Department of Electrical & Electronic Engineering

Independent University, Bangladesh

PROGRESS REPORT (1ST TERM)
OF
FINAL YEAR DESIGN PROJECT (EEE 400)

TITLE OF THE PROJECT

Use of Hybrid Plasmonic Nanoparticle Systems to Enhance the Opto-Electronic Performance of Thin-Film Solar Cells

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1. Introduction

Bangladesh has recently emerged as a country with a thriving economy with one of the highest GDP growth in 2019 **[1]**. It is expected that this growth will continue and with this phenomenal growth, the demand of power will increase exponentially. Unfortunately, Bangladesh is still predominantly dependent on fossil fuels to produce electricity. This dependency will create major problems as the fossil fuel reserve is estimated to dry out within a decade **[2]** and the severe impact on environment of the fossil fuel will make the situation even more difficult.

Solar energy has the potential to address the problem as it provides a greener alternative to the traditional fossil fuel and its cost can be compensated over an extended period of time as it requires almost no cost after installation. Solar energy is abundant in nature and Bangladesh is particularly blessed with a suitable geographic location to harness solar energy for energy applications in large scale **[3]**.

However, two of the major challenges of current Photovoltaic (PV) technology is the relatively high cost of production and the relatively low energy conversion efficiency. Commercially available solar cells have an efficiency that is less than 30% **[4]**. It is absolutely crucial to reduce the cost of the solar cell in order to have large scale implantation in Bangladesh. It is observed that a big portion of the cost of a solar cell made of crystalline Si is the material cost of Si itself as it comprises almost 40% of the total cost of a solar cell **[5]**. Thin-film solar cell has the potential to reduce this cost significantly as it uses a very thin layer of Si (not more than 3 μm) and saves a lot of the bulk material **[6]**. But this reduction of material also reduces the volume of the absorbing layer and thus the efficiency is also reduced. To increase the path length, different light trapping technologies such as anti-reflection coating, surface texturing etc. have been studied **[7]**. Among them, the usage of various metallic nanoparticles has shown favorable results as it can increase the optical absorption significantly through harnessing the unique phenomenon of surface plasmon resonance (SPR) **[8]**.

Along with homogenous metallic nanoparticles, various hybrid nanoparticles such as core-shell (a metallic core with a dielectric shell) has shown promising results **[9]**. These metal core-dielectric shell nanoparticles are characterized by surface plasmon resonance and localized surface plasmon resonance (LSPR) modes that come into play when these nanostructures are stimulated by an incident radiation. These phenomena result in enhancing the amplitude of electric fields in the immediate vicinity of the nanostructures, at resonant wavelengths **[10]**. The metallic core usually exhibits the plasmonic properties and contributes in the field enhancement whereas the shell provides electrical and chemical isolation contributing to the stability of the nanoparticle and also allows the possibility of embedding the nanoparticles inside the substrate as it can preserve the condition of metal-dielectric interface and facilitate the surface plasmon resonance to occur. These nanoparticles' plasmonic properties are highly morphology dependent, meaning that change in shape, size and size distribution may affect them remarkably **[11-12]**. This project intends to study the various properties of these hybrid nanoparticles with respect to size, shape, type and configuration to increase the opto-electrical performance of the thin-film solar cell and thus investigate the possibility of reducing the cost by increasing the efficiency of thin-film solar cells modified by such hybrid nanoparticles.

2. Background and Motivation

The majority of the electricity generated in Bangladesh is through the use of non-renewable energy sources like natural gas and other fossil fuels **[13]**. With the rising energy requirement than ever before, as Bangladesh strives towards development goals by opening new industries in different sectors, providing a reliable electrical energy supply is of the utmost priority. It is of utmost importance to highlight, analyze, and predict the current trends of electrical energy generation in Bangladesh. Figure **(1)** highlights the current electric energy generation capacity sorted using different type of resources. From Figure **(1),** it can be clearly observed that the overwhelming generation of electricity depends on the use of non-renewable energy sources (92.51%) and renewable energy generation makes up a very small percentage (1.6%) in the total generation capacity. For the year of 2019, electrical generation capacity using gas as the fuel accounted for 57.36% (10877 MW) of the total installed generation capacity followed by oil (furnace oil and diesel) with a percentage of 32.239% (6140 MW), imported power with 6.12% (1160 MW), coal with 2.76% (524 MW), hydro with 1.21% (230 MW) and lastly solar PV which only accounted for 0.16% (30 MW) of total generation capacity **[13].** The current annual production of gas is at 0.97 Tcf (trillion cubic feet) (2018) and 11.47 Tcf of reserves remaining **[14]**. Considering the yearly growth and production rate, natural gas reserves in Bangladesh will last up to 2026 **[15]**. In order to tackle this problem, coal generation power plants are expected to play a key role for power generation **[16]**. This can bring about adverse effects on the environment, and decrease the already low air quality in the country. In 2019, Dhaka city has repeatedly been ranked as the city with the worst air quality, with an air quality index (AQI) score ranging from 242 to 252 **[17]**. Bangladesh has a high potential to harness solar energy due to its favorable geographical location. A study conducted estimates that the total grid-connected Solar PV potential in Bangladesh could be 50 GW **[18]**, which is many folds above the current and even future energy demands of Bangladesh. Hence, in order to mitigate the negative environmental impact of fossil fuels (diesel, furnace oil, gas, coal) and decrease the reliance on fossil fuels for energy generation, special attention should be given in increasing the renewable energy sector. More specifically, investments should be made to increase the solar energy generation of Bangladesh.

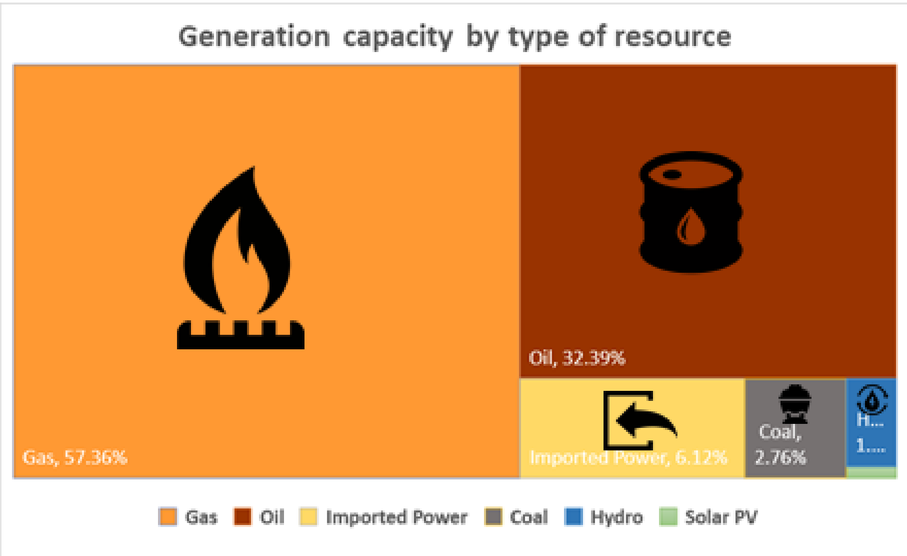

Figure. 1. Electrical Genration capacity of Bangadesh by type of resource used (2019) **[13]**

PV solar cells account for a very small percentage in generation capacity for the national supply grid in Bangladesh (0.16%) **[13]** but there has been a growing market for PV cells in the form of microgrids. Despite the relatively high cost of PV solar cells, it has successfully been adopted for generating electricity in rural areas. These rural PV solar systems are also referred to as microgrids (small electrical grids to supply electricity in places where the national grid cannot reach). Rural areas in Bangladesh and most other developing (or third world countries) still lack access to reliable electricity which impedes economic development and growth in these areas **[19]**.

Moreover, the geographical location of Bangladesh gives it a distinctive advantage if PV solar cells are used, Bangladesh has roughly 300 days with an average of 7 to 10 daylight hours with an average Global Horizontal Irradiance of 5 kWh/m^2 in these days **[20]**. Hence, among the different forms of renewable energies sources available, solar energy has the highest potential and feasibility for energy production in Bangladesh.

There are two major photovoltaic solar technologies that are commercially available: traditional crystalline solar cells and thin film solar cells. This project focuses on increasing the efficiency of thin-film a-Si solar cells (a-Si is amorphous Si). Research has been conducted on various methods through which the opto-electronic performance of thin-film solar cells can be increased, namely, utilizing metal layer to create a reflective surface on the back of the solar cell, employing nano-pyramidal surface textures on the front and back of the solar cell, and using plasmonic metal nanoparticles **[21-23]**. The difference in refractive index between silicon and air is very high which leads to the reflection of a significant part of the incident radiation from the interface of the two mediums (silicon and air), which is otherwise known as strong Fresnel reflectivity **[24-25]**. To reduce this phenomenon, the use of anti-reflection coatings (ARC) on thin-film solar cells have been proposed **[26]**. While these ARCs improve the performance of thin-film solar cells, their fabrication is complex and costly due to the expensive equipment involved and the precise control that is required during synthesis, thereby increasing the cost of fabrication substantially **[27]**. Attempts have been made towards increasing the opto-electronic performance of solar cells using nanostructures like nanopillars, which reduces the Fresnel reflectivity by acting as an additional medium between air and the substrate **[28]**. But this method leads to an increase in surface recombination and a reduction in the amount of charge carries which ultimately contributes to less current generation **[27]**. Approaches towards employing surface textures like surface grating has been reported to aid in increasing the optical absorption of solar cells. However, these surface textures are usually fabricated in the micron scale (10-15 microns in thickness) which is considerably large when comparing with the thickness of thin-film solar cells and is therefore not suitable for use in 2^{nd} generation thin-film solar cells **[29]**. Furthermore, surface texturing using nanoparticles with high aspect-ratio results in higher surface defects thus increasing recombination of electron-hole pairs **[30]**.

Plasmonic nanoparticles in the presence of a metal-dielectric interface exhibit localized surface plasmon resonance (LSPR) when excited by electromagnetic radiation whose wavelength matches the resonant wavelength of the electron density of the metal. The resonant wavelength is dependent on the dielectric medium (surrounding the nanoparticle) and also the physical parameters of the metal nanoparticle (e.g.: radius, length, height, morphology etc.). This phenomenon results in amplifying the radiation in the immediate vicinity of the nanostructure, thereby increasing the absorption of the incident radiation into the absorbing layer, enhancing its light trapping capability, generating more charge carriers and thus improving the solar cells performance. Similarly, metal core-dielectric shell nanostructures have been observed to increase a solar cells light absorption capability while ensuring chemical and electrical isolation due to the presence of a protective shell. This results in greater stability while providing increased performance. Furthermore, such hybrid nanostructures have also been observed to maximizing forward scattering into the substrate while minimizing backward scattering away from the substrate **[31]**.

Metal nanostructures can be fabricated using lithography (ultraviolet, electron beam, scanning probe and optical NF), laser beam processing and machining. Fabrication of these hybrid nanostructures can also be done by altering the chemical structure on a molecular level to arrange them in the desired formation using methods like vapor deposition, laser tapping, colloidal aggregation and, deposition-growth on films **[32]**. Silica shell can be synthesized using the Stöber or sol-gel process. There are many methods to synthesize a-Si thin-films like vapor deposition techniques (physical vapor deposition, low pressure and plasma enhanced chemical vapor deposition,), vacuum evaporation deposition and atomic layer deposition **[33]**.

3. Goals and Objectives

Goal:

To study the feasibility of reducing the cost of solar cells in the perspective of Bangladesh by incorporating hybrid plasmonic nanoparticles to enhance the opto-electrical performance of the thin-film solar cell.

Objective:

- Understanding the physics behind different types of hybrid nanoparticles.
- Using the understanding of particle physics to analyze different optical and electrical parameters through optical and electrical simulations of solar cells modified with hybrid nanoparticles to find the optimal configuration for incorporation into thin film solar cell to increase efficiency.

4. Research Methodology and Implementation / Validation

The steps or methodology can be demonstrated with the flowchart (Figure 2) mentioned below. Extensive literature review regarding solar cell limitations were conducted and possible approaches to address these limitations were identified, as mentioned earlier. The focus was on utilizing hybrid nanostructures as they showed tremendous potential towards overcoming the aforementioned limitations **[10]**. To find the optimal hybrid nanostructure and optimal configuration, optical and electrical parameters will be analyzed. From Figure 2, it can be seen that the analysis can be divided into mainly two parts: 1) optical analysis of plasmonic thin-film solar cells and 2) electrical analysis of plasmonic thin-film solar cells. Optical analysis mainly comprises of optical properties such as plasmon resonance analysis of the hybrid nanoparticles derived from the extinction spectra (summation of absorption spectra and scattering spectra), optical absorption enhancement obtained from thin-film solar cells modified by the hybrid nanoparticles, etc. Whereas the electrical analysis is comprised with short circuit current density ($\mathbf{J_{sc}}$), open circuit voltage ($\boldsymbol{V_{oc}}$) etc.

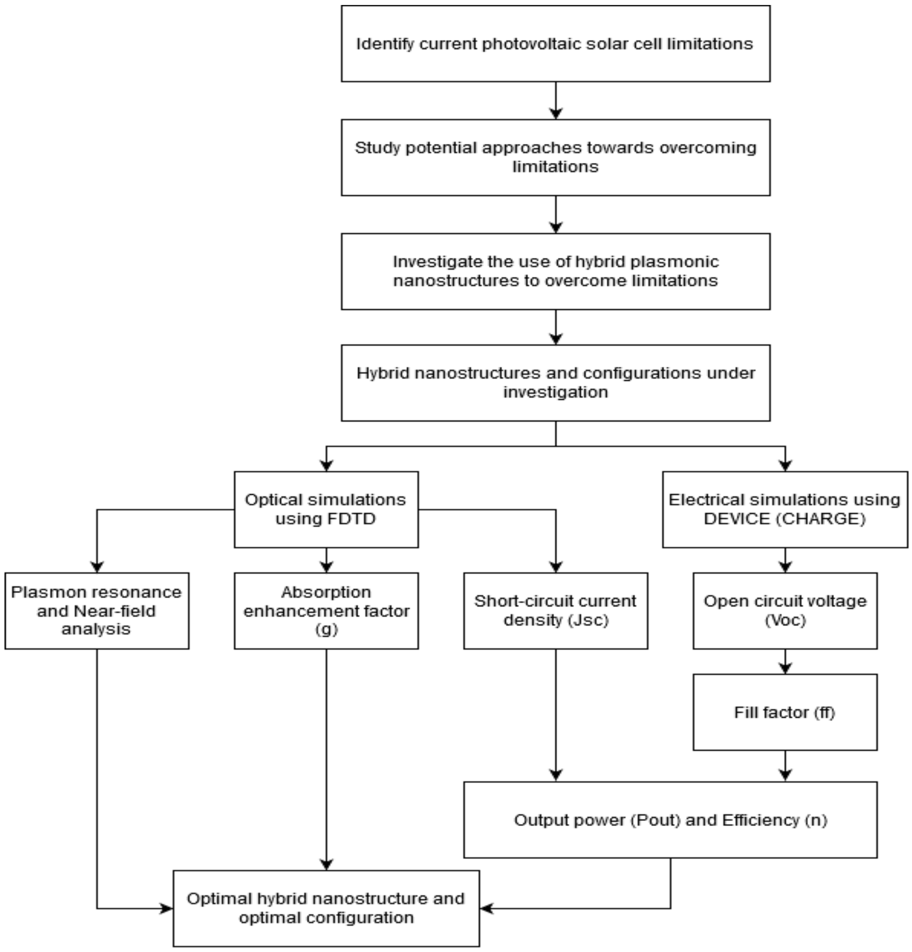

Figure. 2. Flow chart showing the steps that will lead towards establishing an optimal hybrid nanostructure design to aid in increasing the opto-electronic performance of thin-film solar cells.

In order to measure the net amount of light being absorbed as a function of wavelength, the optical simulation in the FDTD software can be setup as shown in Figure 3.

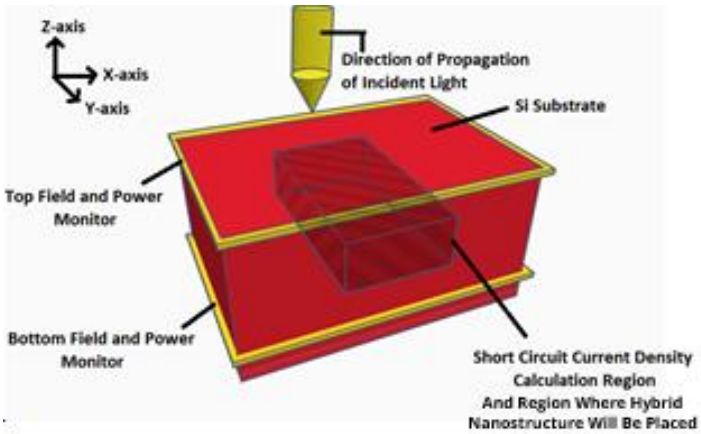

Figure. 3. FDTD Simulation setup for optical absorption enhancement (g) analysis, utilizing frequency domain field and power monitors.

Field and power monitors are used to record data regarding electromagnetic fields and power in the frequency domain. The data sets generated by these monitors can be used to calculate the amount of light passing through them as a function of frequency or wavelength. Using a set of these two-dimensional z-normal monitors, it is possible to calculate the amount of light being absorbed by the substrate. As shown in Figure 3, this can be done by placing one monitor on the surface of the substrate (Top Field and Power Monitor) and another well inside the substrate (Bottom Field and Power Monitor). The transmission data from the bottom field monitor can then be subtracted from transmission data of the top field monitor, thus providing the net transmission of light into the substrate, i.e., the amount of light absorbed by the Si absorbing layer as a function of wavelength. Through this method, the absorption of light for bare Si substrate and the Si substrate modified with various hybrid nanostructures with silicon substrate can be determined.

Additionally, the absorption of light by the bare substrate to that of the substrate with the hybrid nanostructures needs to be compared, in order to understand how much more light is absorbed as a result of employing plasmonic nanostructures. This is determined by dividing the net transmission of light in silicon substrate with hybrid nanostructure by the net transmission in bare silicon substrate. This is called the optical absorption enhancement factor ($\boldsymbol{g}$) and can also be written as **[21]**:

$$\boldsymbol{g} = \frac{\textbf{\textit{Absorption across substrate with composite nanoparticle structure}}}{\textbf{\textit{Absorption across bare substrate}}}$$

It is an important optical parameter since it allows us to plot and analyze the increase in optical energy absorption due to the addition of plasmonic nanostructures when compared to the bare Si substrate solar cell, over the entire spectrum of the incident light. The optical simulations concerned with determining the optical absorption enhancement factor will be carried out using 150 frequency points (in order to compare results with the previous studies) **[34]**. Summing the $\boldsymbol{g}$ corresponding to each frequency point yields a discrete value that can be used to compare the overall absorption enhancement for each hybrid nanostructure configuration. This inevitably means that the sum of $\boldsymbol{g}$ for bare Si substrate will always be equal to 150 as $\boldsymbol{g}$ will be unity for each of its frequency points. Consequently, calculated values that are greater than 150, for any hybrid nanostructure configuration, will indicate an enhancement in optical energy absorption.

However, a greater optical absorption does not necessarily mean higher efficiency and performance of the solar cell because not all electron-hole pairs created due to the absorption of photons result in current generation, due to electron-hole pair recombination before being collected by the solar cell. Quantum efficiency is the ratio of the number of carriers (electron-hole pairs) generated and collected in the contacts to the number of photons of the incident solar radiation of any particular wavelength. Therefore, electrical parameters that are linked to quantum efficiency like short-circuit current density ($\mathbf{J_{sc}}$) need to be determined in order to establish the optimal configuration more accurately **[35]**. The open circuit voltage ($\boldsymbol{V_{oc}}$) should also be determined to calculate the normalized open circuit voltage (used to determine the fill factor) and output power of the solar cell. The aforementioned optical and electrical parameters ($\boldsymbol{g}$, $\mathbf{J_{sc}}$ & $\boldsymbol{V_{oc}}$) can be obtained from optical and electrical simulations using appropriate commercial grade software FDTD Solutions and DEVICE, developed by Lumerical Inc, as shown in Figure 3 **[36]**.

The fill factor (FF) determines the maximum output power capacity of a photovoltaic cell and as such is used to calculate the output power of a photovoltaic cell. It is the ratio of the power at maximum power point ($V_{mp} * \mathbf{I_{mp}}$) by the product of short-circuit current ($\mathbf{I_{sc}}$) and open circuit voltage (V_{oc}). In simple terms, it represents the squareness of the current-voltage curve as shown in Figure 4. The rectangular area, shown in grey, represents the output power of the solar cell **[37]**.

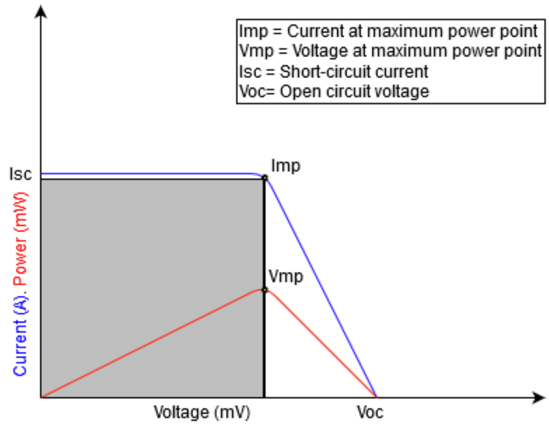

Figure. 4. I-V and P-V curves of a photovoltaic cell **[37]**.

For our purpose, the fill factor (ff) can be determined using the following formula **[38]**:

$$ff = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

where, v_{oc} is the normalized open circuit voltage, and can be calculated using the following equation **[38]**:

$$v_{oc} = \frac{q}{nkT} V_{oc}$$

where, V_{oc} is the open circuit voltage obtained from electrical simulations, q denotes the elementary charge, n represents the ideality factor, k stands for the Boltzmann constant and T gives the temperature in Kelvin.

Finally, the output power (P_{out}) in watts and energy conversion efficiency (η_{conv}) of the solar cell can be calculated from the previously obtained parameters by using the following formulae **[39]**:

$$P_{out} = J_{sc} * V_{oc} * ff * Area\ of\ the\ simulated\ unit\ cell$$

$$\eta_{conv} = \frac{J_{sc} * V_{oc} * ff}{1000\ Wm^{-2}}$$

where, $1000\ Wm^{-2}$ is the standard test condition (STC) input power provided by the incident radiation.

The absorption band of Si, lies between 300nm and 800nm approximately. It is observed that the highest absorption coefficient for a-Si and the peak of the solar irradiation spectrum both lie within this wavelength range **[40]**. Thus, determining the plasmon resonance wavelength for the nanostructures under investigation allows us to identify the particles capable of the strongest light coupling, that fall within the desired wavelength range of 300-800nm, i.e. the visible wavelength spectrum. The optical simulations for plasmon resonance analysis can provide the absorption and scattering spectra of the incident light, the sum of which gives us the extinction spectra for each hybrid nanostructure. The aforementioned spectra can then be plotted as normalized cross-section vs. wavelength. In simple terms, a normalized cross-section is the ratio of the optical cross-section to the geometrical cross-section. For a plasmonic nanostructure configuration, the wavelength at which the peak of the normalized extinction cross-section curve is observed, is the plasmon resonance wavelength. It is at this wavelength where the strongest coupling of the SPR modes in the metal NP with the incident light can be expected to occur. Plasmon resonance analysis also allows us to observe trends like red-shift and blue-shift of the extinction spectra peak, phenomena that take place when varying parameters like shell thickness or particle morphology **[41-42]**. The results obtained throughout the project will be cross matched with published experimental data and built upon to form coherent conclusions.

Furthermore, optical simulations will need to be performed to observe the enhancement of electromagnetic fields in the near-field region for each metallic nanostructure once they are incorporated on or within the Si substrate at its plasmon resonance wavelength. Data from these simulations can be used to plot and generate near-field images that will allow further analysis of the field patterns and features like electromagnetic field intensity, forward-scattering of light, plasmonic coupling, etc. This will further aid in supporting the findings and cementing the conclusions with respect to the calculated optical and electrical parameters **[39]**.

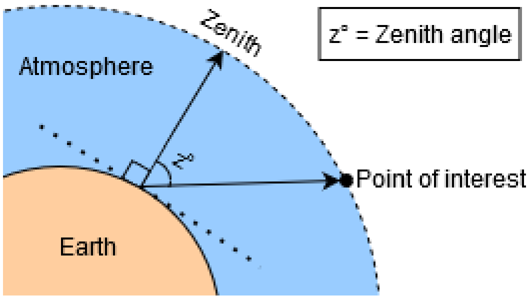

Figure. 5 An illustration of the zenith and zenith angle with respect to the earth's surface and point of interest.

Industry standard test conditions (STC) like temperature (300K) and air mass coefficient (AM 1.5G) were maintained for all simulations **[43]**. The air mass coefficient (AM) is a ratio of the optical path length through the earth's atmosphere (at a certain zenith angle) to that of the path length at zenith. The zenith refers to the normal to the earth's surface as shown in Figure 5. As solar radiation enters the atmosphere and travels towards the surface, its energy is attenuated due to absorption and scattering. Various chemical molecules present in the atmosphere absorb the energy at different wavelengths from the solar spectrum. The more atmospheric thickness that light has to travel through, the greater the attenuation. AM1.5G or ASTM G-173 refers to the spectral irradiance profile for light that has traveled through a 1.5 atmosphere or air mass thickness at a zenith angle of 48.2°. This spectral irradiance distribution was established by the American Society for Testing and Materials (ASTM) for the standardized testing and rating of terrestrial photovoltaic cells across the solar industry worldwide **[44]**. Using AM1.5G solar irradiance for the simulations ensures compliance with industry standards and also allows to get a step closer to obtaining "realistic" results.

5. Work Plan

First semester:

1. Literature review:
   a. Analyze the current state of the power generation in Bangladesh.
   b. Analyze the state of renewable energy power generation globally and in Bangladesh.
   c. Identify the current techniques used to increase solar cell performance.
   d. Investigate the possibility of using plasmonic nanoparticles to enhance solar cell performance.
   e. Study the feasibility of using different kinds of plasmonic metal nanostructures (e.g., metal core dielectric-shell nanoparticles) in enhancing the performance of solar cells.
2. Comparative plasmon analysis: Plasmon resonance analysis of core-shell nanostructure and homogenous nanostructures using FDTD Solutions.
3. Research methodology development: Performing optical simulations using FDTD Solutions, to design and simulate different configurations of core-shell nanostructures that are going to be used in tandem with the absorbing Si layer, to enhance the opto-electronic performance of thin-film solar cells.

Second semester:

1. Core-shell analysis to determine optimal dielectric shell material, thickness, core size, core shape and placement of core-shell nanostructure embedded inside the substrate.
2. Identifying optimal size of the nanoparticle when placed on top of the Si substrate for potential "sandwich" configuration applications.
3. Exploring the sandwich configuration of core-shell nanostructure and homogenous nanoparticle.

Third semester:

1. Exhaustive morphological study of the hybrid plasmonic nanoparticle systems (both embedded inside the absorbing layer as well as in "sandwich" configurations with homogenous metal nanoparticles on top of the absorbing substrate.
2. Investigating the optimal array configuration: by varying the interparticle distance (side to side between nanostructures) to find the optimum pitch size for the composite nanostructures when used in arrays.
3. Reaching conclusion with an optimal configuration to enhance the opto-electronic performance of the solar cell.

6. Expected Outcome

Finding an optimal configuration of hybrid nanoparticle that when incorporated on or within the Si substrate of thin-film solar cells will provide better optical enhancement, superior short circuit current density, open circuit voltage and fill factor when compared to the bare Si substrate.

7. Impact of project on societal, health, safety, legal and cultural issues

The continuous rise in the quantity of greenhouse gases (GHG) have led to an increase in earth's average temperature, the rise of sea-levels and is causing global climate change. Recent erratic weather patterns observed around the world such as the increase in the frequency of droughts, floods, typhoons, hurricanes and the increase in severity of these weather phenomena if compared to the records of the past, point towards an anomaly that can be explained by global warming and climate change which can be attributed to the increase in GHG due to man-made practices. A significant source for GHGs can be attributed to the power generation plants (mainly the fossil fuel powered plants) operated around the world. According to 'Global Climate Risk Index 2020' report published by Germanwatch, in the period from 1998 till 2018, Bangladesh ranked seventh in the long-term climate risk index. The power generation plants are responsible for 52% of carbon dioxide (CO_2) emissions of the country **[45]**. If emission levels from these plants are not brought down, adverse environmental, health and security issues may arise in Bangladesh. With the current rate of use of natural gas for energy generation and plans to further increase usage to meet the energy demands, natural reserves of gas are bound to be depleted by the next decade. To meet this demand, construction of new fossil fuel plants using coal (e.g., Rampal Power Station) have been proposed. Doing so will lead to irreversible damage to the environment and ecology of the area and bring about adverse health effects to the people living around the vicinity of the plants. People living near coal powered plants have shorter life expectancy with higher death rates among the populace and are more prone to respiratory disease, lung cancer, cardiovascular disease and other health problems due to the expulsion of pollutants such as fly ash, sulphur dioxide, cadmium, nickel, and lead contaminates (among others) the air and water in the vicinity of the plant **[46]**. While it may be true gas-fired power plants are more environmentally friendly than coal-fired power plants, due to diminishing natural reserves **[15]**, substantial investments should be made in the renewable energy sector to mitigate the health hazards and environmental pollution created due to fossil fuels.

The production (raw materials extraction and manufacturing of the panels) and operation of solar panels during their lifetimes create lower CO_2 emission in order of several magnitudes lower than fossil fuel power plants do **[47-50]**. There are also no harmful pollutants released into air and water during the operation of Solar PV systems, benefitting both the health of the populace and limiting the adverse environmental effects generally associated with traditional fossil fuel power plants. Second (2^{nd}) generation or thin-film solar cells require lower amount of materials than crystalline solar cells and so thin-film solar cells are more ecologically friendly than traditional soar cells. Due to reduction of thickness of thin-film solar cells, they also tend to be elastic increasing the flexibility in the location for deployment (can lead to reduction in land requirement for deployment and more robust structure to withstand adverse environmental conditions like cyclones, etc).

In order to tackle the problems of power generation (of Bangladesh) stated throughout the report, the government needs to follow in the steps of countries (Germany, Iceland, Kenya, Morocco, China, U.S.A. etc.) that have been successful in adopting renewable energy practices. The policies used to realize their energy goals need to be scrutinized, evaluated and possibly be modified to suit the current situation (socio-economic and political) of Bangladesh. The government's renewable energy policy introduced in 2008 needs to be updated, better incentives need to offered to investors investing in renewable energy sector when compared to making investments in traditional energy sources. For example, according to the plan put forth in 2008 investors investing in renewable energy projects are exempted from corporate income tax for a 5-year period whereas, private power companies operating conventional power plants (coal, gas and oil) are exempted from corporate tax for a period of 10-years. Aside from policy issues another potential barrier this proposed project may face is the use of patented and copyrighted technology during the fabrication process as thin film-solar cell is a relatively new technology with new ideas constantly being brought forth and patented.

Extreme remote and rural areas in Bangladesh still have no access to electricity (5%) due to the high cost and challenges involved in connecting these remote areas to the national grid **[51]**. Hence, using stand-alone power systems (e.g., solar homes) or using microgrids is the only feasible solution to deliver electricity to these areas. Lack of access to electricity in remote areas of the country have impeded the development and growth in these areas and is a hurdle that needs to be overcome for Bangladesh to transition into a developing country.

Facilitating electricity in these rural areas can bring about development and growth. Access to electricity can improve the standard of living, a better quality of education, access to broader markets hence, more trade and income opportunity. It can also lead to the development of communication pathways (cellphone towers, roads, radio, etc.), thereby connecting the remote populace to the rest of the country and the rest of the world (via the internet). It also works to reduce the feeling of alienation and neglect of these people (i.e. minority tribes) living in these rural (hills and jungles) areas and make them finally feel like being accepted as a citizen with equal facilities as the vast majority of people living elsewhere in the country. This can prevent or discourage such estranged communities from indulging in terrorism and other illegal measures to express any form of dissent. Efforts should not only be made to provide electricity to these remote and rural areas via microgrids but also the possibility of using such grids to provide electricity in areas which have an unreliable electrical connection (frequent outages, faulty transmission lines) should be explored. The biggest hurdle in adopting PV solar panel technology is the high initial investment needed. The cost of these PV crystalline solar cells can be reduced substantially if thin-film solar cell technology is used. Initiatives should be taken to increase the awareness of the benefits of using PV thin-film solar cells when compared to crystalline PV cells and in the benefits of solar cells in general. Like most other developing countries, people of Bangladesh are not concerned and, in some case, not even aware of the environmental issues. Implementation of solar energy can give rise to a cultural movement and massive paradigm shift of the minds of the common people and thus can Bangladesh move towards a greener and sustainable future.

8. Impact of project on the environment and sustainability

The looming threat of global warming and climate change has brought in new investments and research focus on renewable energy systems in an effort to make it feasible and comparable to traditional energy resources. Many countries have invested heavily in renewable energy sources to reduce their carbon footprint and meet their carbon goal according to the Paris Climate Agreement 2016. In 2018, 26.1% (26614 TWh) of the world's electricity production was generated from renewable energy sources and globally, the new installed capacity of renewable sources was greater than the installed capacity of traditional sources and nuclear power combined **[15]**. Since 2008, the price for PV solar modules have gone down by a factor of about 5 **[52]** while their efficiency has been improved**,** making PV solar cells be widely adopted globally for power generation. The majority of carbon dioxide (CO_2) emissions in Bangladesh (52%) can be attributed to the power sector **[45]**. The need to adopt renewable energy sources for power generation is more important than ever especially for Bangladesh as most of the grid electricity in Bangladesh is generated by the use of fossil fuels (coal, diesel, furnace oil and natural gas account for 92.51% of total installed capacity of energy in Bangladesh) **[13].** According to PSMP (Power System Master Plan prepared by the Government of Bangladesh) 2016 **[16]**, proposed plans to increase the generation capacity in Bangladesh (shown in Figure 6) point to an alarming scenario where the dependence of foreign imports of fuel for power generation would increase, thereby decreasing the energy security in Bangladesh and lead to an increase in the already high carbon dioxide emission (CO_2) from power sector due to the increase in fossil fuel power plants. From Figure 6, it is observed two of the five scenarios (P1 and P2) show coal to be the primary fuel source for power generation in Bangladesh therefore, for the projected scenarios shown in Figure 6**,** CO_2 emissions are highest for scenario P1 (0.82 CO_2 kg-C/kWh), due to the reliance on a high percentage of coal for fuel, and the lowest in scenario P5 (0.55 CO_2 kg-C/kWh), which uses the lowest percentage of coal among the five scenarios**[16]**. Adopting a scenario more geared towards the use of renewable energy sources such as PV solar systems, therefore, would not only be better for the environment as PV solar systems have lower CO_2 emissions, of approximately 40g CO_2 eq/kWh compared to an approximate1000g CO_2 eq/kWh for coal, 640g CO_2 eq/kWh for natural gas-fired combustion turbine (NGCT) and 460g CO_2 eq/kWh for natural gas-fired combined-cycle systems **[47-50],** it would also decrease the dependency on foreign imports of fuel (such as coal, natural gas) and therefore increase the energy security in Bangladesh.

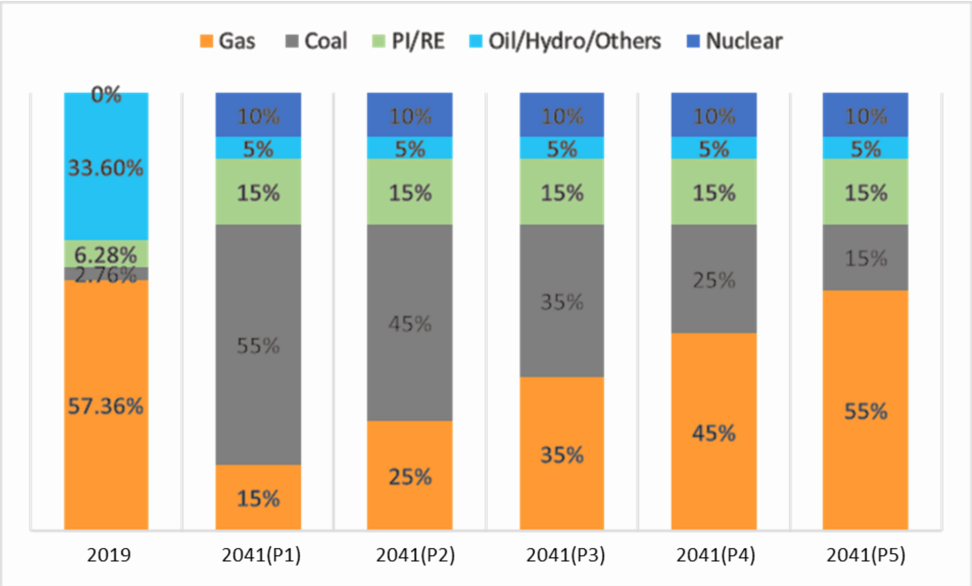

Figure. 6. Current (2019) and planned (2041) composition of fuel type for energy generation in Bangladesh **[16]**.

Traditional or 1st generation PV solar cells are the predominant type of solar cells that are available in the market. Crystalline (monocrystalline and polycrystalline) Si makes up the bulk of the material used in these 1st gen cells and is the main contributor to the high price. The typical thickness of the cut wafers of 1st gen models was around 180 µm with a kerf loss (amount of material that is lost during the cutting process) on the order of 100 µm **[53-55]**. To find an alternative to using high quantities of Si, the 2nd generation of solar cells were developed. These are referred to as thin-film solar cells due to the thin-films (usually only a few microns thick) of materials used. Generally, thin-film solar cells are mainly classified into three types: i) Amorphous Si (a-Si) ii) Cadmium Telluride (CdTe) and iii) Copper Indium Gallium di-Selenite (CIGS). This project focuses on increasing the efficiency of a-Si thin-film solar cells. While amorphous silicon thin-film solar cells require a lower amount of materials than crystalline silicon cells, unfortunately they are also less efficient (than crystalline cells) due to the reduction in the absorbing layer (silicon). The primary focus of this project is on enhancing the opto-electronic performance of a-Si (amorphous Silicon) thin-film solar cells by utilizing the plasmonic properties of hybrid core (metal)-shell (dielectric) NPs. Potentially higher efficiency and fewer amount of materials used can lead to more affordable solar panels and more widespread adoption of renewable energy with significantly lower carbon emissions compared to fossil fuels.

For sustainable development of a technology, it must be ensured that the present needs for it are met while making sure that the development and use can also be supported in the future. For PV solar cells to become a major sustainable competitor in the power generation market, the materials involved in the manufacture of these cells must be abundant, affordable and have a much lower environmental impact than its traditional counterparts. One other criterion that must be met to contend against the major players (fossil fuels) in the electrical energy generation sector, is that the cost of PV power must be equal to or lower than the cost of grid electricity. While 1st generation crystalline PV cells now cost much lower than they did before, it is still expensive, that is why extensive research is being done in developing efficient thin-film solar cells (2nd generation cells) which are cheaper than crystalline Si solar modules by a factor of two **[56]** and require less material than crystalline Si cells. A possible major constraint in the widespread expansion of thin-film PV technology comes in the form of limited availability of the materials used in the fabrication of these cells. Tellurium (Te), Indium (In), Cadmium (Cd), Gallium (Ga) and Germanium (Ge) as these materials are the minor by-products in the purification/extraction of Copper (Cu), Lead (Pb) and Zinc (Zn). Hence, the availability of these products is directly linked to the production of the base metals **[56-57].** Even with the aforementioned constraint in the availability of the materials involved in fabrication, the growth of thin-film solar cells market should be sustainable to provide Terawatts of renewable energy by the mid-21st century **[56-57]**. Sustainability issues due to shortage of materials can further be mitigated by developing more efficient recovery methods for the by-products produced during the extraction of base-metals, using even thinner semiconductor layers, increasing the life expectancy of each PV module and development of schemes to efficiently recycle the modules at the end of their lifecycle **[57]**.

9. Proposed budget for implementing the project

Sl	Item	Justification	Quantity	Unit Price (BDT)	Price (BDT)
1.	16GB 3200MHz DDR4-SDRAM	To meet the computational demands of high accuracy and complex, optical and electrical simulations in large	2	8,900	17,800

		“realistic” surfaces of solar cells.			
Total (BDT)					17,800
In words: Seventeen Thousand Eight Hundred Taka Only					

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