Solar energy

20 TW in the Sahara desert: dream or reality?

S.V. Vasilev (2328135) & D.H.L. Frank (2243865) &
R.T. Verburg(2317966)

University of Twente, Faculty of Engineering Technology
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1 Introduction

With solar energy becoming a more and more common and a financially feasible method of generating electricity, along with it being renewable and sustainable, there is no doubt that it will be an important part of the future's power generation. There is an enormous amount of solar power being provided to the earth constantly, more than 10 000 times the total energy consumption of the entire planet [1]. This begs the question; is it possible to satisfy the global electricity demand with solar energy exclusively? This paper will attempt to answer this question, while narrowing the scope to installation of solar energy collection devices in the Sahara desert. The reason the Sahara desert is to be evaluated is due to the large amounts of solar irradiance it receives as well as the vast amounts of space available. Furthermore, a goal of 20 TW_{peak} to produce is defined, in order to future-proof the potential solution. Subjects covered in the paper include investigation into the location, different forms of electricity generation, the transportation of energy, political issues, as well as the expected environmental impact.

2 Location and other considerations

To reach the goal of 20 TW of solar energy, the chosen location of the considered solar field is vital to the possible success or failure of the entire project. Research by the World Banks' ESMAP group [2] has shown that countries located in the Middle East, North Africa and Sub-Saharan Africa logically exhibit the most Global Horizontal Irradiation (GHI), as can be seen in figure 1.

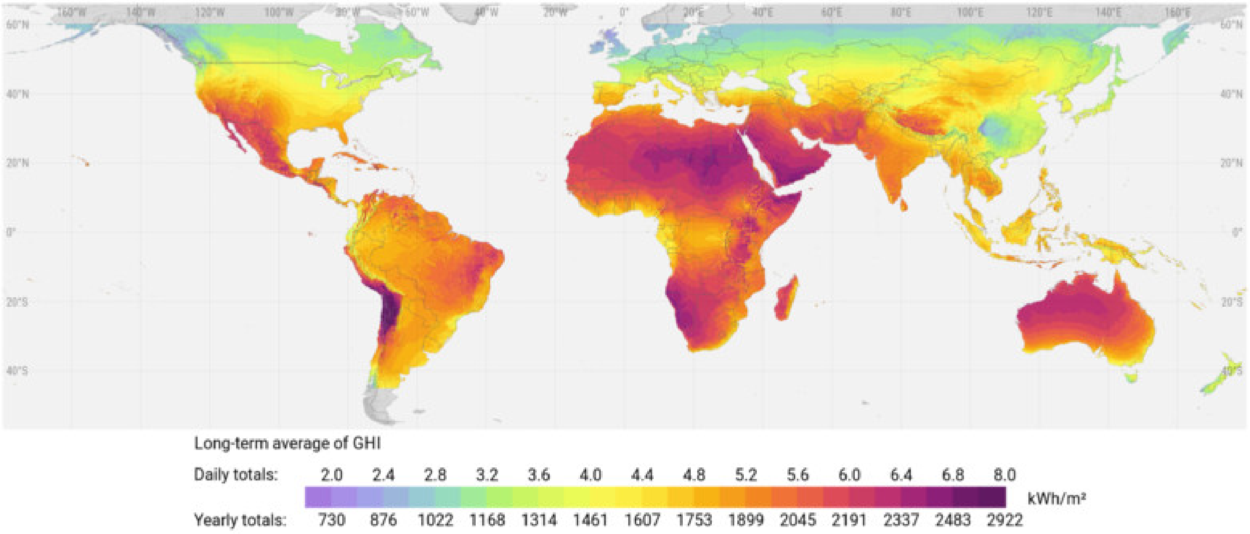

Figure 1: A colored map of the world showing the GHI of each country in kWh/m^2 [2]

ESMAP's research has shown that these countries also have a high potential for a solar field project. Factors such as Human Development index, access and cost of electricity and location based factors such as elevation were used to evaluate many regions based on 3 potential principles:

1. Theoretical solar PV potential, the overall solar irradiation of a country or region, best described by GHI.

2. Practical solar PV potential, shown by the paper as PVOUT, which describes the predicted output of a typical solar field in these regions, meaning it includes limiting factors such as shading, terrain, air temperature, and more.
3. Economic PV potential, which is shown by the Levelized Cost of Electricity, to show how much it would cost to produce a unit of energy, taking into account average expenditure when building a solar field in these countries.

These potentials and other important factors are all summarised in their individual country fact sheets, also produced by ESMAP [2], which is an excellent way to compare the most feasible countries for this project. This also means that it might be necessary for the solar project to span across borders due to the sheer size of the project, which might raise political conflict from the sharing countries, as will be discussed later on in this report.

Based on individual factsheets, a few countries show the most promise: Egypt, Mauritania, Algeria and Libya. In the individual factsheets of these countries [3][4][5][6], areas which are suitable for solar project installations are already identified through 3 levels, as can be seen in figures 3 through 6. Level 0 areas (in grey) indicate areas suitable for solar projects, as level 1 and 2 are areas close to cities and villages, as well as rough terrain and areas protected by conservation laws [2]. However, these large regions largely consists of desert area, which means there is a lot of solar irradiation, but also means that large amounts of work would need to be done to make these areas suitable for installation. Examples are the transport of construction equipment (roads), availability of power (electricity lines) and access to water (pipelines). This would all add to the costs of the entire project.

3 PV

Bhadla Solar Park is the largest PV plant in the world, located in India. It has a capacity of 2.245 GW, spanning 57 km^2. The total capital cost was about $1.4 billion, although it has been built in stages over the course of about 4 years. This PV plant has helped to make solar energy significantly more affordable than coal energy in India [7]. From the capacity and area of Bhadla Solar Park, an effective spacial efficiency of approximately 39.4 $\frac{MW}{km^2}$ can be derived. Thus it can be calculated that approximately 507 614 km^2 are required to reach the goal of 20 TW, if similar plants to Bhadla Solar Park are built. This represents an area the size of 5.5% of the Sahara desert. Important to note is that energy would only be produced during the day, necessitating huge energy storage solutions if electricity is also to be supplied at night.

3.1 Dust accumulation

For photovoltaic cells there are huge losses associated with dust/sand being collected on them in desert environments. A study [8] measured the losses incurred by dust collecting on monocrystalline PV panels after exposure times of one day, one week and one month. The panels' efficiencies were decreased by 6.24%, 11.8% and 18.74% respectively. Measurements were taken in Baghdad city, Iraq. This is not in the Saharan desert, but the climate is comparable. The authors recommend regular cleaning of the solar panels, although a specific method is not mentioned. A study [9] reviewing the literature found that there are three methods of cleaning PV panels: preventative, automatic and manual. Due to the remote areas in the Saharan desert as well as the large quantity of PV panels to be cleaned and the potentially hazardous working conditions due to extreme heat, preventative and automatic methods are preferred. Preventative methods include different forms of coating applied to the PV panels. A self cleaning hydrophobic-based paraffine coating was found to increase the efficiency of PV panels by 14.3% [10], both through reduction of dust and by decreasing the temperature of the PV panel. However, for this method of dust removal to function, water must be deposited on the panels either artificially or through rain. Due to the lack of rain in the Sahara desert and the scarcity of water this does not appear to be an optimal solution.

Automatic PV cleaning methods methods do not necessarily require the intervention of human workers, making it ideal for use in the Saharan desert. Furthermore, it is important that excessive amounts of water are not used as this is a scarce resource in the area of interest. This makes electrodynamic screens (EDS) especially interesting, as no water or moving parts are required. Instead, parallel electrodes are placed on a glass substrate and installed using a dielectric film. To avoid interference with the PV cells, the EDS is as transparent as possible. High voltage pulses will be utilised with the electrodes, after which the dust will become electrostatically charged and be pushed off of the surface by the electrostatic forces occurring [11]. Up to 90 % of dust may be removed within only 2 minutes using this method. Figure 2 shows a screen with accumulated dust before and after use of EDS. The voltage which must be applied is between 7 and 10 kV, with a frequency between 5 and 15 Hz [12].

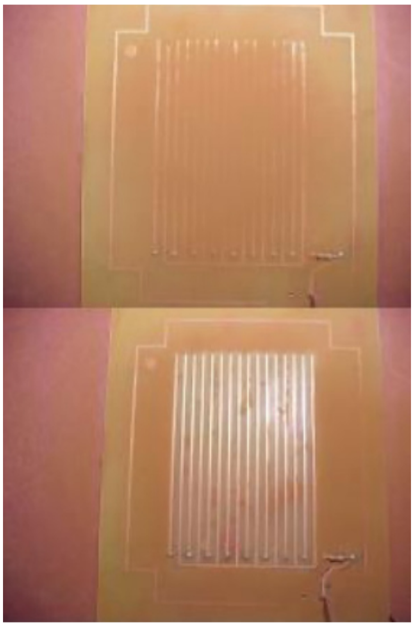

Figure 2: A screen with accumulated dust before (above) and after (below) voltage was applied to the EDS system [9]

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3.2 Temperature issues

Temperatures in the Sahara desert regularly reach as high as 50 °C [13], with an average high of 40 °C in summer [14]. This may pose an issue due to the decrease in PV performance with increasing temperature. Due to direct sunlight, the temperature of the solar panels themselves may be much higher. A study found that the temperature of a PV panel increased up to 100 °C [15] in Hefei, China, which is located at latitude 31 °N (comparable to northern Sahara desert). Solar panels' temperature coefficient is generally between -0.5 and -0.2, meaning that their efficiency decreases by 0.5% and 0.2% per °C respectively [16]. For panels reaching a temperature of 100 °C as mentioned, an efficiency decrease between 15% and 37.5% can be expected. Such large decreases in efficiency are detrimental to the usefulness of PV panels in hot climates, necessitating cooling solutions. Due to the large scale of the proposed system in the Sahara desert as well as its remote location, passive cooling options are preferred. Cooling techniques using Phase Change Materials (PCM) is an option. It has been shown the PCM can, in optimal conditions, increase the efficiency of solar panels by 20% [17]. Thus some of the losses can be mitigated, although initial costs will increase with the installation of any cooling system and a certain degree of efficiency loss due to the high temperatures is unavoidable.

4 Concentrated Solar Power

As of 2020, the largest CSP plant is located in Morroco and has a capacity of about 580 MW (Noor Complex) installed in the Sahara [18]. The mirrors of this power plant cover approximately $1.4 * 10^6\, m^2$[18]. The current global electricity capacity is approximately 8 TW [19], therefore the proposed 20 TW installation in the Sahara is more than twice the current electrical demand. This means that the installation could also supply heat and electricity for desalination, to tackle the limited water supply in the region or hydrogen production for a longer-range energy option. Heat can also be supplied for district cooling during the day via absorption cooling.

If CSP fulfils the full 20 TW capacity, that would require 34 483 power plants of the same output as the Morrocan Noor power plant with 20 690 of these power plants contributing to heating, cooling and storage of energy. Since transporting large amounts of electrical energy is prone to huge losses due to resistance in the wires, an alternative idea is to use electrolysis to produce hydrogen which can be transported using pre-existing natural gas pipelines for transportation across Africa, Europe and Asia and shipped to the Americas.

The spacial efficiency of concentrated solar is lower than the aforementioned PV spacial efficiency of 39.4 $\frac{MW}{km^2}$. The Noor Complex produces 580 MW and spans over 24.3 km^2[20]. As such its efficiency is $23.9\frac{MW}{km^2}$. In order to achieve the targeted 20 TW, that would require $836,820km^2$ occupied by concentrated solar power plants, which is approximately 9% of the entire Sahara Desert.

It is important to note that the aforementioned size of the Noor Complex does not take into account the area covered by mirrors but rather the entire area of the complex. This number is taken into account as additional infrastructure also needs to be considered in order to achieve a more accurate estimate of the required land area. The pure mirror area as mentioned previously is 1.4 km^2, about 17 times less than the area of the entire complex.

A big advantage of using concentrated solar power over PV is that the former is also able to operate during the night due to its utilization of molten salt storage. CSP has a slight disadvantage in terms of the cost per kW as it is higher than that of PV [21]. Due to the aforementioned reasons, however, it could prove to be a viable method for achieving this goal. Another advantage of CSP over PV is that it does not utilize materials such as silicon, indium, gallium, etc., in its design and as such is much safer for the environment as it avoids large-scale mining for said materials.

5 Combined PV and CSP system

The aforementioned methods of utilization of solar power do not need to be mutually exclusive. A combination of both will achieve the goal far easier than if just one method is utilized. As mentioned previously, PV suffers from lacklustre energy storage as electricity is much harder and more expensive to store when compared to thermal energy. As such, satisfying nighttime demand with only PV will be economically unfeasible. However, CSP can be used to fulfil this demand as its utilization of thermal storage allows it to constantly generate electricity. Since nighttime demand is generally half of the daytime demand [22], CSP can be the primary source of energy production during these hours of low demand. This will accomplish two things; reduction in required energy storage and a reduced use of the more expensive method of power generation (CSP). PV will then contribute to energy production during the day when the demand is higher, resulting in a reduction in the average cost per kW. As PV is also more space efficient, the total area required will decrease. To provide 20 TW of energy during the day (assuming that PV and CSP contribute 50% each), a total area including administrative buildings etc. of 632 000 km^2 is required, equivalent to 6.9% of the Sahara desert. This is of course a power plant of unprecedented proportions, but it is significantly smaller than if solely CSP were to be utilised and requires much less energy storage than if solely PV were to be utilised. As such, the combination of technologies provides several of the benefits associated with each, while minimising the drawbacks.

6 Energy Transportation

As is touched on in previous sections, the utilization of the energy produced will be one of the biggest challenges that need to be overcome for the realization of the proposed idea. In 2008, the United States lost approximately 24B$ due to transmission losses[23], which will only be increasing as the grid capacity rises. The state of California itself loses about 6% of the energy it produces which is still transported on a relatively local level in comparison. As such, one of the main goals of this research is to find a way of minimizing such losses and devise a method for intercontinental transportation.

6.1 Short-Range Hydrogen Transportation

Hydrogen is continuing to gain popularity as a viable fuel alternative and there are currently designs being made for internal combustion engines and Brayton power cycles to run using hydrogen. Not to mention, there are also fuel cells which use hydrogen for the direct production of electricity.

Hydrogen does seem like the miracle solution to the problems presented, however, it does have its drawbacks. Storage of hydrogen is an incredibly difficult process as the H2 molecule itself can pass through its containing material due to its small size. For this exact reason, it is incredibly dangerous to store in enclosed spaces such as warehouses as it would be an explosive hazard. Long-range transportation of hydrogen also has its own issues due to the very low mass density of the substance. There are multiple methods devised for transporting hydrogen depending on the range desired.

The research of the Joint Research Center of the European Commission has found the cheapest method of transportation of hydrogen across all ranges up to 25 000 km or more than half of the planet's circumference[24]. The following subsection will largely utilise this piece of literature as it is from a reliable source and data on the subject is otherwise incredibly scarce.

Short-range transport of hydrogen is defined by the European Commission as transport of up to 3000 km, with the cheapest method for that range being a traditional pipeline. This range allows the network (if centred in Egypt) to reach the entirety of the Arabian Peninsula and the Middle East, the vast majority of North Africa (excluding Morrocco) and a majority of Europe (excluding the Scandinavian countries, the United Kingdom, the Iberian Peninsula and the Benelux). This would allow for a system to be designed such that it connects all of the potential locations in North Africa and thus connecting the aforementioned excluded regions of Europe and Africa. The preexisting natural gas pipelines connecting the 3 continents can be used to great effect to extend the reach of this cheap method of transportation.

6.2 Medium-Range Hydrogen Transportation

The category of medium-range transport is classified as ranging from 3000-16,000 km. This wide range of transportation allows the transportation of hydrogen almost worldwide, with the exception of Oceania. The proposed cheapest method for transportation in this range category is liquefied hydrogen. It is important to note that due to the cases considered in the document in question, the aforementioned range will likely be shorter and not reach the far reaches of Australia, East Asia and the southern part of South America, due to the path travelled by common shipping routes. The proposed Egyptian compound would be closer to the Suez Canal and the major port of Suez, allowing the shipping routes to reach East Asia and possibly Australia. The Northwest compounds in Morrocco, Algeria and Mauritania will be close to the port of Tanger Med in Morrocco which will be vital to reach North and South America. As such the possible discrepancy in the range considered could be a non-issue.

6.3 Long-Range Hydrogen Transportation

In case this does prove to be an issue, the last category discussed in the document is the 16,000-25,000 km where the most cost-effective method was deemed to be transporting hydrogen in the form of LOHC, or Liquid Organic Hydrogen Compounds, and ammonia. Methanol was not considered by the study due to it releasing carbon upon dehydrogenation thereby defeating the purpose of producing a carbon-neutral fuel source. Sourcing the carbon required for the production of methanol could also prove to be an expensive issue as mentioned by the European Commission.

LOHC and ammonia usage would require local chemical plants at both the start and endpoints of transportation where releasing the hydrogen would also cost energy. Due to these reasons, this method is only used as a last resort if the liquefied hydrogen proves to be not as cost-effective in these long distances. Nitrogen is far easier to source for the production of ammonia as it is simply supplied via the air which contains 78% nitrogen.

7 Political Issues

A large hurdle that needs to be overcome in order to realise this project is the incredible effects it could have on the global political scene. The stability of the region will also present a challenge as changes in regimes and terrorist organizations will impact the difficulty. Political issues will be the biggest obstacle at play, far more so than any technological, logistical or environmental issues.

7.1 Political Stability

An important issue that needs to be discussed is the vast instability of the entire North African/Saharan political climate. According to the World Bank, the political stability index measures the likelihood that a government will be overthrown or destabilized via violent means such as terrorism or unconstitutional methods [25]. This indicator will be used as the primary method of gauging the stability of a country. It measures from -2.5 to 2.5 with the lesser value indicating a larger likelihood of change. For reference, the Netherlands scores 0.91 as of 2021, and a country with a value close to 0 would be the United States[26].

7.1.1 North African Countries

The countries that are suitable for the large-scale implementation of solar such as Egypt, Algeria and Mauritania all have a largely unstable political climate. According to the World Bank, all North African countries score a political stability index of less than 0, indicating that they are largely unstable. Libya specifically scores incredibly low at -2.37[26]. This is likely due to the unfortunate history of the country with authoritarian regimes and intervention by foreign countries with the aim of stabilization. The rating alone makes it highly unlikely that the project can be realised even partly in that country. A large amount of international involvement will be necessary to make the country a desirable location.

Out of all North African countries, Morrocco, Tunisia and Algeria score the highest in political stability, as such, those countries will be the likeliest locations as they have close proximity to a large body of water as well as a large percentage of arid and semi-arid environments. Egypt is also a great choice in terms of location, as it serves as the gateway between Africa and Eurasia. A large amount of the power consumption comes from Eurasia and as such, a large amount of transportation costs can be avoided due to that proximity. The country itself scores relatively low on the political stability index, at -1.02[26]. Due to the aforementioned reasons, the country will likely still be in contention with other more stable ones.

7.1.2 South Saharan Countries

Out of all South Saharan countries, Senegal and Mauritania score by far the highest in political stability at -0.17 and -0.71[26]. Both of the aforementioned countries also contain a large amount of unpopulated desert land area which, according to topological maps is also incredibly flat, making it one of the better regions to realise at least a part of this project. Other South Saharan countries are landlocked and as such will not serve as viable grounds for local power utilization in the form of desalination and hydrogen production.

7.2 Changes in the Global Power Structure

If the 20TW idea were to be realised, a massive shift in political power will be one of the main effects. The massively unstable African continent will become the major power on the world stage, controlling the majority of the energy and fuel supply. The current world order will be massively overturned if the African countries were to achieve this power capacity on their own. The most likely method to achieve this, however, is with mass global cooperation between competing parties such as the entirety of the western world in the form of NATO and the BRICS alliance.

The major oil exporters such as the countries in the Arabian peninsula will likely do all that they can to prevent this from occurring. In the unlikely event that there is cooperation between the aforementioned parties, the Arabian countries will likely cut oil exports massively thereby causing current energy prices to be elevated to a significant degree and likely causing a global economic crisis, much like what is currently happening with Russia cutting its exports of natural gas to Europe and the generally elevated post-coronavirus fuel prices. This project will likely have to be kept secret to an intense degree by starting off on a smaller scale, firstly, by insuring the self-sufficiency and stability of the Saharan countries, secondly, by becoming a minor exporter of hydrogen, thereby decreasing the dependency of financing countries on fossil fuels. And, finally, by becoming the primary energy exporter with a very close-knit alliance.

8 Environmental Impact

8.1 Positive impact

As mentioned before, this project would produce more than twice the current electrical demand of the entire world [19]. Seeing as this would be done with "emission-less" energy generation (see section 8.2), this would mean that the entire world would be able to continue using energy without contributing to the emission of greenhouse gases, which is a massive turning point for the current global warming crisis and the well-being of the planet, as well as its population. Simply put, if such a project as this would be realized, it would be a giant victory in the battle against global warming.

8.2 Negative impact

Of course, building a solar project of this magnitude does not come without costs, even in the environmental department. Although the project would be able to provide the entire planet with clean energy, by collecting free, emission-less irradiation from the sun, and reducing the need for fossil-fuel based energies, the construction of the project does require materials, energy and manpower. The energy needed for this project can not possibly be realized without fossil-fuel based energy sources. For this purpose, an estimated calculation and comparison of CO_2-equivalent required for the project is helpful. For this estimation, a purely mono-crystalline solar PV field is assumed.

For the first few years of a solar panels lifecycle, it can be argued that the energy required to build the solar panel, exceeds the energy produced by such a solar panel. Because the locations' GHI is more than the usual PV installation for more developed countries, this is assumed to be in the first 3 years of the solar panels' life, after which the energy produced exceeds the energy originally needed, and the solar panel can be seen as energy neutral. Before this 3 year mark, to produce 1 kWh, about 50 grams of CO_2 are produced [27].

By quick calculation, this project's solar panels alone would produce, in the first 3 years of its life:

$$20 \text{ TW} * 3 * 365 * 24 = 5.256 * 10^{14} \text{ kWh} \tag{1}$$

and this would in turn produce

$$50 \text{ grams} * 5.256 * 10^{14} \text{ kWh} = 26.3 \text{ trillion kg of } CO_2 \tag{2}$$

Comparing this to the CO_2 emissions from fossil fuels in 2021, which was 37.1 trillion kg of CO_2 [28], this does not look like much. However, this calculation is purely for the solar panels themselves and does not take into account the CO_2 'needed' for the cables, roads, possible pipelines, transport of materials and many more things that are needed for a construction project of this scale.

Ofcourse, these emissions would not be instantly emitted, as the project would take years to realize and slowly the panels being built can start providing power, possibly for the construction itself, but that does not take away that alot of CO_2 is produced for the project. It would therefore be up to the leading body of the project, as well as more (accurate) calculations, for the decision to be made.

9 Conclusion

Heretofore, this report has discussed the viability of establishing a 20 TW solar power installation within the Sahara Desert by considering aspects that could potentially deter its development and deployment. The location itself has shown enormous potential in the development of both PV and CSP plants. The technology for both methods is mature enough to undertake such a challenge as well as cope with the need for transportation of the energy at a distance, however, factors outside of the technology are proving this concept to be unfeasible. The political issues most of all show that this concept cannot happen in the near future as the rather tenuous political climate of both the desert itself and the entire world would prevent any significant progress. The environmental ramification of the construction of this project also shows that a significant amount of carbon dioxide will be emitted, even when not considering vital infrastructure such as roads, additional pipelines or transport of material. This suggests that the plant itself will need to be operational for a large period of time before it can actually prove to be a net positive for the environment.
Due to the aforementioned factors, the realisation of the project will likely not happen as a concentrated effort by a worldwide organization. A much more probable development would be for countries to focus on the development of solar technology within their own borders, thus striving for energy independence. All in all, currently and likely in the near future, this megaproject will not be possible unless a massive global effort is made to ensure stability in the region and globally is achieved and the necessary capital is readily available.

10 Appendix

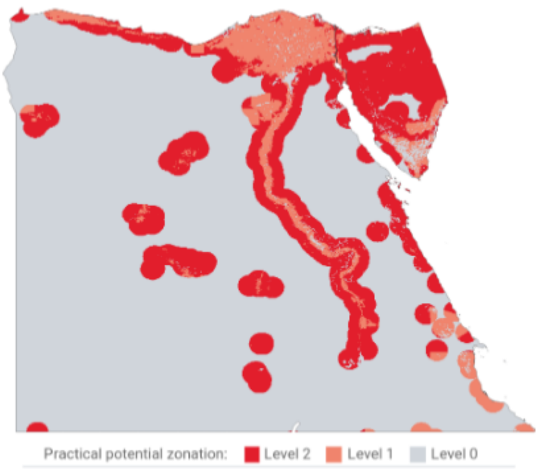

Figure 3: Map of Egypt (∼1 million km^2) with levels of available area for solar projects [3]

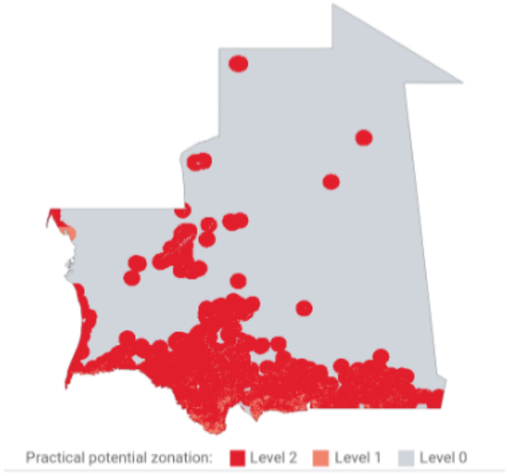

Figure 4: Map of Mauritania (∼1 million km^2) with levels of available area for solar projects [4]

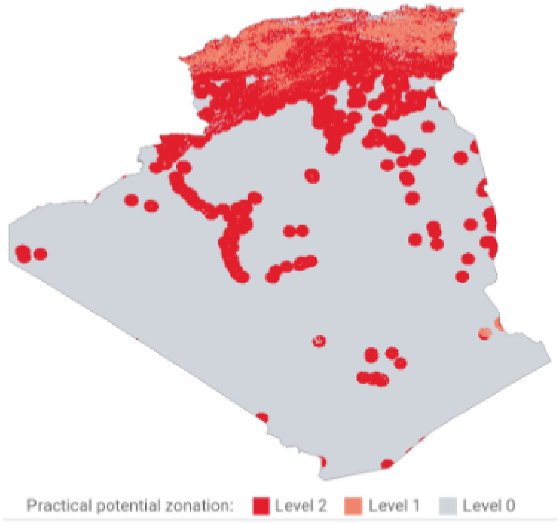

Figure 5: Map of Algeria (∼2.3 million km^2) with levels of available area for solar projects [5]

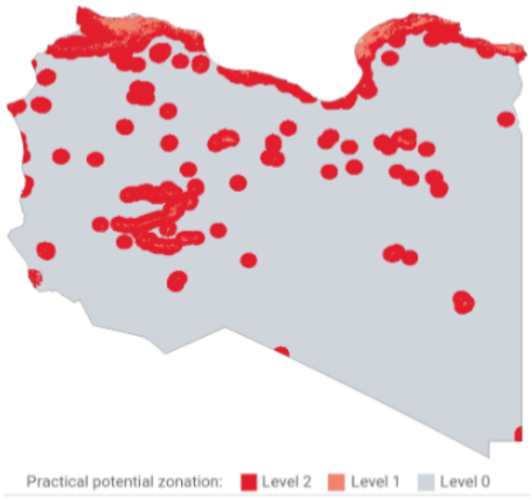

Figure 6: Map of Libya (∼1.7 million km^2) with levels of available area for solar projects [6]

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