On Selecting Optimum Tilt Angle for Solar Photovoltaic Farms

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Abstract- According to the IEA report on Renewables (2016), new solar photovoltaic (PV) capacity grew by 50%, reaching over 74 GW. For the first time, solar PV additions in global energy mix rose faster than any other resource, surpassing the net growth in coal. It has been more than 20 years since the first manufacturers announced and extended guarantee for 25 years for PV panels, which set the market standards that have not been disputed ever since. Most research focuses on the impact of renewable generation, but the operation and maintenance costs, and installation aspects are not generally discussed. Most investors believe that solar projects should be developed to maximize electricity production, and much less attention is paid to lifetime expectancy or the adverse effects of non-optimal tilt angles. The aim of the present paper is to provide a broad review on factors that affect productivity and lifetime expectancy of solar panels. Through an actual construction plan, the correlation among optimal tilt angel and various factors (effect of dust, wind pressure, cooling effect of the wind, warming up, construction cost, temperature, annual takings) were examined. Quantification of both positive and negative effects was also necessary. The authors compare the effects of these seven factors to provide a broader view on the importance of properly determining the tilt angle of solar photovoltaic panels. It is proved that in Europe the installation tilt angle should not exceed 30°.

Keywords solar energy, photovoltaics, optimization, tilt angle.

1. Introduction

In the spring of 1997, Siemens Solar Industries announced that it would extend the guarantee of its solar panels from 10 to 25 years. This event laid down the foundation for today's market standards and started the process of observation and research on the different aspects of this 25-year-long lifecycle by both investors and researchers. However, solar panels' aging process and the resulting reduction in output power are still not an issue in everyday practice today, neither is it a fully explored area. In addition, relatively little information can be accessed publicly about units operating in real-world circumstances. Approximately 85% of the world's installed capacity has been deployed within the past 5 years, so long-term aging tests can dominantly be executed in laboratories.

The price decline of solar panels reached nearly 60% between 2010 and 2013, which gave a huge boost to solar industry, but this has not reduced the concerns about operation in the long term. As a response to the expanding production capacities and favourable financing opportunities, countries whose products have repeatedly fallen short of quality, have also entered the market. Manufacturers typically offer linear power guarantee, which is costly and, in many cases, also difficult to implement. Given that there are at least 500 manufacturers selling their panels in the world, it is reasonable to assume that many of them will not exist in 10 years. It should also be noted that no 25-year guarantee is provided on the supporting structures by the companies. Due to the vulnerability of the plating (zinc), the guarantee usually covers 5-year full and 10-year anti-rusting protection.

For these reasons, assessing the long-term factors is of utmost importance when designing a project, not mentioning the forecast of potential problems. This includes exploring the possible ways of malfunctioning of solar panels, and the impact of certain technical parameters on life expectancy, operation costs and other parameters.

As technology evolves, even the smaller influencing factors of energy efficiency are becoming more important in the further development trends. Also, in the case of existing systems, simultaneous effect of the seemingly insignificant factors can be definitive on the long-term.

Based on the above, even 1-3% decrease in energy efficiency should be investigated, if it is caused by simply manageable reasons.

The current paper surveys three factors: (i) the cooling effect of wind, (ii) slight differences in tilt angle and (iii) dusting to be able to determine their separate and concurrent effect on energy efficiency, but another 4 factors are also touched upon.

This study is organised as follows. Section 2 introduces the standardised background of lifetime testing of solar photovoltaic panels, including case studies for aging. Section 3 provides insight into current industrial practice, while Section 4 gives a summary from the perspective of the factors that affect optimal tilt angles. Conclusions are drawn, and installation suggestions are summarised in Section 5.

2. Standards and Life Expectancy Related Test of Solar Photovoltaic Panels

Here an overview will be provided about the PV panel types, materials used and practices followed with respect to operational experience and extreme weather conditions. Concerning manufacturing, we dominantly refer to European standards, while for test results recent research is also cited. The review aims to reflect on the continuously ongoing renewal of standards as well, which process supports the development of better suiting testing methods and business models.

2.1. Static conditions of the support structure

Basically, the most important part of a PV energy source is the semiconductor panel, but in the case of ground mounted PVs, the support structure can be crucial as well, not only for technical reasons, but also from the point of view of costs according to [1]. Two types of support systems can be differentiated based on structure. The more common solution is when the front and hind legs of the frame are connected by a crossbar and the solar panels are placed on the side-members that run on top of the cross-members. There is, however, a case where the hind legs are connected by the side-member and the front legs by the other side-member. The cross-members, holding the solar panels, are fixed on this bar. The most important advantage of the first type is that it does not require that much accuracy at mounting.

Concerning mechanical load, requirements of the solar cell can be distinguished from those of the support structure like in [2]. In the case of solar cells, it is reasonable to specify the load for economic optimization, because the manufacturer indicates the way in which solar panels can be supported. There are several types of supports; one goes along the long edge of the solar cells, the other along the shorter edge. It is also possible to construct supports from under the solar cells or even a combination of the above is used. It is important to note that in the case of a lying arrangement, usually the intermediate cross-members support two rows of solar cells at the same time, increasing the stress. The IEC 61215 standard contains detailed specifications for the load capacity of solar cells.

The support structures must meet the following standards:

- EN 1990: Eurocode – Fundamentals of the support structure design
- EN 1991: Eurocode 1 – Effects (Loads)
- EN 1993: Eurocode 3 – Design of steel structures

For checking calculations in terms of static load, the weather [3] induced loads must also be considered in addition to the self-weight of structures. In Hungary it can be generally stated that the load of snow represents double stagnation pressure compared to the wind load (0.5-0.6 kN/m^2), but in the case of a panel with steeper inclination angle, the anticipated amount of snow is significantly less on the top. The predominant mechanical stress of the support structures is bending, so the suitability of the profiles used is determined by two factors from static point of view. The first is the elastic modulus resulting from the material of the profile and the second is the moment of area resulting from the material of the profile. During the static design of a support structure of a solar cell unit, these should be taken into consideration in the first place. [4]

For such supporting structures, the most significant load in Hungary is wind load. According to Eurocode, the wind load categories are the following:

- I: Open sea; a lake of at least 5 km in the direction of the wind; evenly flat land area without blockages
- II: Agricultural area with fences, sparsely built farm buildings, houses or trees
- III: Suburban or industrial zones; forests
- IV: Urban zone, where at least 15% of the land surface has buildings with an average height of at least 15 m

Most of the area of Hungary falls into Category II.

Having determined the type of stress and calculated its impact, it is worth deciding which material can be the most cost effective one for support structures. The two most common materials used are aluminium and steel. In Germany, the legs and cross-members are generally made of steel and the rails of side-members are made of aluminium. The elastic modulus for steel is 210 MPa and it is 69 MPa for aluminium. However, the density of steel is 7.83 kg/dm3, while that of aluminium is 2.71 kg/dm3, which makes a significant difference in pricing, as the materials are purchased per weight. Steel profiles are manufactured on bending machines or roller tracks, while aluminium profiles are made by tensile stress, so they can basically create any drawn profile. Thus, in the case of aluminium, the same second moment of area can be reached from a material of less weight. However, the price of aluminium is above 3 EUR/kg, while the cheapest type of steel, S235, can be purchased for 0.5 EUR/kg in large quantities, which does not exceed the 1 EUR/kg price even with the additional costs of galvanization.

Consequently, it is cheaper to manufacture the whole structure of steel, but the side-members are often made of aluminium since aluminium profiles can easily be made of any shape. Rails go along the whole support bar, so it is not necessary to have such high accuracy as with steel. In the case of steel, the material has to be punched in the right places, and there is a high chance of error. For support bars above 10 m of length, it is easy to make mistakes of several centimetres, which is why on-site work is slowing down due to the need of improvisation.

There are three ways of fixing the feet to the ground according to [5]. The most common one is concrete fixing. In this case, the weight of the concrete crown holds against the greatest pulling force, so the concrete must weigh between 700 and 2000 kg. It is also necessary to dig a trench and bring a concrete mixer that can work off-road. If we assume the cost of concrete approx. 30-40 EUR/m3, and its weight as 2.2 t/m3, the limit beyond which it is no longer worth applying is approx. 50 kWp. The second solution, making poles, is almost exclusively used in large photovoltaic parks. A test pole should be driven in to determine how deep the pole may go, so that it would not move out even against the calculated tensile stress. This solution is not very common. The third option is using a ground screw; however, it is advantageous only if the solar panel structure is made of tubes. Additionally, there is quite little operational experience regarding this solution.

2.2. Standardised examination of solar PVs

The accelerated life testing of solar systems is carried out with various aging tests. It is important to mention that although the required tests may be very extensive, in each case they only mean qualification tests, e.g.:

- they consist of aging tests based on reliability indicators;
- they duplicate the errors made in real life using stress tests;
- they apply strict compliance requirements;
- the levels and time periods of the load are limited (so the test can be carried out within reasonable time and for reasonable costs);
- the purpose of the test is to demonstrate that the vast majority of the modules going into commercial use will function properly.

Today's most commonly used standard for such tests is IEC 61215, which is based on the previous JPL Block IV test series but has omitted some tests of that. Such is the (1) dynamic mechanical load test, since its previous definition did not make it compatible for testing large modules and the (2) thermal test of bypass diodes, which did not suit the aims according to international expert opinion. With such antecedents, IEC 61215 became the most important test.

In its second edition, several changes were made:

- the torsional test has been abolished, since no product has failed it;
- the wet leakage current test of IEC 61646 and the thermal test of bypass diode in IEEE 1262 were included;
- the criteria for dielectric resistance and for wet leakage current were harmonized;
- reparatory examination for the UV test has been made;
- it was specified that during 200 thermal test cycles peak-load sized current should pass on the module in order to check the endurance of the solder joints.

It has to be noted that the IEC 61215 tests do have limitations, primarily because they are designed to detect the early malfunctions of each type. Accordingly:

- they are not suitable for recognizing and quantifying wearing mechanisms;
- they are not suitable for handling the specific problems of different climatic conditions and system configurations;
- their aim is not to differentiate between types of short or long life expectancies;
- their aim is not to determine the expected lifetime of the modules.

One of the main topics in solar research is to fill in these gaps. As new measurement and testing methods are published only occasionally [6], significant contribution can be made to the field. In our work, we provide a brief overview that can assist in unfolding the correlation between lifetime, malfunctioning and conditions of deployment and operation regarding solar systems.

2.3. Case studies for aging

Long-term performance monitoring work of several solar photovoltaic plants is reviewed and summarised in [7], providing also a case study for Jordan, and recommendations on optimal cleaning frequency. The referenced PV plants are installed in the Middle East and North Africa, and in many cases the tilt angle of the panels is also included, which provides a valuable basis for examining the correlation between angles and dust accumulation. The experimental setup was installed in Zarqa, Jordan, with a tilt angle of 26° and an installed capacity of 7.98 kWp. By realizing costs of cleaning and electricity tariff, an optimal cleaning frequency can be achieved, which was in the range of 12-15 days for the case study.

The article of [8] gives a novel approach, addressing the production model of solar cells in a holistic way. During their work, they had monitored the output power of a solar photovoltaic system for 5 years, with 20° inclination angle and 2.45 kWp power, installed in Mauritius, and used the IEC 61724:1198 standard for evaluation. During this period, the annual production volume decreased from 3463.8 kWh to

3370.9 kWh, while the utilization factor suffered a downturn from 16.14% to 15.71%. (This decline was not resulting from the stochasticity of the monthly production data, because the changes caused by the sun's orbit were well-followed by the average data.)

[9] present a review on dust accumulation and its effect on solar panel output power. The authors differentiate two types of shading due to soiling; air pollution is considered as soft shading, while solid dust results in hard shading. The first type is found to affect the current of the panel while leaving the voltage unchanged. Effects of the second type are harder to characterise, since they are largely dependent on the proportion of shaded cells. Since properties of the dust and of the local environment influence dust accumulation, this factor should be considered when determining future energy gains from a solar plant.

A similar research is introduced by [10], but in this case more emphasis is put on climatic conditions. Thus, not only dust accumulation, but effects of temperature, humidity and precipitation are all among the factors that are examined in the papers summarised by the authors. They find that existing literature lacks studying the effect of dust types and module cover characteristics on dust accumulation. Multiple mitigation solutions are also presented.

[11] simulate 5 different environmental conditions for the testing of 5 different solar cell raw materials (mono- and multicrystalline, a-Si, CdTe, CIGS). Based on the results, the authors stated that the maximum power output fluctuation was experienced to the greatest extent at the a-Si elements, depending on external conditions (variance of 20.85), while it was observed only to minor extent at monocrystalline types (0.917). Most of the weather based aging effects lead back to constructional failures, reasons (e.g. glass-encapsulated units have higher amount of condensation). It can also be stated that CIGS types perform better under low temperature and humidity conditions, while CdTe types prefer the other end of the spectrum.

[12] summarize the research carried out at Fraunhofer ISE. They discuss the long-term effects of aging as in the previous article, but focus only on the effects of humidity. Water is known to be one of the most important degradation factors for solar cells, as it leads to the hydrolysis of polymeric components, to the corrosion of the glass and metal components. The current testing conditions set by the IEC standard (steam-heat and freezing-melting test) are outdated, primarily because they set quality standards and do not focus on measuring the long-term load capacity. Based on the new method proposed by the authors, solar cells were constructed to resist real environmental conditions. To select the required time of aging, temperature models built on the Arrhenius equation were also used.

[13] discuss that the output power of a PV panel is closely correlated with the temperature conditions that affect it. It is important to note that the temperature of the module is always higher than ambient temperature, since it also absorbs infrared radiation. Due to higher temperature, not only the energy conversion efficiency of the panel, but also its life expectancy deteriorates. Higher temperatures result in higher current, but the voltage will drop, which is unfortunately determining more important factors than the increased current. Beyond a certain level, high temperatures will not only erode the energy conversion efficiency, but also the cell's wiring, the encasing of the enclosure, and the process leads to a significant decrease in lifetime. Also, solar radiation influences solar productivity. There are types of PVs that are less sensitive (thin film) and others that are very sensitive (CIGS, amorphous crystals). overall, it can be concluded that in the long term, high solar radiation significantly influences the lifetime of a PV.

In terms of life expectancy, it is reasonable to calculate for a minimum of 25 to 30 years, so that the investment would return and possibly make profit on the market as well. Based on tests, an annual degradation factor of 0.5% is accepted. In conclusion, the currently used aging tests are not the most reliable ones, better solutions are yet to be developed.

[14] present the operational experience of a 20 kW PV park. An angle of 22.5° was chosen when designing the project, and the park has been subject to significant temperature fluctuations and clearly shows the temperature dependence of the production. The project lasted only for two years; therefore, it did not reveal any data about life expectancy. But, also the short-term effects of temperature result in negative changes in energy conversion efficiency.

3. Current Installation Practice, and Factors Affecting Optimal Tilt Angle

It is a growingly widespread practice that designers/building contractors, when designing solar systems, use computer software to help predict the expected yields, the appropriate orientation, and other parameters. However, it is rarely in the focus of attention that these programs do not necessarily aim to optimize the entire system but only energy gain; in many cases they are solely suitable for theoretical calculations.

Literature also lacks a broader perspective. As it has been shown above, numerous parameters affect the optimal tilting of solar photovoltaic panels. However, literature mostly focuses on a single parameter, energy gain of an installation. A thorough summary of related research activities and results are published by [15], whose paper aims at providing a general picture. A case study for Turkey is presented in [16], where the optimization of tilt angles was carried out using solar radiation data of eight Turkish provinces, but no other parameter was considered relevant. A very similar study is published by [17] for solar collectors deployed in Indian municipalities. Different applications, based on the same physical relations are solar stills, which are used for water distillation and their efficiency is largely affected by tilt angles, as shown in [18]. [19] also consider inclination of solar panels for a proposed wind turbine concept, where the Magnus effect is to be enhanced by the placement of solar panels.

In this section, the authors provide an overview of papers that promise to determine optimal tilting for the panels, but mostly address the aspect of maximising energy generation. In the second part of the section the authors present their recommendation on how other factors should be considered, and what could be considered as an optimal angle. [20] present a similar viewpoint, as they state that the optimal design of photovoltaic plants can be formulated with an objective function, which is able to handle not only energy (like shading, masking and power losses) but economic criteria as well.

[21] present number of different methods used for determining the tilt angle at different locations worldwide. The paper compares the installation practice for 16 locations, and presents 8 closed formulae for determining the correlation between tilt angle and electricity generation. In all examined cases, tilt angles are calculated based on the Sun's position and the latitude of the plant. As it is shown below, these factors are sometimes unreasonably overrepresented in practice. An analogous way of thinking is used in [22], where the estimation of optimal tilt angles is done for Saudi Arabia.

A recent study by [23] presents a complimentary review on previously published papers, focusing on the factors that influence performance of photovoltaic panels. The authors emphasise that current literature does not integrate the effects of all factors, and most papers tend to focus on single issues. The authors, however, do not summarise how these factors depend on tilt angle, and how optimal angles can be determined.

The known literature sources state that any deviation from the ideal orientation and tilt angle results in a decline in output. In Hungary, the online PVGIS database, developed by JRC, is one of the most commonly used software, often considered as a reference. During our research, we examined how much the optimal tilt angles determined by PVGIS are dependent on geographical location, and how the deployments in other countries follow the PVGIS guidelines.

As the available information on solar panels often does not include the inclination angle, the authors have used a database that is freely accessible. From the online database of solar panels (and inverters) deployed by SMA company, European solar power plants with power output above 500 kW were filtered. The 31 power plants combine the practice of 11 countries, with a nominal output of 0.5 to 5.2 MW. For each site, we examined the tilt angles considered as ideal by PVGIS.

Based on the data collected, Figure 1 was created, which shows (depending on the degree of latitude) the actual angles of inclination versus those considered ideal by PVGIS (coloured dots indicate the actual angles and blank ones the ideal ones). It is clearly visible that the latter data line increases almost linearly with latitude, suggesting that the software considers the geographic location as the most important factor. To the contrary, the actual deployment shows that a tilt angle steeper than 30° occurs only rarely and a significant proportion of these cases are implemented in Hungary.

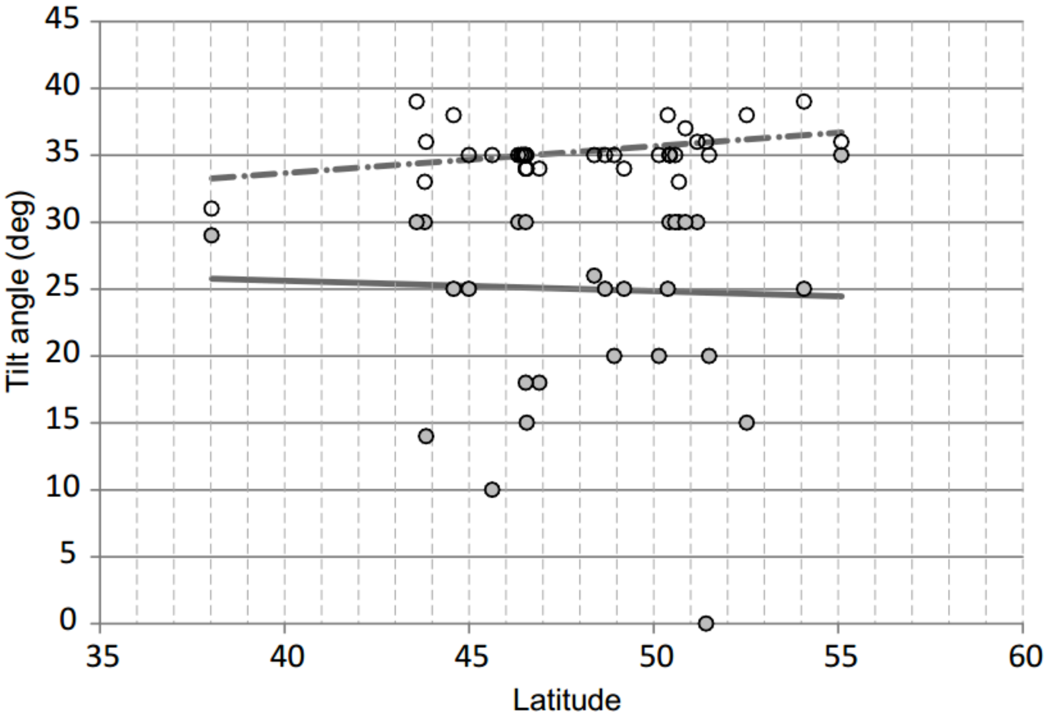

Fig.1. Theoretically optimal (PVGIS) and installed tilt angle of selected European photovoltaic projects. Blank dots represent theoretical, filled dots represent actual tilt angles.

Using the PVGIS database, radiation can be determined for specific areas in case of various tilt angles. Table 1 shows the radiation as a function of the tilt angle, for a location in Hungary. Based on these values, if only a limited installation area is available, it is advantageous to deploy the panels closer to each other with a lower tilt angle, because incoming sun radiation is reduced by only 1-2%. The production of electricity is even less affected by considering inclination-dependent losses of production. For 35° and 25°, the losses caused by low irradiation and temperature changes are 8.9%

and 9.1%, while the losses of reflection are 3.1% and 3%, respectively.

Table 1. Relative solar radiation depending on tilt angle

Tilt angle	Relative solar radiation	Tilt angle	Relative solar radiation
20°	97.61%	31°	99.68%
21°	97.82%	32°	99.80%
22°	98.05%	33°	99.89%
23°	98.28%	34°	99.96%
24°	98.52%	35°	99.99%
25°	98.75%	36°	100.00%
26°	98.97%	37°	99.98%
27°	99.18%	38°	99.93%
28°	99.37%	39°	99.86%
29°	99.54%	40°	99.77%
30°	99.61%	41°	99.65%

When discussing the issue of the optimal tilt angle, the effect of shading cannot be ignored. When the sun stands low (sunrise/sunset, winter time), rows behind each other can be easily overshadowed. Certain line spacing (size Z) should be kept for ensuring the output at a reasonable level. In terms of design practice, it means that on the shortest day of the year (on the winter solstice, 21st December), the rows in the rear should not be shadowed at the time when the sun is at its highest.

To determine line spacing, maximum value of β (the latitude-dependent angle of the Sun's orbit at its highest on 21st December) is needed, which angle is between 18-21°. Connections between line spacing and module heights can be given in closed mathematical form as well, and the formulas can be used to determine the recommended minimum line spacing. Assuming a simplified two-row panel arrangement, with a module height of 3.4 meters and a β of 18-21°, the values shown in Table 2 resulted.

Table 2. Recommended minimum line spacing depending on tilt angle and the Sun's position

Tilt angle	Line spacing [m] (β = 18°)	Line spacing [m] (β = 21°)	Tilt angle	Line spacing [m] (β = 18°)	Line spacing [m] (β = 21°)
20°	6.77	6.22			
21°	6.92	6.35	31°	8.30	7.48
22°	7.07	6.47	32°	8.43	7.58
23°	7.22	6.59	33°	8.55	7.68
24°	7.36	6.71	34°	8.67	7.77
25°	7.50	6.82	35°	8.79	7.87
26°	7.64	6.94	36°	8.90	7.96
27°	7.78	7.05	37°	9.01	8.05
28°	7.91	7.16	38°	9.12	8.13
29°	8.05	7.27	39°	9.23	8.22
30°	8.18	7.37	40°	9.33	8.30

In the following, different physical and environmental impacts are assessed based on their effect on solar photovoltaic gain and the lifetime of the panels. The authors' aim was to present a wide overview of the current state of research and operational experience, thus the list of literature could be expanded, when focusing on a specific issue. To avoid too long reference lists, reviews have been analysed too. A recent and detailed review is presented by [24].

3.1. Effect of temperature and solar radiation

The operational experience of PV parks in the range of 30 kW in deserts may vary slightly from PVs in continental climates, but the most important failure indicators are basically the same, as shown by [25]. The park installed in the Algerian desert has an inclination angle of 17.5°and has a total of 864 modules. The test was carried out in accordance with the IEC 61215 standard. The specialty of the test is that it provides as much as 28 years of operational experience, since the park was installed in 1985. It was proved that the worsening of the degradation index happened mainly due to discoloration and cracks in the protective glass. A module with abrasion-resistant glass has also been tested, but the occurring stresses had almost the same effect in this case as well. The average degradation index corresponded to PV panels of same age and technology in the case of India or Arizona: 1.22 ± 0.04%/year.

[26] present results on EVA (ethylene vinyl acetate polymer), which is one of the most widely used materials for fixing and mechanically protecting PV panels. This polymer is sensitive both to UV radiation and high (>50 °C) temperature. The discoloration or superficial defects on the solar panels are not only optical/aesthetic problems, but also substantially affect the production parameters and the lifetime of the device. One of the reasons for the discoloration is the formation of double covalent bonds within the EVA layer, resulting from UV radiation. In order to avoid this, it is reasonable to incorporate an UV absorbing layer to protect the EVA layer from damage. (The references provide detailed guidance to the possibilities connected to this issue.) With the use of an appropriate UV absorbing layer, handling discoloration and damage to the EVA layer is more effective. Thus, power and efficiency can be maintained close to the nominal value, and the life expectancy of panels also increases.

Competitiveness of PV panels can be increased by improving their efficiency. One of the determining limiting factors is the dust gathered on the surface. [27] review the effects of dust accumulation concerning two factors: as a function of energy production and of life expectancy. Based on the tests, it can be clearly demonstrated that both surface coatings (dust) and degradation due to aging play a role in the worsening of the panel's productiveness.

[28] compare the degradation processes of different PV parks, all operating under extreme conditions in Burkina Faso. The inclination of the tables is 14°. Four types were compared (monocrystalline, two types of polycrystalline and a micro-morph model). The results reflect similar experiences as other sources, since the amorphous type had a

power index of 92%, while the poly- and monocrystalline types had 84% and 80%, respectively. Another result of the test was the determination of temperature dependence. It was not a big surprise that the panels produced less and less energy as the temperature rose, but the difference between the production parameters and the actual measurements (0,48%/°C vs. 0.17%/°C) was more significant. It should also be considered that the measurements took place under extreme conditions in a desert environment. However, this result is very useful: in the case of a large investment (in the range of MWs), as the temperature and climatic conditions have a crucial impact on whether the project is profitable.

[29] examines the behaviour of different PV technologies under climate conditions of Baghdad, Iraq, based on experiments. His results show that amorphous silicon and CIGS modules are a better choice for hot climates due to their lower temperature coefficients.

Cooling of solar panels is a crucial issue, but solutions are usually limited to passive cooling methods (see Section 3.2.). A notable exception is the proposal of [30], where a phase-changing material is placed in a cavity directly in contact with the panels. According to their results, the speed of melting (and thus the efficiency of cooling) is largely affected by the inclination of the panels, as for angles below 45° natural convection is dominating, and conduction of heat is only increasing for steeper panels.

3.2. Effect of wind

Different type of loads of wind affecting the solar panels and the supporting structures have been already mentioned above. In this section, the authors intend to review studies that either discuss the distribution in larger solar parks or show some kind of relationship between wind load and the parameters of the solar cells. Most of the known tests use computer modelling or wind tunnel testing; with the help of the first one, even larger parks can be modelled well, while wind tunnel testing is rather theoretical, and does not provide results that can be readily used for planning.

[31] suggest that the changes in crystal structure resulting from various dynamic effects (wind and other mechanical loads) greatly reduce the efficiency of modern photovoltaic panels. Most design certificates (IEC 61215, IEC 61646), however, are limited to static tests, which are not suitable for describing long-term behaviour, especially for applications where either the site of the installation or the medium is not static. During their research, the authors have developed a test bench that helped to put dynamic and cyclic stresses on solar cells. The amplitude of the load was 7 mm, its frequency ranged from 0 to 40 Hz, which settings are intended to simulate different weather conditions. After carrying out the experiments, they recorded the resulting surface damages (cracks) and the extent to which the panel's peak power was reduced. Based on the results, the first load cycle on the panel reduced the nominal power (from 251.512 W to 248.073 W) by 1.37%, which is below the permitted 3%.

[32] examined the effect of wind-induced vibration on the quality of solar cells as well as on the quality of the voltage they generate, using in- and outdoor measurements. For indoor measurements a specially designed wind tunnel was used, while the outdoor measurements were carried out on the top of a building in the centre of Vienna. The tilt angle of panels was manually set during the measurement to observe different operating states. The measurement results suggest that with respect to the tilt angle, relatively large differences are present in the displacement of the module and the oscillation of the current. The curves prove that the effects have a minimum at 15-20° and above 30° the curves show a significant increase.

[33] use the Reynolds Averaged Navier-Stokes method to examine wind load and the typical wind flow of a solar power plant mounted on the ground. A full-scale three-dimensional model was designed with the OpenFOAM program of the selected 25° inclination angle solar power plant, and four different wind directions (south, southwest, northwest and north) were modelled to test it. For validating numerical modelling, the results were compared to the results of wind tunnel tests. Wind direction has been proved to have a decisive influence on which rows receive greater load. In the case of southern and northern wind, with the exception of the first row, we can see the load rising, but what causes the strongest load at these rows is the winds blowing obliquely. In the latter case, significant vortexes are generated around the corners of the panels in all rows, so the authors strongly recommend addressing this question (similarly to other studies). Since wind tunnel tests have provided the necessary validation, the article concludes that it is worth using numerical modelling for even larger solar farms, for which the 1:1 wind tunnel models can no longer be created.

4. Summary of Factors Affecting Optimal Tilt Angle

The purpose of our work is to comprehensively examine as many impacts as possible and to give a proposal on how to select the inclination angle of the solar panels in order to reduce the negative effects. Figure 2 summarises the effects of different factors, depending on tilt angle. For the sake of clarity, units from the vertical axis have been removed and curves have been rescaled so that all effects can be compared on a single figure. These visual changes did not alter the nature of the curves; thus, dependency and monotony remain the same. For all factors that show dependency on latitude, Hungary was chosen as the fictive installation site. It can be observed that the ideal tilt angle is approx. between 25° and 30° for Hungary. It should be noticed, however, that between 22-25° and between 28°-30° significant changes are seen, thus these ranges should be handled with even more care. Essentially, due to the cumulative effect of the different factors, these are the ranges at which the solar cell is the most sensitive in terms of the change in tilt angle.

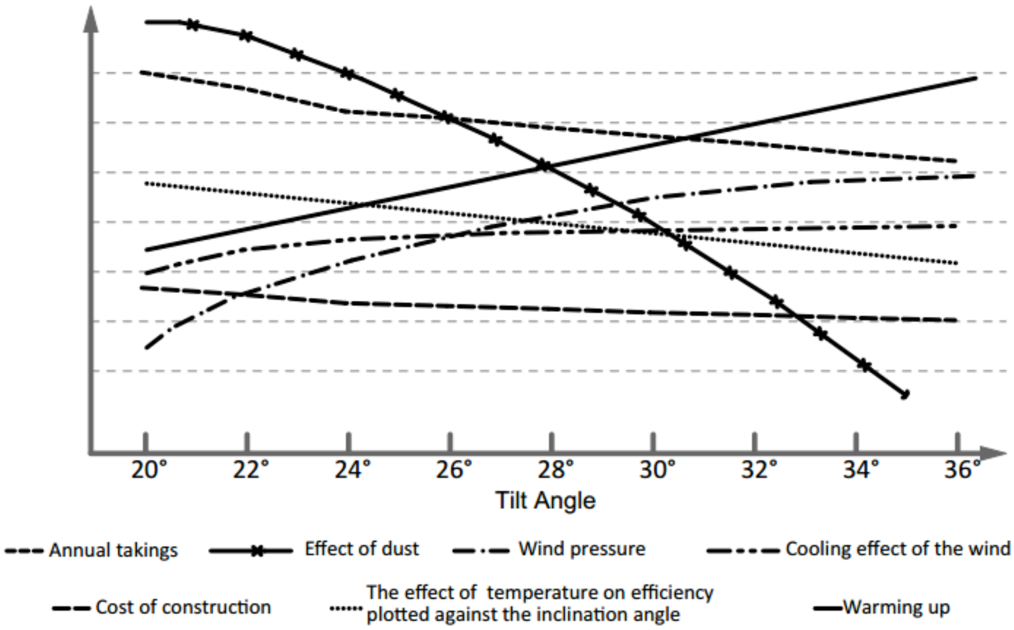

Fig.2. The effects of different factors, depending on tilt angle

To summarise, the following factors have a positive effect as the tilt angle rises:

- By increasing the tilt angle, less dust accumulates on the panels. For angles above 25°, the curve is almost linear.
- The cooling effect of the wind shows a significant increase until 25°, increasing the performance of the panels, while this effect is smaller above 25°.
- Costs of the metal structure decrease with the tilt angle.

The following factors have a negative effect as the tilt angle rises:

- When the angle (and elevation) is greater, wind pressure rises (and reduces life expectancy), but above 30° the rate of this increase is lower.
- Operating temperature increases with solar irradiation, thus as tilt angle is greater, the warming intensifies. This effect is characterised by a linear correlation.
- Considering maximum area utilization, the number of panels that can be installed (and thus the potential energy generation) also decreases with higher angles.

5. Conclusion and Discussion

Several positive and negative impacts have to be considered when installing a solar photovoltaic park. However, the approach of most investors reflects that projects are being developed solely to maximise solar gain and thus to produce as much electricity as possible. Our review has highlighted that several other impacts influence not only the productivity but also lifetime expectancy of the solar panels. Positive and negative effects are both found among these factors, and since their dependency on tilt angle is not always linear. Therefore, determining an optimal tilt angle is a complex task. It can be concluded that the geographical location (more specifically latitude) is an important but not ultimate factor, which is given more importance when using certain software or databases to aid project design and to estimate future electricity production. (It has to be emphasised once again that these programs and databases usually give a fair warning for the user on the limitation of capabilities, but such warnings are too often neglected.) Since slight changes in the tilt angle do not decrease the production significantly, common European installations are in the range between 25° and 30°, considering other influencing parameters as well. The authors have shown that the effect of several factors is smaller above 30° tilt angles and do not decrease productivity beyond a certain level. In contrast, negative impacts that are shortening life expectancy, have much bigger effect on the system in this angle range. It can be concluded that when considering all factors influencing productivity, tilt angles for European installations should not exceed approximately 30°. As existing literature dominantly examines this question from a single point of view (maximising output of the panels), focus should be put onto lifetime evaluations, and better assessment of the effect of multiple factors acting together.

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