SOLAR PV DEVELOPMENT IN NORTH-AFRICA

''Which conditions can be identified that explain the low level of solar PV development in North-African countries with a high solar capturing potential?''

Jasper Dijkema S4500164
Bachelor Project 2022/2023

Content

Abstract

The North-African region has a high theoretical solar capturing potential. However, in practice, this potential remains theoretical, as solar PV development in the region is low. In line with the worlds quest for establishing renewable energy sources in a global spatial-responsible way, solar PV development in this region could be valuable. How is it possible that there is little to no development of solar PV in this region? This research aims to uncover what conditions influence the development of solar PV in North-Africa. Literature and data is being used in order to establish these conditions. After this, the conditions are tested in a case study against a country from the North-African region. It turns out that the established conditions are indeed responsible for the low solar PV development in the region. These conditions that are influencing the solar PV development are a combination of geographical, land-use, governing and financial conditions.

1. Introduction

In recent years, the need for sustainable energy sources has become more evident. Non-renewable energy sources like oil, gas, and, coal have been the primary energy sources across the world for the last hundreds of years (OurWorldInData, 2021). The widespread usage of these non-renewable energy sources has introduced negative consequences for the climate. Non-renewable energy sources are burned in order to generate energy. During this process, additional greenhouse gasses are emitted into the atmosphere. Greenhouse gasses itself are important as they are a part of the 'Greenhouse effect', this effect is responsible for the temperature on earth. Greenhouse gasses trap heat that radiates from the earth's surface (Smithsonian Environmental Research Centre, 2023). Without it, the temperature on earth would become too low (-19 degrees Celsius (EIA, 2022)) and life on earth would not be possible (University of California, 2023). However, due to the extensive burning of non-renewable energy sources, too much greenhouse gasses are entering the atmosphere. This means that more heat is being trapped into the atmosphere, leading to an increased temperature on Earth. An increased temperature on earth has wide ranged consequences within the nature, business and social realms of life. Some noticeable ones are; high-temperature extremes, more droughts and, decreased water quality (European Commission, 2023).

An energy transition is needed in order to mitigate the effects of non-renewable energy sources on the climate. Developing renewable energy sources in order to substitute non-renewable energy sources is a key driver in this transition. Renewable energy sources offer certain advantages in comparison to non-renewable energy sources that make them a suitable option for the future. Renewable energy sources such as wind, solar and, hydro have a significantly lower emissions over their lifecycle compared to oil, gas, and coal (UNECE, 2022). In addition, non-renewable energy sources are finite. This entails that at some point in the future, all non-renewable sources have been used up and are depleted. Renewable energy sources on the other hand, are more available when considering long-term availability (EIA, 2022).

One such renewable energy source is Solar PV. Solar PV is the technology that converts sunlight into electricity. It uses solar panels that consists of PV cells, these cells contain semiconductors that can absorb photons from sunlight and generate it into electrical current (EERE, 2023). The amount of energy from the sun that reaches the earth is estimated to be between 4375–13843 PWh per year (Belyakov, 2019). To put this range in perspective, the total net electricity consumption worldwide in 2021 was 25,343 PWh (Statistica, 2023). Along the abundant energy output of the sun, there is also the longevity of the sun. The sun will continue to provide sunlight for approximately another 5 billion years (Sackmann et al., 1993). The share of electricity produced across the world using solar PV has been rising exponentially in the last decades. As of 2022, solar PV is responsible for 4,52% of electricity produced in the world. In comparison, this number was only 0,15% in 2010 (OurWorldInData, 2022). This indicates that the development of solar PV is on the right track in the context of the global energy transition.

If solar PV were to be developed as the primary energy source for the world in the energy transition, spatial planning would play a crucial role, given that solar panels are physical objects that require space to operate. With an ever increasing population of over 8 billion people, the last couple of decades have seen rising trends in; urbanization, infrastructure, agricultural and industrial development (RIVM, 2000). These developments are taking up increased amounts of space. Just like non-renewable energy sources, space is a finite source. A tool used by spatial planners is 'Land-use planning', this is the process of regulating what land is used for (Baker, 2014). This way, the land is used most optimally and efficient in relation to the intended outcome. In the case of the energy transition, a 'global energy land-use planning' should have the intended outcome to locate renewable energy sources in areas where the renewable energy source can generate electrical current in the most efficient way. Different regions have varying levels of renewable energy resources available. For example, solar capturing potential is higher in regions located near the equator, while wind energy is more abundant in coastal areas or at sea (SolarGIS, 2019)(GlobalWindAtlas, 2023). Area-based renewable energy source development takes advantage of regional strengths and allows for an optimized energy production across the globe.

This would suggest that higher solar PV generation is occurring in areas with a higher solar capturing potential. Thus, when comparing data on countries between their PV potential with data on their solar PV generation, a positive correlation is to be expected. However, when using a map overlay technique to compare these two on a map, there is a particular area of the world where solar PV generation does not match the PV potential. Namely, countries in North-Africa. Despite a high PV potential being available in these countries (SolarGIS, 2019), the energy generated from solar PV is low (OurWorldInData, 2022). This indicates that certain conditions are influencing the development of solar PV installations in North-Africa that prevent an efficient and effective harnessing of the high PV potential in the region. Sampaio & Gonzalez (2017) conducted a systematic literature review on studies that researched solar PV development and found that most studies focus mainly on the technical conditions of solar PV when assessing development. This is where a research-gap exists. Because of the prevalent focus on technical conditions influencing solar PV development in the field of academic research, other conditions influencing solar PV are less well-represented. The aim of this study is to uncover what these conditions are, and how they influence the development of solar PV installations in North-African countries. This introduces the following research question:

''Which conditions can be identified that explain the low level of solar PV development in North-African countries with a high solar capturing potential?''

The paper is organised in the following way. Chapter 2 is the theoretical framework which gives an overview of literature and theories that help answer the research question. Following, chapter 3 is where the methodology is shown, here the research strategy and data collection methods are explained. Chapter 4 analyses the collected data and displays results in a case-specific context. After this chapter, the discussion is located in chapter 5. Lastly, chapter 6 is where conclusions are drawn and suggestions for future research are made.

2. Theoretical Framework

As mentioned in the introduction, Sampaio & Gonzalez (2017) conducted a systematic literature review on studies that researched conditions influencing the development of solar PV. They concluded that the majority of the studies focussed only on technical conditions influencing solar PV development. However, only attributing technical conditions to the low level of solar PV development would be an oversimplification. Sampaio & Gonzalez mention the following research topics that could be further explored in relation to identifying conditions influencing development of solar PV; geographic incentives and barriers, network connection, and economic viability.

2.1 Geographic Incentives and Barriers

In order to establish if solar PV development is suitable in a certain region, the PV potential of a region needs to be established first. This is done by considering geographical incentives and barriers. *'GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY'* (2020) is a rapport created by TheWorldBank in collaboration with SolarGIS. Raster data collected by SolarGIS is used in order to create maps that visualize the PV potential of countries across the world. An important requirement for solar PV to operate is the availability of solar radiation, as without it, solar panels are not able to generate electrical current. Solar radiation refers to the energy released from the sun that reaches the earth in the form of sunshine (EERE, 2023). In this rapport, the term 'Global horizontal irradiation' (GHI) is used to describe solar radiation. GHI is one of the parameters used to calculate PV potential. Theoretical PV potential (TPP) is the level of GHI concentrated in a certain area. In addition to TPP, there is also Practical PV potential (PPP). PPP takes additional factors into account that influence PV potential outside of GHI. By combining the two, an accurate PV potential can be established. Figure 1 illustrates all geographic incentives (TPP) and barriers (PPP) that influence PV potential according to the rapport.

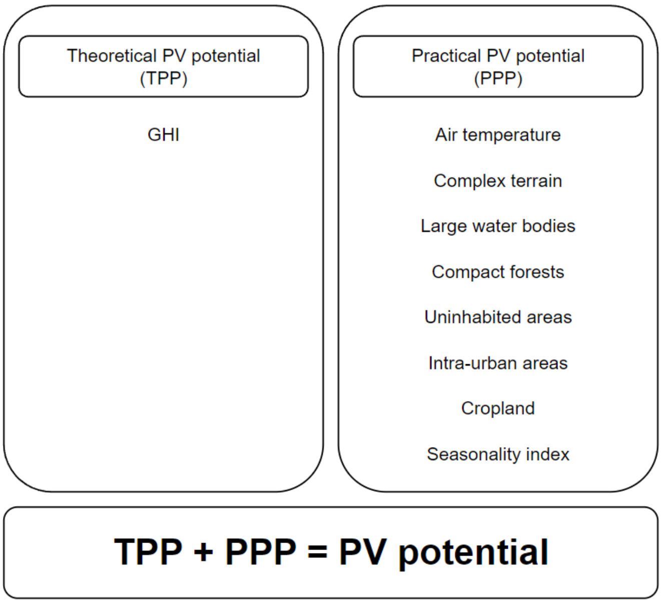


Figure 1: illustration created by author. Input sourced from 'GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY' *(2020).*

Air temperature influences the efficiency of solar panels. Solar panel efficiency rate correlates with the outside air temperature with higher temperatures leading to lower efficiency rates (Dubey et al., 2013). This phenomenon is called ‘temperature coefficient’, in context of solar panels, this refers to the efficiency loss per increase of a degree in temperature (Paudyal & Imenes, 2021). On average, when air temperature reaches 25 degrees Celsius, solar panels experience a -0.5% decrease in efficiency rate per additional degree Celsius (SinoVoltaics, 2016).

The next six PPP conditions indicated in the rapport have shared characteristics, and could be grouped together as they all represent areas in which PPP is negatively influenced by an already existing geographical or land-use situation. Complex terrain refers to terrain with steep elevation levels. These kinds of elevations increase the difficulty of developing solar PV, thus influencing the PPP negatively in these areas. Large water bodies are also influencing PPP as installing solar PV on water is not possible (or very difficult). Floating solar PV is in development. However, this technology is still in an infant developmental stage. So, as of the writing of this study (2023), large water bodies influence PPP in a negative way. Compact forests are forests where the density of tree cover is higher then 50%. These areas are not suitable for solar PV development as GHI is negatively influenced by the tree covers. In addition, uninhabited areas are also not suitable for solar PV development. Uninhabited areas are referred to as remote areas with ‘sparse to no settlements’. These areas are unsuitable due to the lack of infrastructure, workforce, and power consumption. Opposed to uninhabited areas, intra-urban areas also influence PPP in a negative way. Intra-urban areas are where the density of urbanization is higher than 50%. These are included as there is limited space available to develop solar PV in these areas. Croplands make up the last condition that form a barrier for the development of solar PV as solar PV cannot be developed on top of cropland, as the solar PV would block sunshine that is needed for the crops to survive.

The rapport lastly mentions the seasonality index. The seasonality index refers to the ratio between the highest monthly solar yield from GHI and the lowest monthly solar yield from GHI. This basically means the yearly fluctuation between solar yield. During a year, a region might experience periods of high and low solar yield. During the high solar yield periods access electricity cannot be stored (See 2.2), and during low solar yield periods, not enough electricity can be produced to meet demand. The lower the seasonality index rating is, the more stable the PV solar production is throughout the year. A low seasonality index rating has a positive effect on PPP and vice versa.

A study by Okin et al. (2005) mentions the influence of the ‘Aeolian processes’ in environments. The Aeolian process is a process where winds erode and shape the surface of a certain terrain. Particularly prone to this process are desert regions with little to no vegetation. Movement of sand caused by wind is called ‘sand drifting’. Because of this, sand could potentially move up to 9 meters each year (Hereher, 2010). This phenomenon is substantially able to change the surface area. As a result, surface areas in these regions are unstable. Because solar PV requires a stable underground that offers stability and durability to the installation, Aeolian processes negatively affect development of solar PV. In addition, these winds have another adverse effect on solar PV development. A study by Hussain et al. (2017) found that winds in desert regions carry dust particles. These dust particles can potentially land on solar panels and block GHI. This negatively affects the development of solar PV because this leads to a decreased solar panel efficiency rate.

Lastly, a study conducted by Sheikh et al. (2017) investigated the effects of high operating temperature and thermal cycling on solar panel efficiency rate. Thermal cycling, in a geographical context, refers to the air temperature differences that occur during day and night. This negatively affects the development of solar PV because extreme thermal cycling has a negative effect on solar panel efficiency rate and leads to a reduced technical lifespan.

2.2 Network Connection

Sánchez-Lozano et al. (2013) mention the importance of transmission lines in relation to the development of solar PV as solar PV installations must be developed in close range of transmission lines. Network connection refers to the transmission lines that transport electricity from the solar PV installations to the consumer, also known as part of the 'electricity grid'. The electricity grid is a complex network that consists of; generation, transmission, and distribution. This system delivers electricity from areas where electricity is generated to areas where the consumers are located. Before further elaboration on the influence of transmission lines on solar PV development, it is important to understand some characteristics of electricity.

Electricity is a constant flow of electrons that move within a conductor. The form of electricity needs to be changed in order to be able to store it. There are different techniques available that can be used to store electricity. For example; hydroelectric pumping, compressing air, use of flywheels, thermal energy storage, or batteries (EPA, 2022). However, as of 2023, most electricity storage techniques do not have the capacity to store the amount of electricity required that accompanies the size of a national-scale electricity grid (Energuide, 2023). Because of this, grid-storage is not yet possible. This results in a unique situation where demand and supply need to be balanced at all times in order to keep the electricity grid functioning. Additionally, electricity needs to be available and ready at all times (For example, a consumer expects that a light turns on the second a light switch is flicked).

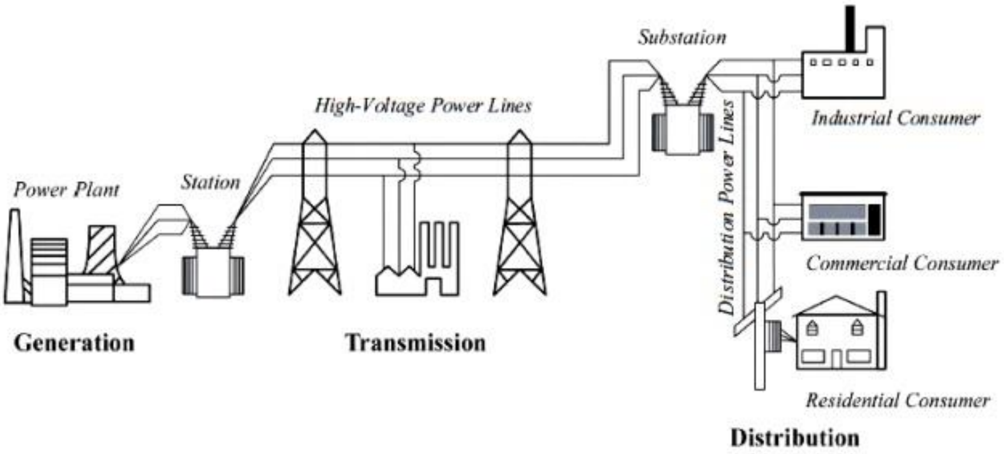


Figure 2: Schematic overview of the electricity grid. Sourced from: Brainkart (2023).

The electricity produced in a powerplant has a certain voltage (indicated with kV and V). In order to reduce transmission losses, it is necessary to increase the voltage. These transmission losses are called 'I2R' losses and are caused by the flow of electricity through resistance (I2RPower, 2023). Increasing the voltage is done by step up transformers that are located in a substation between the generation and transmission system. Higher voltage allows the electricity to be transported over larger distances (P&B, 2020). Afterwards, the voltage is stepped down again in another substation. This way, the electricity is suitable for distribution and consumers.

The availability of transmission lines are important to consider when developing solar PV. It is the only viable option to transport electricity over large distances considering the scale of the electricity grid does not yet allow for electricity storage and the nature of electricity. The availability of already existing transmission lines greatly increases the area where solar PV could be developed.

2.3 Economic Viability

A study conducted by Kaberger (2018) investigated the relationship between costs of energy sources and the corresponding development. Non-renewable energy sources have been traditionally cheaper and more readily available compared to renewable energy sources. These are called substitution energy sources. The cost advantage makes it more difficult for renewable energy sources to compete in the market. When non-renewable energy is cheaper, there is less incentive for businesses and consumers to invest in renewable energy sources. This means that if a region has large access to non-renewable energy sources, the incentive to develop solar PV could decrease.

Hutchinson et al. (2021) mentions that the private sector will most likely finance a large portion of the renewable energy transition. However, they also mention the key role that governments play in this transition. In order for a successful energy transition financed by private investors, governments need to implement regulatory frameworks and policies that incentivize renewable energy development. These frameworks and policies are important to analyse when considering if a region is suitable for solar PV development. This is important because governments can also create a policy environment in which investing in renewables is discouraged or more expensive than investment in non-renewable energy sources. In such a case, solar PV development is negatively affected.

2.4 Conceptual Model

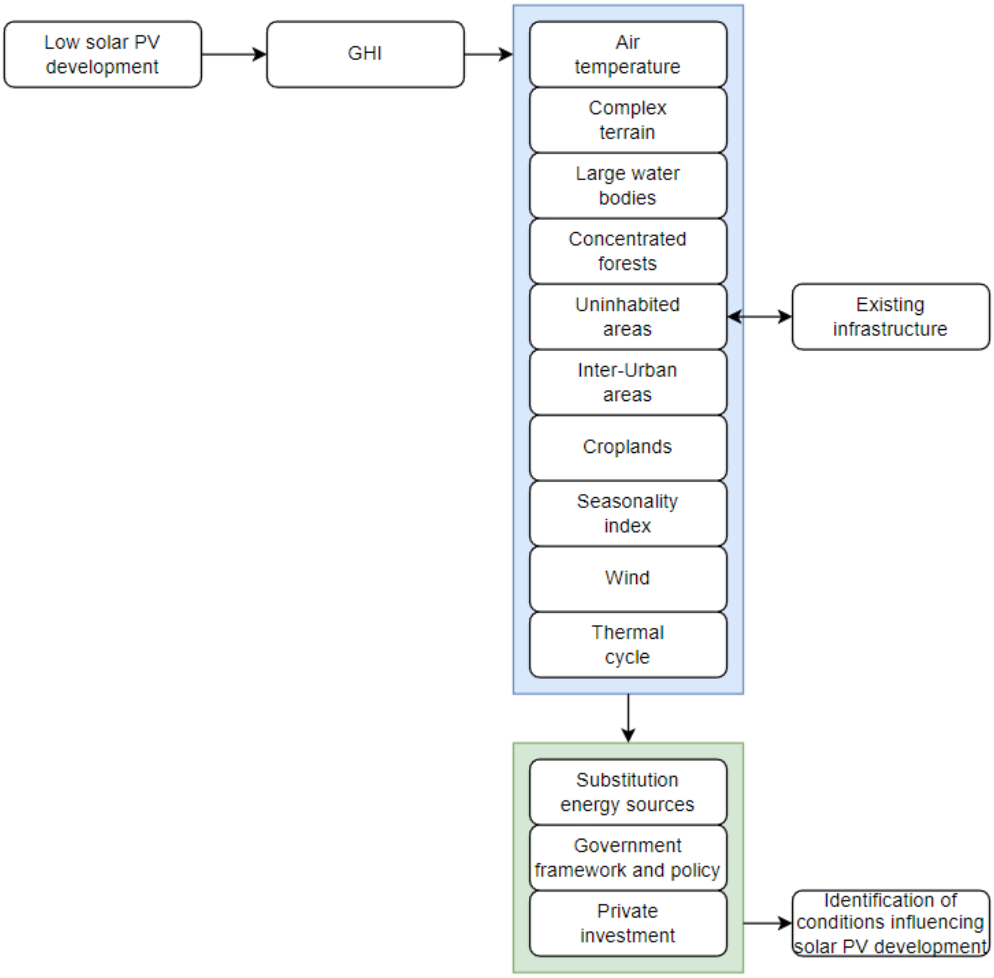


Figure 3: Conceptual model created by author.

3. Methodology

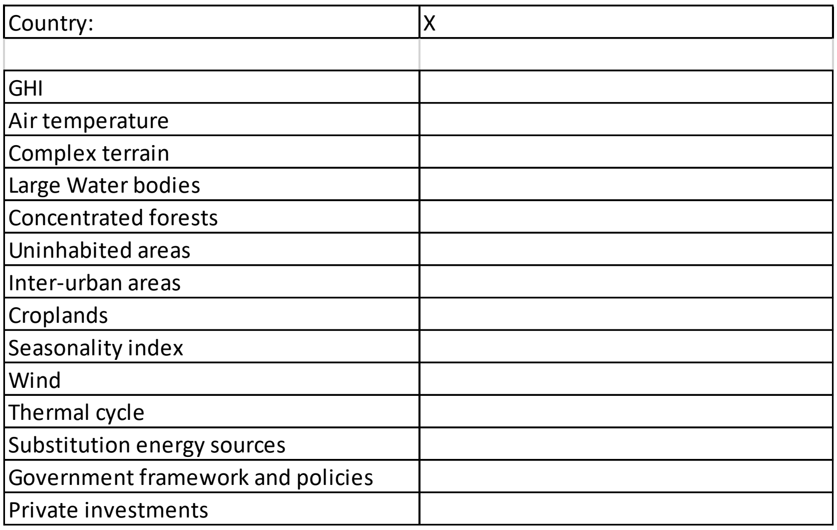
The research strategy that is going to be used in this study is the ‘case study’. A case study is an in-depth, detailed examination of a particular case within a real-world context (Bromley, 1986). What makes the case study suitable for this study is that it manages to captures great details over a broad spectrum of dimensions in a specific context. As can be seen in the theoretical framework, there is quite a large number of conditions that affect solar PV development. Every condition deserves to be adequately covered in the research. In order to achieve this, a case study can make the research smaller whilst remaining accurate in the context of a broad spectrum of research dimensions. It also illustrates a practical example of how the theories and conditions relate to the real-world. In this study, a single case study will be conducted to see if the found theories and conditions apply to a real world example. The case will be a nation within the North-African region, this is elaborated on further in the methodology.

This study utilizes a secondary data collection method, namely the literature review. The literature review was conducted in order to identify academic literature that provide theories and conditions that influence the development of solar PV. Google Scholar was the search tool utilized to identify these articles. In addition, some boundaries were set in order to ensure that the articles were relevant and contained a high degree of validity. The first one being the recency of the published articles. Because the realm of solar PV is changing at a rapid pace, studies can quickly become outdated. In order to combat this, the aim during the search process was to find the most recent articles possible. The limit was set at a maximum of 5 years old. However, this was not a hard limit as some conditions and theories mentioned in the theoretical framework required older literature because recent literature did not have a high relevancy for this study or was insufficient. According to Caon et al. (2020), the number of citations can be a good indicator of research validity. A minimum requirement of 10 citations was set in order to identify articles that have a high degree of validity. Some keywords that were used during the search were: Solar PV development, geographical influence, solar irradiance, solar electricity grid, and government involvement in solar development.

Additional data is required in order to say something about each condition. For example, a certain value is needed in order to say something about the effects of ‘air temperature’. This cannot be accomplished without collecting qualitative and quantitative data. Qualitative data refers to non-numerical information that is descriptive in nature and provides insights into the qualities, characteristics, opinions, and behaviours of individuals or groups (Surendran, 2023). Quantitative data, on the other hand, refers to numerical information that can be measured and analysed statistically. It deals with objective facts, quantities, and measurements (Surendran, 2023). Quantitative data will be collected in order to assert values to the conditions that require numerical input, such as; GHI and, air temperature. Qualitative data will be collected in order to comment on conditions that require a more qualitative input, such as; government frameworks and policies. Large databanks that are trusted in the academic realms such as; OurWorldInData, TheWorldBank and EnergyData are used in order to collect the required quantitative data. For the qualitative data, academic articles are going to be used in order to collect the required qualitative data. The same requirements are in place that were used to ensure relevance and validity for the academic articles in the theoretical framework.

3.1 Results Format

The identified theories and conditions are combined in order to create a 14-point format that can be used in a case-specific context to visualize the data that is collected. This format is going to be used in order to visualize the data. A filled-in version is going to be used in order to analyse which conditions influence the solar PV development in country 'X'. By entering the collected data in the results format, assessment of the conditions can take place. The conditions are going to be labelled as following; positive influence and negative influence. If the conditions are correctly identified, it is expected that most of these will have a negative influence on the development of solar PV. This is the case because at the moment, the North-African region has a low solar PV development. When this process is finished, conclusions can be drawn.



Country:	X
GHI	
Air temperature	
Complex terrain	
Large Water bodies	
Concentrated forests	
Uninhabited areas	
Inter-urban areas	
Croplands	
Seasonality index	
Wind	
Thermal cycle	
Substitution energy sources	
Government framework and policies	
Private investments	

Figure 4: Results format created by author.

3.2 Case Selection Process

As mentioned in the introduction, the focus of this study is on North-African countries that have a high solar capturing potential (PV potential) whilst experiencing a low level of solar PV development. It is difficult to give an exact definition of 'North-Africa' in the context of this study, as the geographic entity North-Africa has no single accepted definition (Britannica, 2023). To avoid confusion, the following countries are considered part of 'North-Africa' for this study; Morocco, Algeria, Tunisia, Libya, Egypt, Mauritania, Senegal, Mali, Niger, Chad, Sudan, and, Burkina Faso.

Figure 5: Map edited by author, base map 'Simple black wireframe outline with national borders, and country name labels on white background' sourced from Alamy Stockphotos (2023).

In order to identify which of these regions has a low solar PV development. Data from OurWorldInData (2022) is collected. The definition of low solar PV development refers to the lowest PV measurement possible in the data, which is a solar PV generation of between 0 TWh and 0.1 TWh. Data visualized in figure 6.

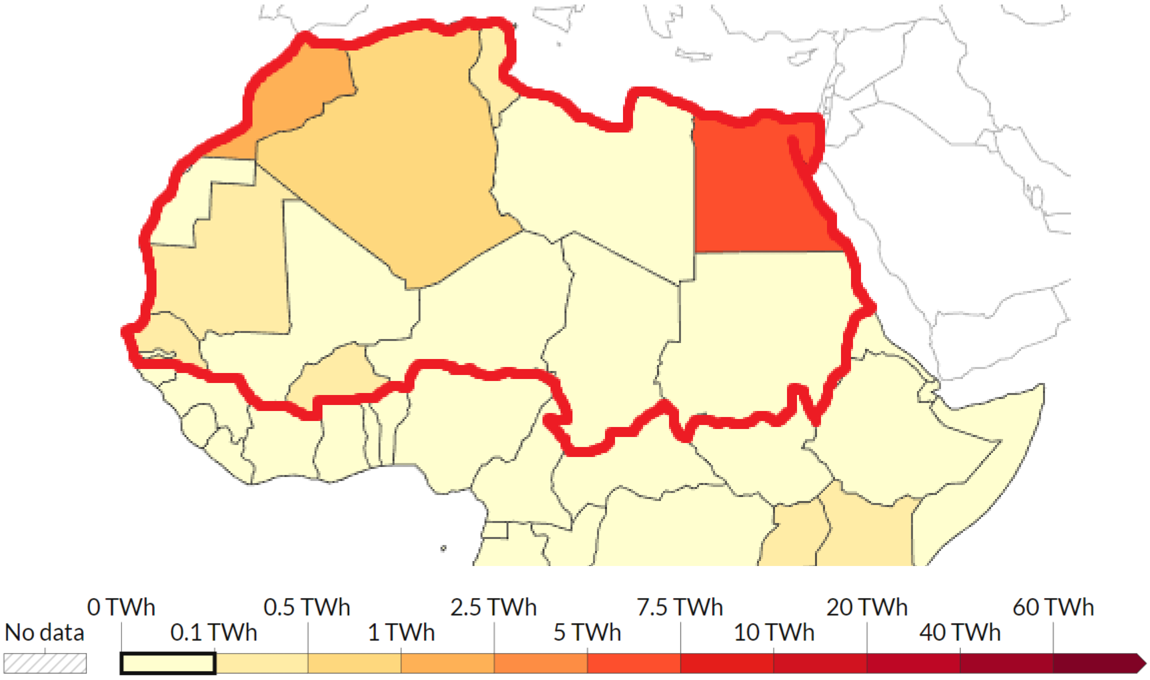


Figure 6: Map edited by author, base map 'Solar power generation, 2022'. Sourced from OurWorldInData (2022).

By using a map-overlaying technique on figure 5 and figure 6, the nations can be identified that are located within the Northern-Africa region that possess a solar PV generation of between 0 and 0.1 TWh. The result of the map-overlaying technique is visualised in figure 7.

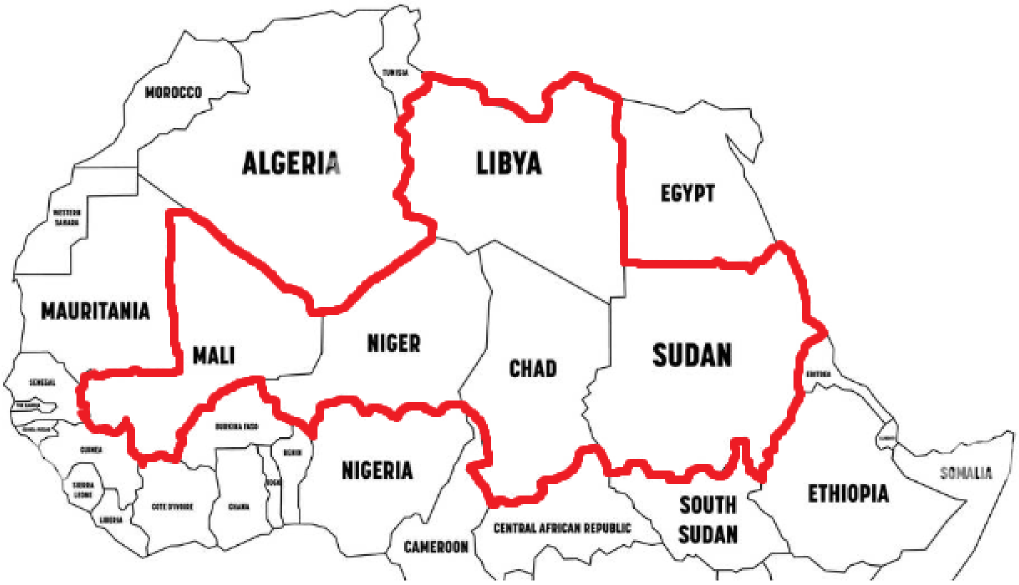


Figure 7: Map edited by author, base map 'Simple black wireframe outline with national borders, and country name labels on white background' sourced from Alamy Stockphotos (2023).

This leaves five countries that can be used for the case study. These are; Libya, Mali, Niger, Chad, and Sudan. From these five countries, the decision is made to identify which of the leftover nations have English as the primary language. This is done because of research motives, as there are more English-language sources available. It also has the additional benefit that the data is easier to comprehend by the researcher. Sudan is the only country that fits this requirement. This means that Sudan is the selected nation that is going to be used for the case study.

4. Results

4.1 GHI in Sudan

GHI in Sudan ranks amongst the highest in the world. According to *'GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY'* (2020), Sudan has the 3rd highest GHI of all countries on earth. Only trailing Namibia and the Republic of Yemen. The GHI is 6,323 kWh/m^2 per day. To put this number into perspective, China, which is a country with a large number of installed solar capacity, has a GHI of 4,127 kWh/m^2 per day. This means that Sudan receives 153% of GHI in comparison to China.

4.2 Air Temperature in Sudan

As mentioned in the theoretical framework, solar panels function most efficiently at 25 degrees Celsius. On average, every degree of Celsius above this reduces the solar panel efficiency rate with -0,5%. Sudan experiences mean annual temperatures between 26 and 32 degrees Celsius (TheWorldBank, 2023). This translates to a solar panel efficiency rate of between 99.5% and 96,5%. In the northern part of the country, mean annual temperatures are even higher. Between 32 and 42 degrees Celsius respectively (NationsEncyclopedia, 2023). This translates to a solar panel efficiency rate of between 96,5% and 91,5%. At first glance, these numbers seem fairly reasonable. However, losing a couple percent of efficiency becomes noticeable on a large scale and timeframe, which applies to solar PV.

4.3 Geography and Land-Use in Sudan

4.3.1 Complex Terrain

Complex terrained referred to areas with steep elevation levels. The solar PV installation process is more difficult in these areas, this decreases solar PV development. In order to locate these areas, a topographic relief map of the region is analysed. Figure 8 shows the relief of Sudan with complex terrain marked in black.

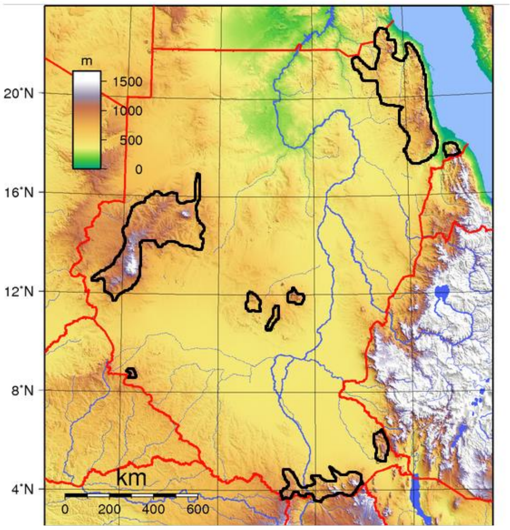


Figure 8: Map edited by author, base map 'Sudan Topography' sourced from Sadalmelik (2007)

4.3.2 Large Water Bodies

Large water bodies are not suitable for solar PV development. In order to locate areas, a topographic map of Sudan is analysed. This shows that there are no large water bodies located in mainland Sudan, only rivers. The following rivers are located in Sudan; The Nile, The White Nile, The Blue Nile, and The Atbarah. These rivers cannot be used for solar PV development. Figure 9 shows the rivers located in Sudan.

Figure 9: Map showing rivers in Sudan, map sourced from Adam et al. (2005).

4.3.3 Concentrated Forests

Concentrated forests are not suitable for solar PV development, as GHI is blocked by vegetation. In order to locate these areas, a vegetation cover map of Sudan is analysed. These show that especially in the south of the country, vegetation is dense. Figure 10 shows the concentrated forest areas marked in black.

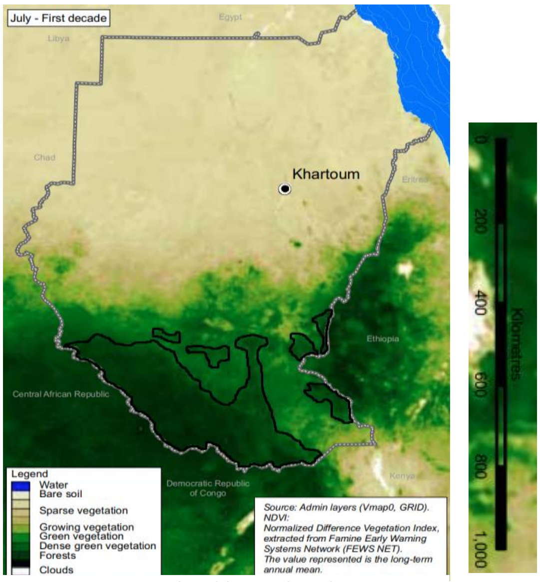
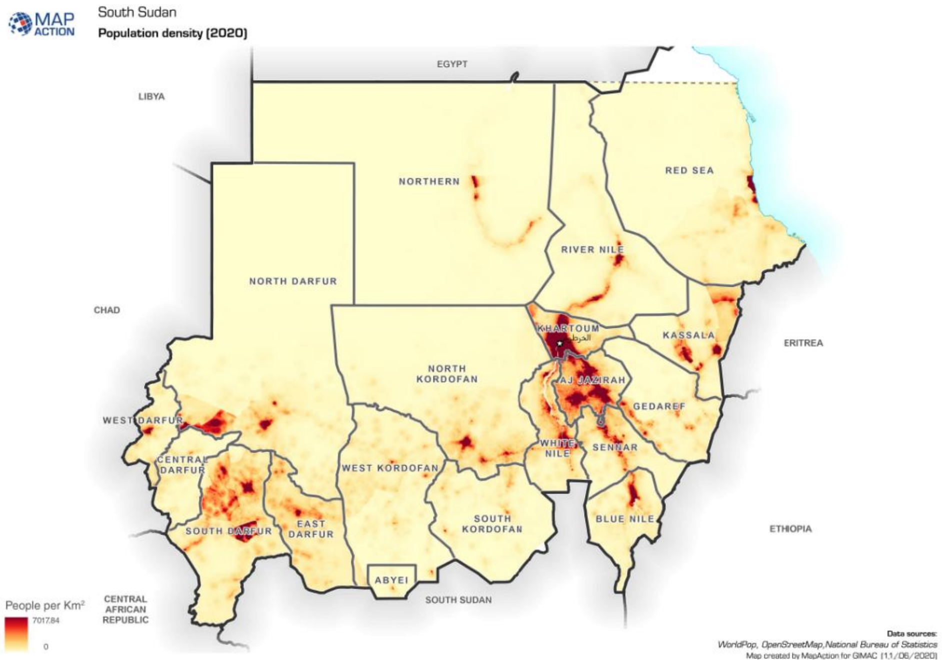


Figure 10: Map edited by author, base map 'Sudan forest cover' sourced from Reliefweb (2007)

4.3.4 Uninhabited Areas and Inter-Urban Areas

Uninhabited areas are referred to as remote areas with ‘sparse to no settlements’. These areas are unsuitable for solar PV development due to the lack of infrastructure, workforce, and power consumption. Intra-urban areas are where the density of urbanization is higher than 50%. In order to locate the areas, a population density map is analysed. Figure 11 shows the areas in Sudan with sparse to no settlements and areas with a high population density.



Data sources:
WorldPop, OpenStreetMap,National Bureau of Statistics
Map created by MapAction for GIMAC (11/06/2020)

Figure 12: Map showing population density in Sudan, map ‘Sudan: Population density’ sourced from ‘ReliefWeb (2020).

4.3.5 Croplands

Croplands cannot be used for solar PV development because the land is already in use and crops require GHI to survive, this means that solar PV cannot be developed on top of this land as GHI will get blocked. The US department of Foreign Agriculture mapped the production of; Cotton, Millet, Peanuts, Sorghum, and Wheat. These 5 production maps have been combined in order to indicate which areas are used for croplands. This is shown in figure 14 with croplands marked in black.

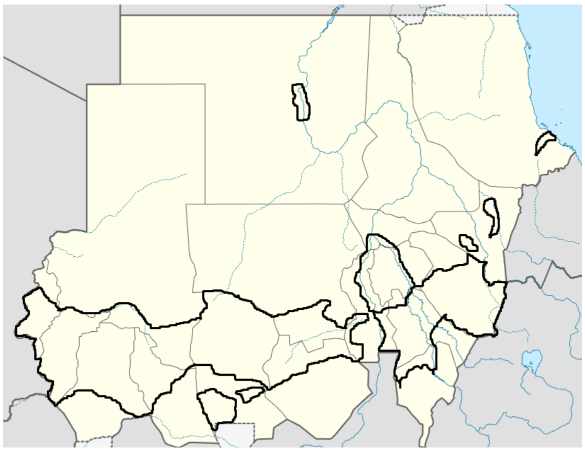


Figure 14: Map created by author, input sourced from USDA (2019)

4.4 Seasonality Index in Sudan

According to *'GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY'* (2020), Sudan has seasonality index of 1,42. The seasonality index refers to the ratio between the highest monthly solar yield from GHI and the lowest monthly solar yield from GHI. A seasonality index of 1 would indicate that there is no difference in highest and lowest monthly solar yield. 1,42 is a good score and indicates that GHI is relatively consistent throughout the year. For example, a country like Germany, with a large number of installed solar capacity, has a seasonality index of 4,37.

4.5 Wind in Sudan

As mentioned in the theoretical framework, wind in an arid-area could lead to build up of dust on solar PV installations. Leading to a decreased solar panel efficiency rate as GHI gets blocked by the sand particles. Wind also leads to the phenomenon of the 'Aeolian process' which also negatively influences the development of solar PV as surface area is not stable enough. Data from 'TheGlobalWindAtlas' (2023) provide mean windspeeds in Sudan that range between 0 and 10 meters from the surface area, these can be analysed. Figure 15 shows areas with high windspeeds are marked in black

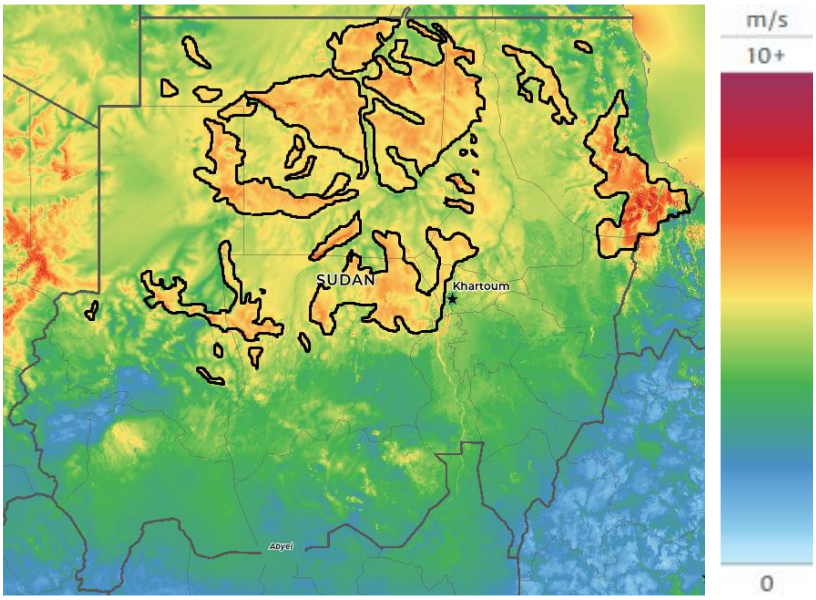


Figure 15: Map edited by author, base map 'Windspeed Sudan 0-10 meter', map sourced from TheGlobalWindAtlas (2023)

4.6 Thermal Cycles in Sudan

During the night, when the sun is not shining, the mean temperature in Sudan drops from 26-32 degrees Celsius to around 21 degrees Celsius (WorldData, 2023). This 5-7 degree Celsius drop is not harmful for solar panels. However, in the northern regions of Sudan, this difference in temperature between day and night is larger. This is due to the fact that this region is part of the Sahara desert. Deserts are known for having extreme temperature differences between day and night (Nicholson, 1998). Solar PV development in the most northern region of Sudan is not advisable, as when components of a solar panel repeatedly expand and contract over time as a result of significant temperature differences between day and night, the lifetime of the solar panel is significantly reduced.

4.7 Infrastructure in Sudan

In order to transport electricity, transmission lines are required. If adequate infrastructure is already available, areas where solar PV could be developed, increases significantly. In order to analyse the transmission lines in Sudan, a map on electrical infrastructure is required (Basheir & Abdelrahman, 2022). Figure 16 shows the electricity grid situation in Sudan. What stands out is that large parts of the country have limited connections to the electricity grid. With HV lines (Lines with 66Kv or higher) only being situated in the East of the country along the rivers and one HV line to connect the south. The entire west side of Sudan lacks medium and high-voltage infrastructure. This reduces the areas that could potentially be used for solar energy installations.

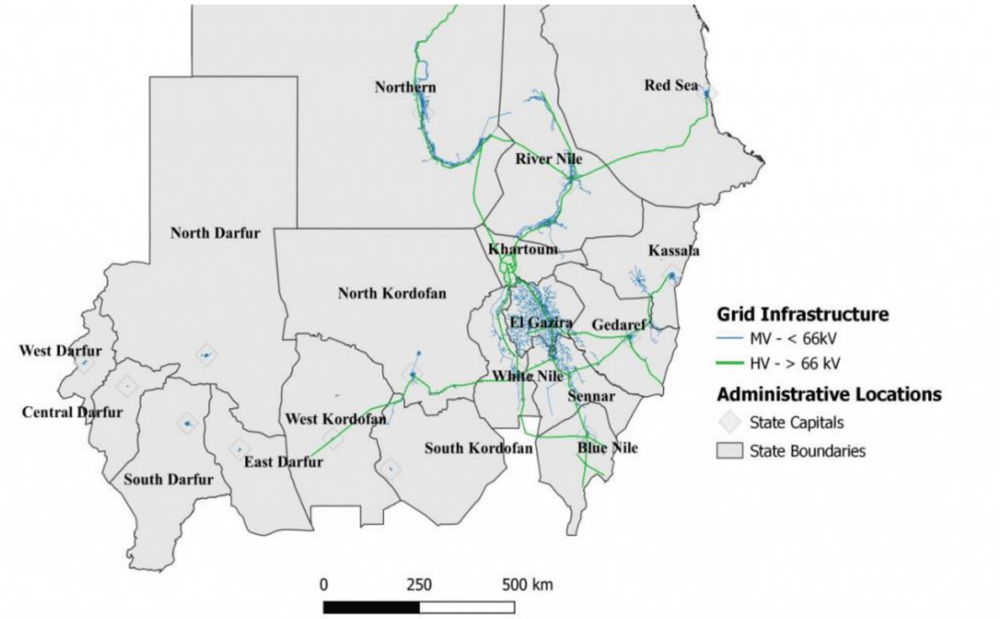


Figure 16: Map of electrical infrastructure, map sourced from 'The electricity crisis in Sudan' (2022).

4.8 Substitution Energy Sources in Sudan

Oil, biofuels, and hydropower are the main energy sources in Sudan (IEA, 2022). WorldData (2023) mentions the following on electricity production in Sudan; *''Sudan can completely be self-sufficient with domestically produced energy. The total production of all electric energy producing facilities is 14 bn kWh, also 148 percent of own requirements. The rest of the domestically produced energy is either exported into other countries or unused. Along with pure consumption, the production, imports and exports play an important role''*. This indicates that Sudan does not experience a shortage in the production of electrical energy. This could potentially result in a situation where the need for solar PV is lower because electricity is already abundant because of substitution energy sources.

4.9 Government Policies in Sudan and Private Investment

Sudan has a experienced a rough political history over the last decades. This is important to consider for the development of solar PV in the country because this effects development priorities and the financial landscape. After two civil wars that originated in 1955, Sudan was split into (North) Sudan and South-Sudan in 2011. Directly after the split in 2011, Sudan lost 75% of its oil fields because these were now located in South-Sudan. This meant that Sudan no longer had the ability to export large amounts of oil (Jadallah, 2019). This led to a decreased import revenue and forced the government to cut down on government spending. This led to a decreased economic situation in the country which negatively influenced the development of solar PV. Because solar PV development requires significant economic investment. In addition, government policies on solar PV are not beneficial in Sudan. Before 2021, a fuel subsidy was in place. This is negatively influenced the development of solar PV because a substation energy source, in this case oil in the form of fuel, was made cheaper (Ndip, 2019).

As for foreign private investment, Sudan was heavily sanctioned by foreign powers. Most notably, the United States and the EU. Even before the country of Sudan was split in 2011, sanctions were already imposed, due to the violent conflicts that had been terrorising the nation for years. The first imposed sanctions were introduced in 1994. The imposed sanctions restricted trade and investment in Sudan. This left Sudan in a disadvantageous position because foreign investment and additional revenue injection became more difficult (Skuld, 2023).

The imposed sanctions are slowly being removed which could offer a positive outlook for the Sudanese economy and thus the development of solar PV in the future because this allows foreign private investors to invest in Sudan. Sudan should aim to attract foreign investments into their country as this could potentially give the Sudanese economy the positive momentum it desperately needs. These foreign investors do not only supply financial improvements but could offer valuable knowledge on technologies and infrastructure that are not yet available in Sudan. The strength of the country lays in its vast amounts of available resources and its strategic location along the Red Sea. Sudan could try to improve the business environment by incentivizing certain sectors such as the renewable energy sector. This can be done by offering low taxes for companies specialised in solar energy or reducing tariffs on solar related goods.

5. Discussion and Conclusion

The main research question of this study is; ''Which conditions can be identified that explain the low level of solar PV development in North-African countries with a high solar capturing potential?''. Appropriate literature and theories were identified in order to discover these conditions. When these were established, the conditions were tested on a case study region in the form of Sudan. This is done to establish if the identified conditions indeed influence the solar PV development and if this explains why the solar PV development is low in the region. By entering the collected data into the results format, the following conclusions can established:

Country:	Sudan
GHI	Positive influence
Air temperature	Negative influence
Complex terrain	Negative influence
Large Water bodies	**No impact**
Concentrated forests	Negative influence
Uninhabited areas	Negative influence
Inter-urban areas	Negative influence
Croplands	Negative influence
Seasonality index	Positive influence
Wind	Negative influence
Thermal cycle	Negative influence
Substitution energy sources	Negative influence
Government framework and policies	Negative influence
Private investments	Negative influence

To conclude, the GHI and the seasonality index are the only conditions that are having a positive effect on solar PV development in Sudan. There are hardly any large water bodies in Sudan, hence the reason to label this condition with 'no impact'. All other identified conditions have a negative effect on solar PV development. Several geographical/land-use conditions such as: air temperature, complex terrain, concentrated forests, uninhabited areas, intra-urban areas, croplands, wind and thermal cycle all have a negative influence on the development of solar PV in Sudan. Additionally, the availability of substitution energy sources, rough governing situations and a bad foreign private investing environment are also not helping. Referring back to the conceptual model, the results show that indeed multiple conditions in the country need to have a positive influence in order to develop solar PV. At the moment, for Sudan, there are too many conditions that are currently exerting a negative influence on solar PV development.

As for this research, a single case study might not be able to give a conclusive generalization as there is only one case, Sudan. There are no cases established to compare against. For future research, it could be useful to compare Sudan to different countries in the region. For example with a country like Morocco, where solar PV development is significantly higher. Establish if significant differences can be found between the identified conditions. In addition, it could also be useful to establish the difference between the severity of the conditions influencing solar PV development. In this study, all conditions have an equal weight. However, I suspect that certain conditions weigh more heavily on the development of solar PV than others.

The research process of this research could also have been better. Next time, I would focus on accurately handing in each research step, on time, as this would steer my research in the right direction at an earlier time stage. Premature vacation, bad time-management, and general procrastination have had a negative impact on the research process. I have learned a lot about the process of developing a project and its accompanying research process during the last few months.

6. References

1. Adam et al., 2005. *Submicroscopic Plasmodium falciparum infections during pregnancy, in an area of Sudan with a low intensity of malaria transmission.* URL: https://www.researchgate.net/publication/7793828_Submicroscopic_Plasmodium_falciparum_infections_during_pregnancy_in_an_area_of_Sudan_with_a_low_intensity_of_malaria_transmission

2. Alamy Stockphotos, 2023. *Political map of Arfica continent. Simple black wireframe outline with national borders, and country name labels on white background. Vector illustration.* URL: https://www.alamy.com/political-map-of-arfica-continent-simple-black-wireframe-outline-with-national-borders-and-country-name-labels-on-white-background-vector-illustration-image360273927.html

3. Baker, 2014. *Encyclopedia of Quality of Life and Well-Being Research.* URL: https://link.springer.com/referencework/10.1007/978-94-007-0753-5

4. Basheir & Abdelrahman, 2022. *The electricity crisis in Sudan.* URL: https://www.printfriendly.com/p/g/qVDdm4

5. Brainkart, 2023. *Basic Electric Power and Structure of Power System.* URL: https://www.brainkart.com/article/Basic-Electric-Power-and-Structure-of-Power-System_12339/

6. Britannica, 2023. *North-Africa*. URL: https://www.britannica.com/place/North-Africa

7. Bromley, 1986. *The case-study method in psychology and related disciplines.* URL: https://www.worldcat.org/nl/title/12235475

8. Caon, 2020. *Citations are a good way to determine the quality of research.* URL: https://link.springer.com/article/10.1007/s13246-020-00941-9

9. Dubey et al., 2013. *Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review.* URL: https://www.sciencedirect.com/science/article/pii/S1876610213000829

10. EERE, 2023. *Solar Photovoltaic Technology Basics*. URL: https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics

11. EERE, 2023. *Solar Radiation Basics*. URL: https://www.energy.gov/eere/solar/solar-radiation-basics

12. EIA, 2022. *Energy and the environment explained.* URL: https://www.eia.gov/energyexplained/energy-and-the-environment/greenhouse-gases.php#:~:text=When%20sunlight%20strikes%20the%20earth's,global%20warming%20and%20climate%20change.

13. EIA, 2022. *What is energy?* URL: https://www.eia.gov/energyexplained/what-is-energy/sources-of-energy.php#:~:text=There%20are%20five%20major%20renewable%20energy%20sources&text=Solar%20energy%20from%20the%20sun,Biomass%20from%20plants

14. Energuide, 2023. *How to store electricity?* URL: https://www.energuide.be/en/questions-answers/how-to-store-electricity/231/#:~:text=Electrical%20energy%20is%20a%20constant,electricity%20when%20you%20need%20it.

15. EPA, 2022. *Electricity Storage*. URL: https://www.epa.gov/energy/electricity-storage

16. European Commission, 2023. *Consequences of climate change* URL: https://climate.ec.europa.eu/climate-change/consequences-climate-change_en#:~:text=Higher%20temperatures%20can%20cause%20increased,geographical%20distribution%20of%20climate%20zones.

17. GlobalWindAtlas, 2023. *GLOBAL WIND ATLAS.* URL: https://globalwindatlas.info/en

18. Hereher, 2010. *Sand movement patterns in the Western Desert of Egypt: An environmental concern.* URL: https://www.researchgate.net/publication/225392798_Sand_movement_patterns_in_the_Western_Desert_of_Egypt_An_environmental_concern

19. Hussain et al., 2017. *An experimental study on effect of dust on power loss in solar photovoltaic module.* URL: https://sustainenergyres.springeropen.com/articles/10.1186/s40807-017-0043-y

20. Hutchinson et al., 2021. *Unlocking a Renewable Energy Future: How Government Action Can Drive Private Investment.* URL: https://www.wri.org/research/unlocking-renewable-energy-future-how-government-action-can-drive-private-investment

21. IEA, 2022. *Sudan.* URL: https://www.iea.org/countries/sudan

22. I2RPower, 2023. *Electrical & Metal Processing Glossary.* URL: https://www.i2rpower.com/engineering/glossary/

23. Jadallah, 2019. *The Dark Side of Sudan's Oil.* URL: https://earthjournalism.net/stories/the-dark-side-of-sudans-oil

24. Kaberger, 2018. *Progress of renewable electricity replacing fossil fuels.* URL: https://www.sciencedirect.com/science/article/pii/S2096511718300069

25. NationsEncyclopedia, 2023. *Sudan – Climate.* URL: https://www.nationsencyclopedia.com/Africa/Sudan-CLIMATE.html#:~:text=Sudan%20%2D%20Climate,months%20are%20May%20and%20June.

26. Ndip, 2019. *Fuel Subsidy Reform in Sudan.* URL: https://elibrary.worldbank.org/doi/abs/10.1596/36100

27. Nicholson, 1998. *Deserts.* URL: https://link.springer.com/referenceworkentry/10.1007/1-4020-4497-6_61

28. Nikolay Belyakov, 2019. *Sustainable Power Generation.* URL: https://www.sciencedirect.com/book/9780128170120/sustainable-power-generation

29. Okin et al., 2005. *Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments.* URL: https://www.sciencedirect.com/science/article/pii/S014019630500162X

30. OurWorldIndata, 2021. *How have the world’s energy sources changed over the last two centuries?* URL: https://ourworldindata.org/global-energy-200-years

31. OurWorldInData, 2022. *Share of electricity production from solar.* URL: https://ourworldindata.org/grapher/share-electricity-solar?tab=chart&country=~OWID_WRL

32. OurWorldInData, 2022. *Solar power generation, 2022.* URL: https://ourworldindata.org/grapher/solar-energy-consumption

33. P&B, 2020. *Basics of an electrical power transmission system.* URL: https://www.power-and-beyond.com/basics-of-an-electrical-power-transmission-system-a-9430aaa14780c59e275d80ca9e4605f1/

34. Paudyal & Imenes, 2021. *Investigation of temperature coefficients of PV modules through field measured data.* URL: https://www.sciencedirect.com/science/article/pii/S0038092X21004837

35. ReliefWeb, 2007. *Sudan forest cover.* URL: https://reliefweb.int/map/sudan/sudan-forest-cover

36. ReliefWeb, 2020. *Sudan: Population density (2020).* URL: https://reliefweb.int/map/sudan/sudan-population-density-2020

37. RIVM, 2000. *Urbanisation, Industrialisation, and Sutainable Development.* URL: https://www.pbl.nl/sites/default/files/downloads/402001015.pdf

38. Sackmann et al., 1993. *Our Sun. III. Present and Future.* URL: https://ui.adsabs.harvard.edu/abs/1993ApJ...418..457S/abstract

39. Sadalmelik, 2007. *Sudan Topography.* URL: https://en.m.wikipedia.org/wiki/File:Sudan_Topography.png

40. Sampaio & Gonzalez, 2017. *Photovoltaic solar energy: Conceptual framework.* URL: https://www.sciencedirect.com/science/article/pii/S1364032117303076

41. Sanchez-Lozano et al., 2013. *Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain.* URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032113001780

42. Sheikh et al., 2017. *Effects of High Temperature and Thermal Cycling on the Performance of Perovskite Solar Cells: Acceleration of Charge Recombination and Deterioration of Charge Extraction.* URL: https://pubs.acs.org/doi/10.1021/acsami.7b11250

43. SinoVoltaics, 2016. *Measuring the temperature coefficient of a PV module.* URL: https://sinovoltaics.com/solar-basics/measuring-the-temperature-coefficients-of-a-pv-module/

44. Skuld, 2023. *INSIGHT: Sudan Sanctions.* URL: https://www.skuld.com/topics/legal/sanctions/sudan/insight-sudan-sanctions/

45. Smithsonian Environmental Research Centre, 2023. *Greenhouse Gases: Too Much of a Good Thing.* URL: https://forces.si.edu/atmosphere/02_04_07.html

46. SolarGIS, 2019. *PHOTOVOLTAIC POWER POTENTIAL.* URL: https://solargis.com/maps-and-gis-data/download/world

47. Statista, 2023. *Net electricity consumption worldwide in select years from 1980 to 2021.* URL: https://www.statista.com/statistics/280704/world-power-consumption/

48. Surendran, 2023. *Qualitative Data – Definition, Types, Analysis and Examples.* URL: https://www.questionpro.com/blog/qualitative-data/

49. Surendran, 2023. *Quantitative Data: What It Is, Types & Examples.* URL: https://www.questionpro.com/blog/quantitative-data/

50. TheWorldBank, 2023. *Current Climate Sudan.* URL: https://climateknowledgeportal.worldbank.org/country/sudan/climate-data-historical#:~:text=Sudan%20experiences%20mean%20annual%20temperatures,between%20northern%20and%20southern%20regions.

51. TheWorldBank, 2020. *GLOBAL PHOTOVOLTAIC POWER POTENTIAL BY COUNTRY.* URL: https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf

52. UNECE, 2022. *Life Cycle Assessment of Electricity Generation Options*. URL: https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options

53. University of California, 2023. *Greenhouse effect.* URL: https://ugc.berkeley.edu/background-content/greenhouse-effect/

54. USDA, 2019. *Sudan Production.* URL: https://ipad.fas.usda.gov/countrysummary/default.aspx?id=SU

55. WorldData, 2023. *Energy consumption in Sudan.* URL: https://www.worlddata.info/africa/sudan/energy-consumption.php

56. WorldData, 2023.*The climate in Sudan.* URL: https://www.worlddata.info/africa/sudan/climate.php