TILT ANGLE OPTIMIZATION OF PHOTOVOLTAIC MODULES CONSIDERING THE EFFECT OF DUST

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Abstract

This thesis presents a detailed discussion on the tilt angle optimization considering the effect of dust, the optimum cleaning frequency model with the estimated cleaning cost for PV modules in Bangladesh. Multiple research works have been carried out on finding the optimum tilt angles for PV arrays. Only few of them considered the effect of dust in the calculation. These works were based on experimental works where the PV modules were installed at different tilt angles and the optimum tilt angle was determined based upon the maximum power output of the dusty PV modules. Besides, the solar radiation model proposed by these works did not incorporate the effect of air mass. Moreover, the cleaning schedule for the solar PV modules was not addressed in any of the work. All of the reported works considered the desert environment and the seasonal dependency of tilt angle and the effect of rainfall were taken into account. In this work, Particle Swarm Optimization based mathematical model has been developed which includes air mass, elevation angle, average sunlight hour, transmittance and tilt angle of solar PV array. The equations for transmittance of PV array are developed including the mass of deposited PM_{10} (particles with diameter 10 micrometer or smaller) particle which was considered as dust due to availability of the data. The model parameters for different regions of Bangladesh are also determined on seasonal and yearly basis. The effect of rainfall and seasonal dependency of the tilt angles is also calculated by determining the equations of transmittance, the model parameters and the declination angles on seasonal and yearly basis. The effect of dust on the transmittance, efficiency and energy generation of solar PV modules are discussed with and without the effect of dust. The changes in yearly and seasonal optimum tilt angles with and without the effect of dust have been determined and the obtained results are compared with the published work. Contrasting to the previously published work, the problems of installing the PV arrays at higher tilt angles were also pointed out. Additionally, the clearness index for the eight divisional cities of Bangladesh are determined and compared with another published work. Finally, the cleaning cost and the revenue are determined on seasonal basis. The result of this work can be useful for the design of solar PV systems in Bangladesh.

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List of Acronym

AM	Air Mass
AI	Artificial Intelligence
ANFIS	Adaptive Neuro-fuzzy inference system
ANN	Artificial Neural Network
BDT	Bangladeshi Taka
COP	Conference of Parties
DEWA	Dubai Electricity and Water Authority
ES	Evolutionary Studies
EPSA	Evolutionary Programming Sizing Algorithm
ELM	Extreme Learning Machine
GW	GigaWatt
GHG	Greenhouse Gas
GA	Genetic Algorithm
GCPV	Grid-Connected Photovoltaic
HDKR	Hay,Davies,Klucher,Reindl
HFPSO	Hybridization of Firefly and Particle Swarm Optimization algorithm
IDCOL	Infrastructure Development Company Limited
KPMG	Klynveld Peat Marwick Goerdeler
KWh/m^2	Kilowatt hours per square meter
LCOE	Levelized Cost of Energy
LLP	Loss of load probability

MW	Megawatt
NDC	Nationally Determined Contributions
NPC	Net Present Cost
NPSS	Nonlinear Step Size Scaling factor
NASA	National Aeronautics and Space Administration
O&M	Operation and Maintenance
PM_{10}	Particulate Matter(diameter less than 10 micrometer)
$PM_{2.5}$	Particulate Matter(diameter less than 2.5 micrometer)
PM	Particulate Matter
PV/T	Photovoltaic/thermal
PSO	Particle Swarm Optimization
SREDA	Sustainable and Renewable Energy Development Authority
SHS	Solar Home Systems
TWh	TeraWatt hours
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization
W/m^2	Watts per square meter
Wp	Watt peak
DWWT	Decentralized Waste Water Treatment

Chapter 1

Introduction

The effects of climate change, and the impact that greenhouse gas emissions have on the atmosphere, are ushering in a reassessment of where our energy supply comes from and, more importantly, how sustainable it is. As the world population rises, so does the demand for energy in order to power our homes, businesses, and communities. Innovation and expansion of renewable sources of energy are key to maintaining a sustainable level of energy and protecting our planet from climate change.

Sunlight is one of our planet's most abundant and freely available energy resources. The amount of solar energy that reaches the earth's surface in one hour is more than the planet's total energy requirements for a whole year. Although it sounds like a perfect renewable energy source, the amount of solar energy we can use varies according to the time of day and the season of the year as well as geographical location. The wind is a plentiful source of clean energy. To harness electricity from wind energy, turbines are used to drive generators which then feed electricity into the National Grid. As a renewable energy resource, hydropower is one of the most commercially developed. By building a dam or barrier, a large reservoir can be used to create a controlled flow of water that will drive a turbine, generating electricity. This energy source can often be more reliable than solar or wind power (especially if it's tidal rather than river) and also allows electricity to be stored for use when demand reaches a peak. Like wind energy, in certain situations hydro can be more viable as a commercial energy source (dependent on the type and compared to other sources of energy) but depending very much on the type of property, it can be used for domestic, 'off-grid' generation. By harnessing the natural heat below the earth's surface, geothermal energy can be used to heat homes directly or to generate electricity. This is the conversion of solid fuel made from plant materials into electricity. Although fundamentally, biomass involves burning organic materials to produce electricity, and nowadays this is a much cleaner, more energy-efficient process. By converting agricultural, industrial, and domestic waste into solid, liquid, and gas fuel, biomass generates power at a much lower economic and environmental cost [1].

The possibilities to use renewable energy are still developing: energy resources evolve dynamically as a function of human engineering ingenuity. There is still a lot to do with regard to installing and developing alternative energy production – energy demand is increasing worldwide, day by day with ongoing population growth and industrialization.

The excessive dependency on fossil fuels such as coal and oil is negatively affecting the planet. Burning these fossil fuels increases the amount of carbon dioxide (CO_2) that is released into the atmosphere, leading to a heightened greenhouse effect and warming of the earth. With governments trying to reduce CO_2 emissions, renewable sources of energy (such as those derived from wind, the sun, and waves) are presenting themselves as a viable, eco-friendly option to meet the world's energy needs.

Besides, renewable sources of energy release little or no particles that cause air pollution or negatively impact human health; wind and solar power consume virtually no water (geothermal and biomass require water for plant cooling), meaning the strain on the local water supply can be significantly reduced; and sources of renewable energy are, generally speaking, vast and inexhaustible.

1.1 Renewable Energy Worldwide

Renewable energy has been a major source of new global generation capacity in recent years. Installed capacity has grown rapidly in the last decade and increased from 1,223 GW in 2010 to 2,356 GW by 2018 [2]. This trend is expected to continue; in 2018, a total of 175 GW renewable energy-based capacity was installed worldwide [2]. and new capacity from renewables exceeded new installed capacity from both conventional and nuclear power combined. Global installed capacity gains in renewable energy are presented in figure 1.1[2] Major gains have been made in solar and wind power. Global solar PV capacity increased from 40 GW in 2010 to 505 GW in 2018, which represents a twelve-fold increase during that period. Global annual additions and cumulative solar PV installed capacity between 2010 to 2018 are presented in figure 1.2 [3]. Wind power capacity also significantly increased in that period, growing from 180 GW in 2010 to 564 GW by 2018. Growth trends for bioenergy and geothermal energy are comparatively smaller due to resource potential, specific project risks and higher investment costs. In 2018, 26.1 percent of the of the total global electricity production (26,614 TWh) came from renewable energy sources [4]. If large hydropower is omitted, renewables still contributed about 9.3 percent to global electricity production. Most of these gains have been made in the last ten years. Figure 1.3 presents the share of global electricity generation at the end of 2018[2]. The marked increase in worldwide renewable energy capacity has been largely due to reductions in capital costs and policy initiatives such as targets set by governments of many developed and developing countries. These policy signals are paramount in attracting investment in the renewable energy sector. Renewable energy development trends in the Asia region are significant when compared to other regions. About 43 percent of total global renewable capacity exists in Asia.

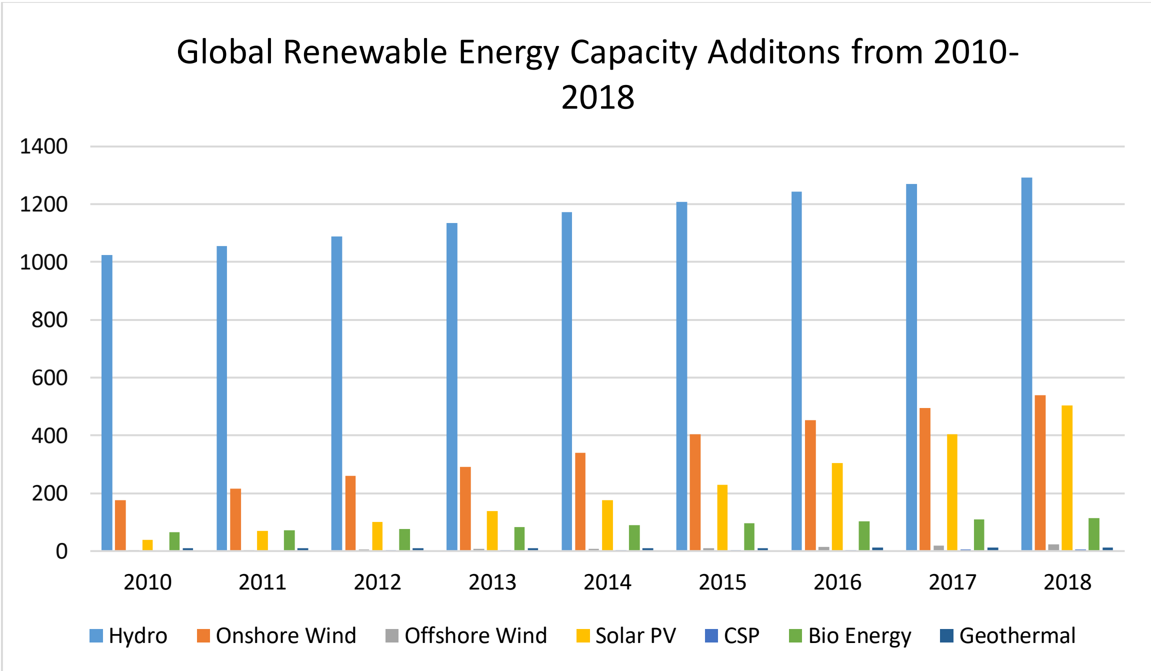

Figure 1.1: Global Renewable Energy Capacity from 2010-2018 [2]

At the 21st session of the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP21) held in Paris, member nations agreed to take action to limit the increase in global average temperatures to less than 2 degrees Celsius (2˚ C) and ideally 1.5˚ C by the end of this century, relative to pre-industrial temperature levels. By the end of 2019, national governments pledged their Nationally Determined Contributions (NDCs) to reduce GHG emissions. However, these commitments are not accompanied by the ability to meet the Paris Agreement goal. To meet the targets of the Paris Agreement, many national governments committed to additional measures at the United Nations Climate Action Summit held in 2019 to further reduce GHG emissions. A total of 70 countries committed to increase the targets in their action plans by 2020 and 65 countries also committed to achieve net-zero emissions by 2050. Most of the UNFCCC parties have recognized the importance of integrating renewable energy technologies in electricity generation in order to mitigate GHG emissions.

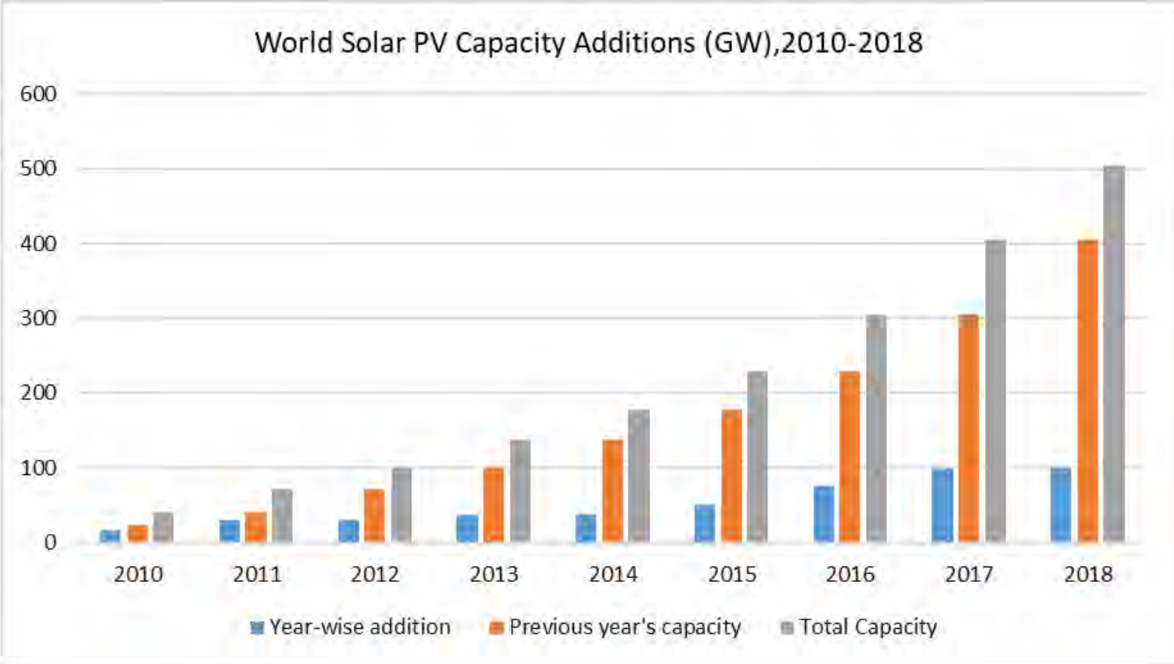

Figure 1.2: World Solar PV capacity additions (GW),2010-2018 [3]

Although hydropower is still the main source of renewable energy with the cheapest LCOE (Levelized Cost of Energy), rapidly falling costs have made solar PV the largest market for new investment. Unsubsidized solar PV generated electricity has now become cost-competitive with fossil fuels in several locations around the world. The recovery that began in 2013 for solar PV continued in 2015, with an estimated 50GW installed for a total global capacity of ~227GW, representing 27% of growth in 2014; this was by far the highest growth rate within all sub-sectors. China, Germany, and Japan accounted for the vast majority of the new capacity. However, significant new capacity was planned for or added in Latin America, parts of Africa, and parts of the Middle East, such as Dubai and Saudi Arabia. In January 2014, DEWA (Dubai Electricity and Water Authority) in Dubai awarded a contract to build a 200MW, US$330 million PV plant to a group led by Saudi Arabia's ACWA Power International, where KPMG ("Klynveld Peat Marwick Goerdeler) was the procurement advisor. In 2015, a further 800MW capacity addition was initiated, which is currently under negotiation with a preferred bidder, with KPMG in Dubai and Singapore as procurement advisors [5].

1.2 Renewable Energy Achievements to Date and Future Targets in Bangladesh

The growth of renewable energy in Bangladesh to date has primarily been through off-grid systems, mainly in rural areas where grid extension is difficult and not economical. 314.8 MW of capacity is present through off-grid systems [6]. Grid connected renewables account for

311.9 MW. Figure 1.3 shows the current installed generation mix of renewable generation. A large proportion of the current capacity is made up of one 230 MW hydropower plant and 81 MW of grid-connected solar PV.

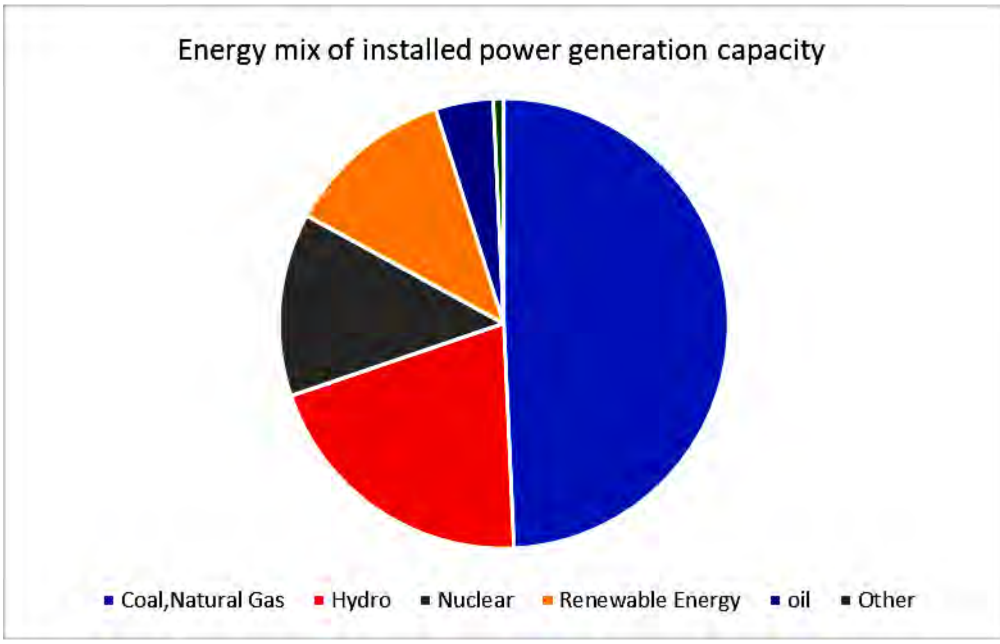

Figure 1.3: Energy Mix of Installed Power Generation Capacity. [6]

Currently, there are only four solar and two wind power projects that are grid-connected. A total of 10 solar projects and two wind projects have also been approved and are under implementation. These will add an additional 614.8 MW of solar and 70 MW wind to the installed power generation capacity.

According to the PSMP 2016 target, the total cumulative grid-connected renewable energy installed capacity ought to have been 1,728 MW by 2019. It is well short, with only 311.9 MW having been achieved to date, mostly as a result of a 230 MW large hydro plant. The target for 2021 was 2,470 MW, and a target of 3,864 MW of renewables is expected by 2041, which is a total additional capacity target of only 1,394 MW in the 20-year period from 2021 to 2041. The government's Sustainable and Renewable Energy Development Authority (SREDA) also lists a 2021 generation target plan [7] with expected yearly increases projected from 2016. SREDA's target to 2021 is larger than the PSMP target to the same timeline and is shown in figure 1.4.

In order to try and meet some of the targets set in the PSMP, the government has approved the development of various new projects. Many of these projects originally had a commercial operation deadline of the end of 2019, although none have reached commercial operation to date. In the interim, the government has stopped any new procurement of power through unsolicited bids and intends to identify and solve the issues with the current projects first. What is clear is that at the current trajectory, Bangladesh will not meet its renewable energy targets in the short term and does not have an ambitious enough target in the long term (2041).

Bangladesh has committed to increase its share of renewable energy electricity generation to 3,864 MW by 2041.44 Bangladesh has also committed [8] under the Paris Agreement that by 2030, it will mitigate GHG emissions by 5 percent without any additional international support, or 15 percent with additional international financial and technical support, compared to the "business as usual" reference case for GHG emissions [9]. It is unclear how the anticipated future installed generation capacity mix scenarios of the PSMP 2016 will enable Bangladesh to meet these commitments, as they are not linked.

Energy policy in Bangladesh consists of key policy, regulations, guidelines and national action plans that aim to support energy development goals. Bangladesh has implemented policy mechanisms to promote the uptake of grid-connected renewables, although limited policy effectiveness is one of the key barriers in the development of renewable energy in the country (a problem faced in renewable energy development by many countries around the world). The Government of Bangladesh launched its first policy regarding renewable energy in 1996. Considering the rapid changes that have occurred in the sector globally, the energy policy was again updated in 2004 [10].

The Government of Bangladesh then introduced a national renewable energy policy in 2008, with the intention of encouraging and facilitating public and private sector investment in renewable energy projects.

This current trajectory clearly demonstrates that Bangladesh will continue to rely on imported oil and liquid fuels, further increasing energy security risks and increasing outside dependency in order to meet its future energy demand. The current renewable energy target of 3,864 MW by 2041 will not improve the country's energy security and will leave the country reliant on imports of fuel and electricity.

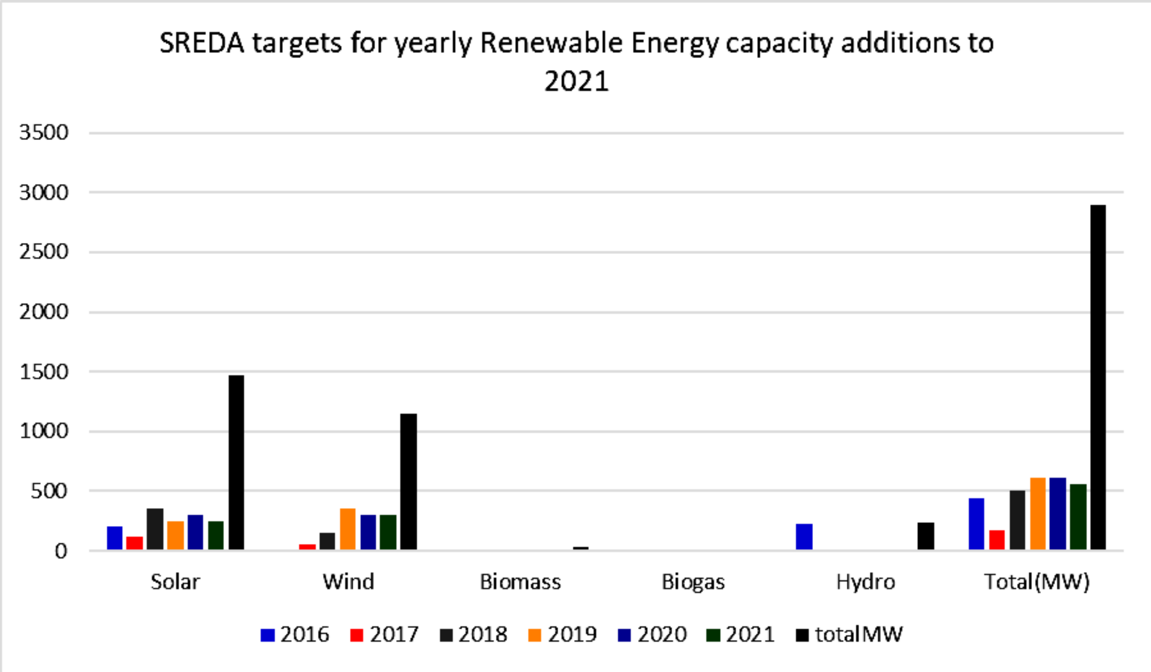

Figure 1.4: SREDA targets for yearly Renewable Energy capacity additions to 2021. [6]

1.3 PV Systems in Bangladesh

In basic terms, solar power is created by converting sunlight into electricity. The most common way this occurs is via the installation and use of photovoltaic panels in areas that catch a lot of rays or via concentrated solar power systems.

One of the biggest benefits of solar energy is the inexhaustibility, ready availability of the source – the amount of sunlight the earth receives per year makes the sun the most abundant source of energy worldwide, trumping coal and other fossil fuels.

The renewable energy resources cannot be alternative to conventional fossil fuel energy resources. They may be supplementary to the long-term energy demand for Bangladesh. As technologies of fuel cells, solar thermal, geothermal, tidal and wave energy require more investigation for their potential in Bangladesh; they have not been covered in this study.

Amongst various sources of renewable energy, solar energy is one of the most viable options for Bangladesh as it has high daily average solar radiation levels ranging from 4-6.5 KWh/m^2 [11] [12]. The photovoltaic energy is the most promising of all available technologies for Bangladesh [13].

Bangladesh has been successful in developing off-grid rooftop solar power (solar home systems). Bangladesh is among the largest users of off-grid solar home systems globally [14].

The Government of Bangladesh has made some progress in tapping solar energy by successfully disseminating solar home systems(SHS) throughout the country, providing electricity to people in remote off-grid areas.

Bangladesh is among the largest users of solar home systems globally. Through 5.5 million SHS installed in remote locations, it provides electricity to nearly 13% of the population. Out of 5.5 million SHS, nearly 4.5 million SHS were distributed through a national program undertaken by Infrastructure Development Company Limited(IDCOL), a government-owned non-banking financial institution. By 2021, IDCOL targets to finance 6 million SHS with an installed generation capacity of 250 MW [15]. Because of the geographical characteristics of Bangladesh, most of the renewable energy projects are based on solar PV technology [16]. Infrastructure Development Company Limited (IDCOL)has initiated the SHS (Solar Home System) program in 2003 to ensure access to clean electricity for the electricity-starved off-grid rural areas of Bangladesh. The program complements the Government's vision of ensuring "Access to Electricity for All" by 2021. About 4 million SHSs have already been installed under the program in the off-grid rural areas of Bangladesh till April 2016. As a result, almost 18 million beneficiaries are provided with solar electricity which is around 11% of the total population of Bangladesh [17].

Solar home systems (SHSs) are the real hope for electrification of the off-grid areas in Bangladesh by utilizing solar energy on a renewable and sustainable basis. Currently, more than 3.8 million SHSs of capacity range 10–135 Wp (watt peak) with a total capacity of 150 MW have been disseminated in rural and isolated areas in Bangladesh. In this paper, ten case studies of capacity 20 Wp, 30 Wp, and 42 Wp were investigated to evaluate economic viability at two randomly selected villages in Sirajgonj and Jessore districts, Bangladesh. The analysis showed that the SHSs for is economically viable small business enterprises and households with small income generation [18] .

However, the contribution of SHS to the total amount of power generated in the country is extremely low. The Government of Bangladesh has made some progress in tapping solar energy by successfully disseminating solar home systems[SHS] throughout the country, providing electricity to people in remote off-grid areas. However, the contribution of SHS to the total amount of power generated in the country is extremely low.

Solar home systems (SHS) have a major problem that is low efficiency. The output decreases day by day because of improper maintenances, effect of dust and shadow. Accumulation of dust on solar panel of solar photovoltaic (PV) system is a natural process. It was found from the study that the accumulated dust on the surface of photovoltaic solar panel can reduce the system's efficiency by up to 35% in one month [16]. Another challenge of installing PV technology is its dependence upon weather [19].

1.4 Problem Statement

Karmekar et al. discussed the "geographical characteristics" of Bangladesh in their work. Bangladesh is located in the "geographical position" from 20°34' N to 26°38' N and from 88°01' E to 92°41' E [20]. The solar insolation varies from 4 to 6.5 KWh/(m^2.day) while the average insolation is 5 KWh/(m^2.day). The suggested available daily sunlight hour for Bangladesh is 7-10h, but because of rainfall, cloudy and foggy environments, this is reduced further by 54% and finally, it is 4.6h [21]. The average temperatures are 20°C to 27.75°C respectively for winter and summertime. Maximum solar radiation is observed during the months of March-April and minimum during December-January.

Since Bangladesh is one of the most vulnerable countries to the effects of climate change, solar photovoltaics (PVs) can help manage climate vulnerabilities and also ensure energy access for all [15]. The government of Bangladesh has outlined a target to install 1.7 GW of solar capacity by 2021 [22]. Among many other things, the output of any solar generator depends on the tilt angle of the PV system [23]. Multiple research works have been carried out to find the optimum tilt angle in different regions of the world [24] [25] [26] [27].The output also depends upon the accumulated dust on the solar PV modules. Dust significantly reduces the energy yield of the solar panel [28] [29] [30]. The dust deposition characteristics of a ground-mounted solar photovoltaic system were investigated in [31]. Effects of dust particle sizes and PV system tilt angles on the amount of dust deposition were studied here. The optimum tilt angle for the PV system in the desert environment was studied in [32]. Both of the works [31], [32] were considered for desert environment so the effects of rainfall were neglected. Since the accumulation of dust varies with seasonal change and rainfall, the tilt angle is to be adjusted according to these. Bangladesh is suffering from poor air quality especially in the winter. The PM_{10} concentrations in Dhaka and its adjacent areas are about three times more than the national standards of Bangladesh [33]. Dust accumulation on the solar panels is much higher in Bangladesh compared to many other countries. So the effect of dust on the efficiency of PV modules is more severe here. The installed PV systems here need regular cleaning. The optimization of this cleaning schedule is also important to minimize O&M(Operation and maintenance) costs. The published works indicate that the problem of dust accumulation upon PV modules is not well investigated to date in the published works. Also, the optimization of cleaning schedules for solar PV modules is not addressed yet in any of the works.

1.5 Objectives of the work

The objectives of the thesis work are:

i) To investigate the effect of dust on the energy performance of solar panel in Bangladesh

ii) To determine the tilt angle and solar radiation for Dhaka, Gazipur and Narayanganj considering the effect of PM_{10} particles in those regions.

iii) To determine the energy loss at different tilt angles due to dust.

iv) To optimize the cleaning schedule for the solar system installed in Dhaka, Gazipur, and Narayanganj.

1.6 Thesis Organization

The thesis is divided into five chapters:

In chapter one, a brief introduction of the photovoltaic systems in Bangladesh is provided. Statement of the problem regarding the tilt angle optimization of the photovoltaic modules is provided along with the objectives of this thesis study.

In chapter two, an overview of relevant literature regarding the optimization algorithms for the tilt angle optimization of the photovoltaic modules is provided. The PM_{10} pollution levels in Dhaka, Gazipur, and Narayanganj and the sources behind this pollution are discussed to determine the effect of dust on the photovoltaic modules in these regions.

In chapter three, the steps of the Particle Swarm Optimization algorithm are discussed. The mathematical model for tilt angle optimization is outlined and the basic theory behind this study is provided in detail.

In chapter four, the effect of dust on the transmittance and efficiency of solar panels for certain regions in Bangladesh was discussed. The cleaning schedule for these regions is optimized. Finally, the cleaning cost was estimated. The average Particulate Matter (PM_{10}) concentration was involved into the optimization of tilt angles of these regions.The yearly and seasonal solar radiation and optimum tilt angles for all divisions of Bangladesh were determined.The results were compared with the published work.Finally,the cleaning cost is estimated for these regions.

The final chapter contains conclusions and recommendations for further work that can be undertaken to extend our results.

Chapter 2

Background

The tilt angle of a solar energy system is one of the most important parameters for capturing maximum solar radiation falling on the solar panels. This angle is site specific as it depends on the daily, monthly and yearly position of the sun. The accurate determination of the optimum tilt angle for the location of interest is essential for maximum energy production by the system. A number of different optimization methods have been used for determining the tilt angle at different locations worldwide. The efficiency of solar PV module depends on the specific mass and size of dust particles deposited on PV module surface. As the mass of dust deposition increases, power output and the efficiency of the module decrease, and as the size becomes smaller, power output decreases as smaller particles block more radiation on PV module surface.

2.1 Different Optimization Techniques

The purpose of optimization is to achieve the best design relative to a set of prioritized criteria or constraints. These include maximizing and minimizing factors such as productivity, strength, reliability, longevity, efficiency, and utilization [34].

2.1.1 Genetic Algorithm

A genetic algorithm(GA) was applied to optimize the monthly optimum PV slope solution [35].GA initializes the tilt angle PV with the specified limit, then calculates to get the optimum total energy value on the inclined plane that PV can accept with crossover, mutation, and selection process. Algorithms were limited to 50 generations.It worked well on mixed discrete /continuous problems while it was computationally expensive i.e. time-consuming. Also, designing an objective function and getting the representation and operators right can be difficult.

GA is an artificial intelligence technique (AI), which was inspired from evolution and inheritance trait in living organism. The algorithm imitates population's evolution, based on survival-of-the-fittest strategy. GA has three operations, which is selection, crossover and mutation. GA method has ability to derive global optimum solution with relative computational simplicity, including complicated problems with non-linear function or constraint. However, GA may suffer excessive complexity if the problem is too large [36]. In 2009 [37], the authors developed an optimum sizing method using genetic algorithm (GA) among list of commercial system devices (PV modules and inverters) in Microsoft Visual C++ software. The sizing process was started by selection of PV module and inverter model, available land area, climatic parameters, cost and economy parameters. The best number of PV modules, inverters, tilt angle, the best arrangement of PV modules among inverters, and optimum arrangement of PV modules within site area was elected based on maximum net economic profit as GA objective function. In this study, total net profit was maximized using NPC analysis, by considering total capital cost of PV modules, inverters, cost of land area, mounting structure cost, cost of installation, and maintenance cost. However, the researchers did not include inverter to PV array sizing ratio as one of optimization criteria. In addition, several power losses were not taken into account, such as temperature, dirt and cables. Moreover, the PV modules arrangement calculation is not suitable if the land area is not face to south. In 2011 [38], a new sizing method was proposed to determine optimal PV modules and inverters by using GA. In this study, authors developed iterative sizing procedure as a benchmark to choose the best optimization methods between GA and evolutionary studies (ES). The proposed GCPV system capacity was capable to fulfil energy requirement as specified by customer in kWh using preselect PV module model and inverter model. Peak Sun Hour at tilted panel angle, temperature reduction factor, manufacture's tolerance reduction factor, cable reduction factor, and inverter reduction factor were considered in sizing calculation. From possible PV modules arrangement among inverters, the highest value of inverter to array sizing factor and minimum excess factor was chosen as optimal design solution. From the methods comparison, GA method has lower percentage error compared to ES method. In 2011, authors in [39] proposed optimization methods for large PV plant design using Greece's time series of one-minute average solar radiation data. The researchers optimize the proposed system by maximizing energy production. From simulation, optimum PV module distribution, optimum PV rows, distance between rows and tilt angle were determined. Then, LCOE was analyzed for the optimal solution. The proposed method can only be used to design PV generation plant at fixed tilted panel mounted on South faced ground. PV distribution system among inverters and PV arrangement layout Appl. Sci. 2018, 8, 1761 22 of 30 at predefined space area was done similar with methods in [37] [40] except the inverter used in design are Central Inverter, Multi-string Inverter and Mini-Central Inverter. In 2012, the same authors from [39] proposed a new optimization method for large PV plant in [41]. By using GA simulation, optimum PV module distribution, optimum PV rows, distance between rows and tilt angle were determined.

However, the new technique was improved by including LCOE analysis within optimization process. The simulation result was compared to cases with non-optimized system, optimized for both minimum and maximum cost. An inclusive GA method presented in 2014, in [42] where the authors use all technical, economic and environmental criteria in their analysis. The authors developed their solar irradiance model using hourly average temperature and clearness index data. Then PV model was developed to maximize energy output using field area restriction and design safety restriction, for predefined PV module model and inverter model characteristic. The PV layout design within space provided was optimized to reduce shading losses. Then, based on the configuration obtained from PV model, evaluation on economic, technical and environmental criteria was done. The authors used IMPACT2002++ for environment evaluation. All of the listed steps were conducted using five different types of PV panel technologies. The best configuration selection was based on weighted evaluation with 15 goals, which were maximizing energy output, minimizing payback time, minimizing energy payback time, and minimizing 12 environmental impacts.

2.1.2 Evolutionary Programming Sizing Algorithm

Similar to GA technique, EPSA (Evolutionary Programming Sizing Algorithm) also involves random process of selection, mutation and crossover in its operation. Individual fitness was defined in objectives function. EP evaluates behavioral connection between parents and offspring, with respect to similarities, differences and their performances [43]. In 2012 [44], Sulaiman,S.I., et al. proposed an optimization sizing with Evolutionary Programming Sizing Algorithm (EPSA). Unlike his previous method in [38], the optimization was able to test all available combination of PV and inverters in system database. The researchers implemented the same technique to determine optimal PV modules distributions among inverter. EPSA sizing was done using different EP modes with nonlinear step size scaling factor (NPSS), and the sizing results were compared. The proposed method could choose to optimize the system based on energy yield or net present value.

2.1.3 Particle Swarm Optimization

PSO (Particle Swarm Optimization) is one of the metaheuristic methods using robust stochastic optimization technique based on the movement and intelligence of swarms. The technique applies concept of social interaction to problem solving. As mentioned in [40], PSO is easily programmed. Besides, the knowledge of good solution is retained and all particles able to share information between them. Meanwhile, in [37], multi-objectives were implemented, to allow optimization of two or more conflict objectives. In 2010, Kornelakis, A., et al. developed two more optimization methods, based on particle swarm optimization (PSO) and multi-objectives particle swarm optimization technique [37, 40], with several improvements compared to his previous proposed method in [40]. In [40], the authors compared his PSO-based findings with GA-based result in term of iterations. They have proved that by using PSO approach, the simulation time is shorter and lower number of iteration was obtained. Besides, GA was proved to fail in locating several optimum solutions during optimization process. In his later findings [37], environmental benefit was added in his optimization process as second objective function, while the decision variables were still the same. Particle swarm optimization was used to solve multi-objectives problem for purposed system. This technique was able to maximize both economic and environmental benefits in the system.

Kennedy and Eberhart [45] put forward the Particle Swarm Optimization algorithm. It starts with a random population of particles in search space and incorporates swarming behavior such as bird flocking, fish swarming, etc. It allocates direction and velocity vectors to each particle, each particle then progresses through the search space following its velocity vector. The objective function estimates the influence exerted upon other particles by one particular particle. The process replicates until some condition is met.

The particles' velocity and position are initialized at random. During the optimization process, each particle memorizes its own best position encountered so far which is called local best. On the other hand, the population memorizes the best position among all individual best positions obtained so far which is called global best. To balance between the global and local exploration capabilities of the particles, inertia weight is introduced. The inertia weight is linearly decreased through the optimization process to emphasize the search globally at initial iterations and locally at final iterations.PSO has several advantages over other optimization techniques including: simple in concept, easy to implement, and computationally efficient. It has been proven by finding the best fitness faster. Figure 2.1 shows the PSO flowchart.

Mansour et al. [46] implemented PSO as a computational method to find optimum angle orientation for solar panel installation to get maximum solar radiation in Sabha city, Libya. Semi-yearly based optimization was determined as the best optimization although there were higher solar radiations for seasonally and daily bases because it would only need twice adjustments of solar panel in a year. Yet, it considers inefficient to adjust solar panel position in every season or even daily with no significant solar radiation increase than semi-yearly.

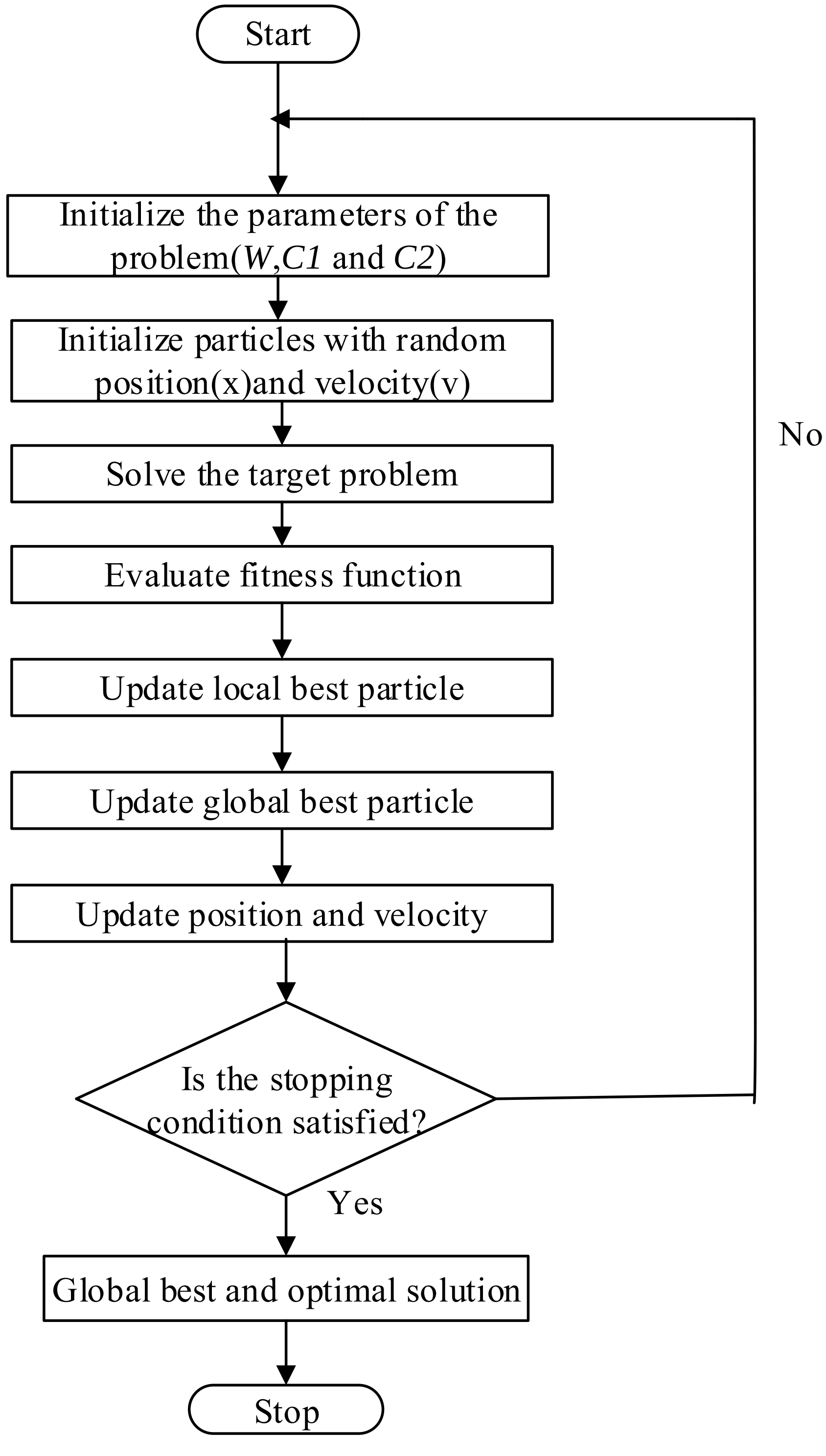

Figure 2.1: PSO flowchart [50]

Elsheikh provided a review of PSO's applications to improve the performance of solar energy systems and to provide a review on the PSO's applications to improve the performance of solar energy systems and to identify the research gap for future work [47]. The literature review used in this study indicates that the PSO is a very promising method to enhance the performance of solar energy systems.

Photovoltaic thermal collector is shown in figure 2.2. In [48], PSO method was applied to obtain the optimal tilt angle setting of the photovoltaic thermal collector shown in figure 2.2. Awad et al. [49]determined optimal system size by carrying out parameter optimization. The primary focus of this study is to develop an optimized system which maximizes generating capacity while maintaining cost-effectiveness of the solar PV system prior to the system implementation. Hence, a multi-objective optimization model is developed. The solar PV system design process is improved by optimizing the tilt angle and the inter-row spacing of solar PV modules. An objective function is developed based on the total solar energy generation per PV system and energy generation per PV module in order to improve cost effectiveness. The goal is to maximize these two outputs of the objective function. The particle swarm optimization (PSO) method is used to accomplish the optimization. Given that the two objectives are different and both have equal and opposite effects on the other, modifications were made to the PSO. Finally, the outputs of the optimization model are compared and validated with a case study. The model presented in this paper will assist users in decision making based on the technical output and financial aspects of the PV system.

In another analysis, Liu et al. suggested the Particle Swarm Optimization method to find the optimum tilt angle of solar collectors under the clear sky [25]. They contrived a famous empirical model for the clear sky to calculate the solar radiation for different locations in Taiwan. PSO was adopted to determine the best installation angle of solar collector in Taiwan under clear sky taking into consideration various periods.

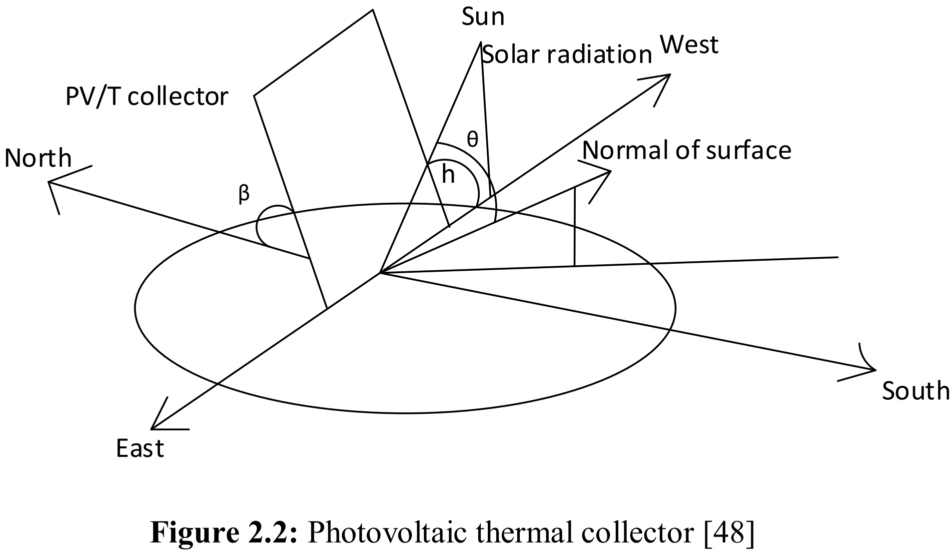

Figure 2.2: Photovoltaic thermal collector [48]

2.2 Solar Radiation and its Components

Solar radiation, often called the solar resource or just sunlight, is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies. However, the technical feasibility and economical operation of these technologies at a specific location depends on the available solar resource [50]. Figure 2.3 represents the three main components of solar radiation.

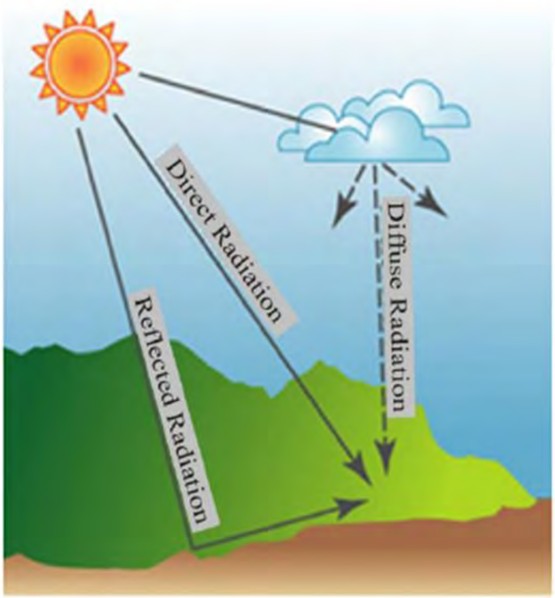

Figure 2.3: The three main components of solar radiation [51]

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid polar regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year.

Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

- Geographic location
- Time of day
- Season

- Local landscape
- Local weather.

The Earth revolves around the sun in an elliptical orbit and is closer to the sun during part of the year. When the sun is nearer the Earth, the Earth's surface receives a little more solar energy. The Earth is nearer the sun when it is summer in the southern hemisphere and winter in the northern hemisphere. However, the presence of vast oceans moderates the hotter summers and colder winters one would expect to see in the southern hemisphere as a result of this difference.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

Countries such as the Bangladesh, which lie in the middle latitudes, receive more solar energy in the summer not only because days are longer, but also because the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months.

The rotation of the Earth is also responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon, when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon. As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by:

- Air molecules
- Water vapor
- Clouds
- Dust
- Pollutants
- Forest fires
- Volcanoes.

This is called diffuse solar radiation. The solar radiation that reaches the Earth's surface without being diffused is called direct beam solar radiation. The sum of the diffuse and direct solar radiation is called global solar radiation. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days.

Scientists measure the amount of sunlight falling on specific locations at different times of the year. They then estimate the amount of sunlight falling on regions at the same latitude with similar climates. Measurements of solar energy are typically expressed as total radiation on a horizontal surface or as total radiation on a surface tracking the sun.

Radiation data for solar electric (photovoltaic) systems are often represented as kilowatt-hours per square meter (kWh/m^2). Direct estimates of solar energy may also be expressed as watts per square meter (W/m^2).

2.3 Importance of Tilt Angle for Solar System

The tilt angle of a solar energy system is one of the important parameters for capturing maximum solar radiation falling on the solar panels. This angle is site specific as it depends on the daily, monthly and yearly path of the sun. The accurate determination of the optimum tilt angle for the location of interest is essential for maximum energy production by the system. Major solar angles are shown in the figure 2.4. Angles involved in calculating solar irradiance on a tilted surface are shown in figure 2.5. Figure 2.6 shows the declination angle,latitude angle and hour angle.

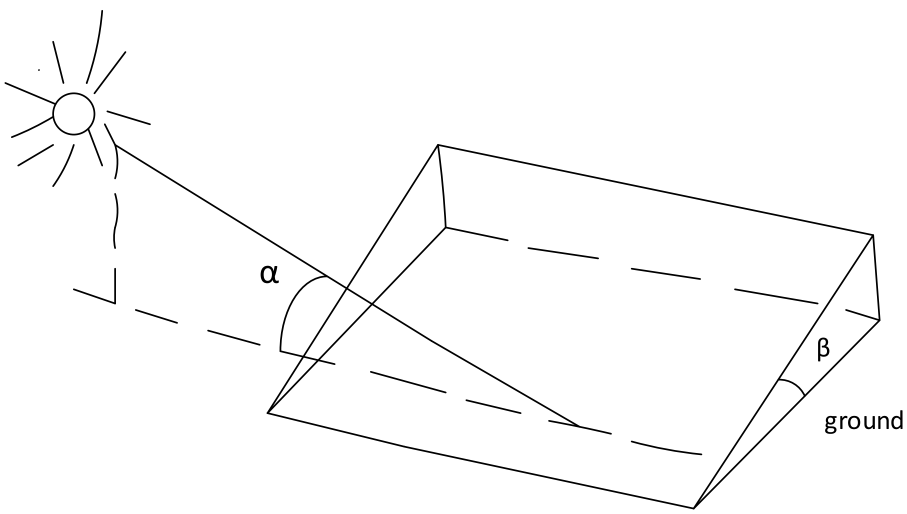

Figure 2.4: Major solar angles: (a)Tilt angle β (b) Elevation angle α [52]

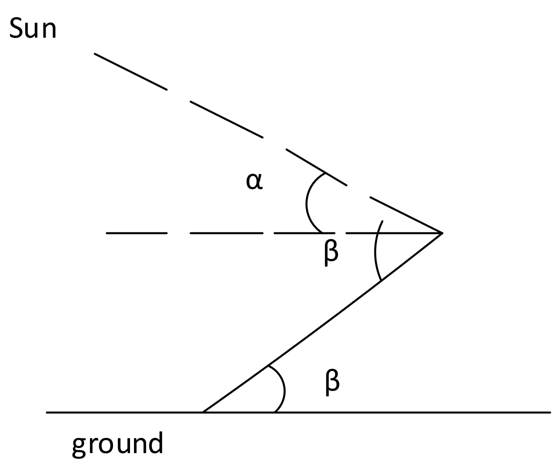

Figure 2.5: Angles involved in calculating solar irradiance on a tilted surface [52]

The tilt of the panels is important because the panels will produce a maximum of energy when the sun is directly perpendicular to them. Therefore, to ensure maximum energy production optimization of the tilt angle is important. Babatunde et al. found that the mean specific yield of PV installations was found 5.6% higher than that at a 6-degree tilt. The mathematical method of obtaining energy output or extracting the global irradiation on an inclined surface presents an average variance of 0.3% between calculated and measured energy [51].

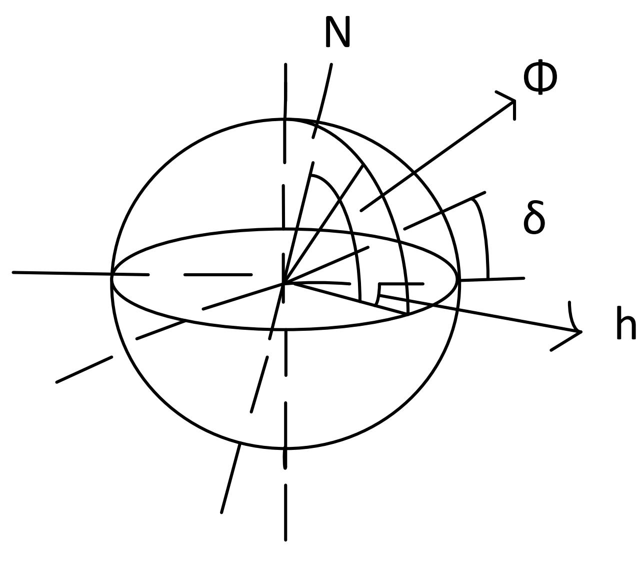

Figure 2.6 : Declination angle,δ , Latitude angle,φ , and Hour angle,h [52]

Ramez et al. estimated the optimum tilt angles for south-facing surfaces in Palestine [52]. PVGIS and PVWatts were used to estimate the solar radiation on south-facing surfaces with different tilt angles.17% more solar energy was found for monthly adjustments than the case of solar panels fixed on a horizontal surface while 15% more energy was found for seasonal and semi-annual adjustments. The yearly optimum tilt angle for most Palestinian cities was found to be 29-degree, which yielded an increase of about 10% energy gain compared to a solar panel fixed on a horizontal surface.

2.4 Dust Effect on Solar PV Performance

Rajput et al. calculated the energy efficiency and power output of the Photovoltaic systems for the effect of deposited dust particles [53]. They came with a deduction that dust significantly reduces the efficiency of solar PV panels.

Experimental investigations were carried out to understand the dust characteristics and its effect on the electrical performance of PV modules under Sharjah, UAE weather conditions [54]. The results of the indoor experiments revealed a linear relationship between the dust density and the normalized PV power with a drop of 1.7% per g/m2. Dust accumulation was a function of the tilt angle and was increased by 37.63%, 14.11% and 10.95% with respect to the clean module for the 0°, 25° and 45° tilted modules, respectively. Outdoor experiments showed that the soiling loss increased by 12.7% while the dust density increased by 5.44 g/m2 for a period over 5 months. By comparing the results of indoor and outdoor experiments, it was concluded that the linear relationship is reliable and can be used to predict the soiling loss of PV systems in UAE and similar weathers conditions.

Xu et al. [55] proposed a new model of the optimum tilt angle of a soiled PV panel. . In this paper, the solar radiation model was studied by analyzing the Hay, Davies, Klucher, Reindl (HDKR) model. The cell temperature of a PV panel was also investigated to evaluate the power output. A fitting formula was derived to express the relationship between the dust deposition density and the tilt angle, and it is integrated in the output model of a fixed-type PV panel. Besides, the effect of dust deposition on the transmittance was analyzed. Furthermore, the relationship between dust deposition and the working temperature of PV panel was investigated by indoor experiments.

Wang et al. developed an improved incident angle model and tilt angle model based on the overlay model [56]. In this work, they concentrated on the modeling of the dust deposition affecting the transmittance of PV modules. Babatunde et al. [57] presented the performances of five different PV installations which amount to 1280 kWp installed in Cyprus International University, North Cyprus was analyzed as a case study. The PV plant, which was planned and commissioned by Sustainable Energy Research Center of CIU, was installed in five different locations on the campus by deploying three mounting techniques. The influence of dust and cleaning on the PV systems were examined. After implementation of the cleaning procedure, an average of 2.5% variance in specific yield was obtained. The effect of the different inclinations on each system was also reported. Mean specific yield of Arazi (25° tilt) plant is 1732.44 kW/kWp which is 17.3% and 5.6% higher than Stonite (6° tilt) and Arena (6° tilt), respectively. In addition, simulation results were compared with the measured data from installed PV plants. The energy production at Arazi, Carpark and Arena PV plants were higher than the simulated results by 7%, 3% and 7%, respectively while Stonite and B-Block energy production dropped by 3% at each. The mathematical method of obtaining energy output or extracting the global irradiation on an inclined surface presents average variance of 0.3% between calculated and measured energy. It was found that the mathematical model is more reliable than simulation and it can be used to extract the solar radiation on inclined surfaces with minimal error when the energy output is already measured.

Kouz et al. [58] proposed computational models to investigate the effects of dust and ambient temperature on the performance of a photovoltaic system built at the Hashemite University, Jordan. The system is connected on-grid with an azimuth angle of 0◦ and a tilt angle of 26◦.The models have been developed employing optimized architectures of artificial neural network (ANN) and extreme learning machine (ELM) models to estimate conversion efficiency based on experimental data. The methodology of building the models is demonstrated and validated for its accuracy using different metrics. The effect of each parameter was found to be in agreement with the well-known relationship between each parameter and the predicted efficiency. It is found that the optimized ELM model predicted conversion efficiency with the best accuracy, yielding an R2 of 91.4%. Moreover, a recommendation for cleaning frequency of every two weeks is proposed. Finally, different scenarios of electricity tariffs with their sensitivity analyses are illustrated.

Figure 2.7 shows the geometry of solar collector. The dust deposition significantly influences the energy gained from the solar power system. The dust deposition of PV modules is decided by many factors, such as weather, location, tilt angle, and so on.

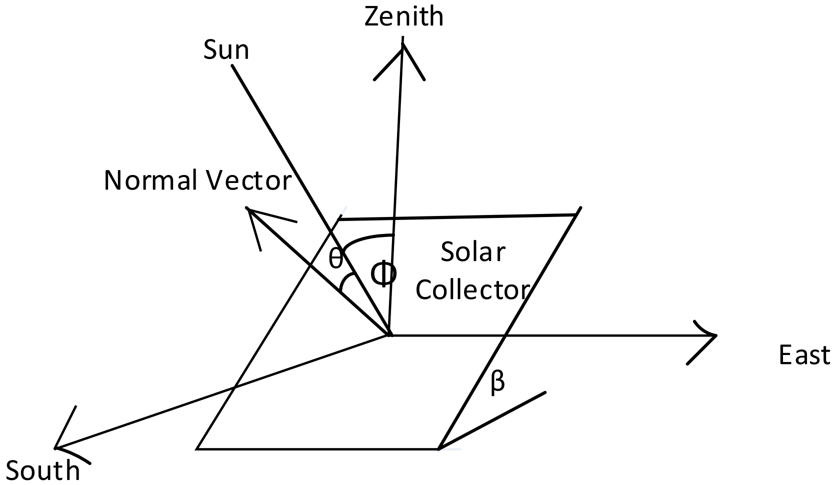

Figure 2.7: Geometry of Solar Collector [25]

2.5 Previous Works on Tilt Angle Optimization

Xu et al. analyzed the optimum tilt angle for a soiled PV panel [55]. Kaddoura et al. investigated PV panel optimum tilt angles for various cities in the Kingdom of Saudi Arabia [59]. Masili et al. proposed a sophisticated radiative transfer model to calculate the direct and diffuse solar radiation for the solar spectrum incident on PV solar panels to determine the best tilt angle of the panel to maximize absorption of solar radiation for selected periods [60].

Sudhakar et al. investigated that the energetic efficiency of the amorphous PV module varied from 2.44% to 3.92% [61]. In another work, Sudhakar et al. observed the energy efficiency to vary between 6% and 9% during the day whereas the exergy efficiency is lower for electricity generation, ranging from 8% to 10% [62]. They concluded that the exergy losses increased with module temperature. Shukla et al. designed a standalone rooftop solar PV system to provide an uninterrupted power supply for a hostel building [63]. Kumar et al. elaborated on the design aspects and annual performance of 10 MW grid-connected solar photovoltaic powerplants. The final yield was found to be 1.96 to 5.07 h/d and the annual performance ratio was 86.12% [64]

Makenzi et al. presented a methodology to establish the optimum tilt angles for solar panels installed at specific locations, thus ensuring maximum energy generation [65]. The modeling is based on the maximization of the solar irradiation incident on the surface of a PV panel by considering multiple site-specific variables. Different sets of transcendent equations have been derived which were used to calculate optimum tilt angles and the subsequent energy generation from specific configurations of photovoltaic arrays. The resulting algorithms were used to determine optimum tilt angles and energy generation for solar PV installations in Athi River, Kenya. Dynamic and static optimal tilt angles were compared with the region's baseline industry practice of using a fixed tilt angle of 15°. It was observed that the dynamic tilt angles improved the daily solar energy output by up to 6.15%, while the computed optimal static tilt angle provided a 2.87% output increment. This improvement presented a significant impact on the technical specification of the PV system with a consequent reduction in the investment and operational cost of such installations.

Chinchilla et al. provided several models for accurately computing the annual optimum tilt angle for fixed solar photovoltaic arrays or solar collectors, in any location of the world [66]. The optimum tilt angle that maximizes the annual energy yield can therefore be easily calculated in the absence of meteorological data and simulation software tools. The proposed models are calculated using global horizontal radiation data collected from 2551 sites across the world. In the process, well-established sub models have been selected to estimate the hourly irradiance on any possible inclined surface, and its corresponding annual energy yield. After selecting the optimum angle for each location, through a regression analysis, a mathematical model that calculates annual optimum angles as a function of latitude had been developed. Furthermore, regression techniques such as neural networks and decision trees had been compared with the polynomial models. The results are analyzed, validated, and compared with previous research proposals proving the good performance of the proposed models.

Martin et al. proposes a series of global models to estimate optimum annual tilt angle (βopt) as a function of local variables (latitude, diffuse fraction and albedo) based on the hourly irradiance data of 14,468 sites spread across the globe from the One Building database [67]. As a result, these models can be used for any location in the absence of local meteorological data. A polynomial regression model, applicable worldwide, is proposed to estimate βopt as a function of latitude. This model fits the global data considered with a 2% RMSE error. Average energy losses are estimated to be 1% for a 10° variation from βopt. A variation of 40° with respect to βopt, implies a 12–18% energy loss depending on latitude. In addition, if only latitude was considered to estimate βopt, different expressions should be used for latitudes >50° depending on the hemisphere. These variations were a result of the influence of diffuse irradiance on βopt, due to the fact that sites with higher amounts of diffuse irradiance have a lower βoptimum.

The optimum tilt angle of photovoltaic panels was determined by applying the Harmony Search metaheuristic algorithm [32]. Their results demonstrate that the tilt angle should be changed once a month and the best orientation is usually due south in the selected cities of China. In a similar investigation, They concluded a simple method to acquire the optimum tilt angles for different climates of China by estimating monthly mean daily global solar radiation on tilted surfaces facing directly towards the equator. . The optimization model presented in [32] did not consider the air mass effect on the available solar radiation.

Kim et al.represented a solar panel tilt angle optimization model using machine learning algorithms [67]. There objective was to find a tilt angle that maximizes the converted energy of photovoltaic(PV) systems. .

Khatib et al. [68] presented a MATLAB based user friendly software tool called as PV.MY for optimal sizing of photovoltaic (PV) systems. The software had the capabilities of predicting the metrological variables such as solar energy, ambient temperature and wind speed using artificial neural network (ANN), optimized the PV module/ array tilt angle, optimized the inverter size and calculated optimal capacities of PV array, battery, wind turbine and diesel generator in hybrid PV systems. The ANN based model for metrological prediction uses four meteorological variables, namely, sun shine ratio, day number and location coordinates. As for PV system sizing, iterative methods are used for determining the optimal sizing of three types of PV systems, which are standalone PV system, hybrid PV/wind system and hybrid PV/diesel generator system. The loss of load probability (LLP) technique is used for optimization in which the energy sources capacities are the variables to be optimized considering very low LLP. As for determining the optimal PV panels tilt angle and inverter size, the Liu and Jordan model for solar energy incident on a tilt surface is used in optimizing the monthly tilt angle, while a model for inverter efficiency curve is used in the optimization of inverter size.

Akhlaghi et al. [69] proposed a novel procedure to select the number of intervals and their durations by solving an optimization problem. The proposed algorithm is consisted of four major steps. First, the solar radiation of the next year is predicted using historical data. Second, using a bee algorithm the optimal tilt angle of each interval is computed. Third, an optimization problem is solved to get new periods for each interval. Finally, a stopping criterion is checked to decide whether the previous step should be repeated or the algorithm had been converged. The effectiveness of the proposed approach was studied at nine different locations across the US. The results show improvement of the solar power generation by using the optimal intervals. Efficient operation of residential solar panels with determination of the optimal tilt angle and optimal intervals based on forecasting model.

Muslim proposed an algorithm to optimize the solar tilt angle based on MATLAB software (m-file) in order to maximize the PV generation [70]. Monthly and annually optimal tilt angles are suggested for different case studies those are: Najaf, California and New Delhi. Also, the estimation of solar radiation for each month was calculated according to their optimal tilt angles. The obtained results indicated that the yearly gain of solar radiation from orientation solar panels is approximately 18% for Najaf city and a high gain values for winter months with very small energy gains for summery months, and so on for other case studies. This proposed algorithm is general program and can be applied for any site on the earth by changing the latitude and longitude of the desired area.

Yadav et al. [71] provided the update status of research and applications of various methods for determining solar panel tilt angle using different optimization techniques. The study shows that for maximum energy gain, the optimum tilt angle for solar systems must be determined accurately for each location. The review will be useful for designers and researchers to select suitable methodology for determining optimal tilt angle for solar systems at any site.

Al-Kouz et al. [58] presented a study to obtain optimum tilt angle and orientation of a solar panel for the collection of maximum solar irradiation. The optimum tilt angle and orientation were determined using isotropic and anisotropic diffuse sky radiation models (isotropic and anisotropic models). The four isotropic models giving varying optimum tilt angles in the range of 37 to 44°. On the other hand, results of the four anisotropic models were more consistent, with optimum tilt angles ranging between 46–47°. Both types of models indicated that the collector tilt should be changed four times a year to receive more solar radiation. The results also indicate that the solar panel should be installed with orientation west or east of due south with a flatter tilt angle. A 15° change in orientation towards west or east of due south results in less than 1% reduction of the total solar radiation received. For a given optimum tilt angle, the effect of photovoltaic/thermal (PV/T) orientation west or east of due south on the outlet temperature was determined using a one-dimensional steady state heat transfer model. It was found that there is less than 1.5% decrease in outlet temperature for a PV/T panel oriented up to 15° east or west of due south from March to December. This result indicates that existing roofs with orientations angles up to 15° east or west of due south can be retrofitted with a PV/T system without changing the roof shape.

Works have been carried out to determine the optimum tilt angle for different divisional cities of Bangladesh [72] [73]. Bangladesh is suffering from poor air quality. Rana et al. investigated that yearly PM_{10} concentration in Dhaka and its adjacent areas about three times than the national standards of Bangladesh[the national standard of Bangladesh is 85.7ugm^{-3} for PM_{10} is a standard to set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children and the elderly][33]. It is perceived that the most polluted season in this area is winter. In this season, the average PM_{10} concentration in Dhaka, Gazipur, and Narayanganj was found to be 257.1,240.3,327.4 μgm^{-3}. Pollution levels during the wet season surpassed WHO guideline values in 50% of the days of the season. Bare sand fields along the banks of the Balu and the Turag rivers, located, respectively about 10 and 15 km away to the northeast direction from the Dhaka station can be one of the most dominant sources of PM at the station during the dry season. A good number of engine-driven trawlers in the Karnafuli river and several heavy industries along the river banks can be possible sources of high pollution at Narayanganj station from the northeast direction. Brick kiln clusters and industries located about 20 km away to the north-east direction from the Gazipur station can be vital sources for pollution at the station during the dry season. Compared to the dry season PM pollution levels from all directions were much reduced in the wet season. Such a decline in pollution level in the wet season can be associated with the absence of seasonal sources (brick kilns, open burning, etc) and the wet deposition of PM due to frequent rain in the wet season. Contribution of re-suspended dust to the PM pollution might have diminished in the wet season because of high moisture content in soil and high water content in bare lands. Construction works in the cities also grew smaller considerably during the wet season. Contribution of re-suspended dust to the PM pollution might have diminished in the wet season because of high moisture content in soil and high water content in bare lands. Construction works in the cities also grew smaller considerably during the wet season. Although there had been research works on optimizing the tilt angle of the photovoltaic modules for different parts of Bangladesh, none of the researchers incorporated the effect of dust on the tilt angle. The seasonal dependency of tilt angles and the effect of rainfall on tilt angle have not yet been addressed. Also, the optimization of the cleaning schedule with the estimation of cleaning cost for the photovoltaic modules in different regions of Bangladesh is still absent in the literature.

Chapter 3

Mathematical Modeling

A particle swarm optimization-based mathematical model was developed to determine the optimum tilt angle for Bangladesh. The model incorporated the effect of a fine dust particle on the tilt angle optimization for different locations of Bangladesh. At first, the particle swarm optimization algorithm is discussed. Then, the overlay model and incident angle model have been discussed to understand the light transmittance property of dust and the influence of dust on solar PV panel. In order to realize the deposition property of PM_{10} particle, the dust deposition model has been mentioned. Finally, an improved tilt angle model has been developed. Additionally, the mathematical model for optimum cleaning frequency is suggested.

3.1 Particle Swarm Optimization

PSO is one of the most famous meta-heuristic algorithms which was suggested by Kennedy and Eberhart [45] before any other, inspired mainly by social behavior patterns of animals that live and interact with large groups. PSO starts with a random population of particles in search space and integrates swarming behavior such as fish schooling, birds flocking, etc. It randomly assigns direction and velocity vectors to each particle that advances through each search space conforming to its velocity vector, which is adjusted by the directions and the velocities of the particle in its neighbor-hood.

How much a particular particle affects other particles is estimated by its objective function [25]. These localized interactions with neighboring particles propagate through the entire swarm of potential solutions, each particle keeps track of its coordinates, this process is repeated until some condition is met. The PSO algorithm [47] can be described in the following steps:

3.1.1 Initialization

At first, n position vectors $(X_k(0), k = 1,2, \dots \dots, n)$ were initialized . The elements of X_k vectors are uniformly distributed in a suitable range. Subsequently, n velocity vectors are randomly initialized $(V_k(0), k = 1,2, \dots, n)$. The fitness of each particle is evaluated by using an objective function. The local best of each particle is initialized to its initial position while the global best is initialized to the best fitness among the best locals. Finally, The range of the inertia weights $w(0)$ is initialized.

3.1.2 Update velocity

Each element j of the velocity vector of the kth particle can be updated as follows [47]:

$$v_{k,j}(t) = w(t)v_{k,j}(t-1) + C_1 r_1 \left(x_{k,j}^L(t-1) - x_{k,j}(t-1)\right)$$

$$+C_2 r_2 (x_{k,j}^G(t-1) - x_{k,j}(t-1)) \quad (1)$$

where t is the iteration number, C_1 is a positive constant called the cognitive parameter and controls the step size towards the particle's local best position. C_2 is a positive constant called the social parameter, and it controls the step size towards the global best position found by the entire swarm. r_1 and r_2 are uniformly distributed random numbers in [0,1] to add randomness to the velocity updates. $x_{k,j}(t)$ represents the current position of the particle, $x_{k,j}^L$ is the particle's best position, and $x_{k,j}^G$ is the global best position, $w(t)$ is the inertia weight to control the acceleration of the particle in its original direction. Lower values of w speed up the convergence to the optima and higher values of w encourage exploration of the entire search space. The first term of the velocity update $w(t)v_{k,j}(t-1)$ is the inertia component to keep the particle moving in the same direction as in the previous iteration. The second term $C_1 r_1 \left(x_{k,j}^L(t-1) - x_{k,j}(t-1)\right)$ is called the cognitive component and acts as a memory of the particle causing it to return to its local best that it has encountered so far. The third term $C_2 r_2 (x_{k,j}^G(t-1) - x_{k,j}(t-1))$ is the social component as it causes the particle to move towards the global best.

3.1.3 Update position

After updating the velocity of each particle, the particle position is updated using the latest updated velocity as [47]:

$$x_{k,j}(t) = v_{k,j}(t) + x_{k,j}(t-1) \quad (2)$$

3.1.4 Update bests

The fitness of each particle is evaluated according to the newly updated position. If the updated position leads to a better objective function value, the local best and the global best are updated.

The process is repeated until the number of iterations since the last change of the best solution is less than a pre-specified number, or the number of iterations reaches a maximum allowable number or the desired value of the objective function is reached.

3.2 Overlay Model

NASA investigated the principle of dust deposition on Mars and the moon, taking the sources, the property, and the spread of dust into consideration. They developed the overlay model [74]to narrate the influence of dust deposition on the solar PV modules. The model is viable under the following theoretical speculations:

- All the dust particles are of spherical shapes
- The ratio of dust-covered area to the panel area is equal to the ratio of transmittance with dust to the transmittance without dust

Besides these assumptions, the total area of the panel was indicated by A, the area of a single dust particle was indicated by α. As a result, the ratio of the area without dust was expressed as $1-\frac{\alpha}{A}$. Since, the number of the dust particles was assumed to be N, the area without dust was written as $(1-\frac{\alpha}{A})^N$. It was assumed that, dust particles affect the light-transmittance by overlapping one another. This assumption was written as $(1-\frac{\gamma\alpha}{A})^N$, where γ was used to indicate the average transmission of light through single layer dust. The overlay model was finally written as [74],

$$\frac{\tau_2}{\tau_1}=\frac{F}{F_o}=(1-\frac{\gamma\alpha}{A})^N \tag{3}$$

Here, τ_1 and τ_2 represent the transmission before and after dust deposition on the PV modules respectively, ${}^{\tau_2}/{}_{\tau_1}$ indicates the relative transmission; F_o and F represent the area before and after dust deposition of PV modules. If the equation (3) is expanded, the factor $\left(1-N\frac{\gamma\alpha}{A}\right)$ is found which refers to the cumulative effect of dust.

Since the number of dust particle N was difficult to measure, the applied overlay model was developed. In this model[56], a variable j was assumed, where $j=\frac{A}{\gamma\alpha}$

The number of the dust particle was described as, $N=\frac{M}{\rho V}=\frac{3M}{\rho 4\pi R^3}=\frac{3Mj\gamma}{4\rho AR}$

Here, $M=$ total mass of the dust particles

ρ = average density of the particles

V = total volume of the dust particles

When the PV panel was covered by N dust particles, the area of the PV panel without dust was illustrated as [56],

$$F = F_o[(1-\frac{1}{j})^j]^{\frac{3M\gamma}{4\rho RA}} \quad (4)$$

The ratio of A to γα was expressed by j. Therefore, $\frac{1}{j}$ means the ratio of $\gamma\alpha$ to A. The ratio $\frac{\gamma\alpha}{A}$ defined the probability that N particles, which have the same size and same relative transmittance γ, would cover a point on the surface. When, $\frac{A}{\alpha} \rightarrow \infty, (1-\frac{1}{j})^j \rightarrow \exp(-1)$. Consequently, it was deduced that, $F = F_o \exp\left(-\frac{3M\gamma}{4\rho RA}\right)$.

Neglecting the scattering of dust, the transmittance with the dust of mass M was written as [56],

$$\frac{\tau_2}{\tau_1} = \exp(-\frac{3M\gamma}{4\rho RA}) \quad (5)$$

3.3 Incident Angle Model

Professor Zang et al. included the incident angle model into the overlay model and deduced an incident angle model [75]. A spherical dust particle was depicted by figure 3.1. In the figure, β represented the tilt angle of the solar panel, R represented the radius of the spherical dust particle and the incident angle was indicated by θ. The shadow of the dust particle was found to be oval-shaped given that the incident angle is not equal to 0 .The major and minor of the axes were individually indicated by $L+L_o$ and R. Accordingly, the area of the shadow was expressed as [75],

$$F(\theta) = \pi R\frac{L+Lo}{2} = \frac{\pi R^2}{cos\theta} = \frac{\alpha}{cos\theta} \quad (6)$$

Collaborating this with equation (4), the relative transmittance involving the incident angle was written as [75],

$$\frac{\tau_2(\theta)}{\tau_1(\theta)} = \exp(-\frac{3M\gamma}{4\rho RAcos\theta}) \quad (7)$$

As a consequence of gravity, it is quite easy to comprehend the magnitude of tilt angle directly influences the accumulation of dust on the solar panel. The dust quantity with the panel being horizontal (with tilt angle 0 degrees) is much more than the panel being in vertical position (with tilt angle 90 degrees). In recent years, many researchers measured the solar panel efficiency with changing tilt angles. It was evident from their results the solar panel tilt angle had an impact on dust deposition. Wang et al. regarded [56] the parameter of tilt angle in their proposed model.

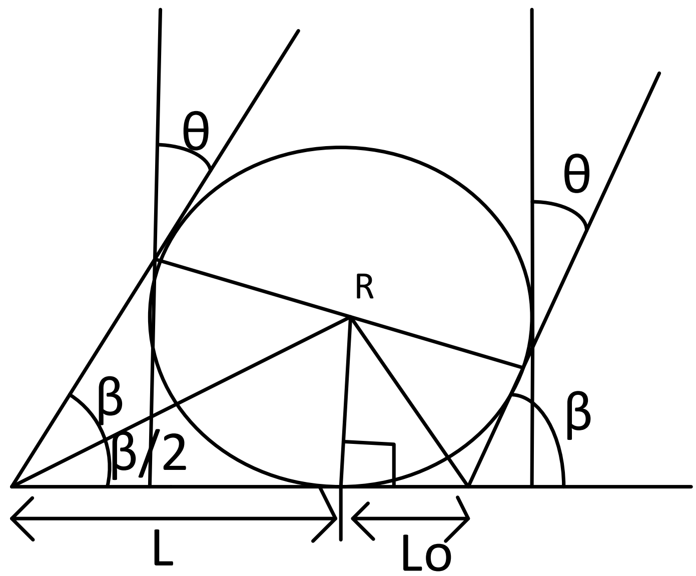

Figure 3.1: Single spherical dust particle [75]

3.4 Dust Deposition Model

The PM deposition model described by Zhang et al. [76] is included in our work in order to understand the deposition property of PM particle. This model included ambient PM concentration, PM size distribution, surface characteristics, and meteorological parameters as inputs. This model used the resistance model of deposition developed by Slinn [77]:

$$v_d = v_g + \frac{1}{R_a + R_s} \tag{8}$$

where, v_g is the gravitational settling velocity and R_a and R_s are the aerodynamic resistance and surface resistance. The model examined the processes necessary for deposition and attempts to quantify them individually. The aerodynamic resistance, R_a, is calculated as [76],

$$R_a = \frac{\ln\left({}^{z_R}/_{z_o}\right) - \Psi_H}{k u_*} \tag{9}$$

where, z_R is the height at which deposition is being calculated, z_o is the roughness length, Ψ_H is the stability function, k is the Von Karman constant, and u_* is the friction velocity. Friction velocity, u_*, is calculated by [76],

$$u_* = \frac{k u_x(h_r)}{\ln(\frac{h_r}{z_o})} \tag{10}$$

where, $u_x(h_r)$ is the wind speed at the reference height, h_r . The surface resistance is calculated by [76],

$$R_s = \frac{1}{3u_o(E_B+E_{IM})R_1} \tag{11}$$

where, E_B and E_{IM} are the collection efficiencies for Brownian diffusion and impaction, respectively, and R_1 is the percentage of particles that stay deposited on the surface . Collection by interception is not included in the model due to the smooth surface of the solar collector. E_B is calculated by [76],

$$E_B = Sc^{-\gamma} \tag{12}$$

Where, S_c is the Schmidt number, and γ is a parameter based on land use; a value of 0.56 is used here for the urban environment. E_{IM} is calculated by [76],

$$E_{IM} = 10^{-3/St} \tag{13}$$

Where St is the Stokes number which was determined for a smooth collector [77]. Finally, R_1 is calculated by [76],

$$R_1 = \exp\left(-St^{-1/2}\right) \tag{14}$$

3.5 Improved Tilt Angle Model without the Effect of Dust

In order to obtain the maximum solar radiation, it is necessary to determine the tilt angle β.The proposed improved tilt angle model was developed to determine the optimum tilt angle.The tilt angle model includes the air mass AM,elevation angle E,declination angle D,tilt angle β,and the number of days N_D .The model is proposed for both one year and six months(both dry and wet season). The mathematical model is written as,

$$\text{Solar radiation} = 1.1*1.353*I*\text{sun hour}*N_D*\sin(E+\beta), \tag{15}$$

$$\text{Here,} \quad I = 0.7^{AM^{0.678}} \tag{16}$$

The solar intensity I is calculated by using Air Mass, which is considered as the direct optical path length through the atmosphere of the earth. It quantifies the reduction in power of light when the light passes through the atmosphere and absorbed by air and dust [78]. The efficiency of solar cell varies with the power and the density of the incident light. In order to facilitate an accurate comparison between solar panels measured at different times and locations, a standard spectrum and power density is defined for both the radiation outside the earth's atmosphere and at the earth's surface.

The standard spectrum outside the earth's atmosphere is called AM0.This spectrum is typically used to predict the expected performance of solar cells in space. The standard spectrum at the Earth's surface is called AM1.5G (the G stands for global and includes both direct and diffuse radiation) or AM1.5D (which includes direct radiation only). The global spectrum is 10% higher than the direct spectrum. These approximations give approximately 970 W/m^2 as the value of AM1.5G. However, the standard AM1.5G spectrum has been normalized to give 1 KW/m^2 due to the convenience of the round number and the fact that there are few inherent variations in solar radiation. The intensity of AM1.5D can be approximated by reducing AM0 spectrum by 28%(18% due to absorption and 10% due to scattering).

3.5.1 Intensity Calculations Based on Air Mass

The intensity of the direct component of sunlight throughout each day can be determined as a function of air mass from the experimentally determined equation [78]:

$$I_D = 1.353 * 0.7^{AM^{0.678}} \tag{17}$$

Where I_D is the intensity on a plane perpendicular to the sun's rays in units of KW/m^2 and AM is the air mass. The value 1.353 KW/m^2 is the solar constant and the number 0.7 arises from the fact that about 70% of the incident radiation on the atmosphere is transmitted to the earth. The extra power term of 0.678 refers to the non-uniformities in the atmospheric layers [78]. The diffuse radiation is still about 10% of the direct component. On a clear day, the global irradiance on a module perpendicular to the sun's rays can be written as,

$$I_G = 1.1 * I_D \tag{18}$$

To calculate the air mass, this simplified formula is applied:

$$\text{AM}=\frac{1}{cos\theta z} \tag{19}$$

The zenith angle, denoted by Θz, is the angle between the sun and the direct overhead point at a measuring location [78]. Θz is determined as:

$$\Theta z = \text{zenith angle} = 90^\circ - E \qquad (20)$$

The elevation angle, denoted by E, is the angle from the sun to the observation point and the horizontal plane [78]. E, is determined as,

$$E = \text{elevation angle} \qquad (21)$$

$$E = 90 - \text{latitude angle} + D \qquad (22)$$

$$\text{And, } D = \text{declination angle} = 23.45 * \sin\left(\frac{360}{365}(N_D - 81)\right) \qquad (23)$$

The tables 3.1 and 3.2 present the improved tilt angle model parameters for eight divisional cities and two neighboring districts of Dhaka. The optimum tilt angles and solar radiation were determined for the eight divisional cities using the model parameters mentioned in the table 3.1.

The number of days N_D, the elevation angle, E and the zenith angle Θz, and the solar intensity I are shown in this table. Gazipur and Narayanganj are the two neighboring districts of Dhaka. Since the data of PM_{10} particles were available for the two districts Gazipur and Narayanganj, the model parameters in the table 3.2 were determined in order to investigate the optimum tilt angles with the effects of dust in these districts.

The declination angle has seasonal variance due to the tilt of the earth on its axis of rotation and the rotation of the earth around the sun [78]. Therefore, the declination angle has different values during wet season, dry season and a total year. The wet season and dry season consist of 183 days and 182 days in Bangladesh. The values of declination angle during wet season, dry season and total year are shown in the table 3.3.

Table 3.1: Improved tilt angle model parameters for eight divisional cities

Division	Number of Days, N_D	Elevation angle, E (Degree)	Zenith angle, θz (Degree)	Solar Intensity, $I=0.7^{AM^{0.678}}$ (KW/m^2)
Dhaka	Wet =183	43.25	46.74	0.631
	Dry=182	43.18	46.82	0.630
	Year=365	43.21	46.79	0.631
Chittagong	Wet=183	44.59	45.40	0.635
	Dry=182	44.52	45.48	0.635
	Year=365	44.55	45.45	0.635
Rajshahi	Wet=183	42.58	47.41	0.628
	Dry=182	42.51	47.49	0.628
	Year=365	42.54	47.46	0.628
Khulna	Wet=183	44.13	45.86	0.631
	Dry=182	44.06	45.94	0.634
	Year=365	44.09	45.90	0.633
Barisal	Wet=183	44.25	45.74	0.634
	Dry=182	44.18	45.82	0.634
	Year=365	44.21	45.78	0.634
Sylhet	Wet=183	42.06	47.39	0.628
	Dry=182	41.99	48.01	0.625
	Year=365	42.02	47.97	0.626
Mymensingh	Wet=183	42.21	47.78	0.627
	Dry=182	42.14	47.86	0.627
	Year=365	42.17	47.82	0.646
Rangpur	Wet=183	41.21	48.78	0.623
	Dry=182	41.14	48.86	0.623
	Year=365	43.21	43.21	0.631

Table 3.2: Improved tilt angle model parameters for the two neighboring districts of Dhaka

District	Number of Days, N_D	Elevation angle, E (Degree)	Zenith angle, ϴz (Degree)	Solar Intensity, $I = 0.7^{AM^{0.678}}$ (KW/m^2)
Gazipur	183	42.96	47.03	0.629
	182	42.89	47.11	0.629
	365	42.92	47.07	0.629
Narayanganj	183	43.33	46.66	0.631
	182	43.26	46.74	0.631
	365	43.29	46.70	0.631

Table 3.3: Seasonal and yearly declination angle

Number of days, N_D	Declination angle, D(Degree)
wet =183	23.05
Dry=182	23.12
Year=365	23.09

3.6 Improved Tilt Angle Model with The Effect of Dust

In order to develop the improved tilt angle model with the effect of dust, solar panel transmittance, ζ has been included in the equation (15). The mathematical model can be written as,

$$\text{Solar radiation} = 1.1*1.353*\text{sun hour}*I*\zeta*N_D*\sin(E+\beta) \quad (24)$$

Dust decreases the solar panel transmittance to a great extent. As the mass of dust deposition increases, the power output and the efficiency of the module decrease. Due to the availability of the data on PM10 concentration, this has been used as the deposited dust concentration on PV panel. In order to determine the PM10 mass, panel area, A and panel depth, d have been considered [79]. The seasonal and yearly PM_{10} concentration are stated in the table 3.4. For wet season, the equation (7) can be rewritten as,

$$\tau_{wet\ season} = \exp\left(-\frac{3C_{wet\ season}Ad\gamma}{4\rho RA\cos\theta}\right) \quad (25)$$

$$\tau_{wet\ season} = \exp(-\frac{3*C_{wet\ season}d\gamma}{4\rho R cos\theta}) \qquad (26)$$

Similarly, for dry season and a total year the equation (7) can be written as,

$$\tau_{Dry\ season} = \exp(-\frac{3C_{Dry\ season}d\gamma}{4\rho R cos\theta}) \qquad (27)$$

$$\tau_{yearly} = \exp(-\frac{3C_{yearly}d\gamma}{4\rho R cos\theta}) \qquad (28)$$

Table 3.4: Seasonal and yearly PM_{10} concentration [33]

District	**Wet season PM_{10} concentration,$C_{wet\ season}$**	**Dry season PM_{10} concentration,$C_{Dry\ season}$**	**Yearly PM_{10} concentration,C_{yearly}**
Dhaka	74.7 μgm^{-3}	240.8 μgm^{-3}	160.7 μgm^{-3}
Gazipur	62.7 μgm^{-3}	233.1 μgm^{-3}	151.7 μgm^{-3}
Narayanganj	79.9 μgm^{-3}	579.8 μgm^{-3}	186.8 μgm^{-3}

3.7 HDKR (Hay, Davies, Klucher and Reindl) Model

The HDKR (Hay, Davies, Klucher and Reindl) model [87] has been used in this work. This model accounts for different type of radiation including beam ($I_{T,b}$), diffuse($I_{T,d}$)(which contains parts of the circumsolar diffuse ($I_{T,cs}$), isotropic diffuse($I_{T,iso}$) and horizontal brightening ($I_{T,hz}$) components) and ground reflectance ($I_{T,ref}$) as shown by the following equation [87] :

$$I_T = I_{T,b} + I_{T,d} + I_{T,refl} \qquad (29)$$

Beam radiation on a tilted surface can be calculated by the following equation [87]:

$$I_{T,b} = R_b.(I_h - I_{h,d}) \qquad (30)$$

$I_{h,d}$ is the hourly diffuse radiation and I_h is the hourly solar radiation . The extraterrestrial radiation (I_{ex}) on a horizontal surface can be calculated by the following equation [87]:

$$I_{ex} = 1.367\left(1 + 0.033.cos\frac{360n}{365}\right) * (cos\varphi cos\delta cos\omega + sin\varphi sin\delta) \qquad (31)$$

In the above equation φ is the latitude angle, δ is the declination angle and ω is the hour angle.

The clearness index k can be defined by the following equation [87]:

$$k = \frac{I_h}{I_{ex}} \tag{32}$$

The value of the coefficient R_b for the northern hemisphere is presented by the following equation [87],

$$R_b = \frac{\cos(\varphi-\beta)cos\delta cos\omega+\sin(\varphi-\beta)sin\delta}{cos\varphi cos\delta cos\omega+sin\varphi sin\delta} \tag{33}$$

In the above equation, β is the tilt angle. Circumsolar diffuse($I_{T,cs}$) , isotropic diffuse ($I_{T,iso}$) and horizontal brightening ($I_{T,hz}$) components of the diffuse radiation can be found considering the anisotropy index as $A=I_{h,b}/I_{ex}$ [87],

$$I_{T,cs} = \frac{I_{h,b}}{I_{ex}}.R_b.I_{h,d} \tag{34}$$

$$I_{T,iso} = \left(1-\frac{I_{h,b}}{I_{ex}}\right).F_{sky}.I_{h,d}$$

$$I_{T,iso} = \left(\frac{I_{ex}-I_h+I_{h,d}}{I_{ex}}\right).F_{sky}.I_{h,d} \tag{35}$$

$$I_{T,Hz} = \left(\frac{I_{ex}-I_h+I_{h,d}}{I_{ex}}\right).F_{sky}.sin^3\left(\frac{\beta}{2}\right).I_{h,d}\sqrt{\frac{1-I_{h,d}}{I_h}} \tag{36}$$

In these equations, view factor to the sky F_{sky} is defined by [87] :

$$F_{sky} = (\frac{1+cos\beta}{2}) \tag{37}$$

The ground reflectance radiation ($I_{T,ref}$) accounts for all existing reflectance from the surrounding environment and it is defined by the following equation [87]:

$$I_{T,ref} = \rho_g.\left(\frac{1-cos\beta}{2}\right).I_h \tag{38}$$

The ground reflectance ratio changes between 0.2 and 0.7 based on the surrounding situation.

3.8 Optimization Using Particle Swarm Optimization Algorithm

The objective function determines the maximum solar energy captured. It can be written as:

$$\varepsilon = Max(I_i) \tag{39}$$

Where, I_i is the incident solar radiation on tilted surface and ε is the maximum solar energy captured. There are six decision variables in our algorithm. The first decision variable is the yearly tilt angle without the effect of dust. The second and third decision variables are the wet and dry season tilt angles without the effect of dust. The fourth decision variable is the yearly tilt angle with the effect of dust. The fifth decision variable is the wet season tilt angle with the effect of dust. The sixth decision variable is the dry season tilt angle with the effect of dust. PSO determines the global best solution by simply adjusting the trajectory of each particle towards its own best location at each iteration. The position and velocity vectors of the particle in search space is shown in the figure 3.2. As shown in the figure, the position and velocity vector of the i_{th} particle in the N- dimensional search space can be expressed as ,

$$X_i = [x_{i1}, x_{i2}, \dots \dots \dots \dots \dots, x_{iN}]$$

and $V_i = [v_{i1}, v_{i2}, \dots \dots \dots \dots .., v_{iN}]$ respectively.

The position of the particle represents the candidate solution of the tilt angle (β) of the solar collector. According to the defined objective function, the best position for the i_{th} particle(local best) is $[P_i = P_{i1}, P_{i2}, \dots \dots \dots \dots \dots \dots, P_{iN}]$ and the fittest particle found so far (global best) is $[P_g = P_{g1,}P_{g2,} \dots \dots \dots \dots \dots, P_{gn}]$. The optimization flowchart is shown in the figure 3.3. Table of parameters is shown in the table 3.5.

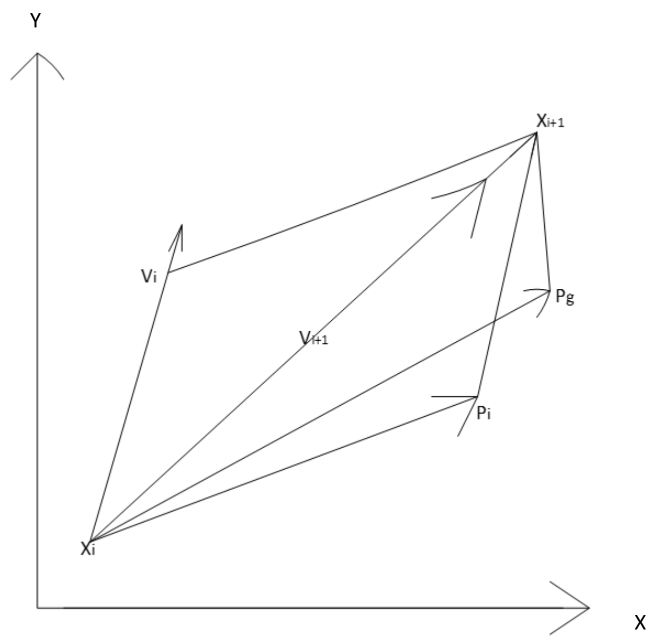

Figure 3.2: Position and velocity vectors of the particle in search space [45]

The new velocities and positions of the particles for the next fitness evaluation are updated as

$$v_{i,N+1} = v_{iN} + C_1 * rand_1() * (P_{iN} - x_{iN})$$
$$+C_2 * rand_2() * (P_{gN} - x_{iN}) \quad (40)$$

$$x_{i,N+1} = x_{iN} + v_{iN} \quad (41)$$

where, C_1 and C_2 are the acceleration coefficients representing the cognitive and social parameter respectively, $rand_1()$ and $rand_2()$ are random numbers uniformly dispersed within the range of 0 to 1.

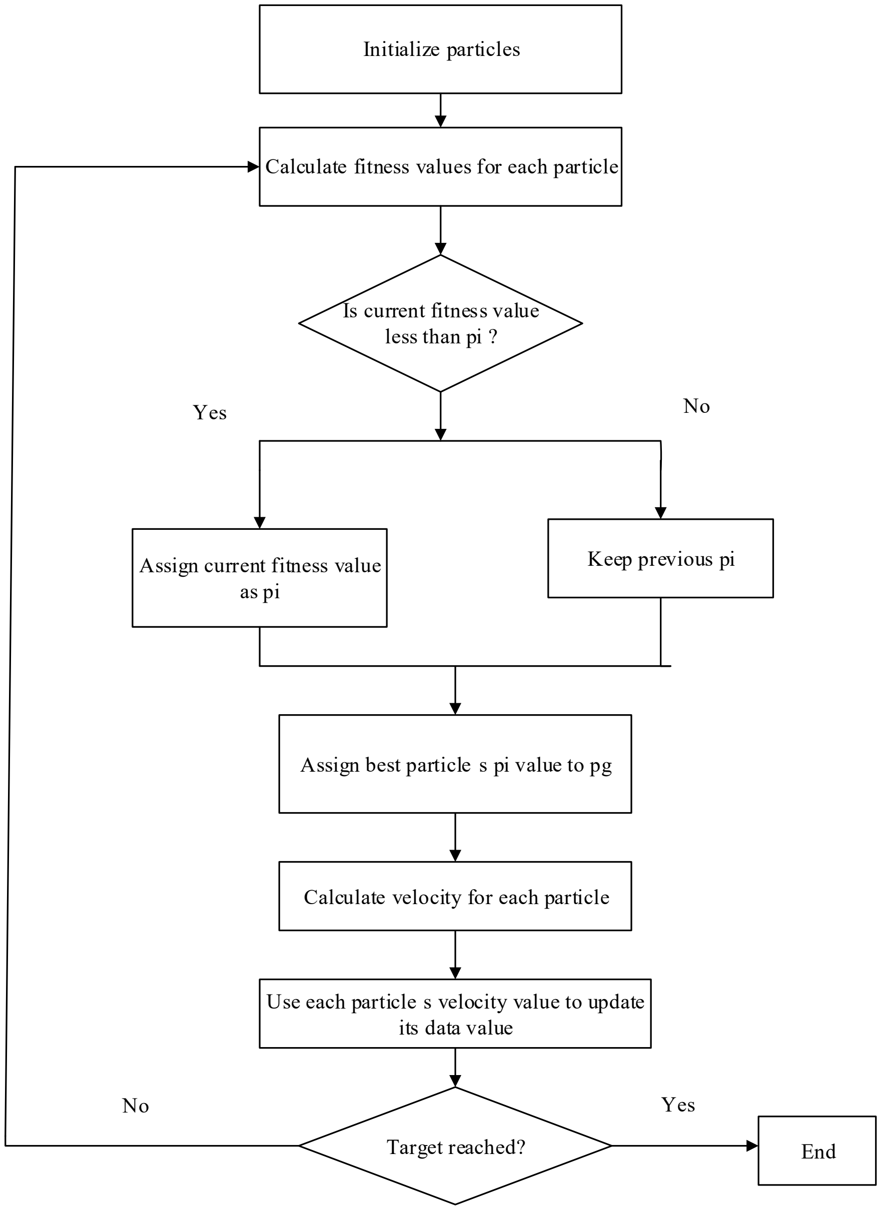

Figure 3.3: Optimization flowchart implemented in this work

The algorithm first initializes the particles. The position of each particle are initialized. The fitness value for each particle is calculated. The lowest value is assigned as the current p_i. Then particles update their position at each iteration. The new fitness value for the updated particle position is evaluated. If the current fitness value is less than the previous pi, then the current fitness value is set as the new p_i. If the current fitness value is not less than the previous pi, then the previous p_i value is kept. The best particle's pi value is assigned as the global best value. The velocity for each particle is calculated. Each particle's velocity value is then used to update the objective function value. This goes on until the target is reached.

Table 3.5: Table of parameters

Inertia coefficient, w	**Personal acceleration coefficient, C_1**	**Social Coefficient, C_2**	**Random number, $rand_1()$**	**Random number, $rand_2()$**	**Number of population**
0.8	1.5	1.5	Random numbers from 0 to 1	Random numbers from 0 to 1	50

3.9 Cleaning Frequency Modeling

The effect of sand dust particle accumulation on light transmittance coefficient is investigated mathematically and experimentally in [80]. A transmittance coefficient 0 means the light beam did not pass and that has been completely reflected or absorbed while a coefficient 1 means light has passed completely without attenuation. The relation between transmittance coefficient, τ and the number of particle accumulated , n had been derived as

$$\tau = 1 - nQ_e\pi r^2 \tag{42}$$

where, r is the radius of the sand particle and Q_e is the particle extinction efficiency which has been assumed to be equal to 2. Since the sand dust particles settle on the surface of the glass of the photovoltaic panel, the transmission of light through the photovoltaic panels is hampered. The transmittance decreases when more dust particles settle on the surface of the panel. In the reference [80] a comparison between the mathematical derivation and experimental observation showed good agreement for light transmittance values in the range of 0.5 to 1. For transmittance coefficient below, 0.5 the relation observed starts to deviate from the linear relationship of transmittance and deposition of dust on the surface.

However, in practice, to maintain the efficiency of photovoltaic panels, the cleaning of panels should be performed before the transmittance coefficient falls to such low values. So in our derivation of the optimal solar panel cleaning cycle, the relationship between efficiency and the amount of dust accumulation will be assumed linear without much loss of accuracy.

Dust accumulation on the surface of the solar panels causes the efficiency of the solar panel, η to decrement from its nominal value.

So,

$$\eta = \gamma \eta_{nominal} \tag{43}$$

$$\gamma = 1 - \alpha N \tag{44}$$

Where, α is the average daily losses in the solar conversion efficiency due to dust and N is the number of days between cleaning cycles.

In another investigation, Kazuhiro et al. [81] depicted that, power generating efficiency and transmittance of solar panels sharply drops in case of larger incident angles. Hence, they are proportional. Accordingly,

$$\tau = 1 - \alpha N \tag{45}$$

where, τ = transmittance of solar panel . So, the average loss in solar conversion efficiency is determined as,

$$\alpha = \frac{1-\tau}{N} \tag{46}$$

3.10 Cleaning Cost Estimation

To estimate the cleaning cost, the financial loss due to power degradation is to be determined. The financial loss due to power degradation as a result of dust accumulation on the PV system for N consecutive days can be written as [82],

$$(1 + 2 + 3 + \cdots \ldots \ldots \ldots . + N)\alpha s I B$$

where s = the average sun hours per day,

I = capacity of the installed PV system,

B = price of kWh

So the financial loss as a result of dust accumulation per annum is [82],

$$C_1 = \frac{365}{N}(1 + 2 + 3 + \cdots \ldots \ldots \ldots .. + N)\alpha sIB \tag{47}$$

$$C_1 = \frac{365}{N}(N + 1)\frac{N}{2}\alpha sIB$$

$$C_1 = \frac{365}{2}(N + 1)\alpha sIB \tag{48}$$

And if P is the cost of cleaning solar array, the cost of cleaning the panel per annum is [82],

$$C_2 = \frac{365}{N}P \tag{49}$$

So the total cost is $J = C_1 + C_2$

$$J = \frac{365}{N}(N + 1)\alpha sIB + \frac{365}{N}P \tag{50}$$

Finding the optimal number of days between cleaning cycles is achieved by minimizing J with respect to N

$$\frac{dJ}{dN} = \frac{365}{2}\alpha sIB - \frac{365}{N^2}P = 0$$

Or, $$N^2 = \frac{2P}{\alpha sIB}$$

Or, $$N = \sqrt{\frac{2P}{\alpha sIB}} \tag{51}$$

Putting the value of α from equation (36), it can be written as,

$$N = \frac{2P}{(1-\tau)siB} \tag{52}$$

The improved tilt angle model with the effect of dust is a function of Air Mass, number of days, transmittance, elevation angle and tilt angle. The mathematical model for determining optimum cleaning schedule is a function of cleaning cost, transmittance, average sunlight hours, price of per unit electricity and capacity of the installed PV system. In both models, transmittance is a common parameter.

Chapter 4

Result and Discussion

The effect of dust on the energy performance of the solar panel was investigated. The loss of solar energy at different tilt angles due to dust deposition was also mentioned. Thereafter, the tilt angle and solar radiation of particular regions were determined. Depending on the available data of PM_{10} particle [33], the tilt angle and incident solar radiation upon the tilted solar panels were determined for three different locations according to the mathematical model developed in the chapter three. Additionally, the cleaning schedules were optimized for these locations. The revenue as well as cleaning cost were also analyzed.

4.1 Dust Effect on the Solar Panel

Transmittance is generally known as the ratio of incident light falling on a body to the light passing through it. The increase in the dust deposition on the panel surfaces means that the dust layer on the panel surfaces got thickened with time which in turn blocks the solar energy transmitting through it. So, dust deposition density and the transmittance are inversely related to each other. From the equations (33) and (34) of the previous chapter it can be inferred that, efficiency of the solar panel is proportional to the transmittance of the solar panel.

4.1.1 Effect on the Transmittance

The change in transmittance was observed for the tilted panels with the deposition of dust. The tilted surfaces were considered because the equations (26), (27) and (35) in the mathematical model are derived for tilted surfaces. Figure 4.1, 4.2, and 4.3 show the transmittance of solar panels in Dhaka, Gazipur and Narayanganj. The black circle represents the wet season data whereas the hollow circle represents the dry season data. In the dry season, the transmittance is observed to have sharp decrease over few weeks due to the thick dust layer upon the panels. On the contrary, the decrease in transmittance during wet season is almost flat due to the increased rainfall which contributes to natural cleaning.

While explaining the curves for Dhaka it can be observed that, during wet season, the obtained transmittance values for solar PV modules vary from 0.93(cleaning every eight weeks) to 0.99(cleaning every one week). Contrastingly, the obtained transmittance values vary from 0.82 (cleaning every eight weeks) to 0.979(cleaning every one week) during dry season.

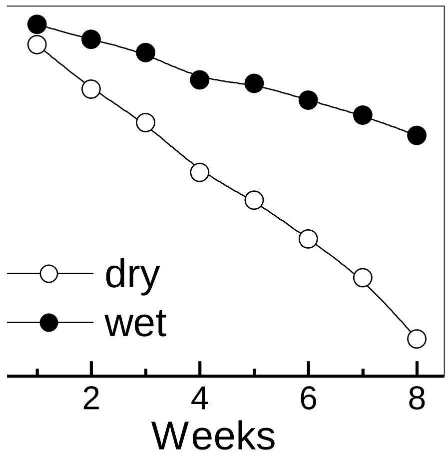

Figure 4.1: Transmittance of solar panels for Dhaka (both dry and wet season).

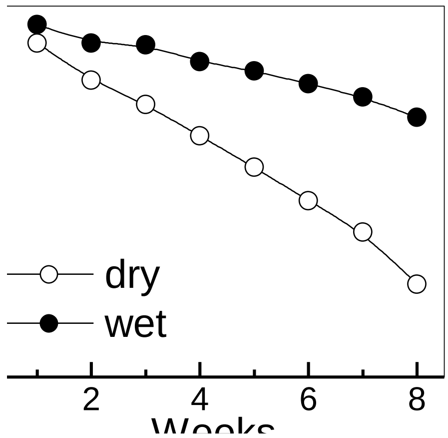

Figure 4.2: Transmittance of solar panels for Gazipur (both dry and wet season).

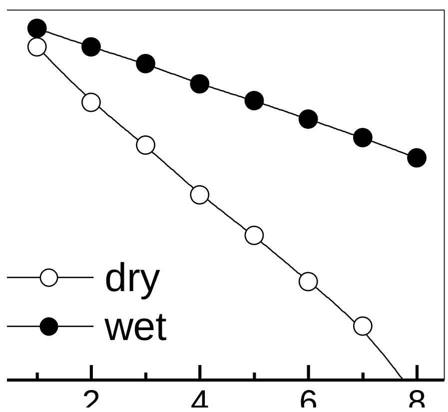

Figure 4.3: Transmittance of solar panels for Narayanganj (both dry and wet season).

While explaining the curves for Gazipur, it has been noted that during wet season the obtained transmittance value for solar PV modules varies from 0.94 (cleaning every eight weeks) to 0.99

(cleaning every one week). Instead, the obtained transmittance values vary from 0.85 (cleaning after eight weeks) to 0.98 (cleaning after one week) during dry season.

The curves for Narayanganj depict that during wet season the obtained transmittance values for solar PV modules vary from 0.92(cleaning every eight weeks) to 0.99 (cleaning every one week). However, during dry season the obtained transmittance values vary from 0.79(cleaning after eight weeks) to 0.98(cleaning after one week). For all three figures, the wet season curves remain higher than the dry season curves indicating the higher transmittance during wet season than dry season.

The transmittance of solar panels at different tilt angles has been discussed in [55]. For the panels tilted at 10^0, the transmittance varies from 0.90 to 0.95. The panels which are tilted at 20-degree, the transmittance differs from 0.92 to 0.95. When the panels are tilted at 30-degree, the transmittance ranges from 0.92 to 0.96. For the panels tilted at 40-degree, the transmittance varies from 0.93 to 0.96. The transmittance of these panels is 1.09-1.13 times higher than the transmittance of the solar panels in Dhaka, 1.06-1.09 times higher than the transmittance of the solar panels in Gazipur and 1.14-1.17 times higher than the transmittance of the solar panels in Narayanganj. These differences are found while considering the transmittance of the panels during dry season at these locations. The wet season transmittance of the solar panels at these locations almost matches with the transmittance of the panels [55].

4.1.2 Effect on the Efficiency

Considering the equations (33) and (34) in the previous chapter it is deduced that, during wet season in Dhaka, the ratio of efficiency of the solar panel to its nominal value varies from 0.93(cleaning every eight weeks) to 0.99(cleaning every one week). During dry season, the efficiency of the solar panel differs from 0.82(cleaning every eight weeks) to 0.979(cleaning every one week).

Considering the same two equations (33) and (34) in the previous chapter, it is presumed that, during wet season in Gazipur, the ratio of efficiency of the solar panel to its nominal value differs from 0.94(cleaning every eight weeks) to 0.99(cleaning every one week). During dry season, the efficiency of the solar panel wavers in between 0.85 (cleaning every eight weeks) to 0.98(cleaning every one week).

Considering the same equation (27) in the previous chapter it has been figured out that, during wet season in Narayanganj, the ratio of efficiency of the solar panel to its nominal value differs from 0.92(cleaning every eight weeks) to 0.99(cleaning every one week). During dry season, the efficiency of the solar panel varies from 0.79(cleaning every eight weeks) to 0.98(cleaning every one week).

Therefore, it can be said that depending upon the cleaning of the panels, the ratio of efficiency of solar panel to its nominal value decrements rapidly in the presence of dust.

4.2 Energy Loss due to Dust at Different Tilt Angles

The accumulation of particulate matter on their surface, can cause significant solar energy loss. Dust grains are modelled as spheres which are homogeneously distributed on the surface of the panel. Each sphere has a reflection coefficient R, which accounts for both specular and diffused reflection. In the dirty solar cell, any sphere of dust shadows the panel thus reducing the light reaching it [33]. However not all radiation reaching the spheres is lost because part of it is reflected (a factor R) and can be partially recovered by the panel. Both effects, the shadowing and the recovery of light, depend on the angle of incidence of the direct radiation and thus vary along the day. On the other hand, there is no such dependence in the diffuse radiation since it is assumed that I_D (solar intensity on a plane perpendicular to sun's rays) is constant along the day. it is very important to quantify energy losses produced by dust. Because, such losses could reach large values and so producing a substantial decrease in the efficiency of photovoltaic systems.

4.2.1 Effect of Dust on the Energy Generation of the Solar Panel

The energy generation at latitude and optimum tilt angles of solar panels for Dhaka, Gazipur and Narayanganj are presented in the table 4.1. The peak wattage of the solar panel has been considered to be 250 Watt and average hours of sunlight has been considered to be 4.6 hours [21].

Table 4.1: Yearly Energy Generation at latitude and optimum tilt angles

District	At latitude			At optimum tilt angles		
	Without dust(kWh)	With dust(kWh)	% loss	Without dust(kWh)	With dust(kWh)	% loss
Dhaka	385.75	297.41	22.9%	392.46	303.37	22.7%
Gazipur	385.75	301.65	21.8%	389.10	305.06	21.6%
Narayanganj	385.75	285.06	26.1%	398.34	295.17	25.9%

The difference between generated energy with and without dust is determined. Then the result is divided by the generated energy without dust to calculate the percentage of energy loss because of dust. Accumulation of dust particles on solar PV systems blocks the sunlight and hence reduces its power to a large extent.

4.2.2 Energy Loss due to Dust at Different Tilt Angles in Different Regions

In order to predict the solar energy loss due to the accumulation of particulate matter, yearly average PM_{10} concentrations based on 2013 and 2014 scenarios [33] were used. Trends in PM concentrations reveal that the pollution levels followed the same pattern from November 2012 to March 2015.Narayanganj was receiving PM_{10} concentrations greater than Dhaka and Gazipur.

Winter was found to be the most polluted season of this region. Brick kilns, vehicular activities, and long-range sources from the north-west direction could be the major contributors to high PM pollutions at these three cities: Dhaka, Gazipur and Narayanganj. The energy loss at different tilt angles in these three regions are presented graphically in the figures 4.4,4.5 and 4.6.

The red bar and green bar represent the energy loss at 21.38-degree and 23-degree tilt angles in the figures. The blue bar in the figure 4.4 represents the energy loss at 26-degree tilt angle. Similarly, the blue bar in the figure 4.5 represents the energy loss at 25.1-degree tilt angle. Likewise, the blue bar in the figure 4.6 represents the energy loss at 28.5-degree tilt angle.

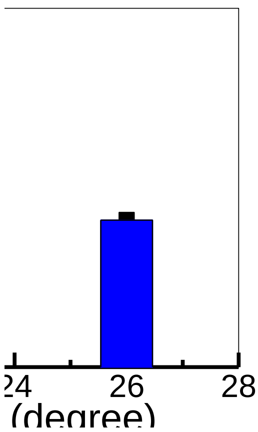

Figure 4.4: Energy loss at different tilt angles for Dhaka.

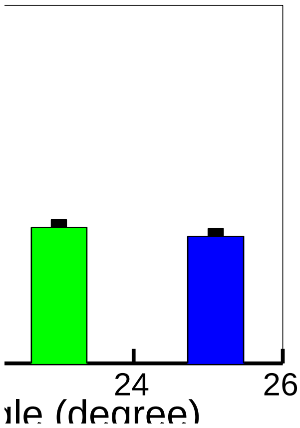

Figure 4.5: Energy loss at different tilt angles for Gazipur.

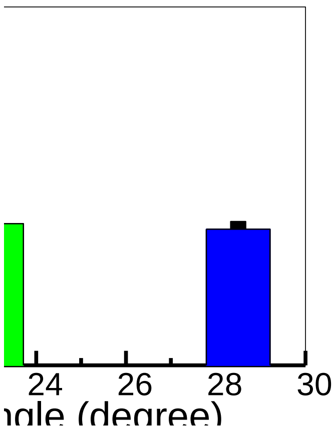

Figure 4.6: Energy loss at different tilt angles for Narayanganj.

The energy loss is the highest in Dhaka and lowest in Gazipur at 21.38-degree tilt angle. At 23-degree tilt angle, Gazipur confronts the lowest energy loss whereas the energy loss for Dhaka and Narayanganj is little higher than Gazipur. At the yearly tilt angles (Dhaka at 26-degree, Gazipur at 25.1-degree, Narayanganj at 28.5-degree) the energy loss shows the same pattern. The loss is the highest in Dhaka, medium in Narayanganj and the lowest in Gazipur. The loss decreases with the increase of tilt angles. All these results depend on the amount and characteristics of dust particle in the air in these cities. The more dust present in the air in, higher will be the loss due to it. The simulation results proposed by Wang et al. [56] proposed that the reduction in relative transmission declines with increasing tilt angle. As a result, the energy loss also decreases with increase of tilt angle. The graphs in the present analysis also suggest the same. From the discussion above, it is evident that, this work conforms to the simulation model in [56].

4.3 Changes in Tilt Angles as an Influence of Dust

Bangladesh, a subtropical country located not very far from the equator, has certain geographical advantages in solar energy generation. But, as the solar energy generation is not as robust as other forms of energy, the solar systems must be optimally installed to reap every physical benefits possible. One very important factor in this matter is the tilt angle of the solar panel. Table 4.2 presents the optimum tilt angles for different locations in Bangladesh.

Table 4.2: Optimum tilt angles for different cities in Bangladesh

City	Latitude (Degree)	Yearly tilt angle (Degree)		Wet season tilt angle(Degree)		Dry season tilt angle(Degree)	
		With dust	Without dust	With dust	Without dust	With dust	Without dust
Dhaka	23.70	26	21.38	12.72	9.76	40.09	38.35
Gazipur	23.99	25.1	22.43	11.62	7.06	40.03	37.10
Narayanganj	23.62	28.5	24.11	12.05	8.21	41.29	37.29

The proportional reduction of solar radiation transmission rate decreases with the increase of tilt angle [56]. This implies, when the transmittance is less due to dust deposition, the tilt angle should be increased. From the simulation result presented in [56], it is observed, when the transmittance of the panel that is covered with dust ranges from 0.6-0.9, the increase in tilt angle should be 3 to 5-degrees. The obtained yearly tilt angles considering the effect of dust vary from 2.6-4.6 degrees in all three districts while compared with the yearly tilt angles without dust. The obtained seasonal tilt angles with the effect of dust vary with the tilt angles without dust from around 1.7-2.9 degrees for Dhaka, 2.9-4.5 degrees for Gazipur and 3.8-4 degrees for Narayanganj. These results show little deviation from the simulation result in [56]. Since the simulation result is based on the deposited dust on the PV modules in Kuwait, the nature of dust is quite different from our country. Therefore, the deviation happened. In [55], it is stated that, when the transmittance of the dusty solar panels ranges from 0.75 to 0.90, the increase in tilt angle is 10-degree, when transmittance is increased by 0.02. The increase in the tilt angle due to dust [55], is 2.17-5.9 times greater than our obtained results.

Each of the yearly tilt angles were compared with the latitudes. Here, wet season is considered from April to September whereas the dry season is considered from October to March. The yearly tilt angles with the effect of dust are found to be 1.21,1.11, and 1.18 times greater than the tilt angles without dust. When it comes to the calculation of wet season tilt angle, the results are found to be 1.3,1.6, and 1.5 times greater than those without dust. Similarly, the dry season tilt angles are 1.04,1.08, and 1.11 times greater than those not considering the effect of dust. The greater dry season tilt angle implies the existence of a higher concentration PM_{10} particle during the dry season. It suggests that, in order to capture more energy and to eradicate the dust, the solar panels are to installed at greater tilt angles. The angles in the wet season present less values referring that the rainfall adds up in natural cleaning of the solar panel allowing less dust to be accumulated.

4.3.1 Comparison with Published Work

The yearly solar radiation is calculated for both one (system that involves one tilt angle for the whole year) and two tilt angle systems (system that involves two tilt angles for two halves of the whole year). The results obtained for both one and two tilt angle systems are tabulated in the table 4.3. The yearly and seasonal tilt angles (both dry and wet season) are shown in the table 4.4. The obtained results are compared with the results in [72].

Table 4.3: solar radiation for one and two tilt angle systems

Division	One tilt angle system		Two tilt angle system	
	Obtained result (kWh/m^2)	**Results in [72] (kWh/m^2)**	**Obtained result (kWh/m^2)**	**Results in [72] (kWh/m^2)**
Dhaka	1390.39	3274.72	1441.17	3382.21
Chittagong	1390.47	3291.75	1474.11	3400.23
Rajshahi	1361.21	3267.82	1457.86	3374.91
Khulna	1383.89	3285.34	1458.39	3393.45
Barisal	1394.22	3286.53	1455.94	3394.71
Sylhet	1346.34	3261.80	1420.37	3368.52
Mymensingh	1324.88	3263.47	1455.95	3370.29
Rangpur	1347.54	3251.16	1420.37	3357.25

In [72], the total length of the day is considered as the average sunlight hour for both one and two tilt angle system. But in our work, the average sunlight hour is considered as 4.6 hours [21] for one tilt angle system. For two tilt angle system, the average sunlight hour is considered to be 4.04 hours for dry season and 5.16 hours for wet season [83]. The obtained results are observed to deviate from the results in [72] may be due to this reason.

When the tilt angle of the solar panel is fixed throughout the year, the system is called one tilt angle system. When the solar panel is tilted differently at two different angles depending on the seasonal variation, the system is called two tilt angle system. The solar panels were south-facing. The purpose of deriving the solar radiation at two different tilt angle system was to know which one between these two systems is feasible.

Comparing the obtained results for one tilt angle system with the results in [72], it is found the results in [72] are 2.26-2.29 times higher than the obtained results for Barisal, Dhaka, Sylhet and Rangpur. Similarly, the results in [72] are 2.23-2.25 times higher than the obtained results for Chittagong, Rajshahi, Mymensingh and Khulna. Comparing the obtained results for two tilt angle system with the results in [72], it is observed that the results in [72] are 2.43-2.45 times higher than the obtained results for Dhaka, Chittagong, Khulna and Barisal division. Likewise, the results in [72] are 2.48-2.54 times higher than the obtained results for Rajshahi, Rangpur, Sylhet and Mymensingh.

Table 4.4: Yearly and seasonal tilt angles

District	**Yearly**		**Wet season**		**Dry season**	
	Obtained result (Degree)	**Results in [72] (Degree)**	**Obtained result (Degree)**	**Results in [72] (Degree)**	**Obtained result (Degree)**	**Results in [72] (Degree)**
Dhaka	21.38	21.40	9.76	8.70	38.35	37.90
Chittagong	23.81	20.20	7.36	7.20	36.99	36.40
Rajshahi	25.75	22.10	8.09	9.30	38.54	38.50
Khulna	23.15	20.70	7.99	7.80	35.19	37
Barisal	22.55	20.60	7.94	7.70	39.86	36.90
Sylhet	23.21	22.50	8.55	9.80	34.09	39
Mymensingh	23.62	22.40	5.07	9.70	38.49	38.90
Rangpur	20.93	23.30	9.72	10.70	37.47	39.80

In [72], the simulation was done using scripting language jQuery and the output was plotted using MATLAB. For various tilt angles ranging from 0 degree to 90 degrees, the resultant radiations were calculated and summed up for a year. Then the tilt angle for which the total radiation is maximum was determined. On the other hand, in our work, the Particle Swarm Optimization algorithm was implemented in MATLAB to obtain the optimum tilt angle and the maximum solar radiation for an entire year, for dry season and wet season. The obtained results are observed to deviate from the results in [72] may be due to this reason.

The obtained results are compared with the results in [72]. The obtained yearly tilt angles for Dhaka and Rangpur vary with the latitudes of these two divisions from 0.8 – 0.9 times. Similarly, the yearly tilt angles for Barisal, Mymensingh and Sylhet differ with the latitudes of these divisions from 0.93-0.99 times. On the contrary, the yearly tilt angles for Khulna, Rajshahi and Chittagong vary with the latitudes of these divisions from 1.01-1.06 times. While comparing with the results in [72], it is observed that the yearly tilt angles of Rangpur and Dhaka differ with the results [72] from 0.89- 0.99 times. The yearly tilt angles of Sylhet, Mymensingh and Barisal differ with the results [72] from 1.03-1.09 times. The yearly tilt angles of Khulna, Rajshahi and Chittagong vary with the results [72] from 1.12-1.18 times.

The highest yearly tilt angle is noted in Rajshahi whereas the lowest is noted in Rangpur. In case of wet season tilt angles, the tilt angles in Khulna, Barisal, Chittagong and Dhaka are found 1.02-1.12 times higher than the results in [72]. The variation in tilt angles in Rajshahi, Sylhet and Rangpur range from 0.87-0.91 times with the results [72]. The wet season tilt angle in Mymensingh is 0.52 times lower than the tilt angle in [72]. When the dry season tilt angles are compared with the results in [72], it is noted that the tilt angles in Sylhet, Khulna, Rangpur and Mymensingh are 0.87-0.99 times lower than the results in [72]. The tilt angles in Dhaka, Chittagong and Barisal are 1.01-1.08 times higher than the results in [72].

It is noticed that the tilt angles in dry season reveal larger value and tilt angles in wet season reveal smaller value in general. In dry season, the sun takes a shorter southern path and the panels are to be fixed at higher tilt angles to capture maximum solar radiation. In wet season, the sun takes a long northern path and the panels are to be fixed at lower tilt angles to receive much solar radiation [59]. The solar panels when held in fixed positions (fixed in one tilt angle throughout the year), may have their productivity compromised when the sun changes its position over different time period. In order to compensate this loss, solar trackers are used which automatically moves to track the progress of the sun across the sky, thereby maximizing output. Therefore, implementation of two tilt angle system (when the panels are tilted differently during wet and dry season) requires the involvement of solar trackers. But the solar trackers are more expensive than their stationary counterparts due to the more complex technology [84]. Since, the system is technically more complex, more site preparation is needed. Also, more maintenance is required than a traditional fixed tracking system. More maintenance contributes to more expenses. When the solar modules are installed at lower tilt angles, the first row blocks the ground reflection from the second row of modules. Since they are tilted lower, less ground reflection(albedo) is received by them. As a result, the overall albedo number is really small, typically 0.1% to 0.3% of sunlight [85]. The problem of shading loss is increased when the solar modules are steeply tilted during dry season. When the solar modules are tilted higher than 30-degrees, the plane-of-array albedo contribution to sunlight actually goes up to over 2% [86]. The first row of the modules again blocks the ground reflection from the second/third row of the modules. As a result, the increased plane-of-array albedo of total sunlight is immediately lost and this is counted as shading loss. The obtained results on solar radiation and tilt angles are also compared with the results obtained from HDKR(Hay, Davies, Klucher and Reindl) model [87].The obtained results of solar radiation and tilt angles are compared with the results obtained by HDKR model in the tables 4.5 and 4.6.

Table 4.5: Comparison with the obtained solar radiation by HDKR model

Divisions	**One tilt angle system**		**Two tilt angle system**	
	Obtained result (KWh/m^2)	**Results obtained by HDKR model (KWh/m^2)**	**Obtained result (KWh/m^2)**	**Results obtained by HDKR model (KWh/m^2)**
Dhaka	1390.39	1404.80	1441.17	1544.26
Chittagong	1390.47	1465.65	1474.11	1514.44
Rajshahi	1361.21	1427.48	1457.86	1515.78
Khulna	1383.89	1434.54	1458.39	1512.83
Barisal	1394.22	1448.12	1455.94	1516.36
Sylhet	1346.34	1399.76	1420.37	1535.94
Mymensingh	1324.88	1428.75	1455.95	1517.35
Rangpur	1347.54	1449.77	1420.37	1582.01

The tilt angles with and without the effect of dust determined using the HDKR model are presented in the table 4.7.

Table 4.6: Comparison with the obtained tilt angles by HDKR model

District	Yearly		Wet season		Dry season	
	Obtained result (^{0}) by proposed model	Results (^{0}) Obtained using HDKR model	Obtained result (^{0}) by proposed model	Results (^{0}) Obtained using HDKR model	Obtained result (^{0}) by proposed model	Results (^{0}) Obtained using HDKR model
Dhaka	21.38	21.56	9.76	8.01	38.35	38.46
Chittagong	23.81	23.62	7.36	8.39	36.99	37.18
Rajshahi	25.75	26.09	8.09	9.85	38.54	39.02
Khulna	23.15	24.29	7.99	9.56	35.19	36.05
Barisal	22.55	23.91	7.94	9.70	39.86	40.04
Sylhet	23.21	24.51	8.55	10.34	34.09	35.38
Mymensingh	23.62	24.02	5.07	7.67	38.49	39.23
Rangpur	20.93	21.73	9.72	11.63	37.47	38.02

Table 4.7: Optimum tilt angles with the effect of dust using HDKR model

City	Latitude (Degree)	Yearly tilt angle (Degree)		Wet season tilt angle(Degree)		Dry season tilt angle(Degree)	
		With dust	Without dust	With dust	Without dust	With dust	Without dust
Dhaka	23.70	27.12	21.56	13.95	8.01	41.46	38.46
Gazipur	23.99	26.07	23.37	13.39	9.67	41.89	38.18
Narayanganj	23.62	29.16	25.12	13.56	9.96	42.06	38.49

From the table 4.5, it is observed that the solar radiation determined for one and two tilt angle systems using the HDKR model are little larger than the solar radiation determined using the proposed model. The percentage of deviation is in between 1-7%. The reason behind this deviation is the consideration of reflected coefficient of solar radiation in the HDKR model.

The solar PV systems are installed in the rooftop which is usually dirty and the reflection does not happen from a dirty surface. Therefore, the reflected coefficient of solar radiation should not be considered. From the table 4.6, the tilt angles determined using the proposed model is almost similar to the tilt angles determined using HDKR model.

Table 4.8: Annual clearness index for eight divisions.

Divisions	Annual Clearness Index	
	One tilt angle system	**Two tilt angle system**
Dhaka	0.89	0.86
Chittagong	0.89	0.84
Rajshahi	0.92	0.86
Khulna	0.89	0.85
Barisal	0.89	0.85
Sylhet	0.90	0.86
Mymensingh	0.92	0.84
Rangpur	0.88	0.84

The clearness index for one and two tilt angle systems is shown in the table 4.8. Analyzing clearness index for one tilt angle system, it is observed that the clearness index from our results remains in between the range 0.88-0.89 for Rangpur, Dhaka, Chittagong, Khulna, and Barisal and ranges from 0.9-0.92 Sylhet, Rajshahi and Mymensingh. When the clearness index is analyzed for two tilt angle system, the clearness index is found to be in the range of 0.84-0.86 for these eight divisions.

4.4 Cleaning Cost Estimation

The process of cleaning the solar array should be performed by professional cleaner. The cost of cleaning include the cost of materials used in the cleaning process plus labor cost [88].The cost will vary from case to case depending on the soiling type and country where the PV system is installed [89] . In the middle east region, for example, the soiling of panels is mainly due to dust accumulation and hence cleaning can be performed relatively easy with basic tools, water, and some cleaning chemicals. In cases where other types of dirt exit such as bird dropping or extra pollution, the cleaning process may involve more cost and labor. Depending on the cost of cleaning and the level of dust accumulation, the cleaning operation may be justified or it may not be justified. In a study by Tanesab et al. [90] it was found that cleaning cost of PV panels installed in Perth, Western Australia will be much higher than loss caused by dust and hence cleaning is not justified. So the system operator can rely on natural cleaning such as rain and wind to clean the panels. In the studies [91] [92]it is found that cleaning is justified in Murcia, and cleaning is justified to some degree in Munich, but cleaning is not justified for Stockholm. From the calculations, the dry season tilt angles with the effect of dust are found to be more than 40-degrees. It is also reported that the shading loss increases when the tilt angle is more than 30-degrees.The nature of dust in Bangladesh is different from other countries and the natural cleaning with rainfall is not enough to completely wipe out the dust.Therefore,the cleaning of solar modules is justified for our country.Capacity of installed PV system is considered to be 100 kW while the price of 1 KWh of electricity is considered as 9.55BDT/KWh [93].Average sun hours per day is considered to be 4.6 hours [21].The cleaning cost of solar panels in Bangladesh includes labor wages,water cost,water treatment cost and cleaning equipment cost.The labor wages have been considered acording to [94].The water cost is assumed using the reference [95].In order to determine the water treatment cost the total operation cost of a DWWT(Decentralised Waste Water Treatment Plant) is considered [96].Since the distance of Gazipur and Narayanganj from Dhaka is 25.7 km and 28.7 km, three DWWT plants for cleaning solar modules have been considered.The operation cost of a DWWT plant includes electricity cost,labor cost,depreciation cost,heavy reapir cost,maintenance cost and interest cost [96].The total water treatment cost is determined by dividing the total operation cost by the total amount of treated wastewater [96].The cleaning equipments include good quality soft brush (which has squeeze with plastic blade at one side and a cloth-covered sponge on the other with a long extension arm) and good quality liquid soap.The water treatment cost is assumed as 3568 BDT(Bangladeshi Taka),the labor cost is assumed as 1500 BDT for three people and the cleaning equipment cost is assumed as 500 BDT for each of the districts.Therefore,the total cleaning cost for each of districts is assumed to be 5568 BDT. The table 4.9 shows the optimum number of days between the cleaning sessions for the solar PV systems. The optimum number of days between the cleaning sessions for different tilt angles are shown in the figure 4.7. The cost is plotted against the intervals between the cleaning sessions for Dhaka,Gazipur and Narayanganj in the figures 4.8,4.9 and 4.10 for dry season.

Table 4.9: Optimum number of days between the cleaning sessions

Districts	Dry season	Wet season
Dhaka	9 days	20 days
Gazipur	9 days	23 days
Narayanganj	8 days	19 days

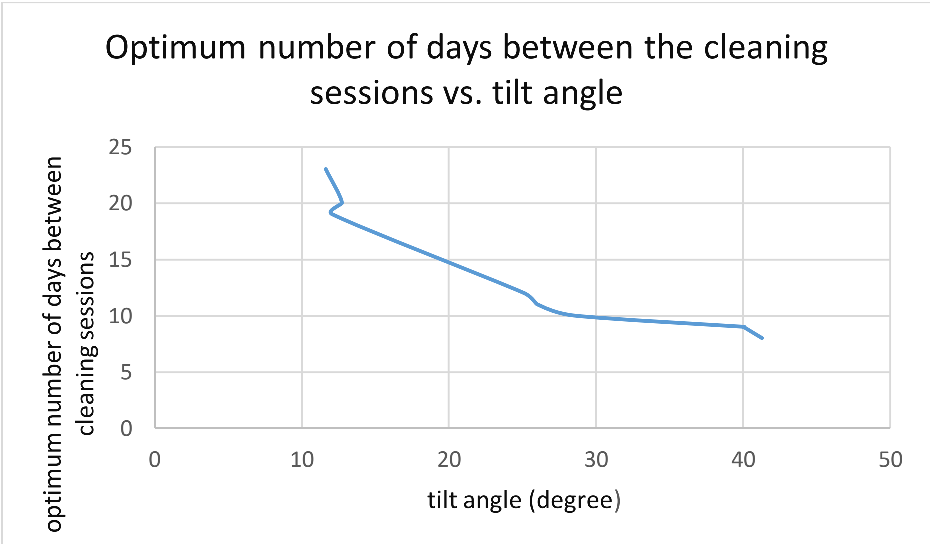

Figure 4.7: Optimum number of days between the cleaning sessions for different tilt angles

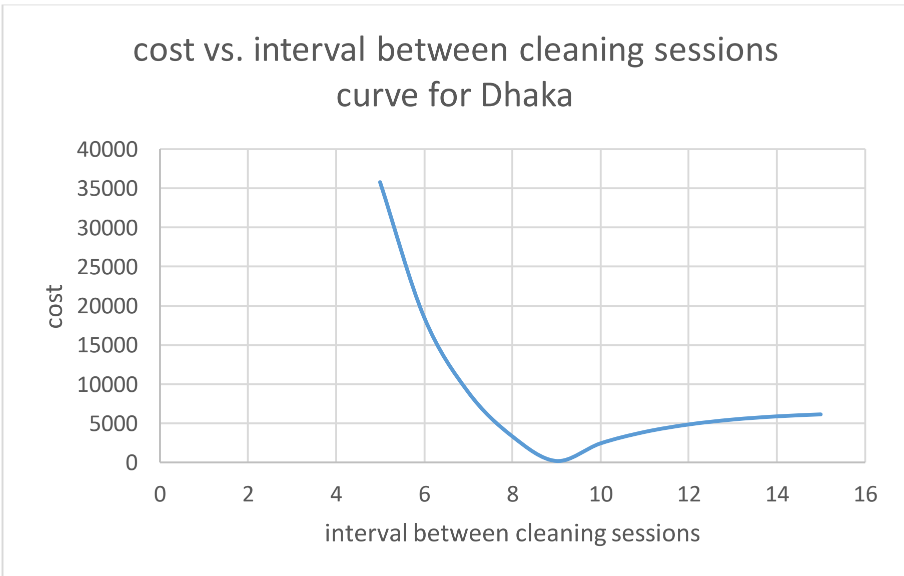

Figure 4.8: Cost vs.interval between cleaning sessions curve for Dhaka

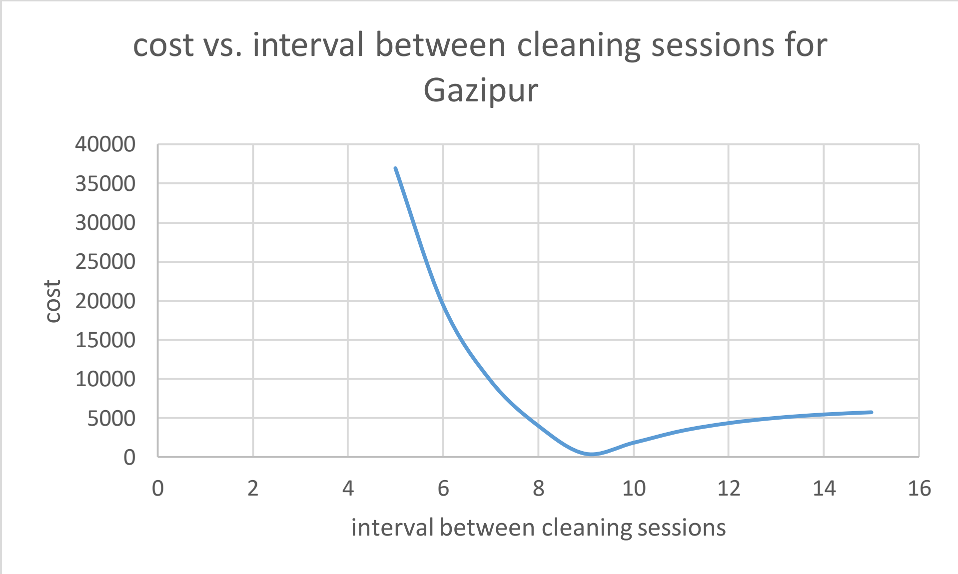

Figure 4.9: Cost vs.interval between cleaning sessions curve for Gazipur

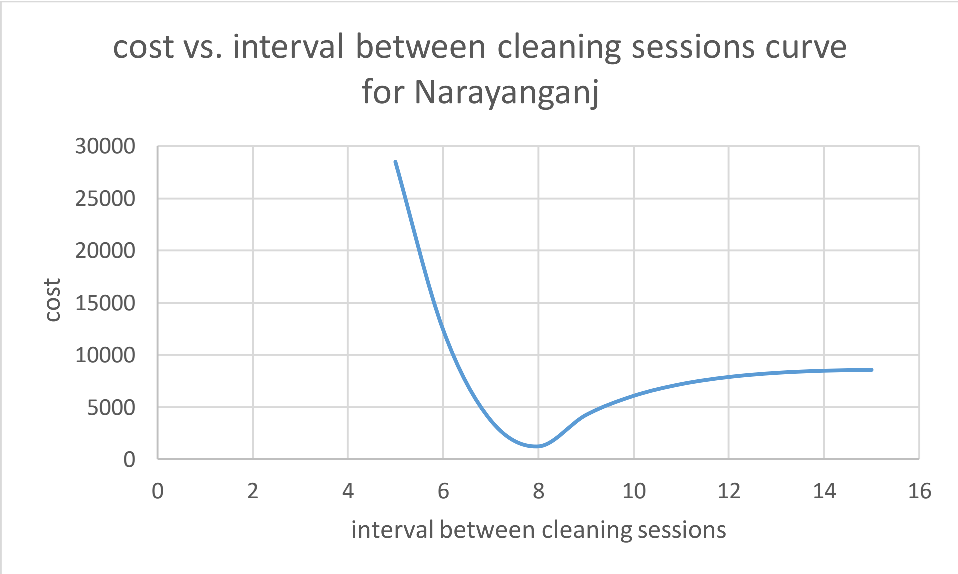

Figure 4.10: Cost vs.interval between cleaning sessions curve for Narayanganj

In the figure 4.7, the dry season tilt angles are larger.The PM_{10} particles are sticky and the panels are to be cleaned frequently during dry season for the higher PM_{10} concetration even at larger tilt angles.In wet season,the increased rainfall helps in natural cleaning.The panels are tilted at smaller tilt angles and the panels can be cleaned less frequently due to natural cleaning process caused by rainfall.

In the figures 4.8,4.9 and 4.10, the intervals between the cleaning sessions found graphically comply with the results found for dry season from the cleaning frequency model for Dhaka.The intervals between the cleaning sessions found graphically comply with the results found for dry season from the cleaning frequency model for Gazipur and Narayanganj.The earned revenue for dry and wet season is shown in the tables 4.10 and 4.11.

Table 4.10: Revenue and cost in BDT for dry season

District	Revenue			Cleaning cost		
	No cleaning (BDT)	With optimized cleaning (BDT)	Without optimized cleaning (BDT)	With optimized cleaning (BDT)	Without optimized cleaning (BDT)	Percentage of change
Dhaka	5.41 lakh	5.67 lakh	5.75 lakh	1.01 lakh	1.35 lakh	25%
Gazipur	5.47 lakh	5.73 lakh	5.81 lakh	1.01 lakh	1.35 lakh	25%
Narayanganj	4.99 lakh	5.33 lakh	5.40 lakh	1.01 lakh	1.35 lakh	25%

The revenue earned with optimized cleaning is around 25,000 taka more than the revenue earned without any cleaning for Dhaka and Gazipur. The revenue earned with optimized cleaning is around 33,000 taka more than the revenue earned without any cleaning for Narayanganj. The revenue earned without optimized cleaning is around 8,000 taka more than the revenue earned with optimized cleaning for Dhaka. The revenue earned without optimized cleaning is around 7,000 taka more than the revenue earned with optimized cleaning for Gazipur and Narayanganj.But, the cleaning cost without optimized cleaning is around 33,000 taka more than the cleaning cost when the optimized cleaning is followed.

Table 4.11: Revenue and cost in BDT for wet season

District	Revenue			Cleaning cost		
	No cleaning (BDT)	With optimized cleaning (BDT)	Without optimized cleaning (BDT)	With optimized cleaning (BDT)	Without optimized cleaning (BDT)	Percentage of change
Dhaka	7.12 lakh	7.16 lakh	7.20 lakh	33 thousand	1.33 lakh	75%
Gazipur	7.26 lakh	7.28 lakh	7.32 lakh	33 thousand	1.33 lakh	75%
Narayanganj	7.06 lakh	7.10 lakh	7.15 lakh	33 thousand	1.33 lakh	75%

The revenue earned with optimized cleaning is around 3,000 taka more than the revenue earned without any cleaning for Dhaka and Narayanganj. The revenue earned with optimized cleaning is around 2,000 taka more than the revenue earned without any cleaning for Gazipur. The revenue earned without optimized cleaning is around 4,000 taka more than the revenue earned with optimized cleaning for Dhaka. The revenue earned without optimized cleaning is around 3,000 taka more than the revenue earned with optimized cleaning for Gazipur. The revenue earned without optimized cleaning is around 5,000 taka more than the revenue earned with optimized cleaning for Narayanganj. But, the cleaning cost without optimized cleaning is around 1 lakh taka more than the cleaning cost when the optimized cleaning is followed.

The cleaning cost without optimized cleaning is much higher than the cleaning cost with optimized cleaning. From the above mentioned tables 4.10-4.11, it is confirmed that, optimized cleaning must be followed in order to keep the solar panels clean and earn good revenue. If the DWWT plant size is expanded, the cleaning cost will be reduced.In that case, the installation cost of the plant will be fixed,but the water treatment cost will be reduced.The cleaning cost will be reduced with the reduction of the cleaning cost.

The optimized architecture of a single layer artificial neural network and extreme learning machine model were used by Kouz et al. [58] to estimate the conversion efficiency of PV systems in Jordan. The optimum cleaning frequency of 14 days was suggested for cleaning the PV systems. The cleaning cost and electricity tariff proposed by Kouz et al. [58] were used in the present model to determine the optimum number of days between the cleaning sessions in dry season for Dhaka. The comparison with the published work by Kouz et al. [58] is shown in table 4.12.

Table 4.12: Comparison with the published work by Kouz et al. [58]

District	**Optimum number of days between cleaning sessions**	
	Present model	**reported by Kouz et al.**
Dhaka	13	14

The optimum number of days between the cleaning sessions in dry season for Dhaka was found as around 13 days which is nearly similar to the optimum number of days between the cleaning sessions in Jordan. This justifies the accuracy of the present model.

Chapter 5

Conclusion

The purpose of this study is to gain some quantitative understanding of the effect of dust on the tilt angle of the solar panel. The effect of dust on energy generation of solar panel has been discussed.The results calculated for both seasonal and yearly-basis for specific regions of Bangladesh have been compared with previously published works. When the effect of dust is considered, the yearly optimum tilt angles were found to be within 25.1-28.5 degrees. For two different tilt angles in a year, the wet season tilt angles were found to be within 11.62-12.72 degrees and the dry season tilt angles were found to be within 40.03-41.29 degrees. In this work, the cleaning schedule is also optimized. The revenue and cleaning cost were calculated.The revenue earned following optimized cleaning is found to be 0.65-1.9% greater than the revenue earned without following the optimized cleaning. Once a cleaning schedule is implemented for the PV system, its efficiency can be increased by reducing the effect of dust on it. Economic benefits can be acquired by implementing the estimated cost mentioned in this work. This optimized cleaning schedule can be a useful tool for the installed PV systems in Bangladesh.

5.1 Future Works

In this work,dust effect is calculated for three different cities of Bangladesh.Similar works can be done for other cities of the country. Here, only the dust was considered in the optimization of tilt angle. A mathematical model considering the effect of wind direction, humidity and temperature on the tilt angle of the PV modules can be derived in future. Also, the viscosity of different dust particle can be analyzed since the cleaning schedule of PV modules depends on this property.

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