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The effects of climate change on the efficiency of solar photovoltaic systems in the Czech Republic by the year 2050

Diploma Thesis

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DIPLOMA THESIS ASSIGNMENT

Bc. Mariia Frolova

Engineering Ecology
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Thesis title

The effects of climate change on the efficiency of solar photovoltaic systems in the Czech Republic by the year 2050

Objectives of thesis

The main research question of the thesis askes what will be the effect of climate change on the performance of the photovoltaic system and what impact will this have on the carbon emission target?

The hypothesis of this thesis is that it is expected that climate change will negatively affect the power generation efficiency of a photovoltaic system and that the energy losses associated with this will be a significant obstacle to achieving the goal of carbon neutrality.

The purpose of this thesis is to determine how much energy in kWh may be lost due to impacts associated with climate change by 2050. The power of photovoltaic modules can decrease for every degree of warming. This research explores how much will lead to energy losses by 2050. The work will take into account the amount of solar panel capacity in the Czech Republic that is planned to be delivered by 2030 in order to understand how much energy needs to be offset by 2050 in order to reach the goal of net zero. The purpose of this thesis research is to identify how much energy in (kWh) will be lost due to climate change by 2050.

Methodology

The work is divided into two main parts: literary and experimental or methodological.

The first part of the literature review considers the phenomenon of climate change and what specific changes it can cause. A description of the utility-scale PV system and its main components, namely Solar array, Mounting, Cabling, Tracker, Inverter, Battery will be described. The last part of the literature review will cover how climate change can affect the peak power of each of the components and a description of the factors that affect the efficiency of the solar system. An IV Curve simulation will be done for the main factors to determine how changing the parameter will affect the peak power of the system.

In the Methodological part, analysis based on the aforementioned IV Curve Simulation will be carried out. This chapter will describe Experimental Design, Methodology, Description of the Hypothesis, Description of the Software used for the analysis, Information about the data and where they were collected, Results of the Analysis, Discussion and Conclusion.

The proposed extent of the thesis

60 pages + attachments

Keywords

Photovoltaic solar panel, climate change, IV curve simulation, Green Deal

Recommended information sources

Al-Baghdadi, M. A. S., Ridha, A. A., AL-Khayyat, A. S. (2022) The effects of climate change on photovoltaic solar production in hot regions. Diagnostyka, 23(3), 2022303

AlSkaif, T., Dev, S., Visser, L., Hossari, M.; van Sark, W. (2020). A systematic analysis of meteorological variables for PV output power estimation, Renewable Energy, 12–22

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Valéry M., Marion B., Jean-Luc S., Xavier B., Aude L. (2014) Solar panels reduce both global warming and urban heat island, Frontiers in Environmental Science, ISSN2296-665X

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Dean

Prague on 01. 03. 2023

Declaration

I hereby declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgement, the thesis presented is entirely my own.

In Prague on   Mariia Frolova

Acknowledgement

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Abstract

The main research question of the thesis asks what will be the effect of climate change on the performance of the photovoltaic system in the Czech Republic and what impacts this will have on the carbon emission target.

The hypothesis of this thesis is that it is expected that climate change will negatively affect the power generation efficiency of a photovoltaic system and that the energy losses associated with this could be an obstacle to achieving the goal of carbon neutrality.

The purpose of this thesis is to determine how much energy in kWh may be lost due to impacts associated with climate change by 2050. The power of photovoltaic modules can decrease with every degree of warming. The work will take into account the amount of solar panel capacity in the Czech Republic that is planned to be delivered by 2030 in order to understand how much energy (kWh) needs to be offset by 2050 in order to reach the goal of net zero.

The analysis showed that climate change has an impact on the performance of solar panels. According to the RCP 2.6 scenario output energy of monocrystalline PV installations will be reduced by an average of 76608 kWh in the Czech Republic, under the RCP 4.5 scenario the output energy will be reduced by 155150 kWh and under the RCP 8.5 scenario it will be reduced by 238103 kWh, using simulation data of the Czech Republic.

Key words: Renewable Energy, Solar Photovoltaic systems, photovoltaic energy in the Czech Republic, PV cell performance, Solar power estimation, climate change

Abstrakt

Hlavní výzkumnou otázkou práce je, jak změna klimatu ovlivní výkon fotovoltaického systému v České republice a jaký dopad to bude mít na cílovou hodnotu emisí oxidu uhličitého.

Hypotéza této práce je, že se očekává, že změna klimatu negativně ovlivní účinnost výroby fotovoltaické energie a že související energetické ztráty mohou být překážkou k dosažení cíle uhlíkové neutrality.

Cílem této práce je zjistit, kolik energie v kilowattech může být ztraceno v důsledku dopadů souvisejících se změnou klimatu do roku 2050. Výkon fotovoltaických modulů může klesnout s každým stupněm oteplování. V průběhu prací bude zohledněn počet solárních panelů v České republice, které jsou plánovány do roku 2030, aby se zjistilo, kolik energie (kWh) je potřeba do roku 2050 kompenzovat, aby bylo dosaženo nulového cíle.

Analýza ukázala, že změna klimatu má vliv na výkon solárních panelů. Podle scénáře RCP 2.6 se výstupní energie monokrystalických fotovoltaických elektráren v České republice sníží v průměru o 76608 kWh, podle scénáře RCP 4.5 se výstupní energie sníží o 155150 kWh a podle scénáře RCP 8.5 bude snížena. na 238 103 kWh s využitím simulačních dat v České republice.

Klíčová slova: Obnovitelné zdroje energie, solární fotovoltaické systémy, fotovoltaická energie v ČR, výkon solarných systemu, odhad solární energie, změna klimatu

Content

1 Introduction

In December 2019, the European Commission announced the transition to renewable energy. Then the European Green Deal was adopted, according to which the EU countries should become carbon neutral by 2050. The Green Deal is the largest correction of the economic course in the history of the EU. The Green Deal covers all sectors of the economy, especially transport, agriculture, construction, and industries such as steel, cement, ICT, textiles, chemicals, and the energy sector. What the Green Deal does is propose changes across a broad range of economic sectors to achieve the global goal - the formation of a carbon-neutral space – within the EU in 30 years. No doubt, this is a very ambitious agenda with the first milestone of the Green Deal rapidly approaching in 2030. By that time, it is expected that the EU will experience at least a 40% reduction in greenhouse gas emissions from 1990 levels. The Green Deal project also provides for an increase in the share of energy from renewable sources to 32% in total energy consumption and approximately the same for energy savings. (European Commission, 2020b). The new EU goal will certainly affect all sectors that produce and consume energy. It is, no doubt, one of the most ambitious agendas undertaken by the EU member states.

The production and use of energy account for more than 75% of greenhouse gas emissions in the EU – much of it comes from the extraction and combustion of coal. Thus, decarbonizing the EU energy system is critical to achieving necessary climate goals by 2030 and the EU's long-term strategy to achieve carbon neutrality by 2050 (European Commission, 2020b). In connection with this goal, large Czech energy companies such as ČEZ Group are planning to focus on creating new renewable resource capacities, namely 1.5 GW of installed capacity by 2025 and a total of 6 GW by 2030. These new resources are planned to be mainly solar power plants, for example, in abandoned or under-utilized fields in northern Bohemia (CEZ Sustainability Report 2022).

Already today, weather conditions have a significant impact on the performance of solar PV systems and the functioning of the balancing components of a photovoltaic system.

The amount of solar radiation and the amount of shade, due to seasonal weather patterns affect the amount of energy produced by the photovoltaic system. But conditions such as hot and humid environments, which may become more frequent in the future due to climate change, could lead to significant losses of solar energy that may not be accounted for on the way to achieving the net zero by 2050 goal (Peters, I.M., & Buonassisi, T., 2019).

Studying solar technologies and understanding the possible risks can significantly reduce possible losses in the future, as worsening climate change could make solar energy less efficient, and it is this technology that is most likely to reduce electricity emissions and help the energy sector on its way to carbon neutrality (Merchant, E.F., 2019).

The purpose of this thesis is to determine how much energy in kWh may be lost due to impacts associated with climate change by 2050. The power of photovoltaic modules can decrease with every degree of warming. The work will take into account the amount of solar panel capacity in the Czech Republic that is planned to be delivered by 2030 in order to understand how much energy (kWh) needs to be offset by 2050 in order to reach the goal of net zero.

The thesis is divided into nine main parts: Introduction part, Purpose and aim of this study, Literature Review part, Characteristics of the study area part, Methodology, Results, Discussion, Conclusion, Contribution of the thesis and References part.

The first part of the literature review considers the phenomenon of climate change and what specific changes it can cause. In the second part, a description of the utility-scale PV system and its main components, namely panel, inverter, and battery unit are described. The last part of the literature review will cover how climate change can affect the peak power of each of the components and a description of the factors that affect the efficiency of the solar PV system. The simulation in the PVsyst software based on the IV Curve will be done for the main factors to determine how changing the parameter will affect the power of the system.

2 Objectives of the thesis

In this thesis, the potential negative impacts of climate change on the performance of a photovoltaic system will be analyzed.

The thesis has three main goals:

- to identify the factors that climate change will affect,
- to determine the factors that affect the production efficiency of the PV system,
- to determine how much PV energy generated by solar parks in the Czech Republic will be lost from 2030 to 2050 due to climate change with also respect to CO_2 emissions equivalent and carbon neutrality carbon target. PVsyst program will be used to determine how changing the parameter will affect the power energy output of the system.

Thus, the aim of this thesis is to determine the potential negative impact of climate change on the performance of a photovoltaic system and to calculate the potential energy loss in terms of CO2emissions. This thesis will model how a solar PV system might perform by the year 2050 when temperatures and other parameters change.

The analysis will be based on the potential capacity of the solar PV systems that will be installed in the Czech Republic by 2030.

This thesis focuses on the different impacts of climate change and how photovoltaic panels work depending on different scenarios of climate change: RCP 8.5, RCP4.5 and RCP2.6.

The main research question of the thesis asks what will be the effect of climate change on the performance of the photovoltaic system in the Czech Republic and what impacts this will have on the carbon emission target.

The hypothesis of this thesis is that it is expected that climate change will negatively affect the power generation efficiency of a photovoltaic system and that the energy losses associated with this could be an obstacle to achieving the goal of carbon neutrality.

In this thesis for the experiment, the energy production in 2050 in the Czech Republic will be calculated from simulation data based on global radiation data from four different locations in four different solar radiation zones: Zlín, České Budějovice, Prague, Karlový Vary. There are two reasons for this.

The first reason is that in the future it is possible to calculate the average value for the whole country, taking into account the differences in the amount of sunlight in the country.

The second reason is to compare the results of energy production in different cities, given the different amounts of solar radiation in the cities selected for the simulation in the Czech Republic. It is assumed that in cities to which irradiation is higher, the amount of energy received will also be higher. In the Czech Republic, system panels cover the whole country, so that the analysis is both by location and the results will be calculated on an average for the country.

The relevance of the thesis lies in the fact that it is necessary to consider climate change and how it will affect the parameters of energy generation. Knowing and understanding what exactly can reduce the efficiency of energy production, one can consider possible risks and try to prevent them in order to maximize power generation capacity and minimize risks and possible negative impacts.

3 Literary research

3.1 Problem discussion

This chapter will provide an understanding of the factors and implications of climate change, as well as an explanation of how photovoltaic systems operate and perform under various climate change scenarios. In the thesis, the response to climate change of solar PV systems will be described rather than the characteristics of the solar PV system themselves.

The problem with the ambitious Green Deal program is that due to the goal of achieving carbon neutrality, many large energy companies such as CEZ Group have set themselves the goal of building minimum 6 GW of solar power plants in the Czech Republic by 2050 (CEZ Sustainability Report 2022), but this does not consider possible future losses due to climate change as a way to reach this goal. Without knowing what exactly could reduce the efficiency of PV energy production, it is impossible to know the possible risks and prevent energy losses in order to maximize the generation capacity and minimize possible negative impacts.

Climate change is likely to have a significant impact on solar energy production, for example, due to the possible change in the amount of radiated sunlight falling in different parts of the world. Some areas will experience more sunlight and others less due to changing factors such as changes in cloud cover, changes in atmospheric water content, changes in aerosols, and so on. Climate change is expected to bring about greater variability in most places.

This thesis will consider three scenarios of climate change: RCP8.5 is the worst-case scenario and global temperature warming averages 2.4 °C by 2050, RCP 4.5 scenario assumes 2 degrees warming by 2050, and RCP 2.6 assumes 1.7 degrees by 2050 (IPCC, 2021). Scenarios will be discussed further in this thesis.

3.2 Climate change problematics

Climate change is fluctuations in the climate of the Earth as a whole or its individual regions over time, expressed in statistically significant deviations of weather parameters from long-term values. Climate change is associated with both human activities and changes in the atmosphere and processes occurring in other parts of the earth, such as oceans, glaciers, and the consequences of these processes (Collins M. et all., 2013).

Current climate change is caused by greenhouse gases such as CH_4 and CO_2, which are generated using, for instance, due to the burning of fossil fuels for heating buildings, power generation and transportation. Methane (CH4) is produced in landfills from the decomposition of waste and from wastewater treatment. Landfills are the third largest source of CH_4 emissions. Land use, industry, construction, agriculture, and energy are among the main sources of emissions (Collins M. et all., 2013). Climate change has consequences such as loss of biodiversity, melting glaciers, increased frequency, and magnitude of forest fires, rising sea levels, severe droughts, and floods (Hitz, S., & Smith, J., 2004).

The UN report from 2022 concluded, that limiting the increase in global temperature to no more than 1.5 °C would help maintain environmental-friendly or healthy conditions and avoid catastrophic consequences in the future. However, for now, if there is no rethinking of approaches in economic sectors with a high impact on the carbon footprint, there is expected to be an increase in temperature by 2.8 °C before the end of the century (UN, 2022).

Following chapter will take a closer look at the main factors that change under the influence of climate change.

3.3 The main environmental and ecological factors attributed to climate change

3.3.1 Temperature

From the time of temperature measurements during the industrial revolution to its measurements, which are carried out today, it is noticeable that the gradual heating of the Earth takes place (Fengfei S. et al., 2022). It is known that the change in the degree of heating of the Earth is not the same, for example, in high latitudes, temperature changes are almost 3.5 times greater than near the equator and are more noticeable during winter. According to the NOAA Annual Climate Report released in 2021, global temperatures rise by 0.08 ºC every 10 years (NOAA, 2021). Moreover, according to the US National Aeronautics and Space Agency, the planet has become warmer by 0.8 degrees per century (NASA 2022).

The figure below shows the change in average surface temperature from 1990 to 2021. Changes are shown in degrees Fahrenheit over 10 years of fawning. The figure was featured in NOAA's 2021 Annual Global Climate Report. It is seen that almost the entire globe has experienced an increase in temperature. This can be seen from the orange, yellow, and red colours on the figure. The figure shows that only four places in the oceans of the hemisphere in the south did not warm up during the observed period when measurements were made (Fig. 1).

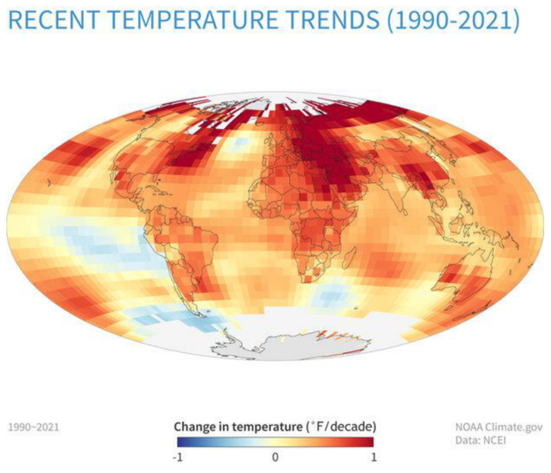

Figure 1: Change in global temperature from 1990 to 2021 (NOAA, 2021).

The graph below (Figure 2) published in the Climate Science Special Report shows the four hypothetical carbon emissions scenarios for annual climate emissions in the period 1990-2100 (on the left) and the predicted temperature increase depending on the scenario (on the right). The scenarios are named "representative concentration paths" or RCPs show patterns of economic growth and energy policy in the world (USGCRP, 2017).

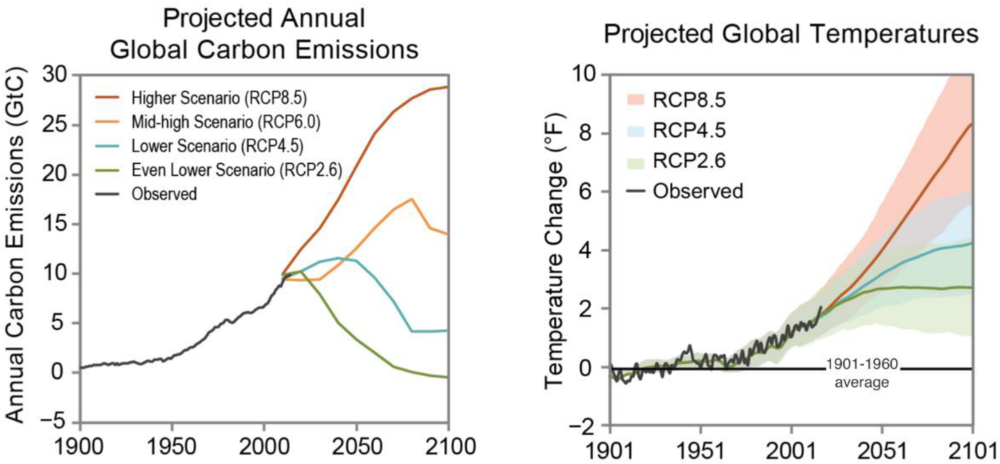

Figure 2: (left) Annual carbon emissions depending on RCP, (right), temperature increase depending on RCP (USGCRP, 2017).

The impact of climate change on temperature changes is hard to prognose univocally. There are more than five possible scenarios for the development of the situation. The most favourable RCP 1.9 scenario means that global warming will occur moderately and will not exceed 1.5 in the period 2021-2040 in accordance with the Paris Agreement. The RCP 2.6 scenario means that global warming will occur more rapidly compared to RCP 1.9 at about 1.7 degrees over the period 2041-2060. The RCP 4.5 is a medium scenario with a 2-degree rise in temperature over the period 2041-2060. Based on the RCP 6.0 scenario, global warming will be replaced by global cooling. The RCP 8.5 scenario is the most unfavourable followed by a rise of 4.4 degrees in the period 2081-2100 and a greenhouse catastrophe. The graph above shows graphs of climate change scenarios (Fig.2, Fig.3) (IPCC, 2021).

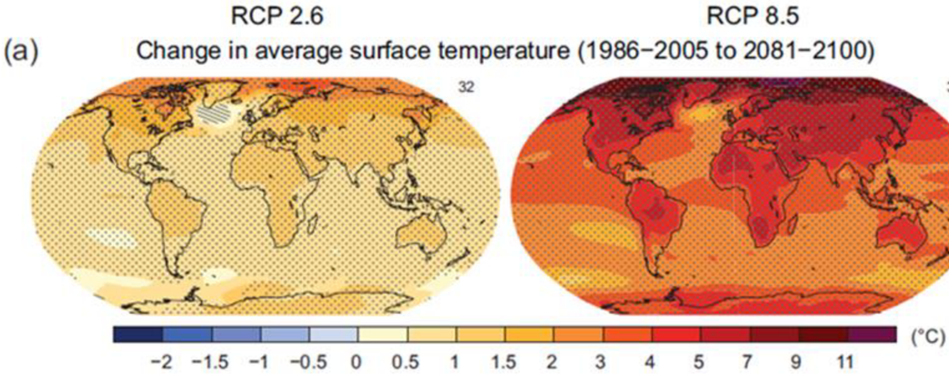

Figure 3: Change in average surface temperature from 1986-2005 till 2081-2100 according to RCP 2,6 and RCP 8.5 scenarios (IPCC, 2021).

The 2017 Climatology Special Report says that according to their climate change projections, warming could reach +10 °C by the year 2100 (USGCRP, 2017).

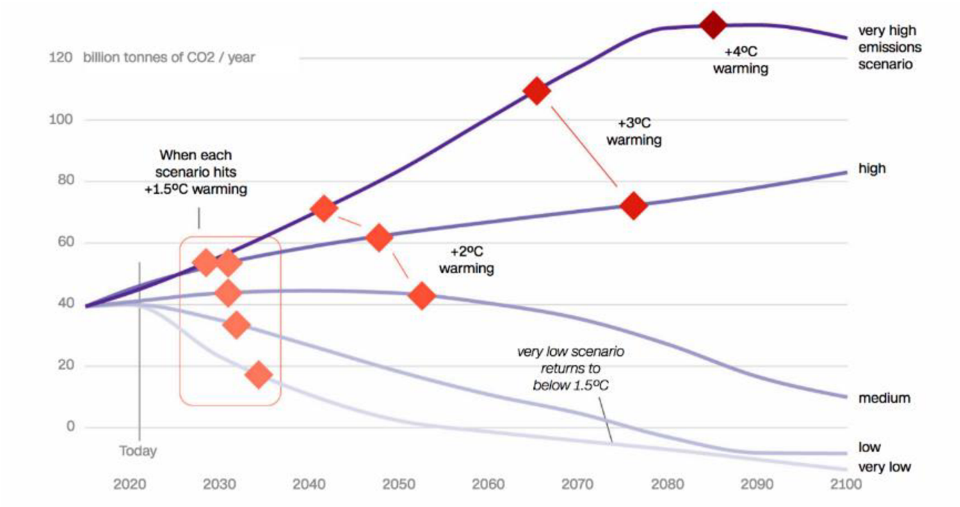

Figure 4: The rate of warming depends on future CO_2 emissions (IPCC, 2021).

The graph above shows the rate of warming as a function of future CO_2 emissions. The purple lines represent warming trends based on various projections of future carbon emissions amount. The darker the curve, the more carbon is emitted. The line labelled "high" is close to the speed of emissions the world is currently throwing out. On the graph, it could be seen rhombuses of different colours. The orange diamonds indicate the points where the temperature will increase by 1.5 ºC, depending on the climate scenario. Dark orange dots mean increase the temperature by 2 ºC and red and dark red diamonds mean a loss of 3 °C and 4 °C respectively (Fig.4). It can be seen that the more CO_2 the world produces, the more the world will follow the worst scenario and, thus, the higher the global temperatures will rise.

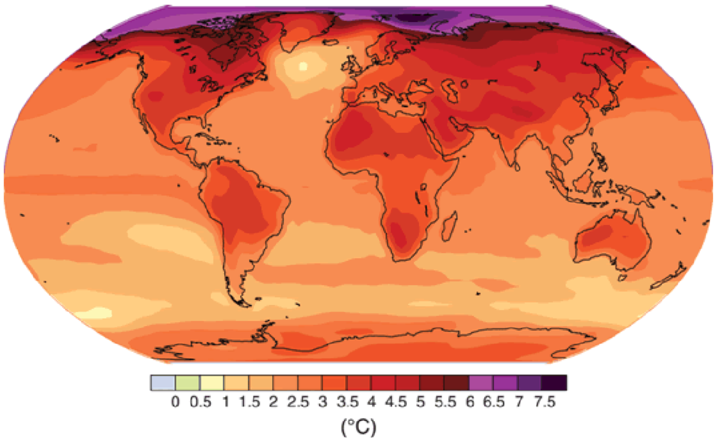

Figure 5: Increase in global temperature that is projected by 2099 (IPCC, 2021)

The graph above shows the increase in global temperature that is projected by 2099. The sharp warming is seen at high northern latitudes (Fig.5).

In order to keep warming within 1.5 °C, cardinal changes must certainly occur. Carbon emissions increased significantly in 2021 with 2 billion metric tons from the burning of fossil fuels such as natural gas, coal and oil. This value is the highest in history, so big adjustments need to be made to how energy was obtained in order to lower the 2021 figure. 195 countries signed the Paris Agreement in 2015 to cut emissions and keep warming to 1.5 °C, at worst 2 °C (IPCC,2021).

3.3.2 **Humidity**

Water vapour is a very important greenhouse gas in the atmosphere. Water in the form of steam participates in the water cycle and is a significant part of it. Thanks to water vapor, our planet is habitable. The gaseous form of H2O absorbs much more infrared energy emitted from the Earth's surface than other greenhouse gases, thus trapping heat. The water cycle is a process of cyclic movement of water in the terrestrial biosphere, which consists of water evaporation, vapour transport by air currents, condensation, precipitation (rain, snow, etc.) and water transport by rivers and other water bodies (NASA, 2022). Moreover, water vapour is the basis for rain and cloud formation, which is why it is critical for sustaining the life of plants and forests (Willett K, 2007).

However, in combination with high temperatures, water vapour can cause heat stress in animals and humans, and with a lack of water vapour in the air, the likelihood of forest fires increases, as does their frequency (Willett K, 2020).

A new study by Song, Fengfei & Zhang, Guang & Ramanathan, Veerabhadran & Leung, L. in 2022 titled "Trends in surface equivalent potential temperature: A more comprehensive metric for global warming and weather extremes" shows that when it comes to measuring global warming, not only heat but also moisture is important factor to create dangerous climate extremes (Song, F & Zhang, G & Ramanathan, V & Leung, L, 2022).

A study by the Proceedings of the National Academy of Sciences, entitled «Climate Endgame: Exploring catastrophic climate change scenarios», also states that increasing humidity is a good way to change the weather. Changes in humidity combined with warming show that climate change has twice the effect as expected (Kemp et al, 2022).

The amount of water vapour is directly related to the rise in temperature due to climate change (Soden, 2005). Thus, due to the increase in temperature, the evaporated amount of water in the air also increases (IPCC, 2022).

The absorbency index of the air depends on its air temperature. The warmer the air, the more water vapour it can absorb. This dependence increases exponentially. If the air temperature rises by 3°C, then the air can absorb about 20% more water vapour. Consequently, the absolute concentration of water vapour on Earth with an increase in temperature by 3°C will become 20% more. For every 2 °C of change in temperature, water vapour in the air increases by approximately 14% (NASA, 2022).

According to the latest data, the concentration of water vapour is increasing, hence the greenhouse effect is increasing. However, it is necessary to take into account many regional features associated with the distribution of land and sea, with the distribution of relative humidity and sources of evaporation, as well as the effect of phase transitions, clouds and precipitation. However, water vapour itself is not a consequence of climate change and is not its root cause (NASA, 2022).

With increasing CO2 concentrations due to climate change, water vapour and clouds on a global scale led to an increase in thermal energy, having a strong impact on further climate change. As a greenhouse gas, water absorbs more heat, the atmosphere to warm even more and causing more evaporation. When CO2 is added to the atmosphere as a greenhouse gas it causes even more warming. This effect further increases global warming and is called Stratospheric water vapour feedback (A.E. Dessler et al, 2013, Solomon et.al, 2010). This effect is shown in Figure 6 below.

For example, due to the fact that water vapour feedback roughly doubles the warming from CO2 and taking into account other feedbacks (such as loss of albedo due to ice melt), warming can reach 3 ºC, when, without this effect, the temperature increase may be about 1 ºC due to CH4 and CO2emissions (Held & Soden, 2000).

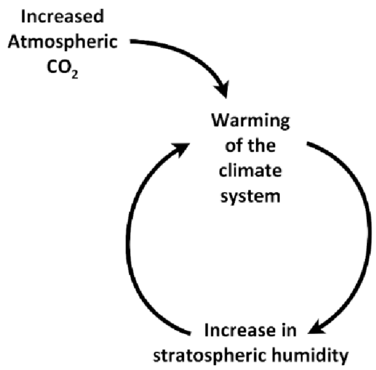

Figure 6: Water vapour feedback. (Dessler A. E. et al, 2013).

Moreover, the increase in water vapour in the atmosphere in the future can lead to more extreme weather conditions such as severe storms due to the increase in the global water cycle. This causes dry regions to become drier and wet regions to become wetter. The more water vapour the air contains, the more energy it contains, and the energy fuels extreme weather conditions (NASA, 2022).

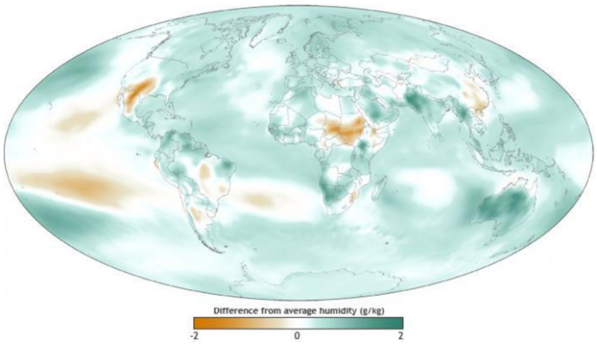

Figure 7: Relative changes in humidity (water content in the atmosphere) at the end of 2010 compared to the average values for the period of satellite observations (1981 - 2010) (NOAA, 2012)

The graph above shows the relative changes in humidity (atmospheric water content) at the end of 2010 compared to the average values for the period of satellite observations (1981 - 2010). In this moisture map, it could be seen wetter green areas and drier brown and orange areas (Fig. 7). Based on the graph, it can be clearly seen that the globe has become much wetter than before (NOAA, 2012).

Moreover, there is a concept as the humidity paradox. The humidity paradox is as the Earth warms, warmer air can hold more water vapour. As the atmosphere, land, and oceans heat up, more water evaporates from the Earth's surface, and because of this, more water can be trapped as gas. As shown in the diagram below, increases in specific humidity occur both over land (green line) and oceans (blue) (Willett K, 2007).

The Clausius-Clapeyron equation connects the derivative of the equilibrium pressure with respect to temperature with the heat of transition, temperature, and the difference in specific volumes of phases in equilibrium. According to the Clausius-Clapeyron Relationship, for every 1 ºC rise in temperature, air can typically hold about 7% more moisture (Manabe & Wetherald, 1967; Allen & Ingram, 2002; Trenberth et al., 2005)

As a consequence, in order for the relative humidity to remain the same at 1°C warming, the moisture content of the air must also increase by 7% (Manabe & Wetherald, 1967; Allen & Ingram, 2002; Trenberth et al., 2005).

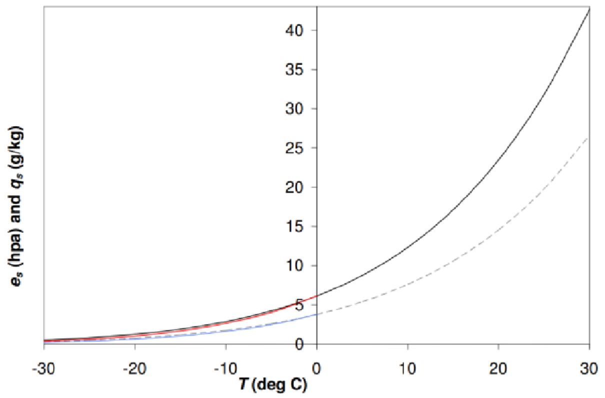

Figure 8: Clausius-Clapeyron equation connects the derivative of the equilibrium pressure with respect to temperature with the heat of transition, temperature, and difference in the specific volumes of phases in equilibrium. (Willett K, 2007)

In the graph above, the black solid line shows water retention and the red solid line shows ice retention. The dotted grey line shows q_s for water retention and the blue line for ice retention. Each line represents e or q at 100% relative dynamics (Fig.8) (Willett K, 2007).

If there were no limiting factors, then exactly this speed would be expected, however limiting factors exist as relative humidity, on the contrary, decreases (Willett K, 2020).

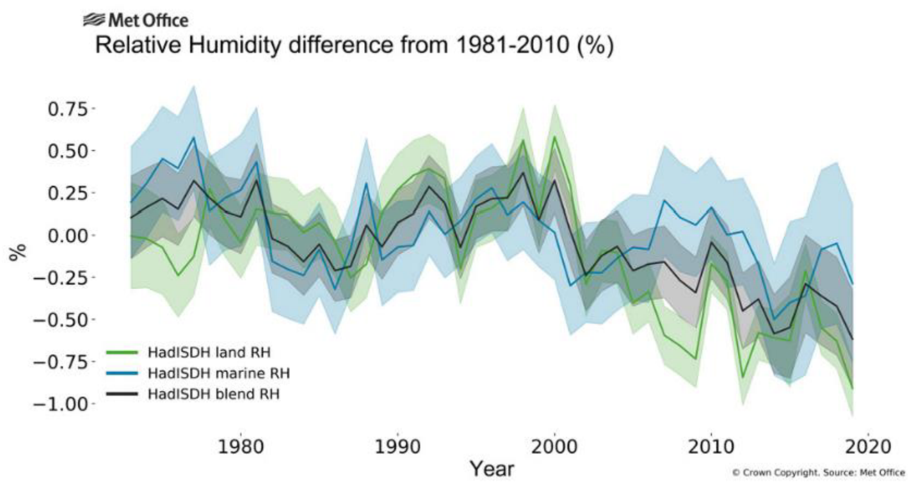

Figure 9: Global time series of annual average relative humidity for the land, ocean and global average relative to 1981-2010 Credit: Met Office Climate Dashboard. https://www.metoffice.gov.uk/

The rate of rise in land surface temperature is higher than that of surface waters. And with an increase in the temperature of the World's Oceans, evaporation will indeed be greater, which means that more water vapour will enter the atmosphere since water droplets do not have enough time to evaporate and remain in the air in the form of steam. Therefore, it is not so much the increase in the maximum possible concentration of water vapour with the increasing temperature that is important, but the change in its real concentration.

Air has the ability to absorb moisture. The amount of moisture that can be measured is called relative humidity. In other words, relative humidity is the ratio of the absolute humidity of the air to the density of saturated water vapour at the same temperature, expressed as a percentage, and is called the relative humidity of the air. 100% humidity means that the air can no longer absorb any more moisture. Due to climate change, patriciates of water linger in the air, due to which humidity concentration in the atmosphere decreases and, accordingly, the relative humidity also becomes lower. This can be seen in Figure 9 above. As climate change affects temperature rise, relative humidity has decreased on average from 1980 to 2020 (Willett K, 2020).

3.3.3 **Irradiance**

Insolation or irradiance is the amount of solar radiation received on a given surface in a given period of time. Insolation varies with the season and the daily change in cloudiness. Daily insolation is the solar radiation incident on a horizontal surface per square meter, integrated per day. That part of the solar energy that reaches the Earth refers to the radiation of energy conducted by the sun. This energy is fundamental for the bulk of the processes in the hydrosphere, atmosphere, and biosphere (Landsberg J. & Peter S., 2011).

Experiments that have studied the correlation between climate change and the amount of solar radiation that reaches the Earth have shown that global warming is not related to irradiation. Since 1975, global temperatures have continued to rise, while solar activity shows little or trend to change, so at least recent warming must be due to other causes (Thomas R. Karl, et al, 2009).

This can also be seen in the graph below, which shows graphs of the average annual temperature (blue line) from 1980 to 2005 and the change in solar radiation that reaches the surface. The graph shows that solar irradiation has an 11-year cycle. While the temperature is gradually increasing, the solar irradiance changes steadily in cycles once every 11 years and does not tend to increase (Fig.10).

It can be concluded that the cause of the change in temperature is CO2and CH4, not a possible change in solar radiation (Karl T. R. et al, 2009).

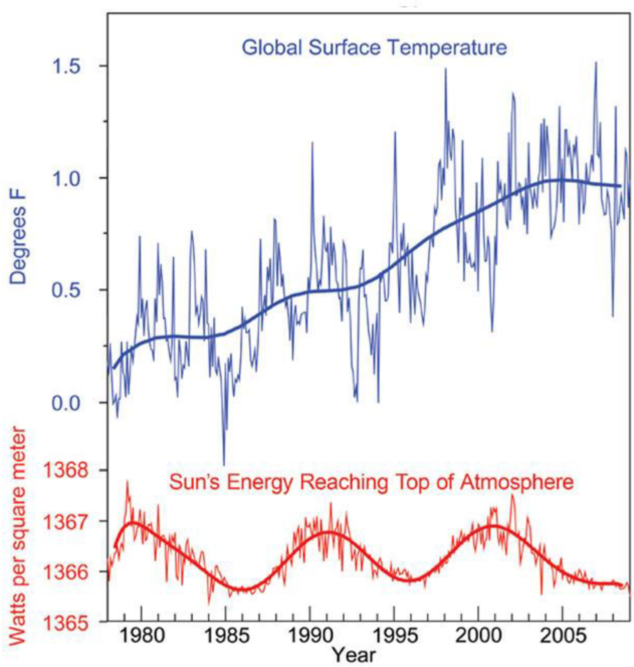

Figure 10: Change in mean annual temperature (thin blue line) and solar intensity with a cycle of 11 years (thick red line). Source: (Thomas R. Karl, et al, 2009).

In the graph below, could be seen total solar radiation data based on observations from the 1600 till present (Fig.11). It can be seen that during solar cycles, the total average brightness of the Sun varies up to 1 W per square meter. As a consequence, changes in solar radiation can be said to have no effect on climate change, since changes since 1850-1900 are not significant (Coddington et al., 2016).

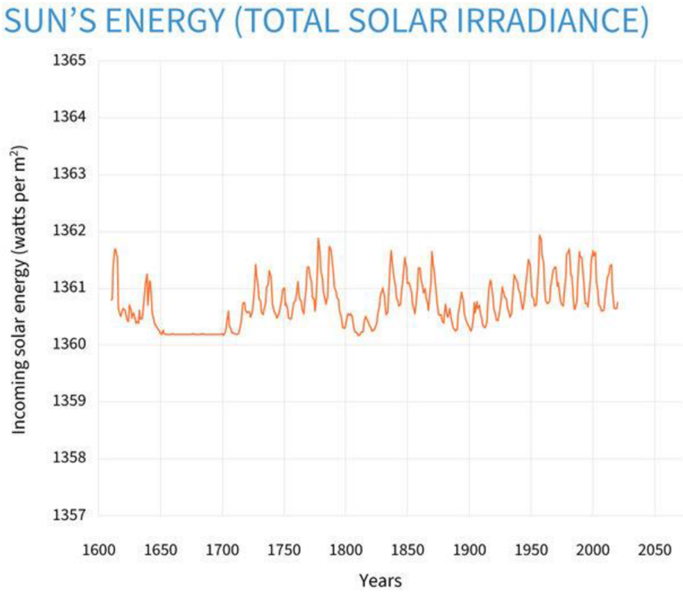

Figure 11: Total solar radiation data based on observations since the 1600s (Coddington, et al., 2016).

Periods of a quiet and active Sun replace each other approximately every 11 years, which is caused by a reversal of the Sun's magnetic poles. During strong cycles at solar maximum, the total brightness of the sun is about 0.1 per cent higher than at solar minimum (Coddington, et al., 2016).

Various scientific studies by the Intergovernmental Panel on Climate Change (IPCC) concluded that, on average over a solar cycle, the best estimate of the change in the brightness of the Sun between the pre-industrial period and the year 2019 is 0.06 watts per square meter. This increase could account for the 0.01-degree Celsius warming (about 1% of warming) that the planet experienced during the Industrial Age (0.95-1.2 ºC Celsius in 2011-2020 compared to 1850-1900) (IPCC, 2021).

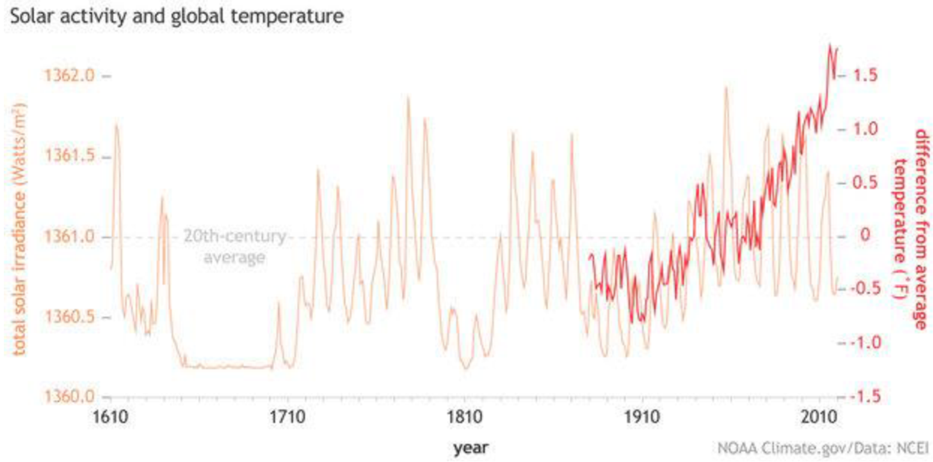

Figure 12: Yearly total solar irradiance (orange line) from 1610–2020 and the annual global temperature compared to the 20th-century average (red line) from 1880–2020 (NOAA, 2021).

In the graph above it could be seen the annual total solar irradiance which is represented by the orange line from 1610 to 2020 and the annual global temperature compared to the 20th-century average from 1880 to 2020 represented by the red line (Fig.12). Based on the graph, while global temperatures have risen significantly, solar activity has declined since the mid-20th century (NOAA, 2021).

Thus, since the beginning of the industrial revolution, the change in the overall solar irradiance of the sun has been minimal, while the rate of global warming has accelerated significantly over the past few decades (Thomas R. Karl, et al, 2009).

3.3.4 Aerosol concentration and cloudiness

Aerosols are a mixture of small liquid and solid particles that are dispersed in the air. Also, aerosols are a climatic dispersion system that can change clouds in many ways (Ginzburg A. S., 2008). For example, they can affect the hydrological cycle, solar radiation, cloud properties, and the reflection and absorption of radiation. (Hansen et. al., 1997).

Aerosols can be of natural and anthropogenic origin. Natural aerosols include particles of volcanic origin, soil particles and sea salt. Anthropogenic aerosols include combustion products, as a result of industry, transport (such as dust, soot from the combustion of various fuels, organic carbon, and sulfates that fall on the surface and into the atmosphere as a result of anthropogenic activities) (Lee S.S., Penner J.E., 2010). Due to industrialization and the development of energy facilities, the composition of aerosols began to change, which contributes to environmental pollution (Ginzburg A. S., 2008).

Aerosols can have direct and indirect influences on climate. Directly, the smallest particles of solid or liquid matter absorb or scatter thermal or solar radiation, thereby affecting the radiation balance of the atmosphere and the underlying surface (Putaud et al. 2010). Indirectly, the smallest particles of solid or liquid matter affect how long clouds stay in the atmosphere, as well as by changing the radiative properties of clouds, such as absorption and reflection (Ginzburg A. S., 2008).

Particles of aerosols and clouds are crucial as they can control the amount of sun and irradiance on the Earth's surface. Layers of aerosol influence the climate equilibrium of the Earth through the absorption of solar radiation and through the reflection of sunlight.

The radiation effect of aerosols on the radiation balance can be either positive or negative. There is the so-called Twomey effect, in which the albedo effect of clouds increases due to anthropogenic pollution, and as a consequence due to an increase in the degree of saturation of moisture in the air. As a result, the sun's rays do not reach the surface of the earth but are reflected (Twomey S., 1977).

Aerosols can have different effects on the climate. Most aerosols shoot solar radiation, but some types of aerosols have the property of absorbing it (Putaud et al. 2010). Reflective aerosols make the property of solar radiation to reflect from the surface even more pronounced. This leads to the result of a temperature reduction (Myhre, G et al, 2013).

Carbon-containing aerosols of combustion can absorb solar radiation. Due to the increase in temperature, relative humidity decreases. This can lead to the evaporation of drops in the clouds (Putaud et al. 2010). Thanks to the equilibrium of absorbing and dispersing aerosols, energy (temperature) equilibrium are also observed (Myhre, G et al, 2013).

What impact aerosols have on the climate and its change is not sufficiently investigated when there is a lot of information about the activities of such gases as CO2 and CH4. It can be concluded that the connection of aerosols with a change in the thermal balance of the Earth is not sufficiently studied and is not well defined in different from many other topics (Mitchell, C, 1997).

However, an example of the relationship between climate and aerosols can be the fact that, during the interglacial period, the distribution of aerosols, and their types were very different than during the ice age. Aerosols can enhance the distinction between glaciers and interglacial and act as positive feedback. For instance, due to stronger winds over bare glacial plains during glaciation, more dust can accumulate, which contributes to a higher planetary Albedo effect, which in turn maintains the cold. Thus, climate and aerosol are interrelated in a complex way (Myhre, G et al, 2013).

Aerosols are critical to cloud formation. In the work of researchers from the University of Michigan, published in the Proceedings of the National Academy of Sciences, it is shown that the aerosols in the atmosphere create the so-called crystallization centres necessary for the formation of clouds and precipitation. (Penner, J.E., Xu, L. and Wang, M., 2011). Absorbing aerosols that are in the troposphere can affect the time of cloud existence. In addition, they can absorb solar energy and thus influence the relative humidity (Hansen, J. & Nazarenko, 2004).

Aerosol particles are centres of moisture condensation, which affects the formation and lifetime of clouds. If the aerosols that are centres for the formation of clouds and the centres of water vapour accumulation become larger, then the particles of water vapour are divided, while the amount of moisture itself does not change. This can lead to a decrease in temperature due to the fact that the reflection of ranges will be more reflected from stunned than before. This effect is called Albedo Clouds (Twomey 1977). The particles of water vapour in the cloud cannot fall out as precipitation due to their small size, causing the clouds to expand and the temperature to decrease due to the reflection of sunlight that is reflected into space (Albrecht 1989). This effect is shown in the graph below (Fig. 13). In general, the Albedo effect is the effect that occurs when the sun's rays hit the cloud and these rays return to space.

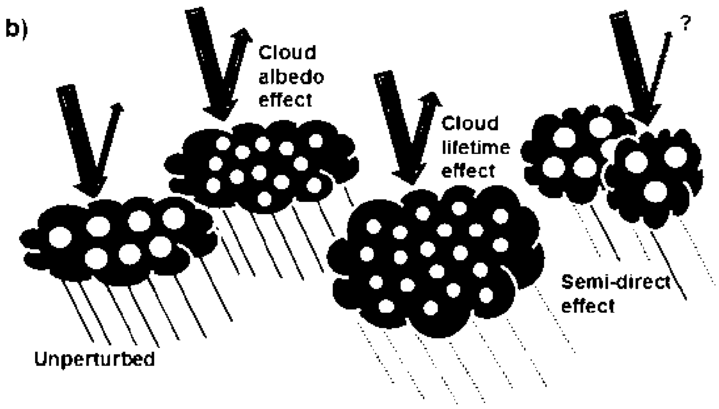

Figure 13: The direct aerosol effect and the cloud albedo effect. cloud albedo effect © 2013 Nature Education (www.nature.com/scitable/)

There is also a direct impact of aerosols on climate change. The fact is that dark and light surfaces have different effects on the behaviour of reflective and absorbent aerosols.

The presence of scattering aerosols in the atmosphere leads to a negative radiation effect, i.e., to the cooling of the earth's surface. However, even partially absorbing aerosol formations over bright (scattering) surfaces (clouds, snow, ice, deserts) can contribute to an increase in surface air temperature, and over dark (absorbing) surfaces (ocean or forest), it can decrease.

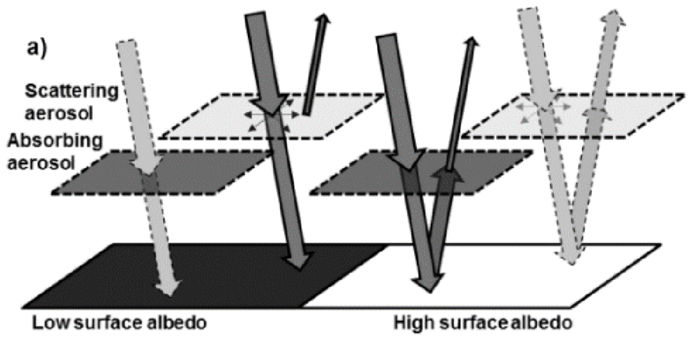

Figure 14: The direct aerosol effect. Direct aerosol impact at low and high surface albedo, scattering and c of aerosols © 2013 Nature Education https (www.nature.com/scitable/)

The Albedo effect affects the properties of aerosols differently depending on the surface and the type of aerosols.

For example, a light surface will reflect absorbing aerosols, which can contribute to warming. Scattering aerosols will also reflect off a bright surface but will not have a warming effect (Fig.14). Conversely, absorbing aerosols that hit a dark surface will not have a temperature increase effect, while scattering aerosols, on the contrary, will have a warming effect (Myhre, G et al, 2013). Moreover, absorbing aerosols that settle on light surfaces such as snow can reduce reflectivity as they can absorb radiation rays. This may lead to an increase in temperatures (Hansen, J. & Nazarenko, 2004).

3.3.5 **Change in precipitation**

As already mentioned in the part where the influence of the climate change process on humidity change was discussed in detail, an increase in the temperature of the world's oceans can affect how many particles of water will be in the atmosphere (USGCRP, 2017). As a consequence, intense rainfall can lead to soil erosion and destruction and erosion of planted areas of land. This, in turn, can affect how often it will rain and their strength. The intensity of the rain plays an important role: the stronger the rain, the more likely it is that the upper layers of the soil will quickly become saturated, and the rest of the water will drain directly into the rivers. It may also lead to other flood-related effects (Bell, J.E., et al., 2016) as well as increase the amount of pollutants in rivers that are washed out of the soil and fall into water bodies. The rains are becoming more intense, although the frequency of precipitation may not always change (EPA, 2022).

According to a new study "Observed Changes in Daily Precipitation Intensity in the United States" published in 2022, authors Ryan D. Harp and Daniel E. Horton say that more precipitation is falling in most of the United States due to climate change. Not only is the intensity of precipitation getting higher, but the frequency of precipitation is also increasing. The authors explained this fact by the fact that due to the increase in temperature, more moisture begins to linger in the air (Harp R. & Horton D., 2022)

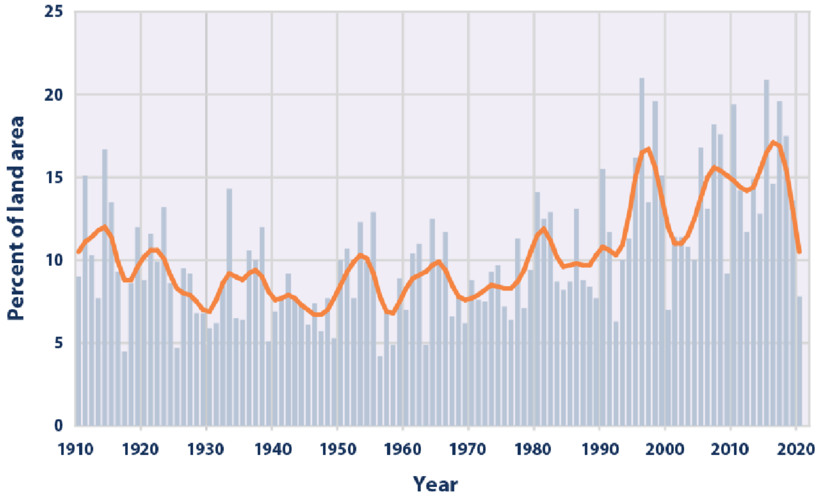

Figure 15: Extreme one-day precipitation from 1910 to 2020 (NOAA, 2021).

In the figure above, you can see the percentage of rain that lasted one day in the period from 1910 to 2020 (Figure 15). The vertical axis of the graph shows the percentage of the area where one-day rains were observed, and the horizontal axis represents time periods of 9 years from 1910 to 2020. The orange line represents the percentage average. According to the graph, it can be concluded that, on average, since 1980, there has been an increase in the area on which one-day precipitation was recorded. (NOAA, 2021).

3.4 Utility-scale PV system

Utility-scale photovoltaic or PV systems also known as solar farms or solar parks, are large-scale ground installations that create solar energy on a large scale (MW capacity and more) through photovoltaic systems.

Solar farms are decentralized and usually consist of solar panels and cover a large area. Most often, they provide electricity to the electrical grid and therefore are part of the energy balance of the enterprise (Hyder, Z.,2021).

There are four types of solar projects: residential, commercial, industrial, and utility scale. A utility-scale solar park produces 10 megawatts (MW) or more of energy. Commercial and industrial solar parks are different in that they are used by commercial and industrial property owners to benefit from the installation of solar energy on the roofs of businesses or factories. Industries that focus on consumer goods, fashion and the high-tech sector consume a significant amount of energy. Residential rooftop solar PV project types are the smallest in size, ranging from 5 to 20 kilowatts (0.005–0.2 MW) (Hyder, Z., 2019).

Solar parks and panels on the roofs of residential buildings have a similar configuration and technology. In both cases, the panels convert sunlight into direct current (DC) electricity. Next, direct current (DC) electricity is converted into alternating current (AC) electricity, which is then used in homes.

The technology helps the panels track the sun's axis and rotate to follow the path of the sun depending on the time of year and day. Thanks to this technology, panels can generate much more energy than if they were in a stationary position. Eighty-eight per cent of new solar power that was installed in 2019 used this technology (Hyder, Z., 2021).

The solar PV system consists of a source of electricity - solar modules, a network inverter and a battery (Hyder, Z., 2019) (Fig.16).

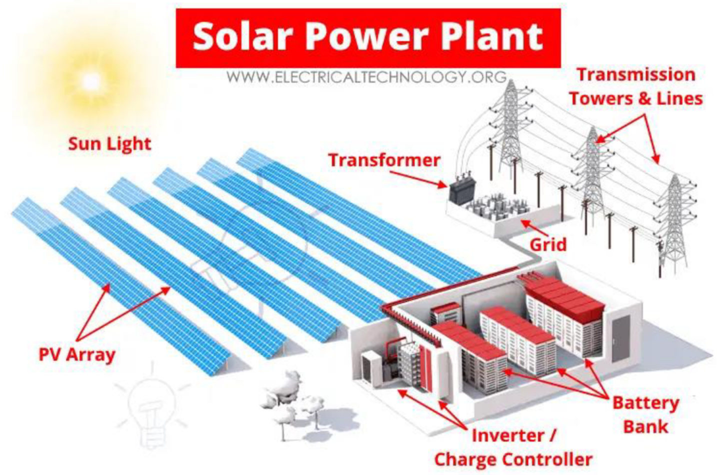

Figure 16: Solar Power Plant: consists of a set of solar modules, charge controllers that use solar energy to charge the battery and an inverter designed to convert direct current into alternating current and transfer it to the consumer's internal network (2021). Available at: https://royalstar.com.tr/en/pv-diesel-hybrid-system-controller/

3.4.1 **Panels**

Solar panels work on the basis that solar radiation stimulates the movement of electrons through solar cells embedded in solar panels. The panels generate DC electricity. The lifetime of solar panels can exceed 20 years and reach up to 25 years. The decrease in module power over 20 years is approximately 10%. Monocrystalline solar panels have a service life of at least 30 years, while polycrystalline solar panels have a service life of at least 20 years. The efficiency starts to decrease from the first year at a rate of 0.5% per year (Rathore N., et al, 2019).

There are two types of solar panels monocrystalline and polycrystalline panels, which differ in technical parameters and appearance (Rathore N., et al, 2019). Monocrystalline-type photovoltaic panels have rounded corners and a uniform surface. The rounded corners are due to the fact that in the production of single-crystal silicon, cylindrical blanks are obtained. The uniformity of the colour and structure of single-crystal elements is due to the fact that this is a single-grown silicon crystal, and the crystal structure is homogeneous. Such types of panels as monocrystals take up less space and have a high-power output. However, the price for these panels is higher than for polycrystalline panels. The efficiency of the latest monocrystalline panel is approximately 23%. The biggest advantage of monocrystalline panels as opposed to polycrystalline panels is that they are much more tolerant to temperature changes and therefore less responsive to temperature increases, unlike polycrystalline panels (Rathore N., et al, 2019).

The second type of panel is polycrystalline. They consist of a large number of small crystals, due to which they can have a different texture and, have some areas darker or lighter than others, being from light blue to dark blue in colour. Polycrystalline panels, unlike monocrystalline ones, are made using molten silicon, which is why they are cheaper than monocrystalline ones and are made faster. The shape of polycrystalline panels is rectangular with an acute angle. Due to the impurities added to the silicon, this type of panel has a blue colour (Rathore N., et al, 2019).

3.4.2 **Inverter**

The energy produced by the solar panel is in the form of direct current. However, the load connected to the power system's grid is represented by alternating current. As a consequence, it is necessary to somehow convert the DC power into AC power. An inverter is a device that can convert direct current (DC) into alternating current (AC). In the solar PV system, constant energy is produced and for its conversion into alternating energy, it is supplied through an inverter (Foster R. et al., 2010).

Inverters are an important part of the system as they operate continuously throughout their lifetime. That is why inverters most often have malfunctions and have a guarantee of 10 years. In addition, inverters are the second most expensive component after solar panels (Foster R. et al., 2010).

Moreover, along with the inverter, a controller is used. The controller is needed in order to control the discharge and charging of the battery. Overcharging the battery can corrode or even damage the battery electrolyte, so the controller prevents the battery from being overcharged.

3.4.3 **Solar battery storage unit**

A battery in a solar PV system is an electrical element that is used to store energy. Thanks to the battery, the energy that was generated during the day can be used during the night since the system does not generate energy at night (Ponnusamy M., 2013).

Battery capacity is a measure of how much electricity a battery can store, measured in amp-hours (Ah) and varies with temperature. For every degree Celsius with an increase in temperature of more than 25 ºC, there is a decrease in power by 0.6 % (Hasan, Md et al, 2017).

Batteries work by chemical reactions to store energy and then release that energy back as electricity. Lithium-ion batteries, unlike other batteries, have a greater depth of discharge, can store more energy, and retain this energy longer than other batteries (Ponnusamy M., 2013).

3.5 Effect of climate change on the PV system energy performance

3.5.1 **"Standard Test Conditions (STC)"**

STC stands for Standard Test Conditions. These are industry standards for the conditions under which solar panels are tested. Thanks to a fixed set of conditions, solar panels can be more accurately compared with each other. After the panel has been tested, its characteristics can be determined (Odeh, S.,2018).

Standard test conditions are the conditions under which the panel operate under ideal conditions. These conditions imply that the solar battery will be illuminated by a light with an intensity of 1000 W / m2 at a module temperature of 25 ° C and the wind speed should be equal to zero (Kuchta, D., 2022). The last condition is an air mass of 1.5. This number is related to the amount of light that must pass through the atmosphere. On top of that, this number is also related to the angle of inclination of the sun relative to the reference point on the Earth. When the sun reaches its highest position in the south and is directly overhead, this number has the smallest value, due to the fact that the light has to travel a minimum distance down. However, when the sun begins to move away from its highest position and therefore begins to be at an angle relative to the surface of the Earth, this value increases (Kuchta, D., 2022).

Based on the standard conditions, it could be concluded that they correspond to noon in spring or autumn in calm weather, in which sunlight falls on a south-facing solar panel tilted at an angle of 37° to the horizon, with a height of the sun above the horizon of 41.81° and with the plane of the solar panel perpendicular to the solar rays. However, such conditions rarely occur (Kuchta, D., 2022).

According to the results of testing on the basis of standard conditions, nameplate power is determined. In other words, the maximum or rated power is determined, which is indicated in the panel's PV module datasheet as P_{max} and is measured in watts. For example, if the panel is labelled as a 100-watt solar panel, this means that this panel, when tested under STC conditions, had a maximum power of 100 watts.

However, it should be borne in mind that, as mentioned earlier, the conditions of the STC practically do not occur in real life, which means that it is very rare when the panel delivers real power. Most often, the panel will have a maximum power of 70% -80% of the power that is indicated in the panel's technical PV module datasheet (a document that contains manufacturing performance data), and this is under conditions of clear and sunny weather. Depending on the amount of shade, the number of clouds and the time of day, P_{max} will have different values (Kuchta, D., 2022).

In addition, in the technical PV module datasheet of the panels, there is also such an indicator as the temperature coefficient P_{max} (Medykovskyy, M., & Melnyk, R., 2021). This percentage indicates how much power the panel will lose when the temperature rises 1 degree higher than the standard test conditions of 25 ºC Celsius (Hadj Arab A., 2020)

3.5.2 **IV curve and performance of Solar Cell**

The solar cell characteristic can describe the short circuit current (ISC) and open circuit voltage (VOC) graph describes characteristics of the solar cell, which is shown below.

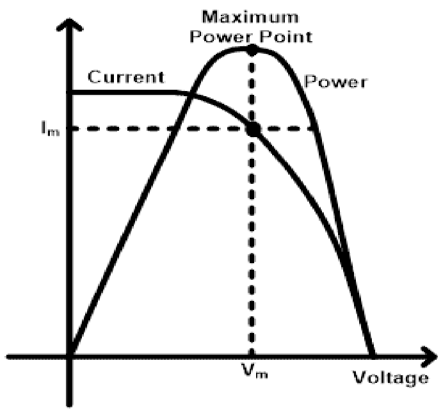

Figure 17: The plot of short-circuit current (ISC) and open-circuit voltage (VOC) (https://www.electricaltechnology.org).

As can be seen in the graph above, the short-circuit current initially remains constant as the voltage increases, but as the open-circuit voltage further, the current decreases rapidly (Fig.17).

Using a plot would be estimated how much power a solar cell develops; the current value is multiplied by the voltage. Based on this, a power graph could be built. As is seen in the power graph below, point P is the maximum power that can be developed, the so-called maximum power point. Under the condition of maximum voltage (Vm) and maximum current (Im), the power will be maximum (Lindholm F. A. et.al, 1979).

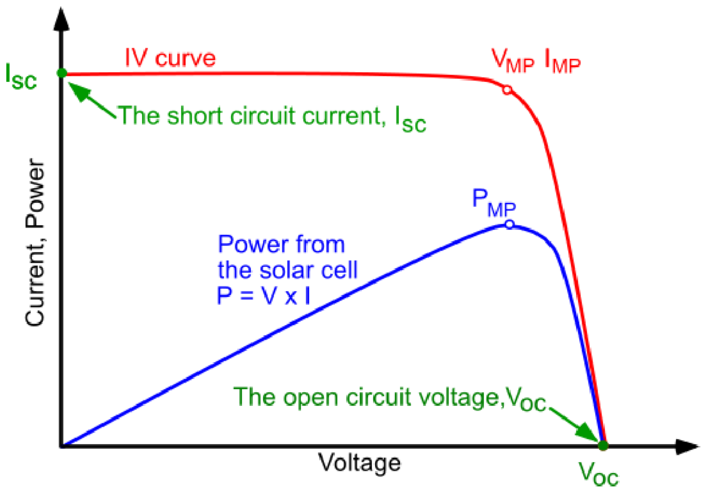

Figure 18: Current-voltage (IV) cure of a solar cell. To get the maximum power output of a solar cell it needs to operate at the maximum power point, PMP (Coulibaly, et al, 2019).

Thanks to the Current-voltage (IV) curve graph, one can determine what affects the amount of energy produced and the peak power output of solar panels and solar PV systems. On the graph, could be seen two axes, the vertical one (Isc) represents Current Power, and the horizontal axes represents Voltage. The point $V_{mp}I_{mp}$ represents the point of peak energy power, that is, the maximum amount of energy that the panel can produce. So, for example, as the temperature rises, the graph and the VI-point shift and the peak power indicator becomes smaller (Lindholm F. A. et.al, 1979) (Figure 18).

Each panel has data based on STC standards on how the panel will behave when the temperature rises. In this thesis, the change in some climate factors will be considered in more detail due to climate change, and the peak power point of both the solar panel and the individual components of the PV system will change (Lindholm F. A. et.al, 1979).

3.5.3 **Factors of climate change affecting the efficiency of the solar PV system**

3.5.3.1. Temperature

As mentioned earlier, solar panels are tested under standard test conditions, the so-called STC. Based on the STC standard, the Temperature Coefficient Pmax of the panel is determined. Pmax is the percentage of energy lost by the solar panel for every degree Celsius above the STC temperature of 25°C. Increasing the temperature may reduce the output efficiency by 9-23% depending on the environmental conditions (Dubey S et al.2013). Thus temperature has an electrical effect on solar panels.

Solar panels need sunlight (irradiation) to generate electricity, but the temperature, on the contrary, reduces their efficiency. The combination of bright sun and low temperatures are ideal conditions for solar panels. Higher temperatures, on the contrary, will reduce the efficiency of solar panels (Jaleel E., et al., 2020).

However, an increase in temperature may not only negatively affect the solar panels, but also the battery and inverter. For instance, temperature significantly affects performance and battery life. Moreover, the capacity of the battery is also reduced. Charge-discharge activity raises the temperature of the cell and results in a higher rate of degradation. The best operating temperature for batteries is 20 ° C. As was mentioned earlier, for every degree Celsius with an increase in temperature of more than 25 ° C, there is a decrease in power by 0.6% (Hasan, Md et al, 2017).

As for the inverter, they reach their peak efficiency when the temperature is the most suitable. However, in inverters, there is a process known as "power derating" in which the inverter gradually reduces its output power by reducing the output current, even before the inverter reaches its maximum operating temperature. Inverters are much more resistant to temperature increase compared to PV solar panels since most inverters derate at about 50-60 ºC and they also have a special cooling system that will not let it overheat. In general, the temperature of a solar inverter does not significantly affect its performance (El Boujdaini, Ibrahim, 2021).

3.5.3.2. Humidity

In their work Panjwani, Manoj and Narejo, G.B., "Effect of Humidity on the Efficiency of Solar Cell (photovoltaic)" based on experimental analysis, it was found that humidity reduces the solar panel's ability to use solar energy to about 55-60% from about 70% of the energy used (Panjwani, Manoj & Narejo, G.B., 2014).

As the humidity increases, fine water droplets collect on the solar panels. These droplets may reflect or refract the light from the solar cells, which can affect the amount of sunlight that falls on them and the amount of electricity generated. If humidity and elevated temperature continue to persist for a long time, this will lead to rapid degradation of the solar panels during their service life.

Moreover, in their paper "Effect of Humidity on the Efficiency of Solar Cell (photovoltaic)", Panjwani, Manoj and Narejo (2014) described their experiment in which a 50W solar panel, a thermometer, tungsten incandescent bulbs, and a humidifier were used to increase humidity levels. Humidity is calculated using a hygrometer. Based on the experiment conducted, the authors of the article concluded that humidity significantly affects the performance of the solar panel and reduces the power generated by solar panels by 15-30% if the humidity level, provided that the humidity level remains high (Panjwani, Manoj & Narejo, G.B., 2014).

In addition, panel rusting, and internal corrosion can occur when moisture seeps into the system. If the humidity of the environment is high, then this can happen. Neither air nor water must enter each module. Otherwise, serious damage may occur. Each panel component must be properly vacuum laminated. However, when the panel components are contaminated, the bond between each layer is broken and begins to flake off over time. That is why humidity can lead not only to the electrical effect of solar panels but also to the material (Segbefia O. K, et al., 2021).

One more part of the solar PV system like the battery is also affected by changes in humidity. Lithium batteries, which are the most popular type of solar panels due to their ability to store this energy longer than other batteries, are also affected by humidity and temperature. The fact is that the electrolyte that is used in a lithium-ion battery cannot be used in an environment with too high humidity. With increased humidity, the pressure inside the battery rises, the effective electrolyte component is lost, and the lithium-ion is lost, due to which the lithium-ion undergoes an irreversible chemical reaction at the negative electrode of the battery. The battery power is getting low. This gas not only negatively affects the environment but also affects the quality of the electrolyte itself, which leads to poor battery performance. The electrolyte inside the battery reacts with water to form gas and hydrofluoric acid. Hydrofluoric acid is a highly corrosive acid that may damage the metal parts inside the battery and cause corrosion. Corrosion, which in turn leads to battery leakage (Gabryelczyk A., et al, 2021).

3.5.3.3. Insolation

The amount of energy generated increases as more solar radiation hits the surface of the solar panel. (Akmam N. N., et al., 2018:, Jerez, S et al., 2015).

Chaaban Mohamed Amer's 2020 paper titled "Irradiance and PV performance optimization, Irradiance and PV Performance Optimization" found how the irradiation changes affect PV output (Chaaban M. A., 2020). Provided that all parameters are constant, it was found that the higher the illumination, the greater the output current and, as a consequence, the greater the generated power.

The graph below shows the relationship between the voltage and current of a photovoltaic module at different levels of solar radiation. On the graph, it can be seen that as the illumination increases, the solar panel generates a higher current along the vertical axis (Fig. 19).

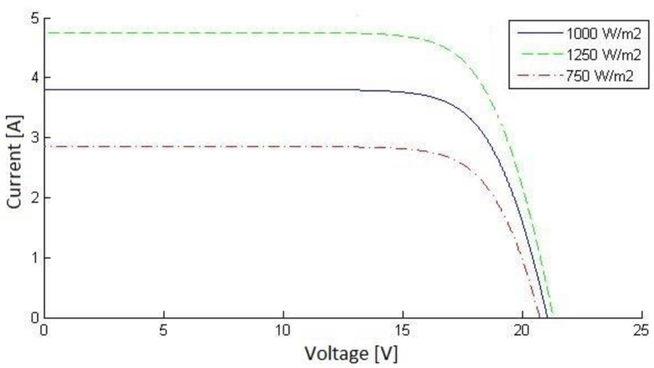

Figure 19: The effect of irradiance on the I-V curve of the PV module (Chaaban M. A., 2020).

In the graph below, it could be seen the ratio of voltage and power of the photovoltaic module at different levels of illumination (Fig.20). Based on the graph, it can be seen that as the amount of light increases, the solar panel can generate more energy, represented by higher peaks in the curves (Chaaban M. A., 2020).

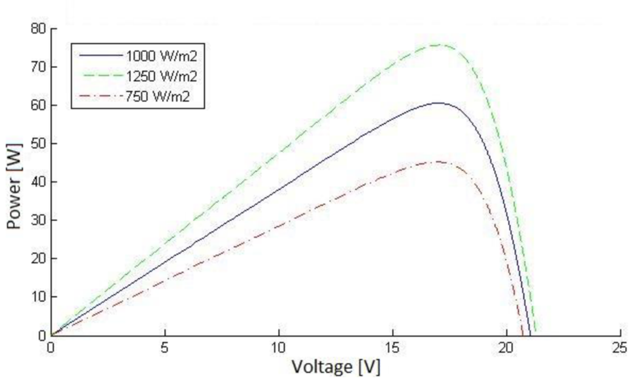

Figure 20: The effect of irradiance on the P-V curve of the PV module (Chaaban M. A., 2020).

Thus, with increasing solar radiation, the efficiency of solar panels may increase. However, as already mentioned, climate change has practically no effect on the global change in solar intensity, and vice versa, solar intensity does not affect the rate of climate change in any way, which is why this thesis will not further discuss the impact of climate change on solar radiation and on the efficiency of panels not be considered (Karl T. R. et al, 2009).

3.5.3.4. Aerosol concentration and cloudiness

In their work by Claudia Gutiérrez et al entitled "Impact of aerosols on the spatiotemporal variability of photovoltaic energy production in the Euro-Mediterranean area" released in 2018, they conducted a simulation experiment in which they determined the effect of aerosols on the change in the efficiency of the photovoltaic system in the region. The experiment was carried out under current climatic conditions for simulations between 2003 and 2009 (Gutiérrez et al., 2017).

The study was conducted in the Euro-Mediterranean part in countries such as Germany, Portugal, Spain, Morocco, Jordan and others. In Germany, because in the country where a large amount of photovoltaic power is installed, because of which any loss in efficiency will greatly affect the amount of energy. The results showed that the most affected areas are mainly in Central Europe. It was there that aerosols most of all influenced the decrease in the efficiency of the solar PV system. In Central Europe, fewer resources, combined with the effects of aerosols, lead to a significant reduction in potential electricity production (Gutiérrez C., et al, 2018).

In experimental simulations which were produced from 1980 to 2012, there was a noticeable increase in productivity in Central Europe. This may have been the result of a decreasing trend in anthropogenic aerosols observed since the late 1980s. This trend may be related to the economic crisis in Western Europe as well as pollution control measures. This means that other countries, such as China and India, which have a high level of emissions, can also assure the efficiency of energy production obtained from PV solar PV systems if effective measures to reduce emissions are implemented in these countries.

It is shown that aerosols reduce the efficiency of photovoltaic modules by 5%-15%. These results showed that, firstly, aerosols significantly reduce the productivity of solar PV panels, and secondly, the results proved that competent measures to reduce pollution that have been taken in Central Europe are effective and can reduce the amount of anthropogenic aerosols that significantly reduce the potential of a photovoltaic system. In addition, the result means that if such measures are not taken globally, this will affect the arbitrariness of renewable energy, namely solar PV energy, by increasing the amount of anthropogenic aerosols in the air. Aerosols must be taken into account when conducting simulation experiments with solar PV systems. Thus, countries with high production of photovoltaic systems have energy losses due to aerosols (Gutiérrez C., et al, 2018).

3.5.3.5. Change in precipitation

How effective the power system may be is highly dependent on the amount of solar radiation. With increased cloudiness, the PV panels are not able to generate more energy. During rainy seasons, the efficiency of solar panels is reduced due to shading. In addition, the amount of incoming sunlight also depends on cloud cover and the amount of water in the atmosphere (i.e., humidity).

During heavy rains, solar panels generate only 10% - 20% of their maximum power, while during cloudy times, solar panels generate 30 - 50% of optimal power. Heavy rain affects energy production more than overcast days, as incident light is backscattered through raindrops and clouds block out the sun (Simsek, E., et al, 2021).

The performance of the panels may be reduced due to dripping condensation or rain falling on their glass panel surface. This is stated in a 2021 study by Simsek, E., Williams, M. J., & Pilon, L., subtitled, "Effect of dew and rain on photovoltaic solar cell performances, which experimentally studied the effect of drops on the performance of photovoltaic solar cells" (Simsek, E., et al, 2021).

An experiment was carried out by applying polydisperse acrylic droplets to glass lids subjected to various surface treatments. It was found that at an angle of incidence less than or equal to 30°, the drops did not affect the generated current, that is, they did not affect their maximum power and the energy conversion efficiency of solar cells. This can be explained by the fact that before the sunlight is absorbed by the solar cell, it is backscattered through the droplets. Moreover, the study showed that when dew forms on the surface of solar panels, depending on actual weather conditions, energy production can be significantly reduced (Simsek, E., et al, 2021).

4 Characteristics of the study area

In this thesis for the experiment, the data from the Czech Republic will be used on the basis of data from four different locations from four different zones of solar radiation: the first zone in the city of Zlín with maximum solar radiation (more than 3.2 kWh/m3) the second zone in the city of České Budejovice with solar radiation of 3.1-3.2 kWh/m3, the third zone is in Prague with solar radiation intensity of 3.0-3.1 kWh/m3, and finally the fourth zone in the Karlový Vary city with indices of 2.9- 3.0 kWh/m3 (ESMAP, 2020) (Figure 21).

In this thesis, both the average change in the parameters for the Czech Republic and the comparison of indicators depending on the level of solar radiation in which the location falls will be made. In the Czech Republic, solar parks are distributed throughout the country, which means that the analysis will be carried out in individual locations as well as the national average.

As already mentioned, in this thesis for the simulation experiment, the energy production in 2050 in the Czech Republic in four different solar radiation zones, since it could possible to calculate the average value for the country as a whole, taking into account differences in the amount of irradiation across the country and in order to be able to compare the results of energy production in different cities in the future, taking into account the amount of solar radiation in the cities chosen for modelling in the Czech Republic (Table 1,2).

	Zlín,	České Budějovice	Prague	Karlovy Vary
Latitude	49.2265°	48.9745°	50.088 °	50.2327°
Longitude	17.6707°	14.4743°	14.4208°	12.8712°
Altitude	228 m	389 m	202 m	364 m

Table 1: The coordinates of the cities in which the simulation will be performed.

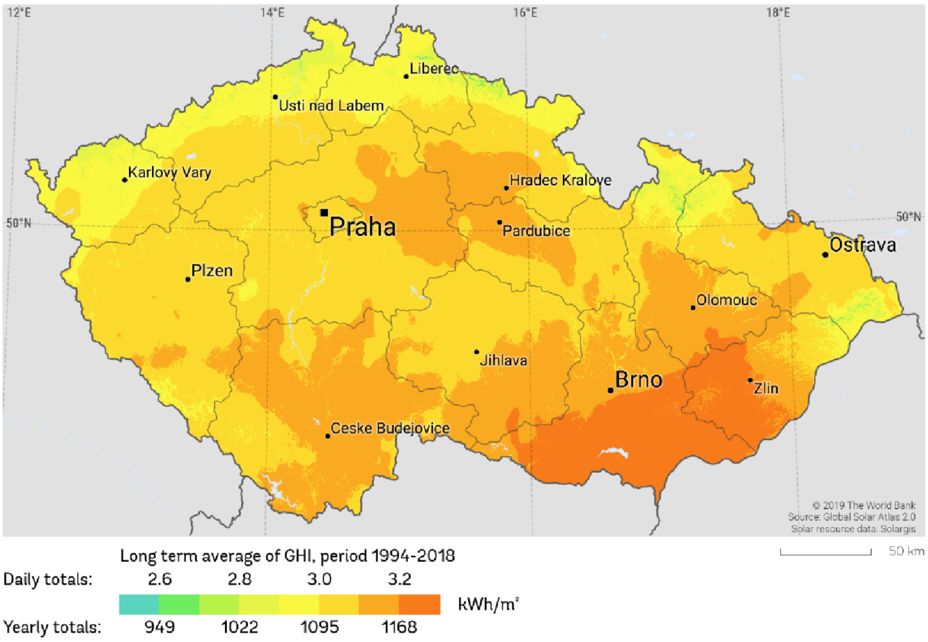

Figure 21: Photovoltaic Electricity Potential in Czech Republic (ESMAP, 2020).

	Zlín	České Budějovice	Prague	Karlovy Vary
Irradiance(w/m2)	1082-1109	1026-1054	1054-1082	940-970

Table 2: Annual total global solar radiation in the Zlin, České Budějovic, Prague, Karlovy Vary [W/m2] (ESMAP, 2020).

To simulate changes in electricity demand due to climate change, it is needed to know projections of explanatory weather variables (air temperature and air humidity) (Table 3,4).

	Zlín	České Budějovice	Prague	Karlovy Vary
January	-1,4	-1,3	-0,2	-0,8
February	0,1	-0,3	0,9	0,2
March	4,4	3,3	4,7	4,1
April	10,1	8,6	9,9	9,1
May	14,7	13,2	14,5	13,7
June	17,8	16,6	17,8	17,0
July	19,9	18,7	20,1	19,0
August	19,6	18,3	19,7	18,6
September	14,3	12,9	14,4	13,6
October	9,7	8,4	9,5	8,9
November	5,4	3,6	4,7	4,1
December	0,2	-0,3	1,2	0,5
Average	**9,5**	**8,5**	**9,8**	**9**

Table 3: Average month temperatures in ºC in the study locations used for the simulation analysis (PVsyst, Meteonorm 8.1).

	Zlín (in %)	České Budějovice (in %)	Prague (in %)	Karlovy Vary (in %)
January	84,1	83,3	82	83,4
February	81,3	80,3	79,5	80
March	72,5	75,7	72,7	72,5
April	66,8	71	66,9	66,3
May	70	72,4	68,6	68
June	71,6	72,1	68,6	68,7
July	67,6	69,4	65,8	66,1
August	69,7	71,2	67,6	67,5
September	75,7	79,2	75,1	75,3
October	80,5	84,5	82,6	82,5
November	83,8	89,2	86,6	86,1
December	86	86,9	84,7	85,4

Table 4: Average humidity data in % in the study locations used for the simulation analysis (PVsyst, Meteonorm 8.1).

5 Methodology

This chapter describes the methodology used to analyze the potential negative impact of climate change factors on solar PV system performance. The analysis will be carried out using the photovoltaic software PVsyst. The program will calculate what will be the variability in the amount of energy due to climate change. Knowing what factors of the solar PV system will be changed due to climate change in the next 20 years, data will be simulated using the program. Based on the literary review, for simulation will be used the most significant factors of climate change and for PV systems such as temperature and humidity.

Simulation data will be used based on the information that is available about the capacities of the panel systems that will be delivered by the year 2030. The average losses will be calculated in the period from 2030 to 2050, taking into account the forecasts for the installation of solar PV systems in the Czech Republic. That means that the analysis will also be based on the expected solar capacity that going to be built by 2050 in the Czech Republic. The data itself was generated within the program based on the characteristics of JAM78-S30-6-MR panels widely used in the Czech Republic and Europe and on the basis of the characteristics of the SUN2000-215KTL-H3 inverter.

An analysis of the efficiency of energy production will be carried out, taking into account the negative impact of climate change in 2050, taking into account three scenarios and in 2030, after which the obtained data will be compared. In addition, data on temperature and humidity in each city were used (Table 3, Table 4).

The resulting energy loss due to climate change will be converted to the amount of carbon dioxide produced using the equivalent: The CO_2 emission factor used is 0.309 kg / kWh, based on the Department for Business Energy & Industrial Strategy's (BEIS) report (Bonifazi E. et al., 2018).

In this thesis, an average of parameter changes across the Czech Republic will be made. In the Czech Republic, system panels cover the whole country, so that the analysis is both by location and the results will be calculated on an average for the country.

To carry out this thesis, the PVsyst program software was used. This software is one of the oldest and the most popular software for solar energy simulation, optimal design of solar power plants, and energy yield estimation. Developed by the University of Geneva, PVsyst is intended for use by architects, engineers, and researchers. The main features are the design of remote and grid-connected photovoltaic systems, a database of photovoltaic panels, inverters, meteorological data, import of radiation data from PVGIS, NASA databases, tools to simulate the behaviour of photovoltaic modules and cells depending on radiation, temperature and shading.

All simulations will be run for one year without considering panel degradation. The degradation feature has been disabled to make performance losses due to climate change more visible and clearer.

As described in the literature, climate change may not affect the amount of sunlight, but may indirectly affect the composition of aerosols. Humidity may be also changed due to an increase in temperature and precipitation intensity. As a consequence, on the basis of a literature review, which described the factors affecting climate change and the efficiency of panels, it was concluded that changes of temperature and humidity as the most significant parameters will be used to conduct the simulation.

PV Array Characteristics

PV module		**Inverter**	
Manufacturer	JA solar	Manufacturer	Huawei Technologies
Model	JAM78-S30-600-MR	Model	SUN2000-215KTL-H3
(Original PVsyst database)		(Custom parameters definition)	
Unit Nom. Power	600 Wp	Unit Nom. Power	200 kWac
Number of PV modules	10833 units	Number of inverters	26 units
Nominal (STC)	6500 kWp	Total power	5200 kWac
Modules	471 Strings x 23 In series	Operating voltage	500-1500 V
At operating cond. (50°C)		Max. power (=>33°C)	215 kWac
Pmpp	5936 kWp	Pnom ratio (DC:AC)	1.25
U mpp	936 V	Power sharing within this inverter	
I mpp	6343 A		
Total PV power		**Total inverter power**	
Nominal (STC)	6500 kWp	Total power	5200 kWac
Total	10833 modules	Number of inverters	26 units
Module area	30282 m²	Pnom ratio	1.25

Figure 22: PV Array Characteristics used for simulation analysis. PVsyst program.

The PVsyst software uses a current-voltage (IV) curve and STC standards within the software to help determine the amount of power a PV system will produce when the environmental factors deviate from the STC conditions. As mentioned earlier, thanks to the curve, is possible to determine how factors affect the amount of energy produced and the peak output power of solar panels and solar photovoltaic systems (Lindholm F. A. et.al, 1979).

In this thesis for the simulation, monocrystalline JAM78-S30-6-MR panels by “JA solar” with a power of 600Wp and temperature coefficient -0.350%/°C will be used. The temperature coefficient means that for every degree above 25°C, the maximum output of the solar panel drops by 0.350%, so for every degree below it increases by 0.350%. Currently, this model of PV panels is one of the most common in the Czech Republic. 10833 PV modules units will be used. The area covered by the panels is 30282m2 (Fig.22).

As for the inverters, 26 inverter units by “Huawei Technologies”, model SUN2000-215KTL-H3, with a total power of 5200kWac and a maximum power of 215 kWac at 33 ºC will be used in the simulation (Fig.22).

5.1 Scenario Analysis

The Intergovernmental Panel on Climate Change (IPCC) released 2021 the Summary of the Physical Science Framework for Policymakers, in which five illustrative scenarios for near-term (2021–2040), medium-term (2041– 2060) and long-term (2081–2100) (IPCC, 2021).

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Table 5: Near-term, mid-term and long-term changes in global temperature, depending on the scenario (IPCC, 2021).

Above is a table of possible scenarios and their most likely range. This thesis will present projections of the impact of temperature rise at the output of photovoltaic installations in the Czech Republic according to three scenarios RCP 4.5, RCP2.6 and RCP 8.5 (Table 5), (Fig.23). For the experiment, the best estimate values will used. To simulate the year 2030 for each scenario, 1.5 temperature changes will be taken based on the table (Table 5).

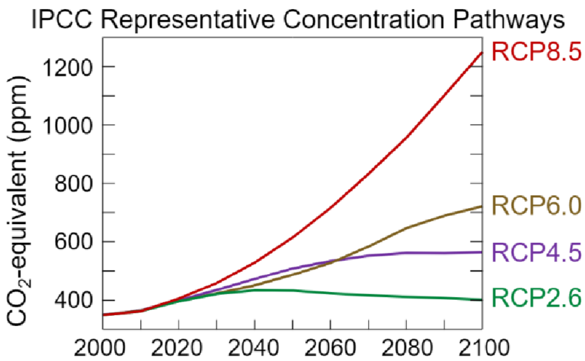

Figure 23: A Representative Concentration Pathway (RCP) shows possible scenarios of Atmospheric CO2 equivalent concentrations of forcing agents from 2000 to 2100 and which was submitted for climate modelling and research for the IPCC Fifth Assessment Report (AR5) in 2014 (IPCC, 2014) http://www.ipcc.ch/report/ar5/

Based on the Representative Concentration Pathways (RCPs) released by the Intergovernmental Panel on Climate Change (IPCC), a table of scenarios has been compiled that will be used in this thesis for simulation. Three scenarios will be considered in each of the four cities in the Czech Republic, which are located in different zones of sun irradiance (Table 6).

	Zlín	České Budějovice	Prague	Karlovy Vary
Scenario 1 RCP 8.5	2.4 °	2.4°	2.4°	2.4°
Scenario 2 RCP 4.5	2.0°	2.0°	2.0°	2.0°
Scenario 3 RCP 2.6	1.7°	1.7°	1.7°	1.7°

Table 6: The best estimate of global temperature increase in ºC based on The Intergovernmental Panel on Climate Change (IPCC) for the period 2041-2060 for four cities in the Czech Republic.

In the table above, can be seen an increase in temperature by 2050 that will be used for simulation in this thesis (Table 6).

5.2 Future solar PV capacity in the Czech Republic

In order to conduct an experiment to simulate the impact of climate change on the production of solar power plants in the Czech Republic, it is necessary to know the forecasts for the development of solar photovoltaic (PV) power by 2030.

The Energy Policy Review of the Czech Republic 2021, released by the International Energy Agency in 2021, states that in the case of the Czech Republic, due to decarbonization, the capacity of renewable sources will increase. By 2030, 3.2 GW of new solar photovoltaic (PV) and wind parks will be added, and natural gas production capacity will also increase. (IEA, 2021b).

The Czech Republic has its own limit on the maximum capacity of solar panels that can be reached. Based on data from the International Energy Agency, the maximum capacity that can be achieved by 2030 is 8 GW of solar PV. In order to provide 15% of energy from renewable energy sources of total production by 2030, the Czech Republic needs to have about 6,5- 7 gigawatts (GW) of solar photovoltaic (PV) capacity. In comparison, in 2019, the energy generated from solar panels, percentage of energy from solar panels was only 0,6 % (IEA, 2021b).

In general, according to the roadmaps published by the IEA (International Energy Agency) and their report "Zero Emissions by 2050: Roadmap for the Global Energy Sector", solar power plants can produce up to 9,000 TWh of energy per year in 2050 globally (IEA, 2021a).

Thus, to conduct an experiment on modelling the impact of climate change on the production of solar power plants in the Czech Republic, it is necessary to use a forecast of 6,5 gigawatts of solar photovoltaic (PV) capacity by 2030.

6 Results

6.1 Results in 2030 with temperature and humidity changes

	Produced Energy (kWh/year)
Results Zlín	7 189 671
Results České Budějovice	7 314 019
Results Prague	6 822 378
Results Karlovy Vary	7 120 844

Table 7: Table of produced energy data with temperature changes in 2030.

A simulation based on 1.5 °C of warming according to all three scenarios and 7% increase in humidity per degree of warming (Manabe & Wetherald, 1967; Allen & Ingram, 2002; Trenberth et al., 2005) showed productivity of 7 189 671 kWh in Zlín, 7 314 019 kWh in České Budějovice, 6 822 378 kWh in Prague and 7 120 844 kWh in Karlovy Vary estimated for the year 2030 (Table 7).

6.2 Scenario 1 (RCP 8.5) results

	Produced Energy (kWh/year)
Results Zlín	7 158 387
Results České Budějovice	7 292 127
Results Prague	6 801 713
Results Karlovy Vary	7 099 444

Table 8: Table of produced energy data with temperature in 2050 according to RCP 8.5 scenario.

A simulation based on RCP 8.5 climate change scenario showed productivity of 7 158 387 kWh in Zlín, 7 292 127 kWh in České Budějovice, 6 801 713 kWh in Prague and 7 099444 kWh in Karlovy Vary in the year of 2030 (Table 8).

Average of loss of energy from 2030 to 2050 (for 20 years) (kWh)	238 103
CO2- equivalent in kg for 2030-2050 energy losses	73 573.67
Average inverter losses energy from 2030 to 2050 (kWh/20 years)	438

Table 9: Table of Average of loss of energy from 2030 to 2050 (for 20 years) in kWh, CO2-equivalent for 2030-2050 energy losses and Average inverter losses from 2030 to 2050 (for 20 years) (in kWh).

The average energy losses under the RCP 8.5 scenario calculated for the period from 2030 to 2050 amounted to 238 103 kWh (Table 9). In terms of emissions equivalent, this will be 73 573.67 kg of CO2 equivalent based on the 0.309 kg/kWh CO2 emission factor according to BEIS's government GHG report (Bonifazi E. et al., 2018). The inverter losses will be 438 kWh per 20 years.

6.3 Scenario 2 (RCP 4.5) results

	Produced Energy (kWh/year)
Results Zlín	7 167 284
Results České Budějovice	7 300 277
Results Prague	6 809 488
Results Karlový Vary	7 107 803

Table 10: Table of produced energy data with temperature changes in 2050 according to RCP 4.5 scenario.

A simulation based on RCP 4.5 climate change scenario showed productivity of 7 167 284 kWh in Zlín, 7 300 277 kWh in České Budějovice, 6 809 488 kWh in Prague and 7 107803 kWh in Karlovy Vary estimated for the year 2030 (Table 10).

Average of loss of energy from 2030 to 2050 (for 20 years) (kWh)	155 150
CO2- equivalent in kg for 2030-2050 energy losses	47 941.35
Average inverter losses energy from 2030 to 2050 (kW/20 years)	365

Table 11: Table of Average of loss of energy from 2030 to 2050 (during 20 years) in kWh according to RCP 4.5 scenario, CO2-equivalent for 2030-2050 energy losses according to RCP 4.5 scenario and c

The average energy losses under the RCP 4.5 scenario calculated for the period from 2030 to 2050 amounted to 155 150 kWh (Table 11). In terms of emissions equivalent, this will be 47 941.35 kg of CO2 equivalent based on the 0.309 kg/kWh CO2 emission factor according to BEIS's government GHG report (Bonifazi E. et al., 2018). The inverter losses will be 365 kWh per 20 years.

6.4 Scenario 3 (RCP 2.6) results

	Produced Energy (kWh/year)
Results Zlín	7 174 578
Results České Budějovice	7 308 697
Results Prague	6 816 933
Results Karlovy Vary	7 116 061

Table 12: Table of produced energy data with temperature changes in 2050 according to RCP 2.6 scenario.

A simulation based on RCP 2.6 climate change scenario showed productivity of 7 174 578 kWh in Zlín, 7 308 697 kWh in České Budějovice, 6 816 933 kWh in Prague and 7 116061 kWh in Karlovy Vary estimated for 2030 (Table 12).

Average of loss of energy from 2030 to 2050 (for 20 years) (kWh)	76 607.5
CO2- equivalent for 2030-2050 energy losses, kg	23 671.7
Average inverter losses energy from 2030 to 2050 (kWh/20 years)	365

Table 13: Table of Average of loss of energy from 2030 to 2050 (for 20 years) in kWh according to RCP 2.6 scenario, CO2-equivalent for 2030-2050 energy losses according to RCP 2.6 scenario and Average inverter losses energy from 2030 to 2050 (kWh/20 years)

The average energy losses under the RCP 2.6 scenario calculated for the period from 2030 to 2050 amounted to 76 607.5 kWh (Table 13). In terms of emissions equivalent, this will be 23 671.7 kg of CO2 equivalent (Table 13) based on the 0.309 kg/kWh CO2 emission factor according to BEIS's government GHG report (Bonifazi E. et al., 2018). The inverter losses will be 365 kWh per 20 years.

6.5 Results with temperature and humidity changes

	Zlín	České Budějovice	Prague	Karlovy Vary
Scenario 1 (RCP 8.5)	7 158 387	7 292 127	6 801 713	7 099 444
Scenario 2 (RCP 4.5)	7 167 284	7 300 277	6 809 488	7 107 803
Scenario 3 (RCP 2.6)	7 174 578	7 308 697	6 816 933	7 116 061

Table 14: Table of produced energy data (in лWh/ year) with temperature and humidity changes in 2050 according to RCP 8.5, RCP 4.5 and RCP 2.6 scenario.

The amount of energy gained from simulations with both temperature and humidity changes and a 7% increase in humidity per degree warming (Manabe & Wetherald, 1967; Allen & Ingram, 2002; Trenberth et al., 2005) showed that solar PV system performance did not change in comparison with the results obtained only with temperature changes (Table 14).

6.6 Summary

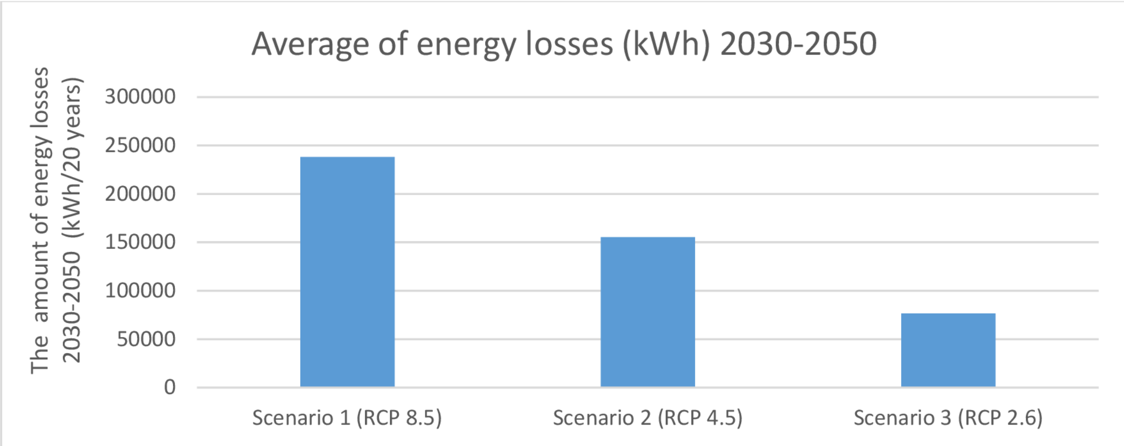

Figure 24: Average of energy losses (in kWh) depending on the climate change scenario: RCP8.5, RCP 4.6, RCP 2.6, 2030.

In the graph above, it could be seen the energy losses depend on the climate change scenario (Fig.24). Based on the graph, it can be concluded that the losses under the RCP 8.5 scenario are the most significant, while under the RCP 2.6 scenario the lowest of them all. The losses under the RCP 4.5 scenario are moderate compared to the other two.

Significant losses under the scenario of RCP 8.5 are due to the fact that this scenario predicts an increase in the average global temperature by 2050 by about 2.4 ° C (IPCC, 2021). As already mentioned in the literary review of the thesis, the high temperatures reduce the energy efficiency of the solar panels. The lower the temperature, the more energy can produce by PV system. Low temperatures with high irradiance are ideal conditions for solar panels (Jaleel, et.al, 2020). In addition, according to "Standard Test Conditions (STC)" also mentioned earlier, for each degree in Celsius with a temperature rise of more than 25°C, the power efficiency will decrease. The panel used in this simulation has a temperature coefficient of -0.350%/°C, meaning that for every degree above 25°C, the maximum output of the solar panel drops by 0.350%.

This means that the higher temperature due to global warming and the influence of climate change, the higher the loss of energy from solar PV panels. It can also be clearly seen in Figure 24, since the experiment conducted in this thesis also confirmed this. Thus, with an increase in the global temperature of 1.7 °C by 2050, according to the RCP2.6 scenario, PV energy losses will be less significant than under RCP 4.5 and RCP 8.5 scenarios.

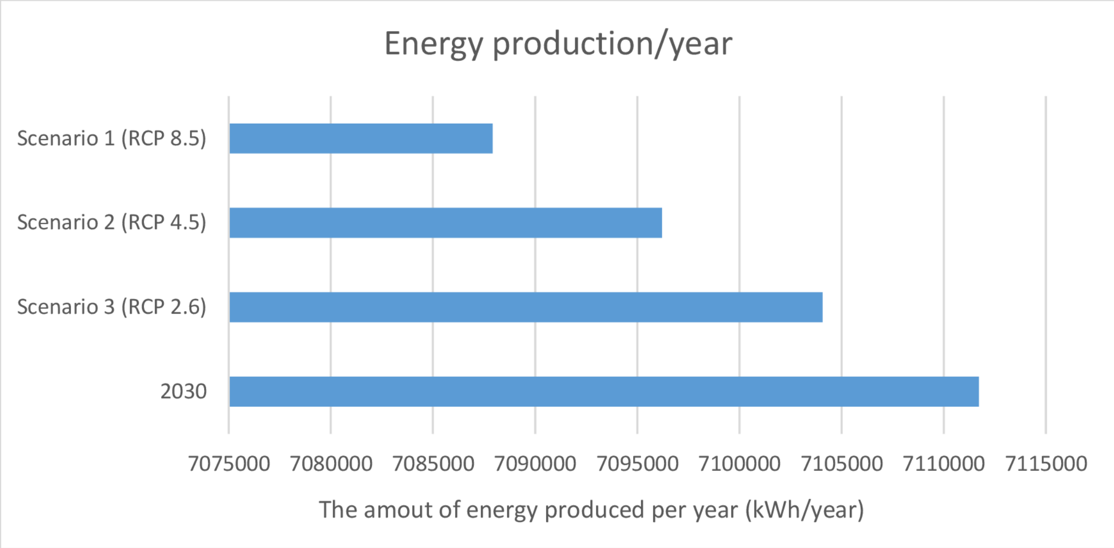

Figure 25: Change in efficiency (in kWh/year) depending on the climate change scenario: RCP8.5, RCP 4.6, RCP 2.6 in 2050 and 2030.

In the graph above, it could be seen the amount of energy per year according to the climate change scenario.

It can be seen that the amount of energy that may be received by 2030 is higher compared to 2050. Under scenario 8.5, the amount of energy produced is minimal (Fig.25).

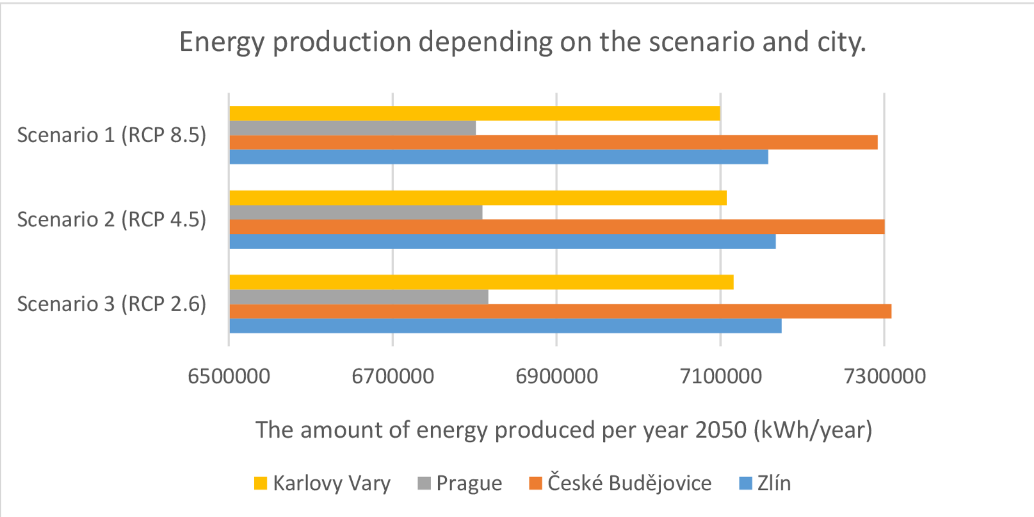

Figure 26: The difference in the amount of energy produced per year in 2050 depends on the scenario and on the city.

The graph above shows energy production in 2050 depending on the scenario and the city where the simulation was carried out. In general, it could be seen that the largest amount of energy is in České Budějovice, and the lowest in Prague. Zlín and Karlový Vary are average relative to other cities, with Zlín having an overall higher energy production than Karlovy Vary (Fig. 26).

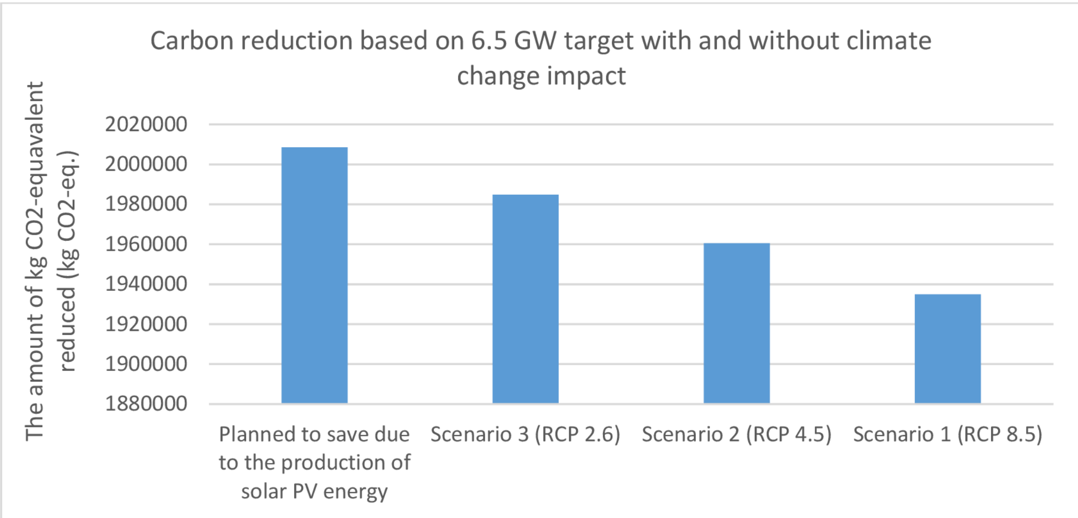

Figure 27: Carbon reduction (CO2 equivalent in kg) with and without climate change impact.

In the graph above, can be seen the amount of CO2 equivalent in kilograms according to the 6.5 GW capacity planned to be avoided by PV solar energy production as a renewable source of energy, as well as the amount of CO2 equivalent in kilograms that will be reduced till 2050 under different climate change scenarios. It can be seen that due to climate change, the amount of CO2 will be higher than planned due to losses that could not be compensated. Moreover, the more significant the consequences of climate change, the less CO2 can be avoided (Fig.27).

	Planned by 2030	Scenario 3 (RCP 2.6)	Scenario 2 (RCP 4.5)	Scenario 1 (RCP 8.5)
Amount of energy (kW)	6 500 000	6 576 608	6 655 150	6 738 103

Table 15: The planned energy capacity (kW) compared to the capacity, taking into account energy production compensation due to climate change.

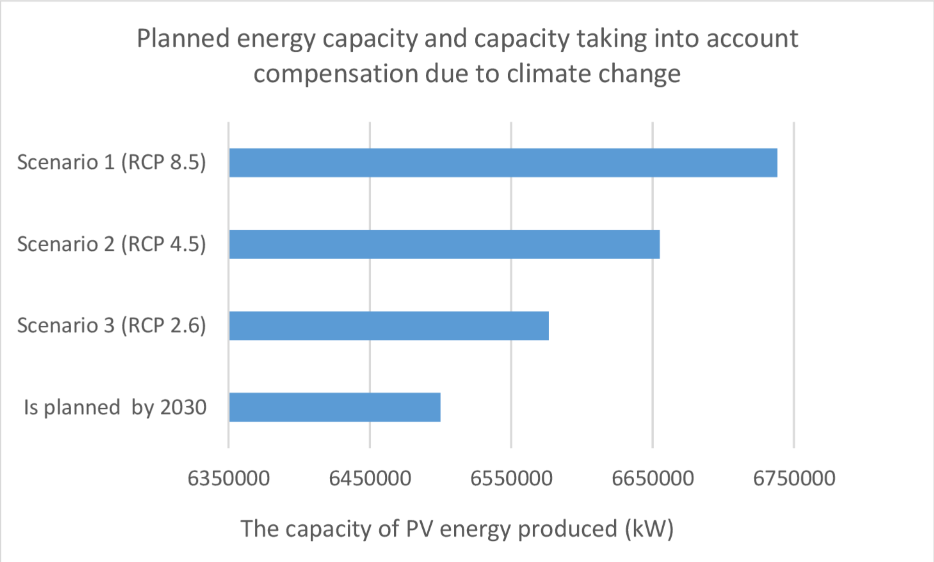

Figure 28: The amount of the planned PV capacity in 2030 in comparison with the amount of PV energy in 2030 that takes into account compensation due to climate change.

In the table and graph 28 above, can be seen a comparison of how much solar PV energy will be supplied in the Czech Republic by 2030 in order to achieve carbon neutrality and how much would be supplied in 2030 to compensate for energy losses and in order to achieve the goal of reducing CO2 emissions equivalent up to the year 2050 to such an extent as to achieve the goal of carbon neutrality in Europe (Table 15, Fig. 28).

Discussion

The main research question of the thesis asked what effect is that climate change will have upon the performance of the photovoltaic systems and what impact will this have on the carbon emission target stated at the beginning of this thesis. Specifically, the aim of the thesis was to determine how much energy in kWh could be lost due to the effects of climate change by 2050. Three climate scenarios were considered, depending on which it was assumed how strongly climate change would affect the capacity of photovoltaic modules and, accordingly, the energy losses that could prevent the achievement of the goal of carbon neutrality by 2050 in Europe. The obtained results predict a decrease in the productivity of photovoltaic energy in the period from 2030 to 2050 (over 20 years) in the Czech Republic by an average of 76 608 kWh under the RCP 2.6 scenario, 155 150 kWh under the RCP 4.5 scenario and 238 103 kWh under the RCP 8.5 scenario. The main energy losses occurred due to PV losses, since, as already mentioned in the literature review of the thesis, when the temperature rises above 25 °C, for each increased degree, the power efficiency will decrease. The panel used in this simulation has a temperature coefficient of -0.350%/°C, meaning that for every degree above 25°C, the maximum output of the solar panel decreased by 0.350%. However, the loss due to the inverter was 438 kWh/20 years according to RCP8.5, 365 kWh for 20 years according to RCP4.5 and 365 kWh according to RCP2.6 from 2030 to 2050. The losses are not significant, which means that climate change will not affect the efficiency of the inverter. This can be explained by the fact that inverters are much more resistant to temperature increase since most inverters derate at about 50-60 °C and they also have a special cooling system that will not let them overheat. The temperature of the solar inverter has no significant effect on its performance (El Boujdaini, Ibrahim, 2021).

In addition, it turned out that in different cities of the Czech Republic, the amount of energy produced in 2050 was different. For example, that the most energy was generated in České Budějovice, and the least in Prague, Zlín and Karlovy Vary are average compared to other cities, with Zlín having a higher total energy production than Karlovy Vary. It was expected that those cities in which irradiation is higher will have high energy production (Zlín and Prague). It can be assumed that the difference is due to the difference in the average annual temperatures in these cities. For example, the average temperature in Prague is 9.8 °C, and the average temperature in České Budějovice is 8.5 °C. As the climate changes, the average annual temperature rises even more. It can be assumed that at lower temperatures are more suitable for solar PV energy production, compared to high temperatures. In general, the relative consistency of the climate between cities in the Czech Republic (not including the surrounding mountain regions) is most likely due to the relatively small size of the country.

Factors that could contribute to climate change and factors that could affect the production efficiency of a photovoltaic system have been considered. These factors were: temperature, humidity, intensity of the sun, the concentration of aerosols and the amount of precipitation. As was described in the literature rereview, climate change may not affect the irradiance, but may indirectly affect the composition of aerosols. Humidity may be also changed due to an increase in temperature and precipitation intensity. As a consequence, on the basis of a literature review, changes in temperature and humidity as the most significant parameters were used to conduct the simulation. A conclusion that can be drawn from the results obtained is that the change in humidity did not affect the results obtained. Possibly, humidity could affect the increase in degradation of the PV system but did not affect the amount of energy in this simulation. As already mentioned in the chapter that discussed in more detail the effect of humidity on the PV system, humidity can lead to degradation and rapid deterioration of solar panels and batteries during their service life. In addition, when moisture enters the system, panel rust and internal corrosion may occur (Segbefia O. K, et al., 2021). The amount of power that a PV system will produce when environmental factors deviate from STC conditions due to climate change was determined using the PVsyst software, which uses a Current-Voltage (IV) curve for prediction. However, as it turned out during the simulation, humidity does not affect the amount of energy produced, but as was mentioned in the literature review, it can incur material losses (corrosion).

The hypothesis that was put forward at the beginning of this thesis was confirmed; that climate change will indeed negatively affect the efficiency of photovoltaic power generation. Energy losses associated with climate change can be a barrier to achieving the goal of carbon neutrality, so it is necessary to take energy loss estimations into account when calculating a plan to reduce direct emissions by switching to renewable energy sources.

The results obtained represent only three climate scenarios and three representative temperature coefficients were used. The RCP 4.5 scenario refers to the medium level of the assumed temperature changes. The lower and upper levels are covered by the RCP2.6 and RCP8.5 scenarios, respectively.

However, there are still uncertainties in the results obtained. The results of this thesis cannot be regarded as absolute, but they are highly probable.

First, the results obtained represent only three climate scenarios out of the seven main scenarios that have been published. Over the next eight decades, there are several scenarios based on many variables, the main one being, of course, emissions. In addition to RCP2.6, RCP 4.5 and RCP8.5, there are also RCP 1.9, RCP 3.4, RCP 6 and RCP 7 scenarios (IPPC, 2021). The level of emissions in the coming decades may have a significant impact on the actual performance of solar panels. The energy losses obtained in the simulation may seem not to be very significant, however, do not forget that the simulation experiment is carried out only in the Czech Republic, only for the period 2030-2050 and only using a capacity of 6.5 gigawatts of solar energy per year per country. If a longer period of time will be taken into account and an experiment on a global scale will be conducted, then the losses would be even more significant. However, even with the results presented in this thesis, one cannot deny the fact that climate change may definitely reduce the amount of energy produced by solar panels, and this fact must be taken into account.

Second, in this thesis, such factors as temperature and humidity were used to run the simulation, but other factors that are also likely to affect the performance of solar energy were not taken into account. Anthropogenic aerosols, changes in precipitation, and the insolation cycles can also affect the efficiency of solar energy.

In addition, only one calendar year in 20-year intervals was simulated each time, and interannual natural variability was not taken into account. For example, there are years when the temperature may deviate from the trend, although this is not due to the fact that climate change has become generally milder. Thus, the modelling of PV energy should be carried out by different research groups around the world.

Third, the loss of PV energy production associated with increased climate variability is likely to be overcome through technical improvements to future PV systems. In particular, it could be expected that future solar installations will be more resistant to temperature changes. In this thesis, emphasis was placed on the fact that the effectiveness of the panels themselves will remain at the current level. It is necessary to make the solar PV system more resilient to the effects of climate change. Moreover, the natural degradation of the panels was not taken into account as this would have affected the performance and it would have been very difficult to detect changes due to climate change rather than degradation. It is predicted that there will be a new generation of solar PV panels may be constructed with materials less susceptible to climate change impacts described in this thesis. Currently, most panels are made from silicon, which tends to reduce the performance of the panels as the temperature rises. Scientists from the University of Wuppertal together and the Institute of Physical Chemistry at the University of Cologne have developed a solar panel made from perovskite and organic absorbers with an efficiency of 24%. These panels have a lower cost than conventional silicon solar cells. Further development of this technology will make solar energy even more sustainable (Brinkmann K. et al., 2022).

Meanwhile, Seraphim Energy Group has introduced new solar modules with an efficiency of 22.45% and a temperature coefficient of -0.30% per degree Celsius, which means that the panels will not only be powerful but also more efficient at every degree Celsius increase in temperature, which means that energy losses due to global warming will be less (Bellini, E., 2023).

Cooling technologies for photovoltaic panels are also actively developing. In the study "Advanced cooling methods by P.V. modules: state of the art" by a group of international researchers from the University Malaysia Pahang, National Institute of Technology. Maulana Azad in India and South Ural State University in Russia, the authors argue that methods such as active water cooling and combined cooling using heat pipes and radiators are quite simple but at the same time have their drawbacks. For example, water-cooling requires a constant supply of cold water in the vicinity of the PV system (Dwivedi P. et al., 2020). This could sometimes be a problem, as photovoltaic plants do not always have water bodies nearby, and the infrastructure for a permanent water supply requires financial investments, so this method can only be useful and economically viable if the source of cold water is not very far from the PV station itself. However, in general, this method is effective and needs to be studied and applied more widely. The authors also concluded that further study of cooling methods should be directed to the study of promising cooling methods such as active water cooling and combined cooling using heat pipes and radiators (Dwivedi P. et al., 2020).

In addition, scientists at South Ural State University in Russia announced that they have patented a new technology to prevent overheating of photovoltaic modules. The proposed method consists of a holographic film based on prismatic concentrators known as "prismacones", which are made of a transparent material containing very small holographic lenses. The authors of the article argue that the new technology significantly reduces the operating temperature of solar panels, including thermal photovoltaic devices, and increases the efficiency of photovoltaic modules even in cloudy weather (Kirpichnikova I.M. et al., 2022).

The carbon equivalent of average losses was also calculated for each scenario for the period from 2030 to 2050. By delivering 6.5 GW of solar PV parks by 2030, the Czech Republic will have an energy loss of CO2-equivalent in kg for 2030-2050 of 23 672 kg CO2-eq. (RCP 2.6), 47 941kg CO2-eq. (RCP 4.5) and 73 574 (RCP 8.5). This means that in order to achieve the goal of reducing CO2 emissions equivalent up to the year 2050 to such an extent as to achieve the goal of carbon neutrality in Europe, it is necessary to compensate for the losses and deliver solar PV energy in the Czech Republic in 2030 more than planned, namely 6.7381025 GW under the RP8.5 scenario, 6.65515 GW under the RPC 4.5 and 6 scenarios, 6.57661 GW under RCP2.6 scenario. The extent to which CO2 emissions will be significant strongly depends on which warming scenario humanity will follow. It is very important to consider when planning roadmaps to achieve the goal of net zero consumption. Which scenario of climate change will be chosen by society and whether we can achieve carbon neutrality based on the Paris Agreement depends only on our actions.

7 Conclusion and contribution of the thesis

According to the literature review, it could be concluded that the main factors that affect climate change and the efficiency of solar PV system are temperature and humidity, while temperature leads to energy losses and humidity lead more to the material losses of the solar PV system.

Thus, climate change has an impact on the performance of solar panels. Three scenarios were used to simulate energy performance in order to predict the possible energy amount decrease of solar PV systems. Using the RCP 2.6 scenario output energy of monocrystalline PV installations will be reduced by an average of 76 608 kWh in the Czech Republic, under the RCP 4.5 scenario the output energy will be reduced by 155 150 kWh and under the RCP 8.5 scenario it will be reduced by 238 103 kWh, using simulation data of the Czech Republic. The Europe's carbon neutrality target by 2050 and the Czech Republic's targets for installing 6,5 GW of solar PV capacity by 2030 are very ambitious, energy losses due to climate change need to be taken into account in order to offset the losses by 2050 and reach targets. Through simulation, it was found that due to climate change and energy losses in the Czech Republic, by 2030, instead of 6.5 gigawatts of solar energy, it would be necessary to supply 6.7 GW of solar energy in order for the Czech Republic to reach its goal of reducing CO2 equivalent emission target by 2050.

The loss of productivity associated with increased climate variability is likely to be overcome through technical improvements and innovations. It is necessary to make the solar PV system more resilient to the effects of climate change. This thesis could be the basis for the development of new-generation panels and the modernization of existing panels to adapt to climate change.

The results obtained in this thesis could be used by climate mitigation planner organizations such as the Intergovernmental Panel on Climate Change (IPPC) in the Czech Republic, the Ministry of the Environment of the Czech Republic and the Czech Hydrometeorological Institute for future forecasts related to the achievement of carbon reduction in the energy sector and for the development of a strategy adaptation to cope with the risks of climate change. Also, this thesis could be the basis for further research in the field of the impact of climate change on renewable energy production. Consideration must be given to climate change and how it will affect energy generation sources. Knowing and understanding what exactly can reduce the efficiency of energy production, one can consider possible risks and try to prevent them in order to maximize the generation capacity and minimize risks and possible negative impacts.

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