficient.*mean(Rr).*( direct_hourly_Ingolstadt + diffuse_hourly_Ingolstadt
);

tilted_hourly_global_irradiance_Ingolstadt_Jan =
sum(tilted_hourly_global_irradiance_Ingolstadt(1:31*24));
tilted_hourly_global_irradiance_Ingolstadt_Feb =
sum(tilted_hourly_global_irradiance_Ingolstadt(32*24:59*24));
tilted_hourly_global_irradiance_Ingosltadt_Mar =
sum(tilted_hourly_global_irradiance_Ingolstadt(60*24:90*24));
tilted_hourly_global_irradiance_Ingolstadt_Apr =
sum(tilted_hourly_global_irradiance_Ingolstadt(91*24:120*24));
tilted_hourly_global_irradiance_Ingolstadt_May =
sum(tilted_hourly_global_irradiance_Ingolstadt(121*24:151*24));

```

```

tilted_hourly_global_irradiance_Ingolstadt_Jun =
sum(tilted_hourly_global_irradiance_Ingolstadt(152*24:181*24));
tilted_hourly_global_irradiance_Ingolstadt_Jul =
sum(tilted_hourly_global_irradiance_Ingolstadt(182*24:212*24));
tilted_hourly_global_irradiance_Ingolstadt_Aug =
sum(tilted_hourly_global_irradiance_Ingolstadt(213*24:243*24));
tilted_hourly_global_irradiance_Ingolstadt_Sep =
sum(tilted_hourly_global_irradiance_Ingolstadt(244*24:273*24));
tilted_hourly_global_irradiance_Ingolstadt_Oct =
sum(tilted_hourly_global_irradiance_Ingolstadt(274*24:304*24));
tilted_hourly_global_irradiance_Ingolstadt_Nov =
sum(tilted_hourly_global_irradiance_Ingolstadt(305*24:334*24));
tilted_hourly_global_irradiance_Ingolstadt_Dec =
sum(tilted_hourly_global_irradiance_Ingolstadt(335*24:365*24));

Monthly_Tilted_Radiation_Ingolstadt = [tilted_hourly_global_irradiance_Ingolstadt_Jan
tilted_hourly_global_irradiance_Ingolstadt_Feb
tilted_hourly_global_irradiance_Ingosltadt_Mar
tilted_hourly_global_irradiance_Ingolstadt_Apr
tilted_hourly_global_irradiance_Ingolstadt_May
tilted_hourly_global_irradiance_Ingolstadt_Jun
tilted_hourly_global_irradiance_Ingolstadt_Jul
tilted_hourly_global_irradiance_Ingolstadt_Aug
tilted_hourly_global_irradiance_Ingolstadt_Sep
tilted_hourly_global_irradiance_Ingolstadt_Oct
tilted_hourly_global_irradiance_Ingolstadt_Nov
tilted_hourly_global_irradiance_Ingolstadt_Dec ];

%%%%% Choices %%%%%%
Spain = global_hourly_Almeria;
Turkey = global_hourly_Mersin;
Germany = global_hourly_Ingolstadt;

% REQUEST USER INPUT !!!!! %
Country = 'Please select the country (Germany, Spain or Turkey?)';
global_hourly = input (Country);

```

Error using input

Cannot call INPUT from EVALC.

Error in AgriPV\_Deneme (line 339)

```
global_hourly = input (Country);
```

### **Tomato Production**

```
% kWh MJ çevrimini unutma burda !!!!! %
PPFD = global_hourly* 3.6 * 0.47 * 4.57 * 1 ;    % MJ/m2 -- umol ... % joule çevirime
bir bak !!!
% PGRED Calculation %
Almeria1 = dlmread ('hourly_humidity_Almeria.m');
Almeria = dlmread ('Hourly_Temperature_Almeria.m');
Ingolstadt1 = dlmread ('hourly_humidity_Ingolstadt.m');
Ingolstadt = dlmread ('Hourly_Temperature_Ingolstadt.m');
Mersin1 = dlmread ('hourly_humidity_Mersin.m');
Mersin = dlmread ('Hourly_Temperature_Mersin.m');

City = 'Please select the city (Almeria, Ingolstadt or Mersin?)';
TMP = input (City);

if TMP == Almeria;
    hourly_humidity = Almeria1;
    Tilted_Radiation = tilted_hourly_global_irradiance_Almeria;
    electricity_cost = 23.84;
    feedin_tariff = 23.84 %cents

elseif TMP == Mersin;
    hourly_humidity = Mersin1;
    Tilted_Radiation = tilted_hourly_global_irradiance_Mersin;
    electricity_cost = 9 ;%cents
    feedin_tariff = 9

else TMP == Ingolstadt;
    hourly_humidity = Ingolstadt1;
    Tilted_Radiation = tilted_hourly_global_irradiance_Ingolstadt;
    electricity_cost = 30.43;
    feedin_tariff = 7 %cents

end
```

```

global_irradiance_Jan = sum(global_hourly(1:31*24));
global_irradiance_Feb = sum(global_hourly(32*24:59*24));
global_irradiance_Mar = sum(global_hourly(60*24:90*24));
global_irradiance_Apr = sum(global_hourly(91*24:120*24));
global_irradiance_May = sum(global_hourly(121*24:151*24));
global_irradiance_Jun = sum(global_hourly(152*24:181*24));
global_irradiance_Jul = sum(global_hourly(182*24:212*24));
global_irradiance_Aug = sum(global_hourly(213*24:243*24));
global_irradiance_Sep = sum(global_hourly(244*24:273*24));
global_irradiance_Oct = sum(global_hourly(274*24:304*24));
global_irradiance_Nov = sum(global_hourly(305*24:334*24));
global_irradiance_Dec = sum(global_hourly(335*24:365*24));

Monthly_Global_Radiation_SelectedCity = [global_irradiance_Jan global_irradiance_Feb
global_irradiance_Mar global_irradiance_Apr global_irradiance_May global_irradiance_Jun
global_irradiance_Jul global_irradiance_Aug global_irradiance_Sep global_irradiance_Oct
global_irradiance_Nov global_irradiance_Dec]; % Monthly Horizontal Radiation

PGRED=zeros(size(TMP));
for ii=1:length(TMP)
    if TMP(ii) < 9
        PGRED(ii)=0;
    elseif 9<=TMP(ii) && TMP(ii)<10
        PGRED(ii)= TMP(ii)-9;
    elseif 10<=TMP(ii) && TMP(ii)<29
        PGRED(ii)= 1;
    elseif 28<=TMP(ii) && TMP(ii)<40
        PGRED(ii)= -0.083*TMP(ii) + 3.33;
    else 40 >= TMP(ii) % this condition is not required. Just give a default condition.
        PGRED(ii)=0;
    end
end

%VPD Calculation%

a = -1.044*10^4;

```

```

b = -1.129*10;
c = -2.702*10^-2;
d = -1.289*10^-5;
e = -2.478*10^-9;
f = -6.545;

TMP_Rankine = TMP + 493.47;
vp_sat = exp(a./TMP_Rankine + b + c.*TMP_Rankine + d.*TMP_Rankine.^2 + e.*TMP_Rankine.^3 +
f.*log(TMP_Rankine));

vp_air = vp_sat.*hourly_humidity./100;

VPD = vp_sat - vp_air;

% PVPD Calculation %

CK = -0.8;
VPDL = 4.0;

PVPD = exp(CK*(VPD-VPDL));

% Pmax Calculation %
to = 0.0693;
CO2 = 407; %ppm -- İnternetten bak kaç olduğuna yine !!!

Pmax = to*CO2.*PVPD.*PGRED;

% Hourly Gross Phtosynthesis (GPh)
XM = 0.091;
XK = 0.58;
QE = 0.0645;
LAI = 3; %%% BUNUN ÜZERİNE ARAŞTIRACAKSIN BABY !!!
%TRANSPARENCY of Module%
M72 = 0.12;
M50 = 0.4;
B32 = 0.53;
B72 = 0.1200001;

```

```

Module = 'Please select Your Module--->> M72-330W(12%); M50-250W (40%);B72-380W (12%);
B32 (53%)<<<---';
Transparency = input (Module);

if Transparency == M72;
Module_Power = 330;
unit_cost = 157;
tr_factor = 1;
elseif Transparency == M50;
Module_Power = 250;
unit_cost = 215;
tr_factor = 1;
elseif Transparency == B32;
Module_Power = 190;
unit_cost = 302;
tr_factor = 1.15;
elseif Transparency == B72;
Module_Power = 437;
unit_cost = 148;
tr_factor = 1.15;
end
GPh = Pmax./XK .* log( ((1-XM)+QE*XK.*(PPFD*Transparency))./((1-
XM)+QE*XK*(PPFD*Transparency).*exp(-XK*LAI)));

% Daily Gross Photosynthesis (GPd)

PLM2 = 2.5974; % Plant density !! KAYNAKÇADA VAR ! Dosyada simulation papers !
GPh2 = reshape(GPh,[24,365]);
GPd1 = sum(GPh2);

GPd = GPd1 * 3600 * 30*10^-6 / PLM2;

% Daily Maintenance Respiration %
Humidity_average = mean( reshape (hourly_humidity,[24,365]));
TMP_average = mean( reshape (TMP,[24,365]));

```

```

plot(TMP_average)
Q10 = 1.4;
RMRL = 0.015; %g CH2O g-1 DM d-1
RMRF = 0.01; %g CH2O g-1DMd-1
!!!! Leaves-Stem and Fruit Weights !!!!! Bunları kendim ürettim, kaynakçalardan
DML = 19.9; %leaves g per plant
DMS = 16; %stems g per plant
DMF = 20.9; %fruit g per plant

Mres = Q10.^(0.1*(TMP_average-2.0)) * ( RMRL*(DML+DMS)+RMRF*DMF);

GREF = 0.75;
Dmp = (GPD - Mres)* GREF ;% TOTAL DRY MATTER PRODUCED a day %

%Dry Matter Distribution%
a1 = 0.044;
b1 = -0.005;
c1 = 0.547;
d1 = 0.251;
af = 51.34;
bf = 0.006;
cf = 0.521;

Tef=zeros(size(TMP_average));
for iii=1:length(TMP_average);
    if TMP_average(iii) < 10 ;
        Tef(iii)=0;
    else %TMP_average(iii) < 28;
        Tef(iii)= TMP_average(iii) - 10;
    end

end

end

for i = 120:1:190 ; % Mayıs ayından 70 gün ekim-biçim süresi !! %
    TT(i) = Tef(1,i); % Temperature time %

```

```

end

ATT = sum(TT); % accumulated temperature time %

DMl = DMp * ( c1 / (1+a1*exp(-b1*ATT)+d1)); %leaves%
DMf = DMp * (cf / (1+af*exp(-bf*ATT))); %fruit%
DMs = DMp - (DMl+ DMf+0.09*DMp); % Yüzde9 root%

for i = 120:1:190
    DMf_April(i) = DMf (1,i);
end

TDMf = sum(DMf_April);
a_rf = 10829;
b_rf = 0.009;
c_rf = 0.668;

%Size of the Area%
Area = 'Please specify size of planting area in m2----->';
PlantingArea = input (Area);

Ripe_Tomato = TDMf * ( c_rf / (1+a_rf*exp(-b_rf*ATT))) *PlantingArea/PLM2 /1000000; %tons
Ripe Tomato

%Electricity Production%

NOCT = 45 ;%% Nominal operating cell temperature - Bizim modüllerin 45 C derece
T_cell = TMP + (NOCT - 20)*Tilted_Radiation/800;
Coeff_T = -0.004; %Temperature coefficient
T_ref = 25; % Referans sıcaklık 25 derece
delta_T = T_cell - T_ref;
PR_T = 1 - (Coeff_T * delta_T);
PR_DC = 0.02;
PR_AC = 0.02;
PR_Shading= 0.03;
PR_WI = 0.03;

```

```

PR_other = 0.02;

PR = PR_T * ( 1-(PR_DC+PR_AC+PR_Shading+PR_WI+PR_other));
PR_avg = mean(PR);

number_of_modules = 0.6*PlantingArea;

Hourly_Peak_Solar_Hour = Tilted_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 * (number_of_modules) /
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));

%Economical Analyses%

Investment = unit_cost * Module_Power * number_of_modules /100 /tr_factor;

Annual_Income = Annual_Energy_Production * 1000 *electricity_cost /100 *0.30 +
Annual_Energy_Production * 1000 * feedin_tariff * 0.70 /100;

insurance = Investment * 0.2/100 ;
maintenance = 14 * Module_Power * number_of_modules /1000;

```

```

ROI = Investment / (Annual_Income - insurance - maintenance );

Less_tomato = 40/10000 * PlantingArea - Ripe_Tomato;
Less_tomato_income = Less_tomato * 1 * 1000; %€

x = linspace(1,1,365);
y1 = TMP_average;
y2 = Humidity_average;
tiledlayout(2,1) % Requires R2019b or later

subplot(221);
bar([Monthly_Global_Radiation_SelectedCity])
xlabel('Months of the Year', 'FontSize',9,'Fontweight','bold');
ylabel('Solar Radiation (Wh/m2)', 'FontSize',9,'Fontweight','bold');

subplot(222);
plot(y1);
xlabel('Months of the Year', 'FontSize',9,'Fontweight','bold');
ylabel('Air Temperature (°C)', 'FontSize',9,'Fontweight','bold');

subplot(223);
plot(y2);
xlabel('Months of the Year', 'FontSize',9,'Fontweight','bold');
ylabel('Humidity', 'FontSize',9,'Fontweight','bold');

I=imread('C:\Users\Bahri\Desktop\THI\Master Thesis\Simulation\simulation-tomato-pv.png');
resim = imresize(I,[250 500]);

subplot(224);
imshow(resim);

title({ ['                                GENERAL RESULTS
'];
        ['Total Produced Ripe Tomato = ',num2str(round(Ripe_Tomato)), ' tons.'];

```

```

    ['Produced tomato is ' num2str(round(Less_tomato)) ' tons less than world
average'];
    ['Total energy production from PV modules = ' num2str(Annual_Energy_Production), '
MWh.'];
    ['Cost of energy in the selected city is ' num2str(electricity_cost), ' c€ '];
    [' Annual income from electricity production ' num2str(Annual_Income) ' €'];
    ['Annual loss from less tomato production ' , num2str(round(Less_tomato_income)),
' €'];
    [' Investment Cost of Agricultural PV System ', num2str(round(Investment)), ' €'];
    [' The Return of Invest (ROI)of APV System = ', num2str(round(ROI)), ' years']
}); % Place title here

```

