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Solar Energy; Sand-Dust build-up and Removal
Solution

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Abstract:

The major project aim, to recognise a specific engineering problem and to propose a possible solution, was directed at improving the efficiency of solar panels when used in Saudi Arabia. The problem is that recognised is that in the desert condition, sand and dust build-up on the panel surface, and if not removed can cause a 60% loss of efficiency (Javed, et al. 2017). However, it is also recognised that cleaning off the sand and dust must use some power.

In view of this, the designed solution had to save more power than it uses – the maximum power it could use and still be cost-effective was in the region of 200W, but calculations showed that a 25W motor would be sufficient to power the device as designed, proving that it would save much more than it uses, and is therefore a design worth pursuing and developing, allowing an increase in the use of Solar Power as a renewable energy source.

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1.0 Introduction:

The major project is intended to identify an engineering problem, and to propose a solution based on appropriate research into the specific area. In this case, the problem is the sand or dust accumulated on the surface of PV cells in the use of Solar Panels to produce electricity in Saudi Arabia.

The need to use renewable energy in Saudi Arabia and the Middle East and North Africa (MENA) has led to the trial of various schemes including solar power – the continuous sunlight during daylight hours is an enormous benefit (see Figure 1), but problems have been found due to the lack of precipitation which causes a build-up of sand or dust on the panels.

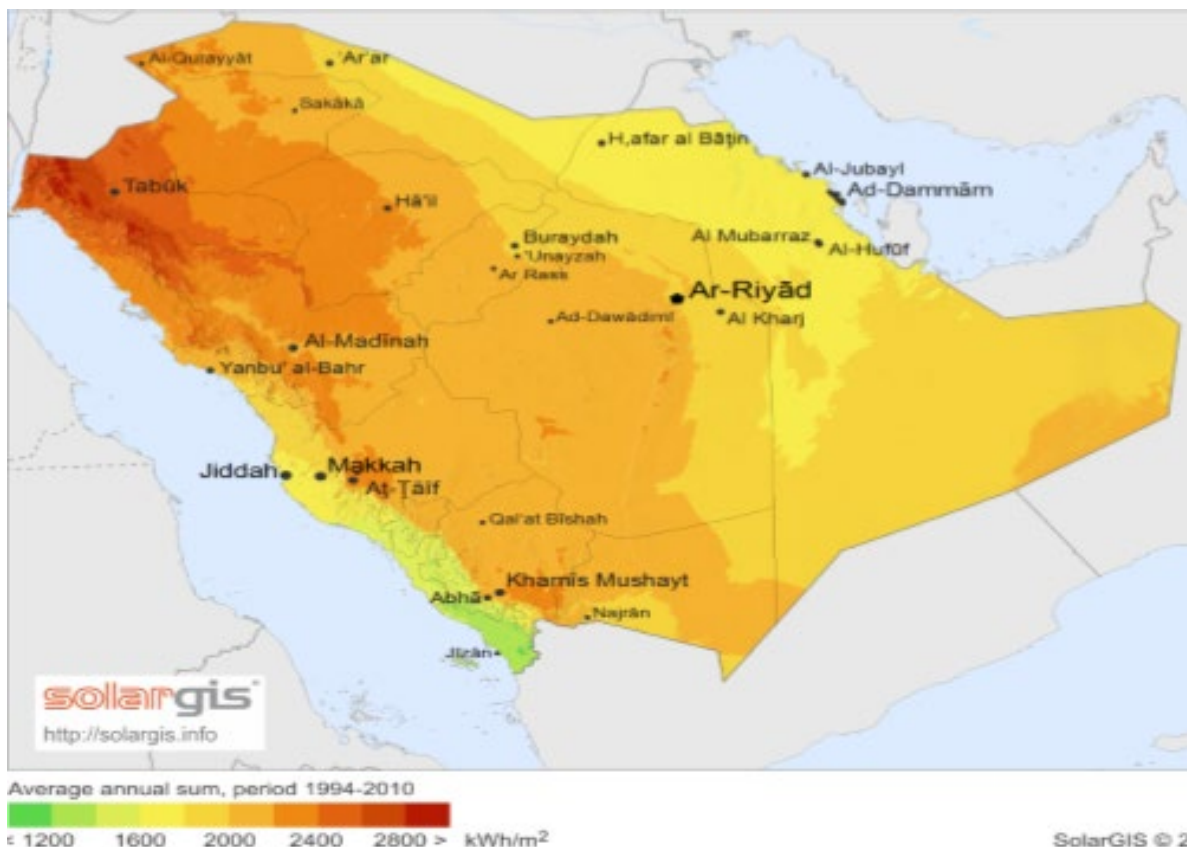


Figure 1: Potentially, Saudi Arabia is ideally placed to make extensive use of solar power. Source: (SolarGis 2014)

This build-up of dust or sand has been examined by a wide range of field research projects, all of which have obtained very similar results with regard to both the deposition speed of the sand and dust and also the detrimental effect which it has on the output of the panels. As well as examining the other studies, this project also includes a practical experiment to determine the effect of sand deposition on a solar panel in laboratory conditions.

1.1 Project Aims and Objectives:

The overall aims and objectives of the project are simple – to recognise a specific engineering problem and to propose a possible solution which would help engineers to select suitable components for the construction of a similar system. the chosen engineering problem is the difficulty imposed the dust and sand accumulation reducing the efficiency of solar panels in Saudi Arabia.

This is a well-known effect, and is one of the major obstacles to the country becoming a major exporter of solar power (Climate Home 2015). The difficulty has been that many of the suggested systems to overcome the problem actually use more energy than they save, so it is essential that this project clearly shows an energy saving.

1.1.1 Aims:

To show at least one possible engineering solution that will allow these problems to be overcome or at least reduced, within the parameters of the previous paragraph – the system must show an energy saving rather than an energy loss.

1.1.2 Objectives:

To demonstrate a simulation of the way in which the power output steadily declines due to the build-up of sand and dust.

To demonstrate the point below which cleaning is unnecessary.

To demonstrate a method for removing the sand/dust.

To demonstrate that the suggested method saves more energy than it uses.

2.0 Review of Existing Literature:

Even the most optimistic view of remaining oil reserves in Saudi Arabia and other oil-producing countries indicates that 'peak oil' has been passed and that the reserves are declining (Ison, Peake and Wall 2002). This has led to a dramatic increase in the world interest in renewable energy (Roberts 2004), although there is still a very strong reliance on fossil fuels. All of the oil producing countries are looking into broadening their economy in the interest of sustainability (Chaharsooghi, Rezaei and Alipour 2015), and for countries in tropical and desert areas where sunlight is guaranteed, the choice of solar energy appears at first to be the obvious choice.

Research into materials has ensured that the latest solar panels are far more efficient than early examples (Arif, et al. 2015). Researchers have also developed a way to decide if solar energy is the best choice for any specific developing nation (Kassem, et al. 2016) and methods to track performance of solar panels (Lyden and Haque 2015). All of this research is, according to some authors, not enough (Roberts 2004), although the growth of interest in corporate social responsibility (CSR) is steadily improving the efforts of many companies (Wong 2014). At government level, 'green' policies are rising in popularity (Ison, Peake and Wall 2002), and "ethical

business” has become the ‘norm’ in many companies both in Europe and elsewhere (Lyden and Haque 2015).

When using solar power in the MENA, however, specific problems have begun to arise – the general lack of precipitation (Li, et al. 2015) means that panels are not ‘self-cleaning’. The dust and sand that therefore builds up must be removed, and the energy cost of removal that must be weighed against the energy produced by the panels. Another factor that has arisen, particularly in coastal areas of the MENA, has been the ‘micro-climate’ that develops in cities (Shafaghat, et al. 2016). These factors all affect the speed of adoption of alternative energy by supply companies (Roberts 2004), and the fact that existing infrastructure tends to support the use of the private car and the subsequent use of fossil fuels (Glancy 2014).

Clearly, these two factors are not the only things inhibiting the introduction of solar energy in countries such as Saudi Arabia – long-distance transmission lines and most household appliances operate using alternating current (AC) whereas solar panels produce direct current (DC). DC power is far easier to store (*i.e.* in batteries) than AC (Darbyshire 2010) but the difficulties in usage and transmission outweigh this small advantage, and converting from DC to AC is inefficient and reduces the viability of solar energy as an alternative. However, there is also a strong driver in favour of solar energy – the idea that Saudi Arabia could become the supplier and exporter of everyone’s electricity (Riyadh Connect 2012) supplying solar electricity to the rest of the world at an affordable price. A move to export power would also help other aspects of diversification of the economy, since among other factors it would reduce the need for KSA to change its policies towards tourists; in much of the

country tourists other than pilgrims are not readily accepted, and this would not need to change if power became the main export.

At the present time, most of the electricity produced in the KSA is sold for use in private houses which account for 52% of the electricity used (Alrashed and Asif 2015), most of which is produced using fossil fuels (Alkhathlan and Javid 2015). There is no question or doubt that solar (Photo-Voltaic (PV)) production across the world has grown (see Figure 2), and Bahaidarah, et al.'s (2015) research has shown the climate in the KSA to be perfect for solar Photo-Voltaic generation, even though factors such as the weather in coastal areas (Slamova, et al. 2016), and the levels of dust contamination (Costa, Diniz and Kazmerski 2016) are also relevant to discussions on the use of this energy source. These issues have led to research into innovative materials (Slamova, et al. 2016), and to try different glass combinations to assist cleaning (Said, Al-Aqeeli and Walwil 2015).

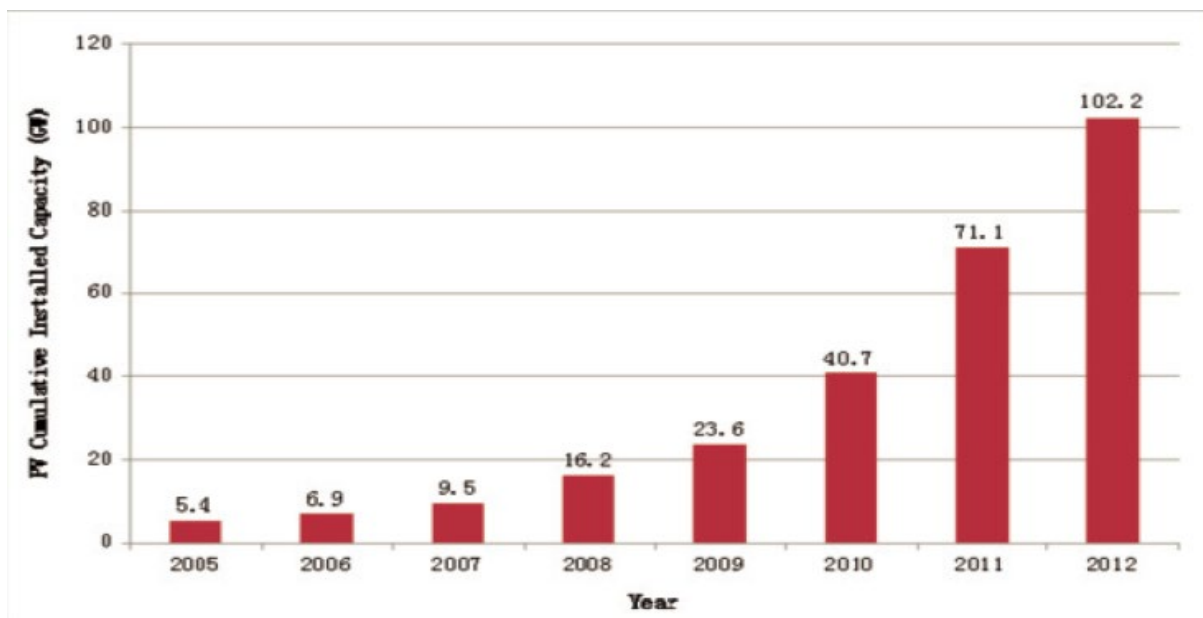


Figure 2: The Steady Increase in the use of Solar PV Energy. Source: (Bahaidarah, et al. 2015, p. 910)

Solar Photo-Voltaic cell arrays work most efficiently when the light strikes them at exactly 90° (Bird and Ross, Mechanical engineering principles 2012), so that

calculation of the correct angle for the panels is essential (Kaddoura, Ramli and Al-Turki 2016) as Figure 3 clearly demonstrates.

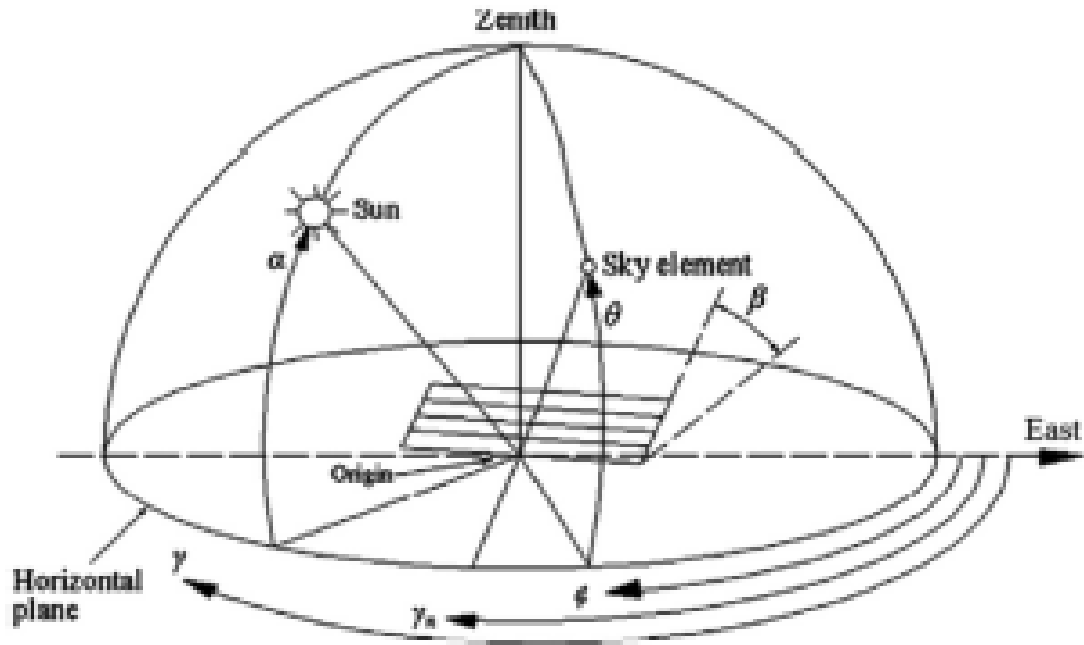


Figure 3: Zenith, azimuth, and hour angles. Source: (Kaddoura, Ramli and Al-Turki 2016, p. 628)

Unfortunately, this angle does not remain the same throughout the seasons, and even changes during the day, so that panels may be moveable, to follow the path of the sun. For static panels, the situation is different in every location, and new calculations must be made before each installation. The closer a country is to the equator, the smaller the variation is – in the KSA for instance, the variation is much less than it is in northern Europe, but is still quite large, as Figure 4 shows.

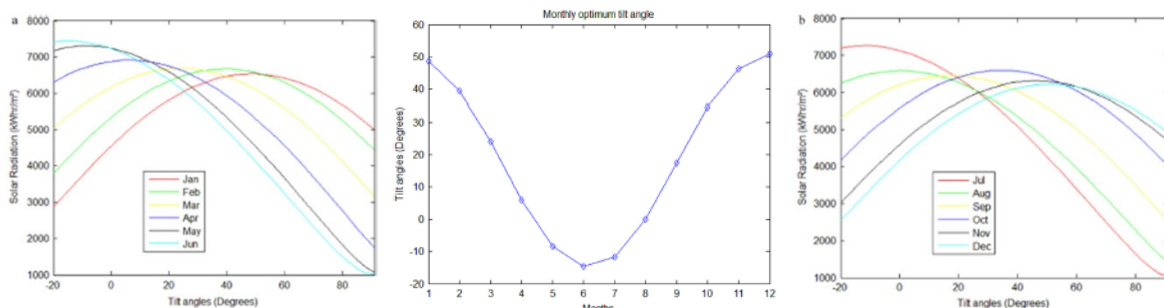


Figure 4: Solar Movement. (I) Solar Energy in the first half of the year (c) Best angle varies through the year. (r) Solar energy in the second half of the year. Source: (Kaddoura, Ramli and Al-Turki 2016, p. 630)

Thus, the idea of 'tracking' the panels to follow the sun, either on one axis or on two, gains importance, even in face of the fact that it is much cheaper to install a fixed array, which does not catch the optimum level of light (Alrowashed, et al. 2017). This is lower cost is partly because the large electric motors required to move the panel array also use the electricity they produce, which means this needs to be included in the calculations of efficiency (Batunlu, Alrweq and Albarbar 2016).

2.1 The effect of Temperature on PV cells:

Most of the advantages and disadvantages of the climate in the KSA have already been briefly mentioned, but there is one additional trouble which is that solar PV panels are most efficient below 30°C, as can be seen in Figure 5 (Bahaidarah, Baloch and Gandhidasan 2016). In northern Europe, this is not a major difficulty, but daytime temperatures in the KSA greatly exceed the ideal of 30°C.

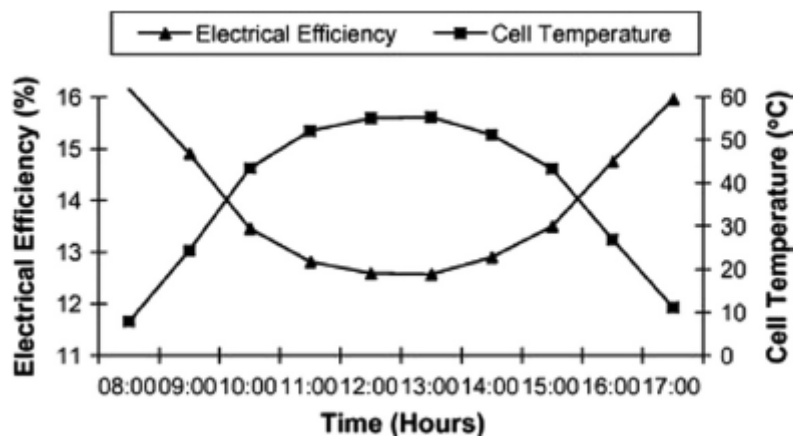


Figure 5: Efficiency of PV cell Vs Cell Temperature. Source: (Bahaidarah, Baloch and Gandhidasan 2016, p. 1521)

Because of this, there needs to be some kind of cooling mechanism included in the design. One way of cooling the cells would be to flow water across their surface. This would also overcome some of the problems associated with dust, but in a desert country with low levels of water, this is not a practical solution. Bahaidarak, Baloch, and Gandhidasan (2016) do suggest several alternative cooling methods but still

stress the requirement for keeping the cells as cool as possible. Failing to cool the PV cells reduces their potential output and efficiency as shown in Figure 6.

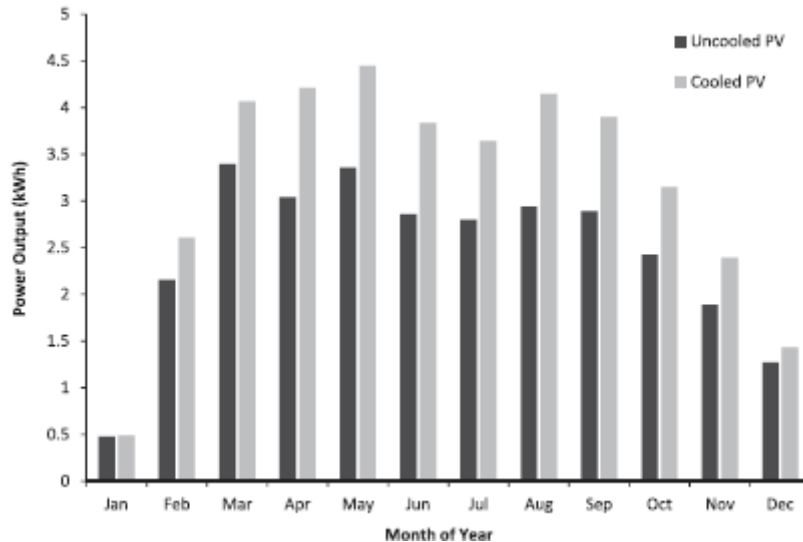


Figure 6: Comparison of output across the year of cooled and uncooled PV panels. Source: (Bahaidarah, Baloch and Gandhidasan 2016)

2.2 Previous Studies Regarding Dust Contamination:

One of the major difficulties experienced with solar PV energy world-wide is the build-up of dirt, dust, and sand which can form on the surface of the cell (Costa, Diniz and Kazmerski 2016, Said, Al-Aqeeli and Walwil 2015). As the dirt or sand builds up on the surface of the panel, its efficiency decreases accordingly as can be seen in Figure 7. The magnitude of the dust problem is subject to argument, with some researchers claiming that it is, realistically, negligible, and therefore not worth the cost of cleaning (Javed, et al. 2017, Saidan, et al. 2016) except after a major dust storm, whilst conversely

“It is well known that the presence of dust on the surface of a PV modules have significant impact on their efficiency” (Cristaldi, et al. 2014, p. 207).

Thus, even the most conservative of observers would argue that some kind of cleaning is needed, but many suggestions are simply not energy efficient.

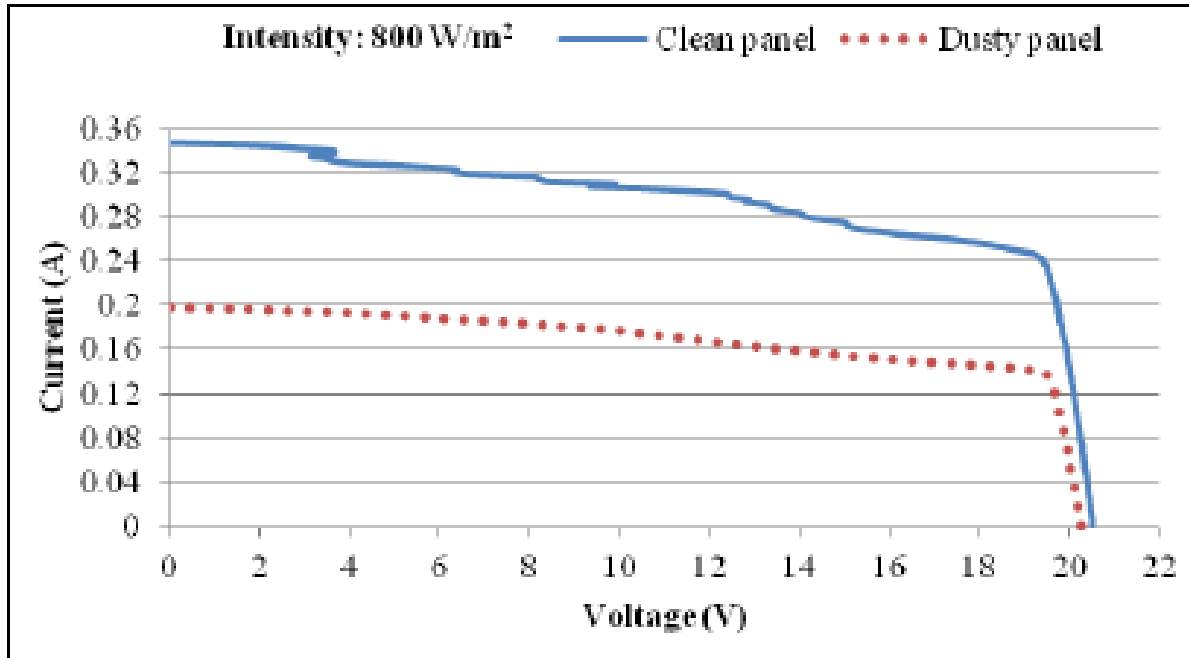


Figure 7: Degradation of output at 800W/m² and 30°C. Source: (Rao, et al. 2014, p. 696)

However, even Cristaldi, et al., (2014, p. 208), point out that “*the aging process and degradation*” also lead to a similar decline in efficiency. This is the reason that they have proposed a simplified way of estimating the effect of each of these three factors to help engineers in determining the effective life span and usefulness of a solar PV panel that has been installed. Overall, however, the research has indicated that dust and sand are the specific difficulties experience in a desert environment, and that to maintain efficiency, both cleaning and cooling are required.

2.4 Efficiency of Solar PV cells

Solar cells have, historically, been considered an inefficient means of producing electricity, and were often seen as being of technical interest but little more. However, with the increased drive for RES and improvements in solar PV cell, that is

no longer the case – as Figure 8 shows, with an efficiency of around 35%, third generation cells are producing affordable electricity.

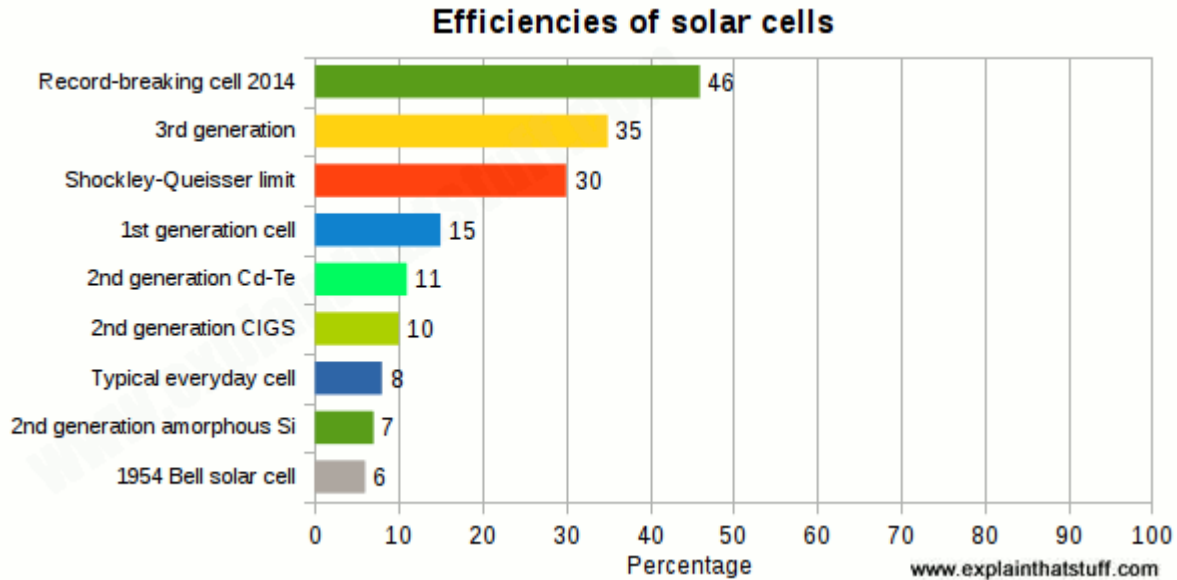


Figure 8: The relative efficiency of different solar PV cells. Source: www.explainthatstuff.com

N.B. The Shockley-Queisser limit of 30% efficiency is the theoretical limit for a single pn junction solar cell, as calculated in 1961 by William Shockley and Hans J. Queisser (Shockley and Queisser 1961).

Over the last decade, the efficiency of all types of solar PV cell has steadily improved (Costa, Diniz and Kazmerski 2016), with even domestic panels for home use regularly exceeding 16% (Green, et al. 2015). Despite these increases in efficiency, the most important factor remains the angle of incidence of the sunlight on the panel. Basic physics explains that light illuminates according to the inverse square law, the larger the area illuminated, the less light it receives (see Figure 9), and the same is true for the energy in sunlight. At a 90° angle, the panel receives maximum light, and therefore produces maximum power. When the light strikes the panel at an angle other than 90° the light is spread over a larger area, so the same amount of light will yield less power.

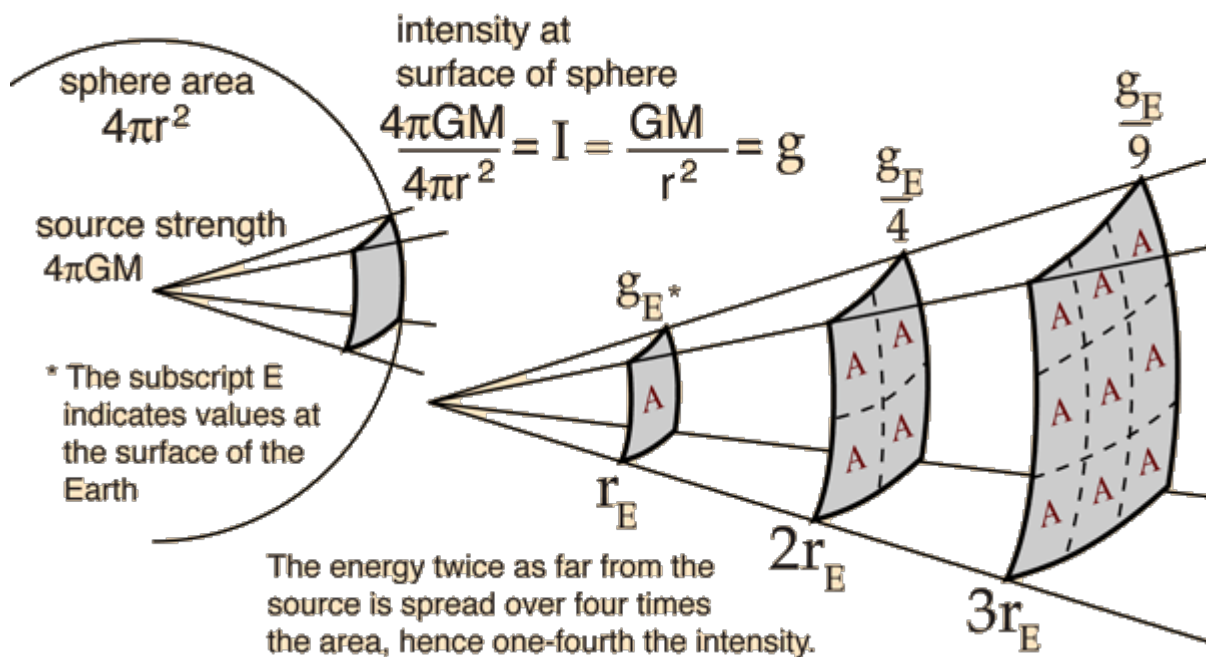


Figure 9: Illustration of the inverse square law. Source: (Hyperphysics 2017)

This variation according to angle can be calculated by using 'Lambert's cosine law' (Bird and Ross, Mechanical engineering principles 2012), demonstrated in Figure 10. Using these calculations and statistical observations of the position of the sun at a location, the panel can be positioned so that the angle of incidence is 90° , and the panel can be moved to track the sun across the day and the seasons. This way, maximum efficiency is always maintained, although as already noted, tracking does have an energy cost. That cost is minimised in third generation cells because they are much lighter in weight, and it can be reduced further by the use of concentrators, where effectively only the lens has to be moved, not the entire panel. All of these factors have improved the overall efficiency of solar PV panels, but nevertheless, research continues into methods to achieve an even higher efficiency. One of these methods is to use solar concentrators, with a lens and mirror directing the sunlight onto the panels. This method can track the sun's movement with a very small motor, and is therefore possible a more efficient method.

Cosine Law: $E_{\theta} = E * \cos(\theta)$

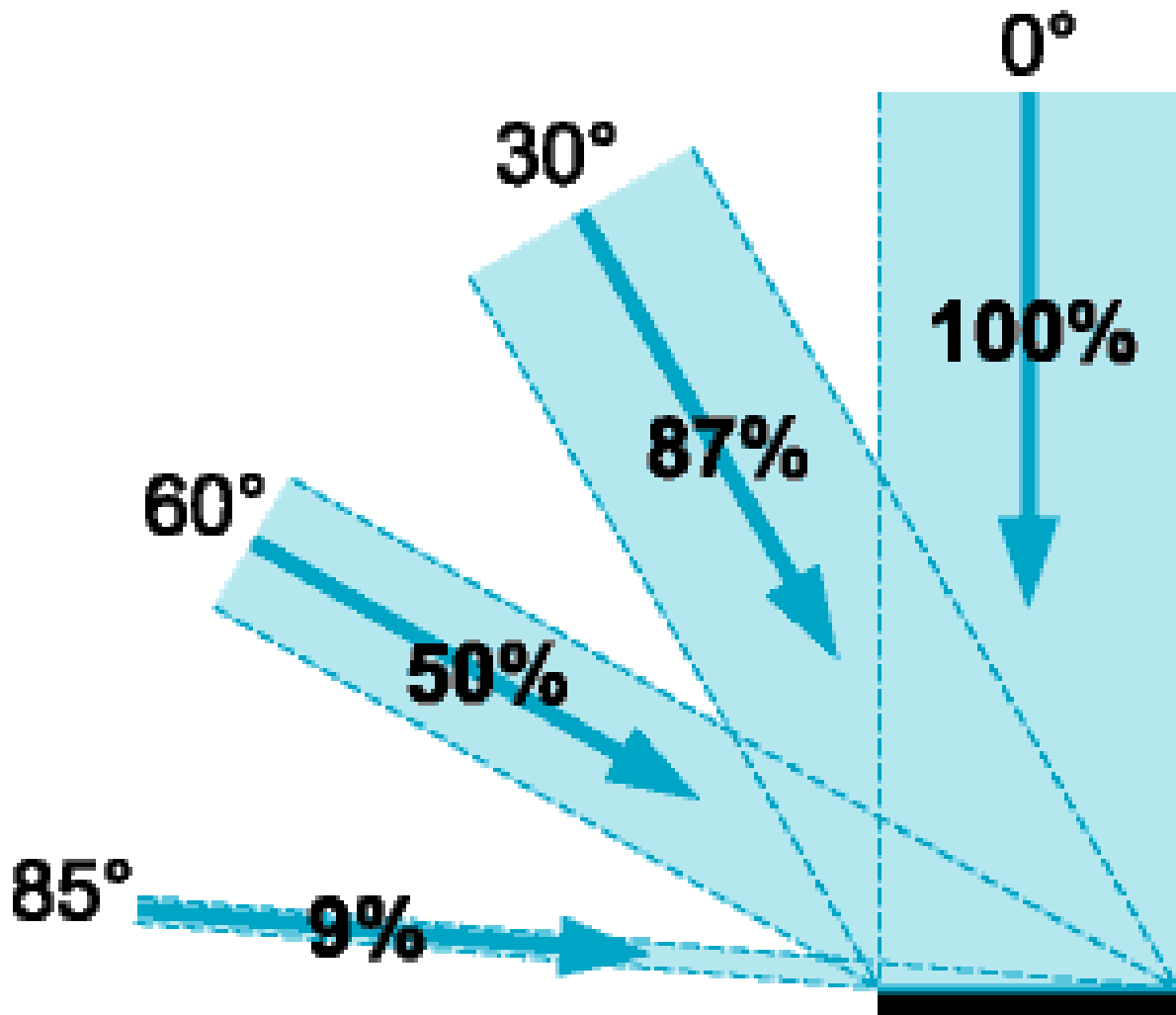


Figure 10: Lambert's Cosine Law. Source: (Architecture47 2012)

2.4.1 Calculations

When considering the potential output of a solar panel array, the overall efficiency calculations begin with knowing the intensity of the sun at the location where the array is to be sited. This is measurable, and in many places, has already been measured, with statistics available. Then, using both the inverse square law;

$$\frac{4\pi GM}{4\pi r^2} = I = \frac{GM}{r^2} = g$$

and Lambert's Cosine law;

$$E_{\theta} = E \times \cos(\theta)$$

and the known output of the panels, it is possible to calculate the area of panels required for a specific output, and the optimum angle and position of those panels. It is then possible to calculate whether the energy required for tracking is greater or less than the additional electricity produced – in some parts of the world, tracking may well not be cost effective, whilst elsewhere single-axis or double-axis tracking could prove to be the best way forward for the use of solar PV panels.

2.4.2 Small-Scale Solar Installations

In many countries, individual householders are being encouraged to generate solar energy for their own use, with any surplus energy being sold to the energy company (Calsolar 2014). If the panels produce less than the house requires, or during the night, the customer remains connected to the grid, and supplied with power (see Figure 11), and a small-scale installation of this nature would be ideally suited to the type of cleaning that is investigated in this project – it would be just as prone to dust and sand build-up as a large field, and would require cost effective cleaning routines. An installation of just two panels, as shown in Figure 11 could be cleaned manually, but if it was mounted on the roof of a house, would require mechanical cleaning.

Although in Saudi Arabia the drive is to produce solar energy on an international scale (Riyadh Connect 2012), small-scale domestic installations could still prove to be an effective additional resource, if enough were installed. These small-scale operations usually involve fixed panels, rather than moveable, but that may increase the need to clean the panels in the desert environment. In Europe, domestic

installations are not usually cleaned, except annually (SolarGis 2014), but in Europe, sand and dust are not prevalent, and rainfall keeps the panels clean if self-cleaning glass is used (Said, Al-Aqeeli and Walwil 2015). In the Saudi Arabian context, encouraging the domestic installation of this type would require a cleaning programme, and it would, necessarily, have to save more power than it used.

Figure 11: A Typical Small-Scale Solar Installation, Ideally Suited to this Project. Source: (Calsolar 2014)



The calculations related to the experimental section will be detailed as they are used, but these will be calculations regarding the effect of dust, dirt, and sand compared to the cost of cleaning the panels. Again, this may vary depending on local climate, but

it is hoped that a generalisation can be made from the Saudi Arabian data and the results of the tests carried out.

2.3 Other Possible Renewable Energy Sources in Saudi Arabia:

Solar Photo-Voltaic cells are not the only source of renewable energy, and investment continues into the other Renewable Energy Sources (RES). It is worth noting that solar PV cells are not even the only solar energy source, as Figure 12 demonstrates. The solar thermal, where the heat of the sun is concentrated to make steam to drive a turbine and generator can use existing infrastructure, and the expansion of the use of concentrators (HCPV and LCPV) (mentioned above) is also growing.

The PV panel that will be tested here will be a modern, multi-junction design, and as such represents the usual solar panel encountered in a commercial array, making a reasonable comparison to the 'real thing', with equivalent output figures to an array, but on a smaller scale. It is also comparable with the small-scale domestic installation mentioned above – slightly smaller, but nevertheless an ideal comparison, as the scales is much easier to comprehend than a Mega-Watt (MW), national installation. When there are thousands of Mega-Watt installations, and the measurement are Giga-Watts (GW), Tera-Watts (TW), or Peta-Watts (PW) it is even harder to visualise the scale of both the losses and the savings involved; the nation-wide savings in Peta-Watts will easily be equal to an entire city's annual consumption, thus demonstrating the importance of the research. Example; if cleaning saves only 10% of the output, then on a national scale of, say 100PW, the saving is 10PW, or 10,000TW, or 10,000,000GW, or 10,000,000,000MW – certainly an amount worth saving.

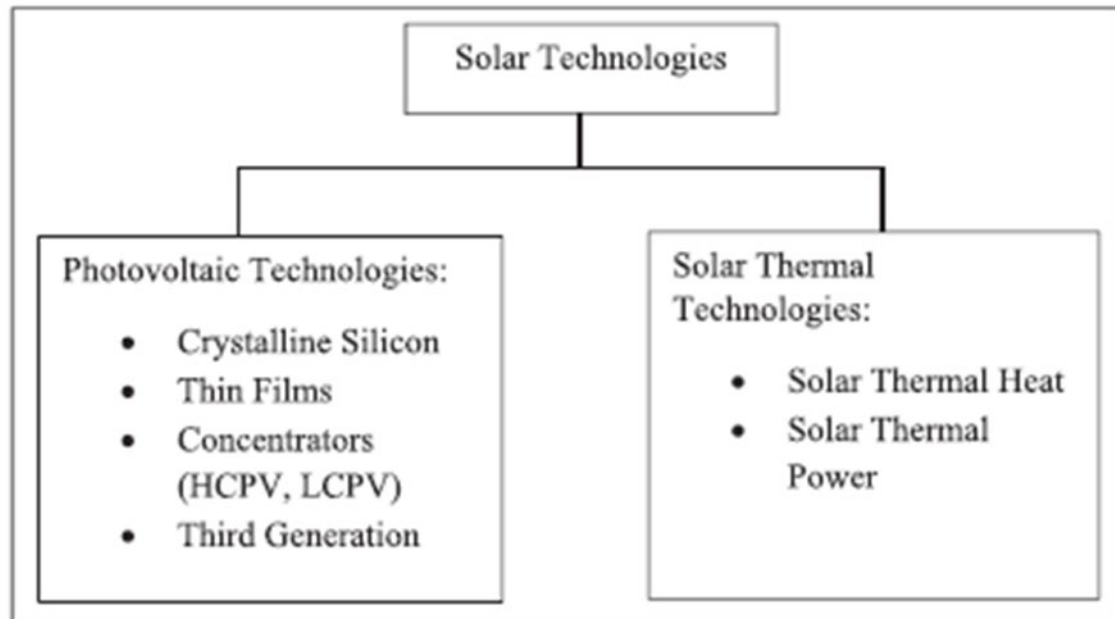


Figure 12: The Classification of Solar Energy Technologies. Source: (AlYahya and Irfan 2016, p. 700)

Moving away from solar technologies, there are several other power generation methods which have been tried in the KSA; Geo-Thermal, Wind Power, and Wave Power. The list of RES in Table 1 is not exhaustive, but covers the main options and sources of renewable energy. These RES are not in any specific order, and the descriptions are minimal, but it is clear that different RES are applicable to different locations – if there is a lot of wind, wind energy should be used, where there is a lot of sunshine (as in Saudi Arabia) then logic dictates the use of solar energy in one form or another. Equally, geothermal and wave energies can only be utilised in parts of the world where there is access to a tidal sea, or where geothermal hot springs or hot rocks are naturally present. Biomass and Biogas are also gaining popularity, because they make use of what would otherwise be waste material, but wind and solar energies still remain the top contenders to be used as an RES.

Table 1: A list of the most well-known RES. Source: adapted from (Terna Energy 2014)

RES		Description	Technology
Wind Energy		The kinetic energy of the wind is converted to electricity by the use of a wind-turbine.	Well tested world-wide, large-scale, small-scale, and personal-level – all good and effective.
Solar Energy	Active	Converts solar energy to heat.	Well tested, used for generation and for heating in cold places.
	Bioclimatic	Concerns architectural solutions and construction materials to maximise the direct use of solar energy for heating, air conditioning or lightning of interior spaces.	New technology – works well so far. Helps with energy efficiency.
	Photo-Voltaic	Converts solar energy directly to electricity.	Discussed here, well tested advanced technology for all levels of use.
Geothermal Energy		Thermal energy from the earth's interior seen as natural steam releases, surface or underground hot waters and in hot dry rocks.	Well tested technology, mainly used on small-scale or personal-scale projects, but can be large-scale.
Wave/Tidal Energy		Uses the rise and fall of waves and tides to produce electricity.	Used world-wide for many years – needs a coastline.
Biomass		Biodegradable fraction of wastes agriculture, forestry and industrial activities, as well as municipal sewage and municipal solid wastes.	Used to create gas, or burned direct for small scale projects.
Biogas		The gas produced from Biomass, purified and used as fuel.	Growing technology, effective so far.
Hydraulic Energy		The energy of waterfalls, which is exploited by small hydroelectric plants (up to 15 MW)	Small-scale, but with dams can be major hydro-electric.

3.0 Experimental Section:

In the following section, a series of experiments is described which measure the decline in power output from solar panels as the sand and dust level increases. This then allows the calculation of energy wasted, so that it can then be seen what the maximum figure is to make cleaning worthwhile – it must use less power to clean the panels than is lost through sand build-up.

3.1 Introduction:

The experiments used were to measure how the level of dust or sand on the surface of a panel affects the voltage output with a standardised light source. The light source was a fixed distance (92cm) from the surface of the panel. When the room was darkened, the output of the solar panel was measured under standardised illumination, and then at various levels of sand build-up until the point was reached where there was effectively no output from the panel.

The purpose of this is to establish the amount of sand that must be deposited before it is necessary to clean the panel – thus, in any location, if the build-up rate is known or measured, it will be possible to calculate the frequency of cleaning needed to optimise the output – if it is done too soon, the cost of cleaning outweighs the gain, and if left too long the power loss is too great.

Before describing the experiment in detail, the theoretical operation of the solar cell is considered, briefly explain how it converts sunlight into electricity and the advantage of the multi-junction device over the original single junction pn semiconductor solar panel.

3.2 Solar Cell Theory

When the principle of converting light to electricity was discovered by Alexandre Edmond Becquerel (1820-1891) in 1839, no practical use was immediately foreseen, and it was not until silicon semi-conductors were invented in the 1940s that solar cells were made on a commercial basis. Figure 13 shows the basis of operation of a single junction solar cell as explained by Smets, et al., (2016). Figure 14 shows why the inverse square law and the cosine law are applicable to solar energy by showing the distribution of light on the earth.

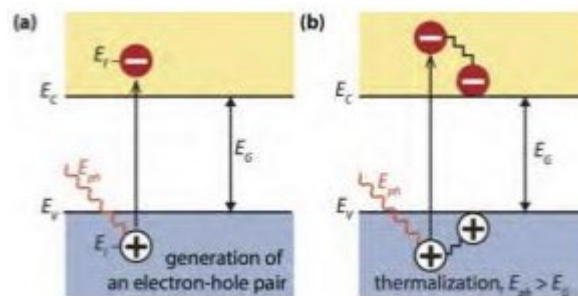


Figure 13: (a) Illustrating the absorption of a photon in a semiconductor with bandgap E_g . The photon with energy $E_{ph}=h\nu$ excites an electron from E_i to E_f . At E_i a hole is created. (b) if $E_{ph}>E_g$ a part of the energy is thermalized. Source: (Smets, et al. 2016, p. 22)

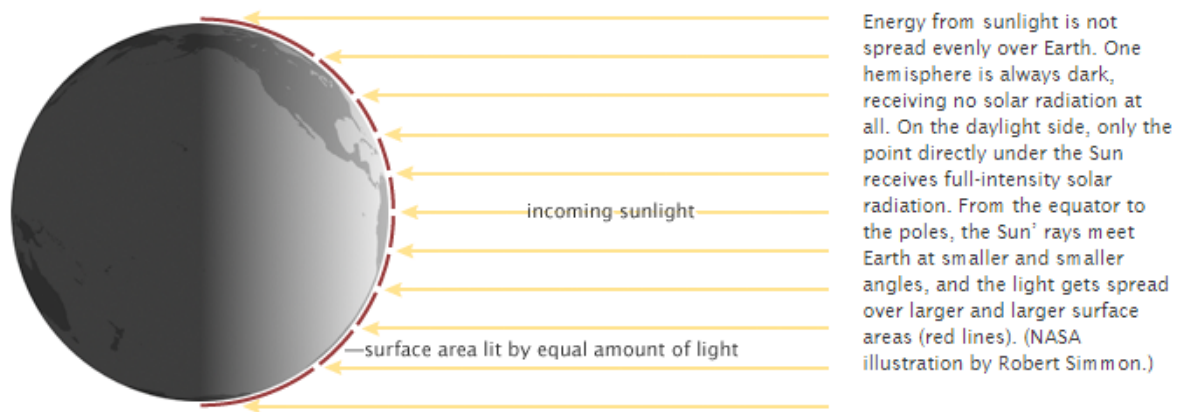


Figure 14: The way that Sunlight is Spread on the Surface of the Earth. Source: (NASA 2016)

Thus, from Figure 13 it is seen that, by absorbing a photon, it is necessary for the excited atom to release an electron in exchange. By connecting an electrode to each side of the panel, a flow of electrons (electricity) is produced - a solar panel consists of thousands of individual photovoltaic cells.

The difficulty that arises is that certain materials are only sensitive to certain wavelengths of light, which is the cause of the Shockley-Queisser limit (Shockley and Queisser 1961) mentioned above. Third generation solar cells are of a multi-junction design, which is achieved by using several layers of different semiconductor materials each of which has a different frequency response, increasing the efficiency of the cell.

Figure 15: A Triple Junction Cell. Source: (Esfandyarpour 2012)

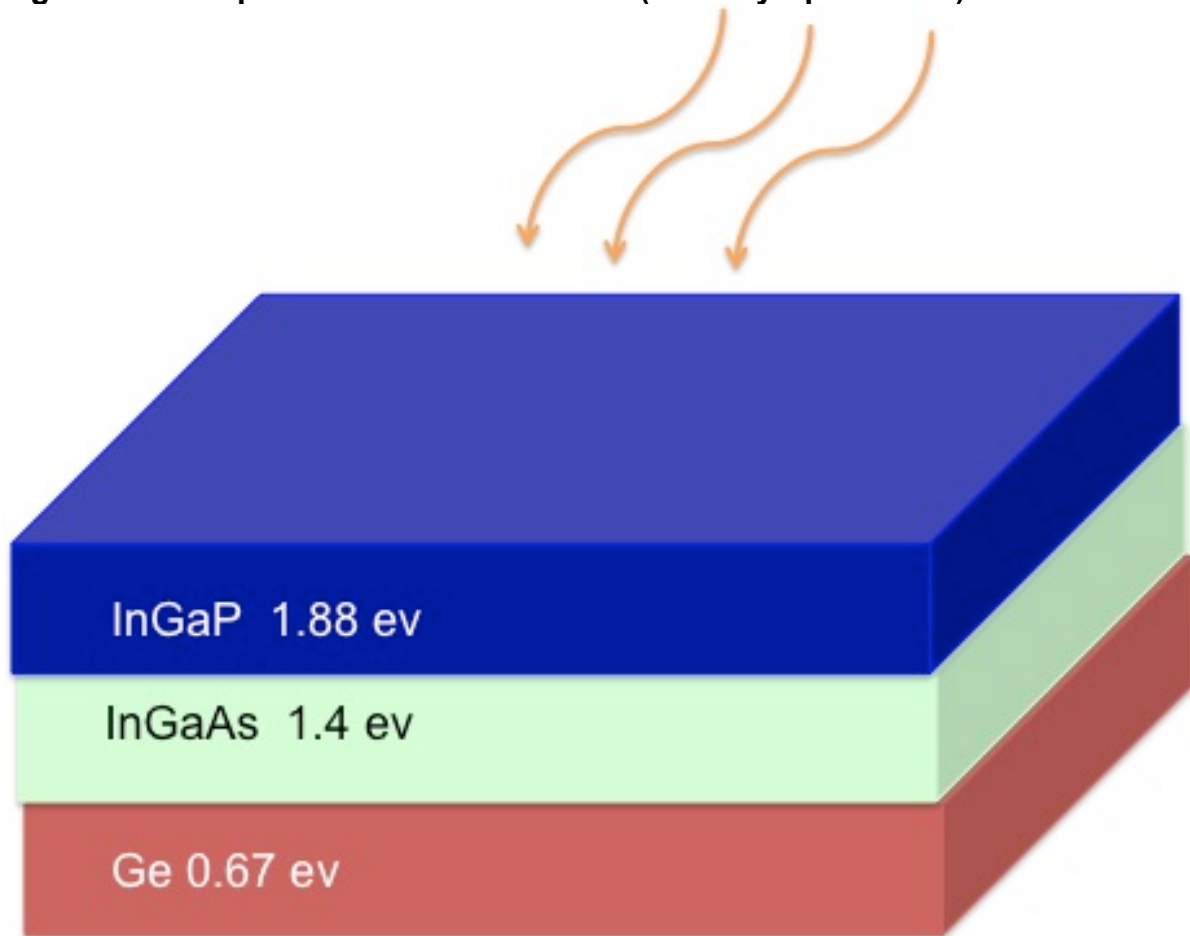


Figure 15 shows a triple junction cell, but it is possible in some cases to increase this further. The key to the symbols used in the Figure are; As=Arsenide, Ga=Gallium, Ge=Germanium, In=Indium, and P=Phosphorous. Some cells also do include the original Silicon (Si), giving at least one more junction, depending on the arrangement of the 'sandwich' (*i.e.* $\text{InGaP/Si/InGaAs/Ge}$ or $\text{InGaP/InGaAs/Si/Ge}$ are both possible).

3.3 Experiment:

3.1.1 Experimental Procedure

The equipment was set up as shown in Figure 16. It was ensured that the room was completely dark, so that the solar panel would only receive illumination from the standardised light source. The procedure was to evenly spread sand across the

surface of the panel 1g at a time, recording the output. The room temperature throughout the experiment was 22.5°C.

Figure 16: The Experimental Set-Up, Showing Panel. Light-Source. and Meter.
Source: (Own Photo)



The first reading recorded was with the room darkened, no sand on the panel, and then illumination by the standard source. Then 1g of sand was spread evenly across the surface of the panel and the experiment was repeated. This was then repeated with 2g, 3g, 4g, 5g, 6g, 7g, 8g, 9g, and 10g of sand, and the output noted for each level. Additional photos can be seen in [Appendix III](#). The measured results are tabulated in the next section. The panel used for the test was a Monocrystalline Solar Module. The details are shown in Table 2.

Weight	1.5kg
Size	430*350*20mm
Power Tolerance	±3%
Max. System Voltage	DC 600V
STC (Standard Test Conditions):	
1000W/m² AM = 1.5 T = 25°C	
Max. Power (P_{max})	20W
Max. Voltage (V_{max})	17.60V
Max. Current (A_{max})	1.14A
Open Circuit Voltage	21.50V
Short Circuit Current	1.25A

Table 2: The Specifications of the solar panel used in the experiment.

From this, the working area of the panel is calculated as 0.15m². thus, the output and sand levels can be scaled to a figure of per square metre for calculations with larger panels. It is also possible to measure the output in similar terms: 20W from 0.15m² is equivalent to about 130W/m². This figure equates to approximately 1kW per 8m² of panels, and many Saudi Arabian solar fields are measured in km².

3.4 Results and Tabulation:

As expected, the results (see Table 3) showed a steady decline in voltage as the sand level increased. This decline in voltage is more clearly seen in the graphic representations in Figure 17 and Figure 18.

No	Sand Added	Total Sand	Voltage o/p	Comparative Efficiency
1	0	0	7.1v	100%
2	1g	1g	6.2v	76.2%
3	1g	2g	5.8v	66.8%
4	1g	3g	5.0v	49.6%
5	1g	4g	4.4v	38.4%
6	1g	5g	3.5v	24.3%
7	1g	6g	2.9v	16.7%
8	1g	7g	1.8v	6.4%
9	1g	8g	1.3v	3.4%
10	1g	9g	1.1V	2.4%
11	1g	10g	0.7v	<1%

Table 3: The Experiment. The Panel was exposed to the light source and the voltage obtained was noted down. Sand was added 1g at a time until a total of 10g had been added, at which point the voltage output was 0.7V

Figure 18 shows how, although the voltage has dropped by less than one volt from 7.1v to 6.2v, this is equivalent to losing 23.8% of the output the realisation of this being that, in the case of a uniform build up, the panel must be cleaned before this stage is reached to minimise losses.

Figure 17: The decrease in voltage as the sand is applied

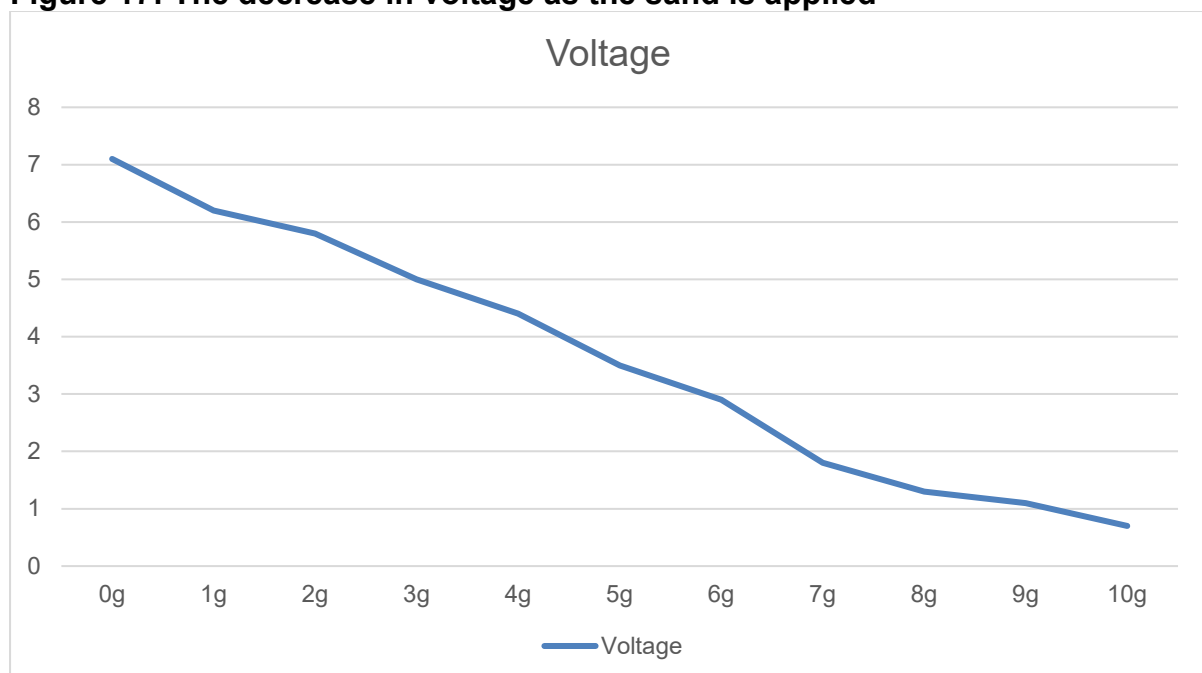
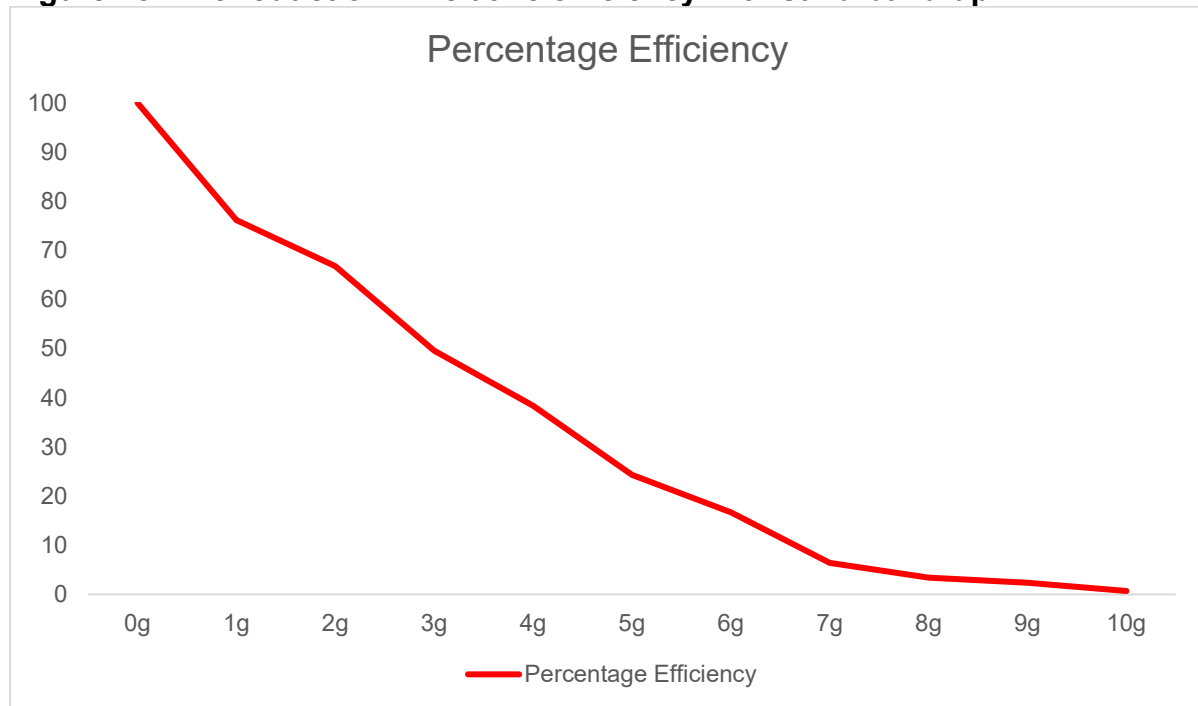


Figure 18: The reduction in relative efficiency with sand build-up



The addition of 1g of sand to the test panel is the equivalent of 6.6g/m^2 , which may appear to be a large figure, but research has indicated that in one day, the sand settling on a panel in Saudi Arabia can reduce efficiency by 60% per day. From Figure 18, 60% loss occurs at about 5g or 33g/m^2 (Maghami, et al. 2016, NOMADD 2017). Over a twelve-hour day, this equates to $2.8\text{g/m}^2/\text{hr}$.

3.5 Analysis of Results:

When the results are examined and compared with known figures of sand build-up of around 33g per day (based on the loss of 60% efficiency (Maghami, et al. 2016, NOMADD 2017)) it becomes clear that despite recommendations that the panels are cleaned daily, cleaning twice daily would reduce the losses by half to around 30%.

Thus, provided the energy used in cleaning the panel is less than 30% (which it would be expected and designed to be), the cost-efficient cleaning point would be twice per day, or every six hours (the panels are only in use during daylight).

4.0 Discussion:

Having seen that 60% of the original output is lost when about 5g of sand are deposited on the test panel, and that in use in Saudi Arabia 60% loss is typical across one day operation, the equivalent daily build-up is shown to be 33g/m^2 per day, or $2.8\text{g/m}^2/\text{h}$. this indicates the ideal cleaning cycle for the panels is once every six hours provided the power used per square metre is less than 30% of the six-hour output.

If the hourly output per square metre is 130W (in fact it will be more, as the sun power in Saudi Arabia greatly exceeds the 1000W/m^2 used to test the panels) then $30\% \times 130\text{W} \times 6\text{hrs} = 234\text{W}$ would represent the maximum limit to be cost-effective for six-hour cleaning. If the design power can be halved, then three hourly cleaning would be a possibility. In the final design, the motor will run continuously, but the wiper will move very slowly.

The alternative to this would be to have an interrupter gear mechanism, so that although the motor continued to run continuously it would only drive a wiper once every three hours. This is less efficient for two reasons – the first is that most of the time the running motor is simply wasting energy, and the second is that the torque multiplication from very low gearing is not present, so a more powerful motor may be required.

Other alternative design possibilities are discussed in depth in the following section, but essentially the chosen design has the advantages of an enclosed mechanism which will keep out dust and sand, and an ability to sweep 100% of the panel area with no waste effort or unswept areas. Every other design considered left some areas unswept, and required complex mechanisms which were not easily enclosed.

The experimental procedure itself provided results very close to those of Rao, et al. (2014) and Saidan, et al. (2016), but despite this similarity the experiment could be repeated using much smaller quantities of sand per application so that a very slow sand build-up could be demonstrated. However, even without this the experiment confirms the findings of many other researchers and indicates an optimum cleaning period of three hours – more frequent cleaning seems unnecessary, and could use more energy than it saved, making it unhelpful. If cleaning is to be carried out it is essential that it saves more energy than it uses, anything more would mean that it was not worth cleaning the panels until they actually stopped working.

5.0 Application:

In this section, the design concept for the application will be laid out in detail, with a product design specification (PDS). The PDS details what must work, when, where, and under what conditions – in other words the operating parameters of the device as well as a description of its purpose. After the PDS the initial design will be described, followed by some of the alternatives considered. This leads to the limitations of the research, and finally to a conclusion.

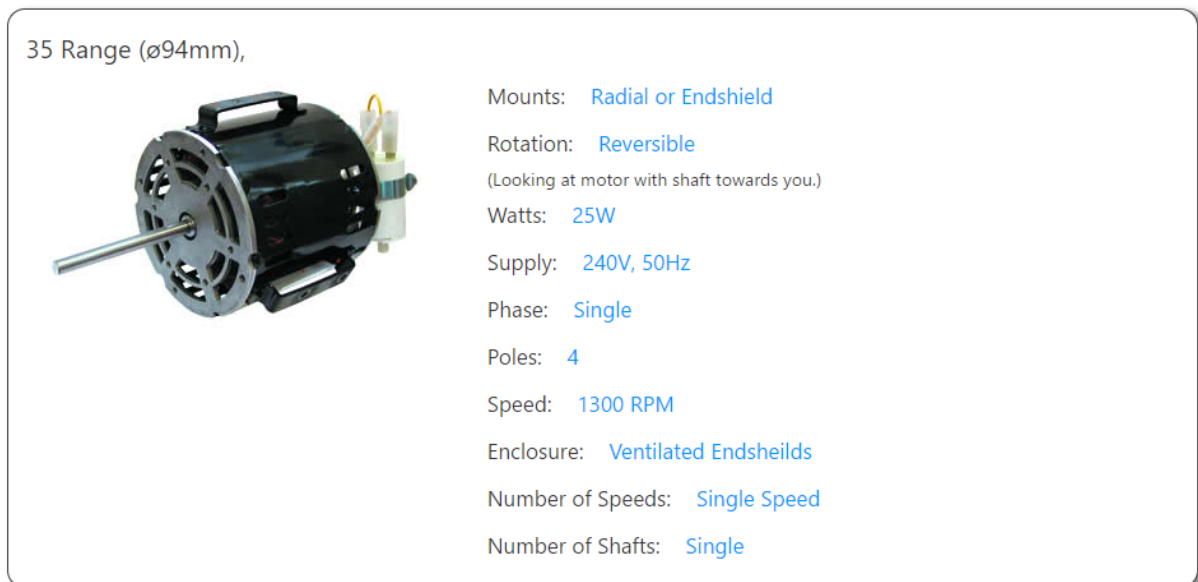
5.1 Design Concept

The concept of the design is to create a slow-moving wiper, which obscures only the smallest area of the panel as it cleans it. The panel size for the prototype is 1m x 500mm, (0.5m²). The optimum cleaning period for the panels has been determined to be three hours, but small electric motors are generally more economical when run at a constant speed (Bird 2013). Therefore, the action must be continuous, so the 25W motor, running at 1,300 RPM (see Figure 19) needs to be geared down so that one complete revolution of the mechanism (Figure 24) takes three hours. This

overall gear ratio of 234,000:1 multiplies the torque to such a degree that the losses in the mechanism, linkage, sliders and rollers may effectively be ignored.

This ratio is obtained from the timing. Three hours contain 180 minutes, which means that, at 1,300 revolutions per minute, in 180 minutes, the motor will have rotated $180 \times 1,300$ times, or 234,000 times, but the mechanism will have rotated only once, giving a ratio of 234,000:1 and when the motor is running, the movement of the wiper bar is only perceptible if it is watched for several minutes – it will move one metre in 150 seconds, or 6.67mm per minute. On the return, it will move one metre in 30 seconds, or 33.33mm per minute so the return movement will be clearly visible. As previously explained, this has advantages of efficiency and the torque multiplication obtained from very low gearing.

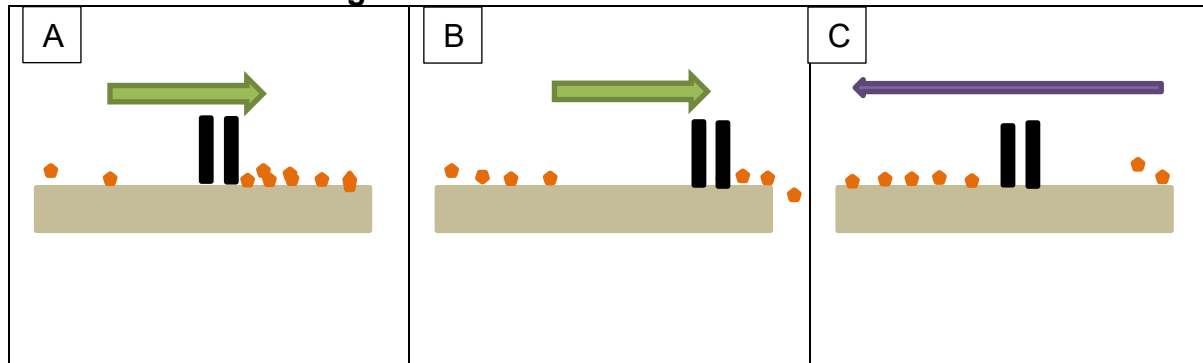
Figure 19: A 25W Motor suitable for the project. Source: 35-4-25R1



The actual intended operation of the cleaning wiper is illustrated in Figure 20: in the Power Stroke (Green Arrow, A & B) the sand that has built-up (orange hexagons) on the surface of the solar panel is pushed ahead of the brush until cleared at the end.

In the time taken for the power stroke, some sand has settled behind the brush (A and B), but on the rapid return (long purple arrow), this is also cleared.

Figure 20: The Action of the Wiper. A. Power Stroke clears build-up of sand. B. Power Stroke Ends after 2hr 30min. C. Rapid Return (30min) clearing the sand that has settled during the Power Stroke.



The drive arms are at each side of the panel, and have low-friction nylon rollers to guide them along the edges of the panel. The wiper arm supports the brushes and connects to the shaft on which the roller turns, making a robust design that is unlikely to jam. The constant action and fast return mean that the whole panel surface is brushed clear once in each direction every three hours, as recommended by the research.

In addition, it would be possible for two wiper bars to be operated by one motor, if these were mounted side by side. *i.e.* one mechanism cleans two panels that are adjacent. This is described more clearly in the PDS that follows.

5.2 Product Design Specification

5.2.1 General Overview

The product must wipe clean the surface of the solar panel at a predetermined frequency to combat the build-up of sand. It is assumed for this design that the solar panels to be cleaned are all the same design and have a standard size. An array of panels could share a wiper if horizontally arrayed, but each vertical layer would

require its own cleaning. The 25W motor used is sufficient for two panels, but if the array was wider it would either require an additional mechanism or a slightly more powerful motor. On one panel a 25W motor uses less power than it saves, so on two panels the efficiency is doubled. Therefore, increasing the power to 50W for four panels would represent the same saving, with a very small improvement because only one mechanism was moving.

5.2.2 Architectural Design

The wiper must be designed so that it is drawn steadily across the surface of the panel, cleaning 100% of the active surface. A wiper such as that used on a car windscreen is not suitable, as it does not cover the entire surface, but only an arc. The speed of the wiper in each direction will depend on the panel area and the rate of sand build-up so that most of the surface area is covered in less than the optimum time. The actual speed setting would be variable according to local conditions.

The maximum power used must not exceed 230W for six-hour cleaning or 115W for three-hour cleaning (this figure is for each square metre of panels). If the power required for each square metre exceeds this, cleaning would cost more in terms of power use than it could save in terms of power gained, however, this should not represent a design difficulty. As described in the Design Concept, a 25W motor should be more than powerful enough for the job.

5.2.3 Performance

The wiper motor will run continuously during daylight, and will be geared to run at a speed that one forward stroke and its return take a total of 3hrs to cover 1m. geared to move this slowly, the wiper will have sufficient force to clear any dust or debris, and the panel will be wiped completely every three hours. In the event of a water

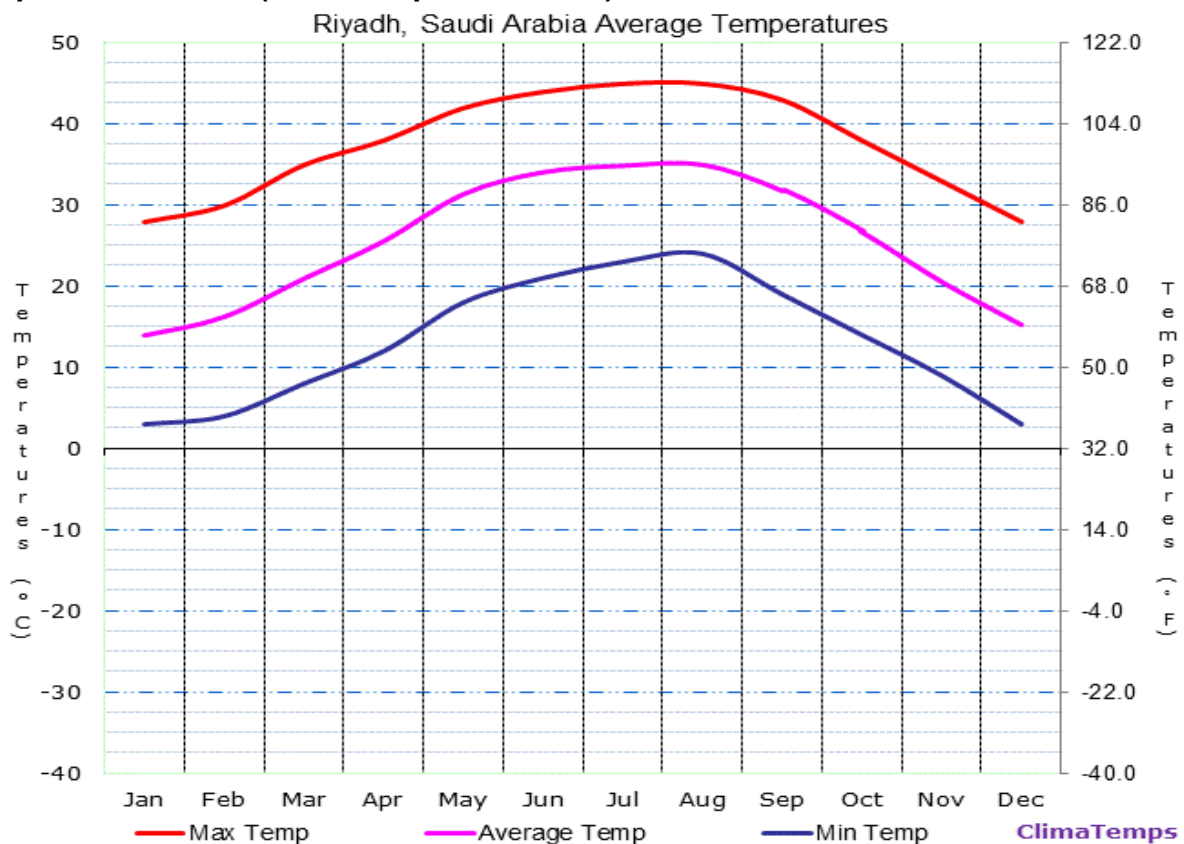
source being available nearby, the system could be designed to wash the panel, which could also cool the panel, which has also been shown to be important (Bahaidarah, Baloch and Gandhidasan 2016).

5.3 Operating Environment Specifications

5.3.1 Operating Temperature

The wiper mechanism must be designed so that the expansion and contraction of the components does not affect the operation of the wiper across the range of daytime temperatures it will encounter in Saudi Arabia. Although the range of temperatures shown in Figure 21 is a typical figure, the maximum often exceeds 50°C.

Figure 21: An example of the temperature range over which the wiper must operate. Source: (Climatemps.com 2017)



5.3.2 Operating Humidity

This can also affect the operation of the wiper, but it is essential that all bearings are well lubricated and sealed, minimising both the effect of humidity and of dust and sand which could contaminate the mechanism. The use of sealed bearings also reduces the maintenance requirements of the mechanism to occasional cleaning and annual checks on the movement of each part. With nylon or PTFE wheels running in nylon or PTFE tracks, neither humidity nor heat should adversely affect the mechanism.

5.3.3 Duration of Operation

The wiper only needs to operate during daylight. The speed of operation is calculated from the length of travel and the frequency of sweep needed to keep it clear, but the wiper can be inactive for at least twelve hours per day. The local start/finish times will be dependent on local sunrise/sunset times.

5.3.4 Other factors

Although in the desert, rainfall is not high, it does occur, and it is essential that this does not in any way interrupt the operation of the wiper. In addition, although the lowest temperatures encountered rarely drop into single figures, frost does also sometimes occur – therefore the mechanism must be able to operate over a very wide range of temperature, from 0-55°C.

5.4 Initial Design

The support bar for the wiper brushes is shown in detail in Figure 22, and the engineering drawing for it is shown in Figure 23. The wiper bar will be mounted onto the roller shafts of a framework which runs the 1m length of the panel (panel size for

this initial design is 1m x 500mm). this framework is driven by a small, low power electric motor and is a 'Whitworth quick return mechanism' (see Figure 24). The forward stroke of the mechanism is very slow, and including the 'quick' return, one cycle is intended to take three hours. This would be in the ratio of stroke: return = 5:1, taking 150 minutes (2.5hrs) for the stroke, and 30 minutes for the return. Allowing for the losses in the linkages and bearings, moving at this speed a 25W motor should provide adequate power.

The material for the wiper support bar is PTFE, as this material will not be affected by the extreme heat and is rigid enough to support the brushes. These are clipped into the holes along the length of the support bar, and the 'leading' brush which operates during the 'stroke' would be a much denser, coarser brush than the 'trailing' brush which operates mainly on the 'return'. The ratio of the quick return mechanism is adjustable to a small degree, and the speed is determined by the motor gearing; because the electric motor spins very fast, and the mechanism moves very slowly, the torque is multiplied, so that a 25W electric motor would provide sufficient torque without straining the motor or bearings.

Figure 22: The PTFE Wiper bar for the cleaning system. Source: (Own Drawing)

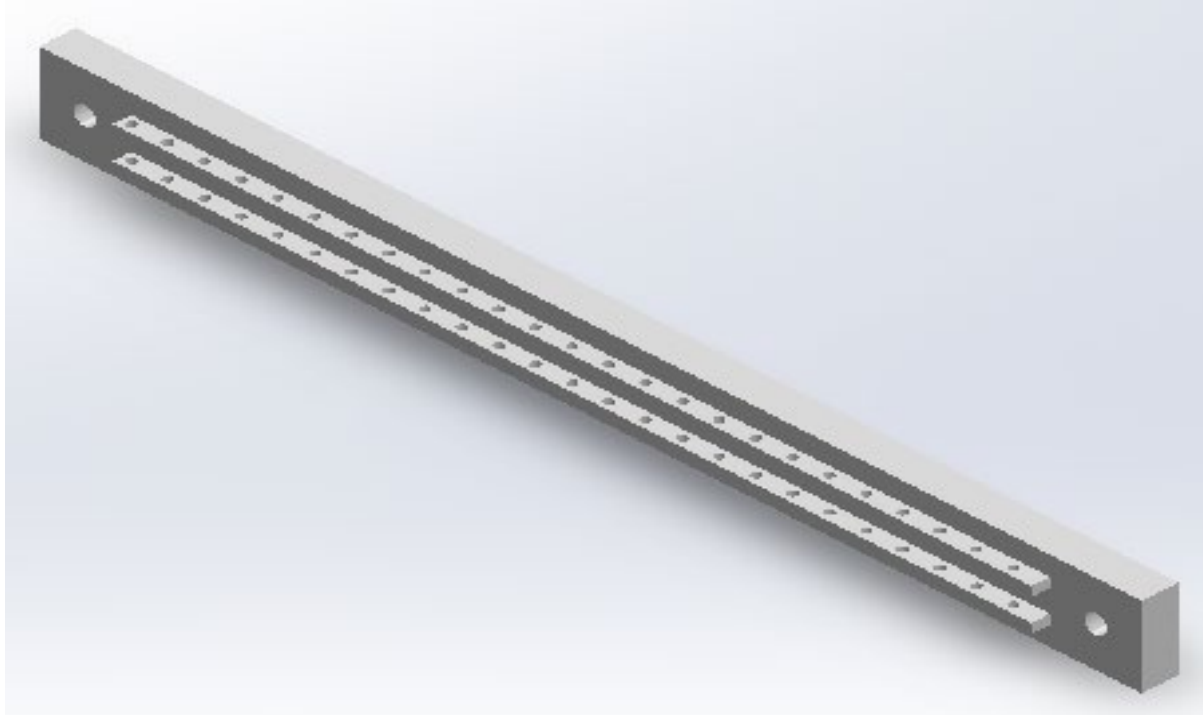


Figure 23: Engineering Drawing (A3) of Wiper Bar. Source: (Own Drawing)

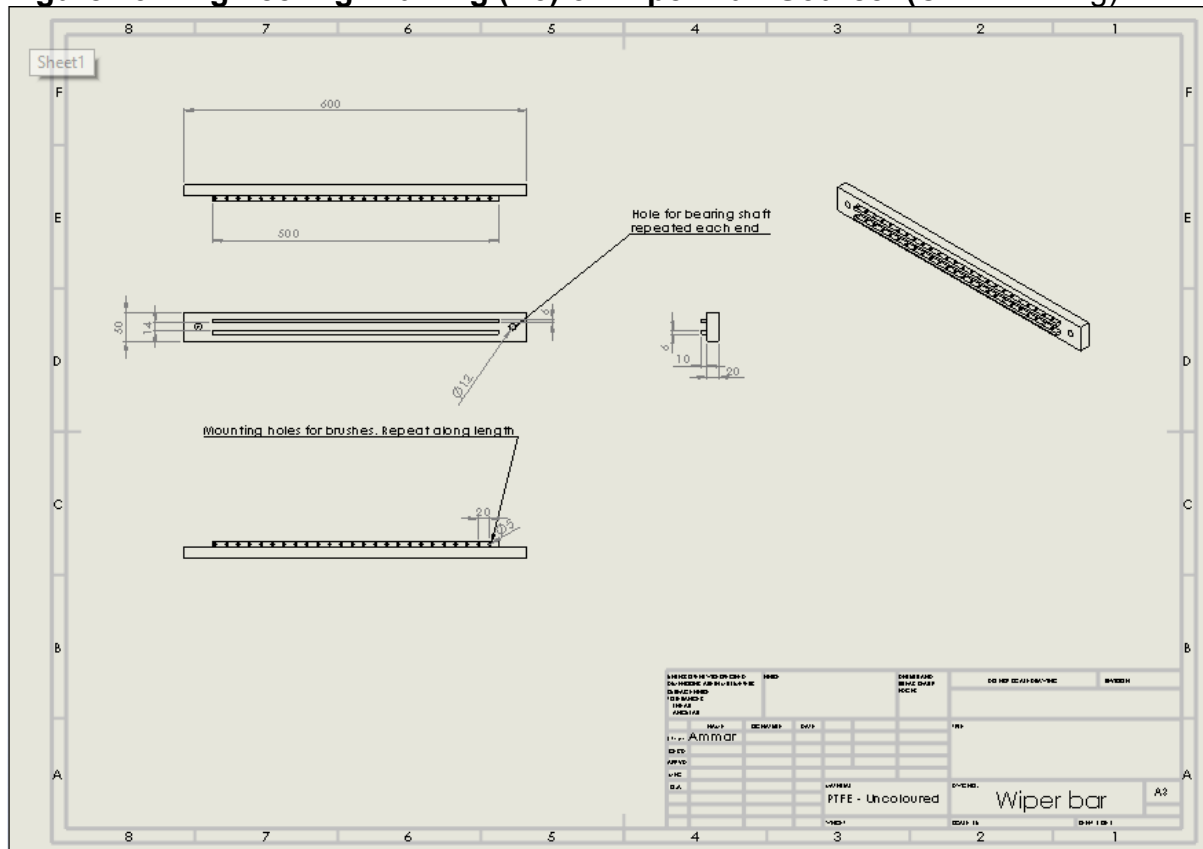
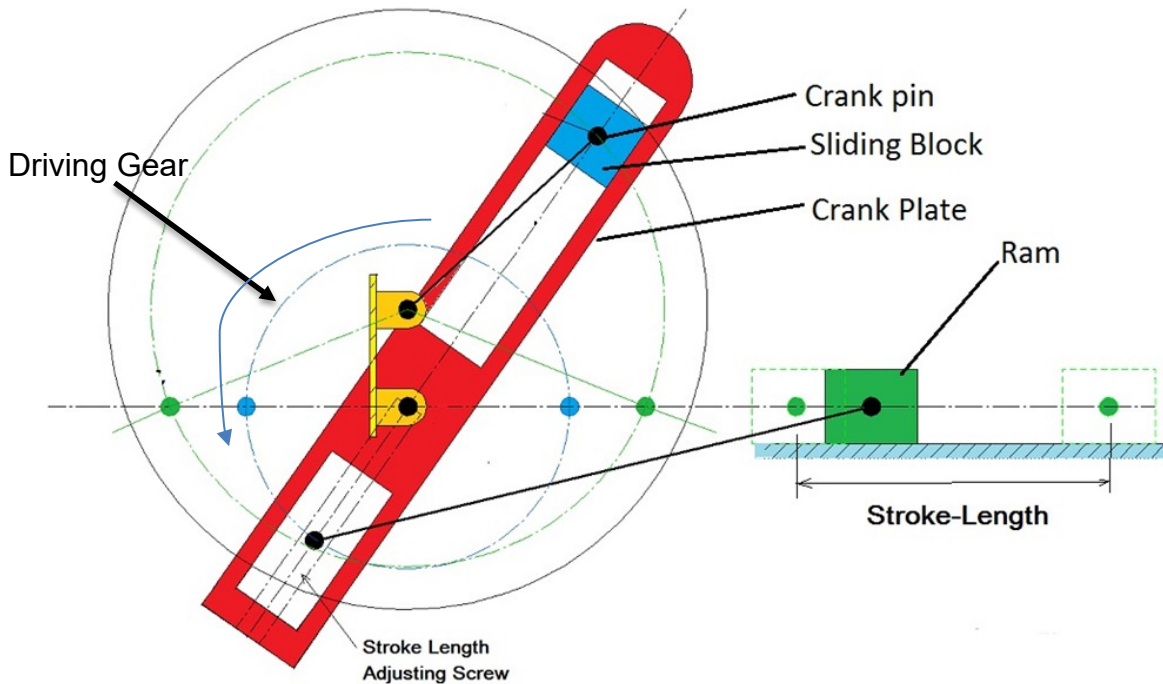


Figure 24: The Whitworth quick return mechanism. Source: (Mechanical Engineering 2015)



Withworth quick return mechanism

The mechanism which operates the slider arm is a very common mechanism in engineering. The Whitworth quick return mechanism was first used on shaping machines, and is shown in Figure 24. The driving gear turns the outer gear and forces the ram forwards at full power, but the length of the crank pin the determines the return speed, which has less power. Therefore, the 'leading' brush will be much denser and coarser than the 'trailing' brush – in the slow movement across the panel the sand will be building up as the brush moves, so there will be a heavy load, but during the quick return the load will be much less.

Having determined that the motor must have a gear ratio of 234,000:1, and that the desired cycle time is 3 hrs with a ratio of 5:1, the torque multiplying effect of the low gearing will have the following effect;

$$Torque (Nm) = 9.5488 \times Power(kW) / Speed(RPM) \quad \therefore$$

$$9.5488 \times 0.025kW / 1300RPM = 0.000183Nm \quad \therefore$$

$$Effective\ torque = 0.000183 \times 234000 = 42.97Nm$$

Thus, the available torque for power stroke and return stroke is;

$$Power\ Stroke = \frac{5}{6} Effective\ torque$$

$$Power\ Stroke = \frac{5}{6} 42.97 = 35.81Nm$$

AND

$$Return\ Stroke = \frac{1}{6} Effective\ torque$$

$$Return\ Stroke = \frac{1}{6} 42.97 = 7.16Nm$$

Even with an efficiency of 50% (due to losses) this is ample for the purpose.

5.5 Alternative Design Possibilities

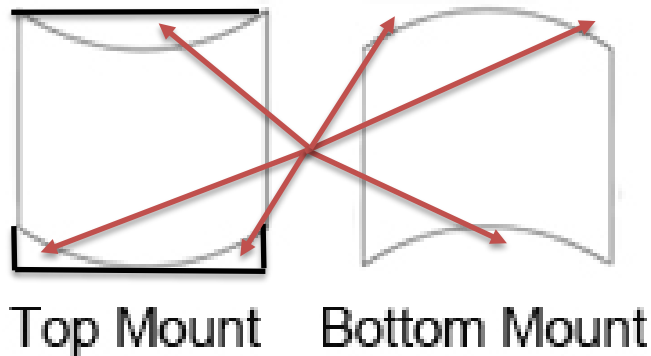
Other possibilities were considered for the design, including a wiper producing an arc, with another diagonally opposed to it also producing an arc. These designs initially seemed easier to produce than the finalised design, but in practice, arranging the gearing of the blades so that they did not interfere with one another required a more complex gearing mechanism that could not easily be enclosed, and was thus likely to become clogged with sand or dust in a relatively short time, requiring regular maintenance.

The single wiper with a parallelogram (pantograph) arc was also considered, but this presented two difficulties. The first was that encountered for the arc wipers – the exposed nature of the mechanism made regular maintenance a necessity. The second was that however carefully the wiper was designed, unless it was larger than the panel there were unswept areas, as Figure 25 shows. Although these are smaller than the unswept areas of an arc, they were still not acceptable for this project,

although they could be considered as a second best alternative apart from the exposed mechanism.

Figure 25: The Unswept Areas with a Pantograph Wiper are Shown with the Arrows. Source: Generic Picture

Pantograph Sweep Pattern



5.6 Research Limitations

Several assumptions have been made for this project, mainly regarding the size of the panels and the dust accumulation rate. The figures for the latter are approximate, but based on the results of several different research projects (Bahaidarah, et al. 2015, Costa, Diniz and Kazmerski 2016, Cristaldi, et al. 2014, Javed, et al. 2017, Maghami, et al. 2016, Rao, et al. 2014), all of these had examined the dust build-up in desert locations, and the figure used here is an approximate average of the figures that they found. The panel size was based on what is easily available – it is probable that the panels used in a real solar field would be considerably larger, but the figures can be scaled-up if necessary.

The experimental section of the research is also a possible area of limitation; ideally, an even finer distribution of smaller quantities of sand (0.25g?) would give a more accurate view of the way that the power is reduced. That said, the figures obtained

experimentally were quite close to those observed by the researchers listed above regarding deposition rates for the sand.

5.7 Conclusion

The project set out to discover a solution for a specific engineering problem – ensuring that sand is cleaned off solar panels sufficiently frequently to maintain an acceptable level of efficiency. The research shows that the optimum period is every three hours during daylight (cleaning at night is not necessary), so a constant cleaning brush was envisaged, that could either clean a single panel, or, connected side by side, two panels. The power consumption of the drive motor for the wiper is only 25W (0.025kW), to clean up to 1m² (2 panels of the size on which the design is based). This is much less than the calculated ‘cost limit’ – to be cost-effective, the motor must have a maximum power of 234W, therefore the 25W motor will clearly improve the overall efficiency of the design.

The mechanism chosen to operate the cleaning wiper is the ‘Whitworth Quick Return’ mechanism, as this is a ‘tried and tested’ technology and is efficient. In this design the stroke and return are much slower than the name implies - very slow, in fact, as the intention is to make the complete cycle take three hours. This would be two and a half hours for the drive stroke and half an hour for the ‘quick’ return. This design ensures that every part of the panel is cleaned within the 3-hour optimum period. This means that the efficiency of the panels is maintained at approximately 85% of the rated output, instead of allowing the panels to be uncleaned and lose 60% as tested by Javed, et al. (2017). Thus, the saving equates to nearly 30% of the rated output in the course of the day.

During the course of the research, alternative options were considered, but these all had disadvantages or drawbacks when compared to the selected design. Although estimates were made of the rates of sand deposition, these were found to be very close to the empirical figures obtained by researchers in the field, and the experimental procedure, although fairly coarse, also aligned well with the findings of others. If the research were to be repeated, the concentration would be on increasing the accuracy of the experimental work with a finer sand distribution, and perhaps some temperature variation to see if any cooling was required. Although solar PV panels work best at around 25°C, and the desert temperatures may double this, the unknown factor is whether the coating of sand also cools the panels, increasing their efficiency to make up for the loss through being obscured. Although it is unlikely the two would balance one another out, it is possible that, if this effect is present, the cleaning interval could be made four hours instead of three.

In this experiment, it has been shown that, across a twelve-hour period, between 25 to 30% of the output of the panels is 'saved' by cleaning. This is a worthwhile amount, and would be a strong attraction for the companies operating the solar fields in Saudi Arabia – some of these are 25MW or more, so the saving 6 or 7MW per day per field is substantial. If considered in another way, without cleaning the panels in this way is reducing the efficiency, and therefore the company profits by nearly one third, and no business is likely to put up with that situation for very long.

Finally, this research project has shown a level of agreement with other researchers with regard to the losses caused by dust and sand, but additionally has offered a possible solution. This does not claim to be the only possible solution to the problem, but does demonstrate that a relatively simple idea can be modified to do the required

job, using a small, low-power electric motor and a simple brush arrangement. It has also been indicated that, if there is a sufficient water source nearby, the system could be modified to wash and cool the panels at the same time. Although it has been demonstrated that the coastal areas are less conducive to the use of solar PV energy, the cooling/cleaning water does not need to be 'fresh water' salt water would work just as well, particularly with the nylon/PTFE construction proposed, which is not affected by the salt.

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Appendix I

Project Timetable:

The timetable below (Table 4) shows the approximate duration of each stage of the project from proposal to completion. The total time allowed according to the brief is 400hrs of study. Phase two should ideally be completed by January, although additional hours have been allowed here in case of any difficulty arising. The 20hrs margin shown in February 2017 would only really be needed if the project ran into major difficulties.

Table 4: Projected Timetable for the Entire Project (400Hrs total)

Phase	Oct	Nov	Dec	Jan	Feb	Mar	Apr
One-Proposal	10hrs						
Two – Initial Research		100hrs total		40hrs	20hrs margin		
Three – Project Completion			200hrs total				30hrs

Appendix II

Initial Search Strategy:

This search strategy in Table 5 has concentrated on the period of the previous twelve months – it would be very easy to extend this period, or to widen the acceptable criteria, but at this stage the small number of articles found fits well with the intent to produce an initial guide or proposal. Only one article has been excluded from the final list, and only then because it was specifically aimed at an agricultural setting rather than the residential and industrial setting where the thrust of the research is aimed.

However, the next search strategy that was used was to search for any existing studies regarding dust contamination etc. on panels used in desert conditions in Saudi Arabia, The United Arab Emirates (UAE), and other countries in the MENA. This new strategy gave the results shown in the following table (Table 6).

Table 5: The search strategy used for the literature review and the results obtained.

Search Criteria/level	Include	Exclude	No. Found
Initial: Search for “difficulties of using solar energy in Saudi Arabia”			1,100
Then: Full Text Online	✓		
Scholarly and Peer Reviewed	✓		1,000
Date Range: Last 12 months	✓		112
Type: Journal Article	✓		31
Book Review		✗	30
Discipline: Engineering	✓		31
Economics		✗	26
Environmental Sciences		✗	21
Geology		✗	16
Biology		✗	12
Subject Terms: Energy & Fuel	✓		12
Solar Energy	✓		10
Energy	✓		10
Engineering	✓		10
Green & Sustainable Science	✓		10
Language: Latvian		✗	9
Русский		✗	8
English	✓		7
Title: One paper reject as title unconnected = “Ventilation in Agricultural Buildings: Characteristics and Measurements Methods (Review)”		✗	6
Remaining: 1: (Arif, et al. 2015) 2: (Chaharsooghi, Rezaei and Alipour 2015) 3: (Kassem, et al. 2016) 4: (Li, et al. 2015) 5: (Lyden and Haque 2015) 6: (Shafaghat, et al. 2016)			

Table 6: Second search for previous studies

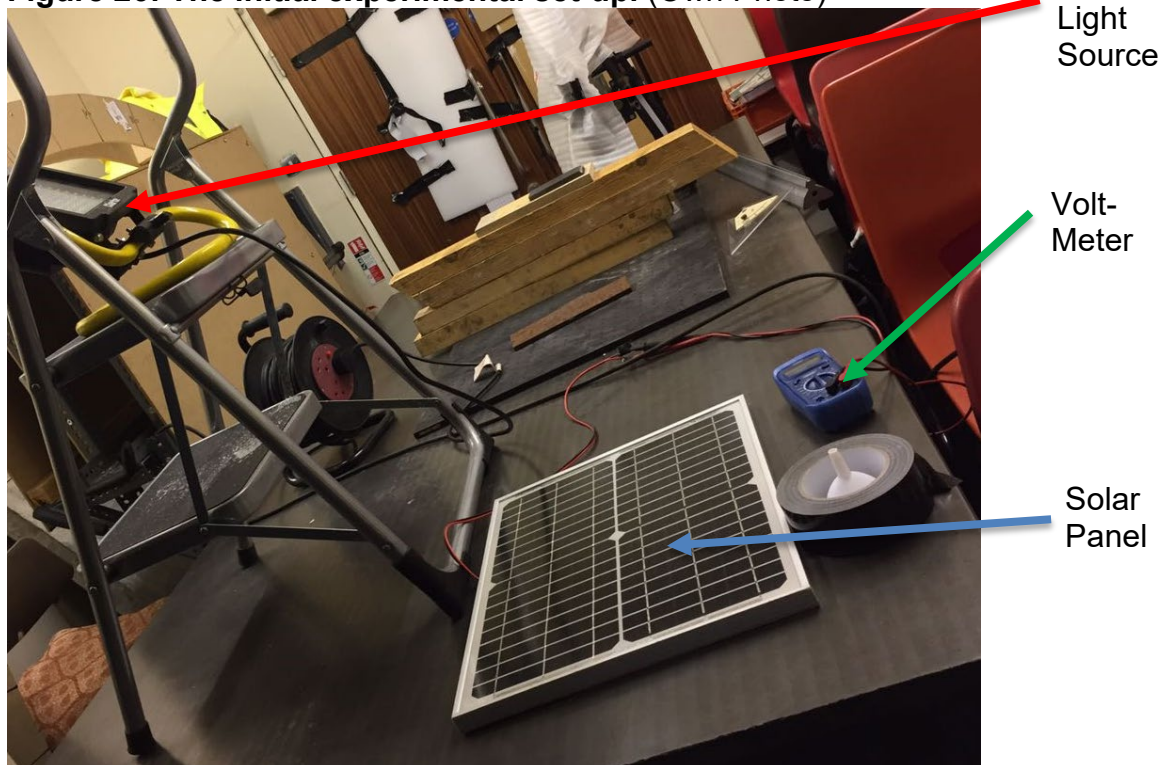
Search Criteria/level	Include	Exclude	No. Found
Initial: Search for “difficulties of using solar energy in Saudi Arabia”			1,100
Then: Full Text Online	✓		
Scholarly and Peer Reviewed	✓		1,000
Date Range: Last 12 months	✓		112
Type: Journal Article	✓		31
Book Review		✗	30
Discipline: Engineering	✓		31
Economics		✗	26
Environmental Sciences		✗	21
Geology		✗	16
Biology		✗	12
Subject Terms: Energy & Fuel	✓		12
Solar Energy	✓		10
Energy	✓		10
Engineering	✓		10
Green & Sustainable Science	✓		10
Language: Latvian		✗	9
Русский		✗	8
English	✓		7
Title: One paper reject as title unconnected = “Ventilation in Agricultural Buildings: Characteristics and Measurements Methods (Review)”		✗	6
Remaining: 1: (Arif, et al. 2015) 2: (Chaharsooghi, Rezaei and Alipour 2015) 3: (Kassem, et al. 2016) 4: (Li, et al. 2015) 5: (Lyden and Haque 2015) 6: (Shafaghat, et al. 2016)			

Appendix III

Experimental Work

The experimental set up consisted of a solar panel, light source, and voltmeter, as shown below.

Figure 26: The initial experimental set-up. (Own Photo)



A sand shaker was improvised

Figure 27: The sand shaker. (Own Photo)



And a weighing scale for the sand was also used;

Figure 28: Scales with 100g of sand. (Own Photo)



Initially, a reading was taken from the panel, and then 1g of sand was added, and a new reading was taken using the same light source.

Figure 29: The panel with 1g of sand. (Own Photo)



This experiment was then repeated, each time adding 1g of sand and taking another reading of the output of the solar panel.

Figure 30: The panel covered completely with sand. (Own Photo)

